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# Status of the ENUBET Project

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The ENUBET Collaboration is designing the first "monitored neutrino beam": a beam with an unprecedented control of the flux, energy and flavor of neutrinos at source. In particular, ENUBET monitors the $\nu_e$ production mostly by the detection of large angle positrons from three body semileptonic decays of kaons: $K^+ \to e^+\pi^0\nu_e$. In this paper, we present the status of the Project and the 2018-2019 advances on proton extraction, transfer line, particle identification in the decay tunnel and beam performance.

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## 1. ENUBET: the first monitored neutrino beam

A new generation of cross-section and short baseline experiments requires beams with superior control of the neutrino production at source. In particular, the uncertainty on the initial flux in conventional neutrino beams currently limits all $\nu_e$ and $\nu_\mu$ cross section measurements. The "monitored neutrino beams" [1] address this limitation in a very straightforward manner. In ENUBET [2, 3] electron neutrinos are monitored by detecting large angle positrons in the decay tunnel from the three body semileptonic decay of the kaons, $K^+ \to \pi^0 e^+ \nu_e$ ($K_{e3}$). The ERC ENUBET ("Enhanced NeUtrino BEams from kaon Tagging") project [4] addresses all technical challenges of monitored neutrino beams: the proton extraction scheme, the focusing and transfer line, the instrumentation of the decay tunnel and the physics performance.

The ENUBET beamline is a narrow band beam with a short ($\sim$20 m) transfer line followed by a 40 m long decay tunnel. In monitored neutrino beams, the decay tunnel is not placed in front of the focusing system (horns) and the proton extraction length is short (a few ms in the horn option and 2 s in the static focusing option). Particles produced by the interaction of protons on the target are focused, momentum selected (momentum bite: $<$10%) and transported at the entrance of the tunnel. The rates of transported particles in the decay pipe are several orders of magnitude smaller than those of currently operating beams and the production of particles (e.g. positrons from kaons) in the decay tunnel can be monitored at single particle level by instrumenting part of the decay tunnel. In the last twelve months, ENUBET achieved three important milestones: it performed experimental tests at the SPS for the horn-based proton extraction scheme, completed the implementation of the single and double dipole beamlines in FLUKA (doses) and GEANT4 simulations, and selected the detector technology for the instrumentation of the tunnel.

## 2. Beamline and proton extraction schemes

The current baseline for the beamline is depicted in Fig. 1, top. The line consists of an "on-axis" quadrupole triplet followed by a single dipole and an "off-axis" quadrupole triplet. The bending angle of the resulting neutrino beam with respect to the proton axis is $\sim 7.4^\circ$. The magnetic elements (quadrupoles and dipoles) achieve a collimated beam of pions and kaons at an average momentum of 8.5 GeV/c and a momentum bite of 5-10%. The optimization is performed to achieve the shortest length in order to reduce losses from early decays of kaons ($\beta\gamma c\tau \sim 63$ m at 8.5 GeV/c). A complete simulation with secondary interactions to assess the beam composition is then performed with G4BeamLine. Magnet parameters (apertures, gradients, etc.) are conventional and cost-effective since they were already used in existing or past beamlines. The optimization of the position and size of the proton dump is in progress.

In 2019, the same setup has also been modeled with GEANT4. The GEANT4 modeling is useful for parent-neutrino association and the study of systematic uncertainties. A FLUKA model of the single-dipole beamline (Fig. 1, middle) has been used for the assessment of irradiation levels and reduction of beam-related backgrounds. A double dipole beamline (Fig. 1, bottom) is also under development to achieve a better containment of the beam and reduce off-momentum background.



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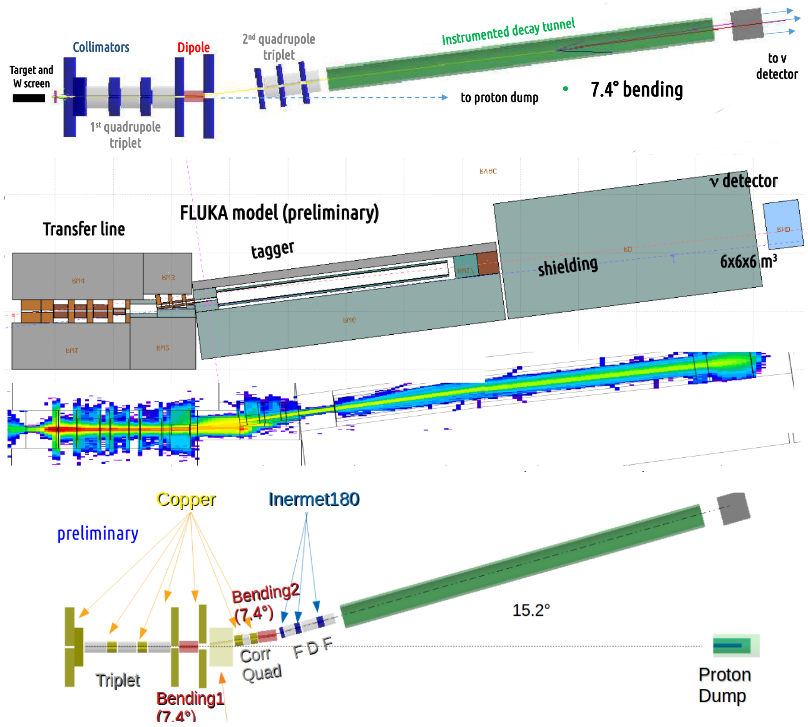


**Figure 1:** The present layout of the ENUBET beamline in the single-dipole (top) and double-dipole (bottom) options. FLUKA simulation of the single-dipole beamline (middle) where the colors provide the level of irradiation along the beamline.

Beam focusing before the first quadrupole can be substantially improved ($\times 5$) by a magnetic horn. The horn focusing option is studied in ENUBET in parallel with the static option. It is based on few ms (2-10 ms) pulses at 180 kA with a 10 Hz repetition rate during the CERN-SPS flat top (2-4 s). In 2018 we carried out machine studies at the SPS to test an extraction scheme ("burst") in which the slow-extracted protons are accumulated in $\mathscr{O}$(ms) wide bunches. In the actual facility, these bunches will be synchronized to the horn pulsed current [5].

## 3. Decay tunnel instrumentation

The ENUBET instrumented decay tunnel consists of a calorimeter for $e^+/\pi^+$ separation and of an inner light-weight detector ("$t_0$-layer") for $e^+/\pi^0$ separation. This light-weight detector also provides absolute timing of the events. During 2016-2018 we performed tests at the CERN East Experimental Area to validate prototypes for the $t_0$-layer and the calorimeters both in shashlik and lateral readout modes [4, 6, 7, 8, 9].

The lateral light readout mode was validated during the tests performed at CERN in 2018. Instead of embedding the SiPMs in the bulk of the calorimeter [8, 9], light was collected from lateral grooves that run along the sides of the scintillator tiles. The 40-cm long wavelength-shifter fibers are bundled to a single $4 \times 4$ mm$^2$ SiPM. This scheme was implemented on a calorimeter with full electron and partial pion containment. The FLUKA simulation of the beamline indicates that the neutron reduction obtained using the lateral readout scheme when operating the SiPM after a shield of 30 cm borated polyethylene amounts to a factor $\simeq$18. Since the lateral readout calorimeter shows performance similar to the shashlik detector tested in 2017 but has has much less irradiation damage than the shashlik detector, it has been chosen as the preferred option for ENUBET. A large size demonstrator of the ENUBET instrumented tunnel will thus be built in 2020-2021 using this technology.

The ENUBET Collaboration set up a full GEANT4 simulation of the detector and validated it by prototype tests at CERN in 2016-2018. The simulation includes particle propagation and decay from the transfer line to the detector, hit-level detector response and pile-up effects [10]. The ENUBET analysis selects a sample (S/N $\simeq$ 1) that is directly linked to the $\nu_e$ flux. It is based on an Event Builder that performs a clustering of energy deposits in space and time. Particle identification is then applied on reconstructed events i.e. a collection of calorimeter modules compatible with localized energy deposits (candidate positrons). Event selection is performed by a multivariate analysis (TMVA package) built upon six variables characterizing the pattern of the energy deposition in the calorimeter. The $e^+$-$\gamma$ separation is performed a posteriori using the information from the photon veto.

Unlike conventional beams, the uncertainties from $K$ yields, efficiency and stability of the transfer line do not contribute to the systematic uncertainty since ENUBET measures directly the large angle $e^+$ produced by kaons. The study of the final flux systematics budget is in progress by using toy Monte Carlo simulations, which embed as input the detailed description of the system.

## 4. Beam performance

For a 500-t neutrino detector located 100 m after the target, the Charged Current neutrino interaction samples achievable with $4.5 \times 10^{19}$ protons-on-target (pot) at the CERN-SPS or $1.5 \times 10^{20}$ pot at FNAL are $1.2 \times 10^6$ $\nu_\mu^{CC}$ and 14000 $\nu_e^{CC}$. As a consequence, the ENUBET monitored neutrino beam can be implemented to serve medium-size neutrino detectors with good reconstruction capabilities for $\nu_e^{CC}$ interactions. Ideally such a detector could be the ICARUS LAr TPC at FNAL or the ProtoDUNE-Single-Phase and/or Double-Phase detectors at the CERN-SPS North Area or even a new Water Cherenkov tank at J-PARC. The energy spectrum of interacting neutrinos is shown in Fig. 2 for $\nu_\mu^{CC}$ (left) and $\nu_e^{CC}$ (right). The $\nu_e$ and $\nu_\mu$ components from $K$ can be constrained by the tagger measurement with good acceptance using $K_{e3}$ and $K_{\mu 2}$ decays respectively. Muon neutrinos from pions are constrained by muon detectors downstream of the hadron dump. High precision muon monitoring is under study in the framework of NP06/ENUBET as an extension of the original ENUBET design. The yellow (red) bands indicate the typical energy range of the DUNE (Hyper-K) neutrino beams. Since ENUBET is a narrow band beam, the neutrino energy is a function of the distance of the neutrino vertex from the beam axis. The colored plots in the left plot indicate subsamples of events occurring at a specific distance from the center of the beam spot in the neutrino detector. The relative beam energy width ($\Delta E_\nu / E_\nu$) at fixed $R$ (i.e. the neutrino energy resolution for the pion component) is 8% for $R \simeq 50$ cm with $\langle E_\nu \rangle \sim 3$ GeV and 22% for $R \simeq 250$ cm with $\langle E_\nu \rangle \simeq 0.7$ GeV. $R$ is the distance of the neutrino interaction vertex from the axis of the beam where the detector is centered. As a consequence, $R$ provides a direct measurement of the energy of the neutrino without relying on final state reconstruction. This is a major asset for cross section studies, where final state interactions and detector inefficiencies cause systematic biases in experimental measurements. Binning in $R$ allows to explore the energy domains of DUNE/HK and enrich samples in specific processes (quasi-elastic, resonances, DIS) for cross section measurements.

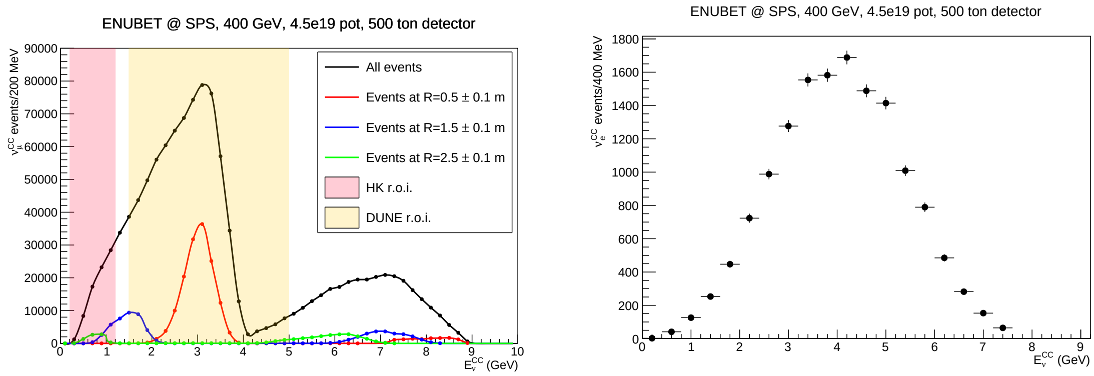


**Figure 2:** Charged Current neutrino interactions samples recorded by a 500 t detector located 50 m from the hadron beam dump with $4.5 \times 10^{19}$ pot at the SPS (about one year in shared mode) or $1.5 \times 10^{20}$ pot at FNAL. The total number of interactions per year is $1.2 \times 10^6$ $\nu_\mu^{CC}$ (left) and 14000 $\nu_e^{CC}$ (right). The yellow (red) bands indicate the typical energy range of the DUNE (Hyper-K) neutrino beams. The colored lines in the left plot indicate subsamples of events occurring at a given distance from the beam axis in the neutrino detector.

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