PROCEEDINGS OF SCIENCE

The ENUBET project: a monitored neutrino beam

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The ENUBET project intends to reduce the flux related systematics in an accelerator neutrino beam to the 1% level by monitoring associated charged leptons produced in a narrow band meson beam. Large angle leptons from kaon decays are measured in an instrumented decay tunnel, while low angle muons from pions can be monitored after the hadron dump. A key element of the project is the design of a meson transfer line with conventional magnets that maximizes the yield of K^+ and π^+, while minimizing the total length to reduce meson decays in the not instrumented region. The transfer line is optimized for 8.5 GeV/c mesons with a momentum bite of 5-10%, considering various proton drivers and target designs and it is based on conventional quadrupoles and dipoles and provides a large bending angle that can ensure a reduced background from the untagged neutrino component at the neutrino detector. The ENUBET Collaboration presented at NuFact2021 the latest design of the hadron beam line, the performance of the positron tagger prototypes tested at CERN beamlines, a full simulation of the positron reconstruction chain and the expected physics reach.

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[*] Speaker

1. The ENUBET Project: a monitored neutrino beams

The uncertainty associated to the beam flux contributes the most to the uncertainty on high-precision neutrino cross-section measurements that are fundamental for next generation long baseline oscillation experiments. The facility envisaged by the ENUBET project [1] adresses directly this problem by aiming primarily at the measurement of the large-angle leptons emitted with the neutrinos in kaon decays with a conventional narrow-band meson beam where the the decay tunnel is instrumented with calorimeters in order to measure the leptons while the associated neutrinos travels toward a neutrino detector. In this way, lepton counting allows for a direct flux prediction by-passing the uncertainties coming from hadro-productions in the target, the beamline simulation, and POT counting. The realization of such monitored neutrino beam would allow the measurement of neutrino cross-section and flavor composition at 1% precision level and the energy of the neutrino to be known at 10% precision level.

Pions and kaons are produced conventionally by proton interactions on a fixed target and selected particles are transported to a 40 meters long instrumented decay tunnel. K_{e3} decays ($K^+ \to e^+ \nu_e \pi^0$) thus become the only source of ν_e accounting for ~97% of the total ν_e flux. ENUBET has also the capability to measure large-angle muons from $K_{\mu 2}$ and $K_{\mu 3}$ decays and to monitor the muons from pion decays by using muon monitor stations after the hadron dump to constrain the low energy ν_μ flux.

There are two possible focusing options: a purely static system where conventional quadrupoles and dipoles are placed directly downstream the ENUBET target and work with a proton slow extraction scheme and, alternatively, a horn-based beamline where a focusing magnetic horn is included in the transferline that would then need a proton fast extraction method. They present different advantages and disadvantages so the project is pursuing both options. Various exisiting accelerator complexes could feed the ENUBET beamline so different protons energies have been simulated to estimate the secondary yield: 400 GeV (CERN-SPS), 120 GeV (Fermilab Main Ring) and 30 GeV (JPARC). The nominal SPS energy is a good choice for ENUBET, especially for cross section studies in the region of interest for DUNE. Several possible targets have been simulated as well with FLUKA, the best one resulted in a graphite, 70 cm long target with a radius of 3 cm.

2. The beamline and accelerator studies

2.1 The static transferline

There are several advantages in using a static tranferline: the full proton intensity can be extracted continuously in few seconds as there is no need for fast-cycling a horn, possible pile-up effects in the instrumented decay tunnel are avoided thanks to the strong rate reduction that at the same time offers the possibility to monitor the muon rate after the hadron dump at percent level. Moreover, it would pave the way to the so-called *tagged neutrino beams*, where a single neutrino interaction is associated to a tagged lepton in the tunnel through time coincidence. The price to pay is that more POT are needed to reach the wanted ν_e statistics.

ENUBET has designed a narrow band beam with a 5-10% momentum bite centered at 8.5 GeV. The optics is optimized with TRANSPORT requiring the beamline to be as short as possible to minimize early kaon decays and a small beam size so that non-decaying particles exit the decay tunnel without hitting the tunnel walls. The focusing system is composed by normal-conducting magnets: quadrupoles with apertures below 40 cm and two dipoles providing 7.4° bending each. Particle transport and interactions are simulated with G4Beamline. The hadron dump is placed after the decay tunnel and the neutrino detector is 50 m from the tunnel exit. The schematics of the static transferline is shown in Fig. 1.

The rates obtained at the tunnel entrance for a momentum of 8.5±5% GeV are 4.2 10^{-3} π^+/POT and 0.4 10^{-3} K^+/POT for 400 GeV/c protons. When considering a neutrino detector located 50 m downstream the tunnel with a 6×6 m^2 front-face perpendicular to the beam axis this beamline produces the ν_eCC spectrum of Fig. 2: 73.5% of the total ν_e flux is generated in the tunnel, amounting to more than 80% considering only energies above 1 GeV (below 1 GeV the main component is produced in the proton-dump region). At a nominal SPS 4.5 10^{19}POT/year one can expect to reach 10^4 ν_eCC in a 500 ton detector in about 2 years.

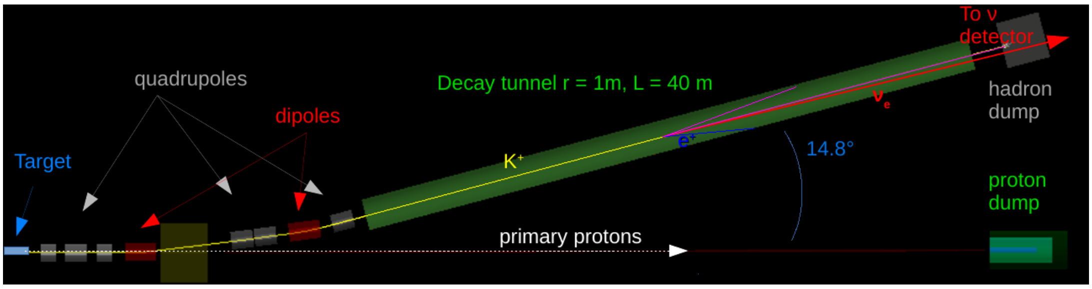


Figure 1: Schematics of the static line design.

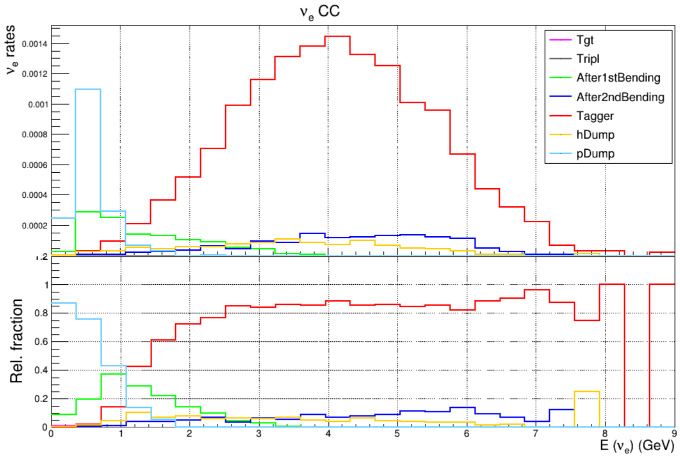


Figure 2: Top: ν_eCC interactions in a neutrino detector 50 m from the decay tunnel, the events are divided into categories corresponding to the position along the transferline where the neutrino was generated. The red spectrum corresponds to neutrinos generated inside the decay tunnel. Bottom: relative fraction of each category to the total ν_eCC rate.

2.2 The horn option

One could aim at having more ν_e/POT by focusing more pions and kaons in the wanted momentum range by using a focusing horn. That would need to be pulsed at 2-10 ms in the flat top of a proton fast extraction where all protons are extracted in O(1-10μs) and would create pile-up problems for the instrumentation of the decay tunnel. To cope with it, ENUBET has studied and developed in collaboration with CERN (BE-OP-SPS and TE-ABT-BTP) a novel pulsed-slow extraction method called *burst-mode slow extraction* [2], an example of measured spill profiles is presented in Fig. 3 where 2-to-10 ms proton pulses repeated at 10 Hz for the full duration of the extraction.

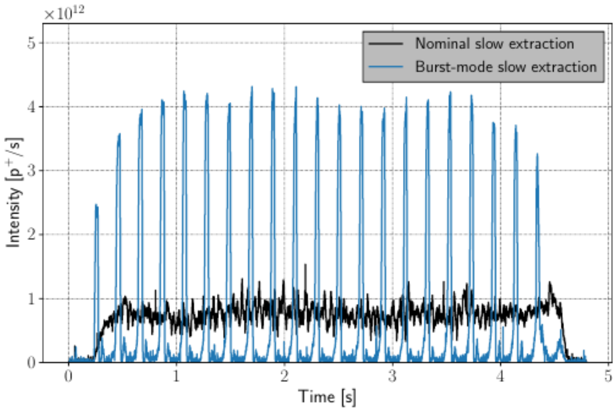


Figure 3: Comparison between a nominal slow extracted proton spill and a burst-mode slow extracted one. The same intensity is extracted in both cases.

ENUBET has its own framework to optimize the horn design using a Genetic Algorithm and further studies are on-going to design a dedicated beamline specific to the horn to take advantage of the flux increase.

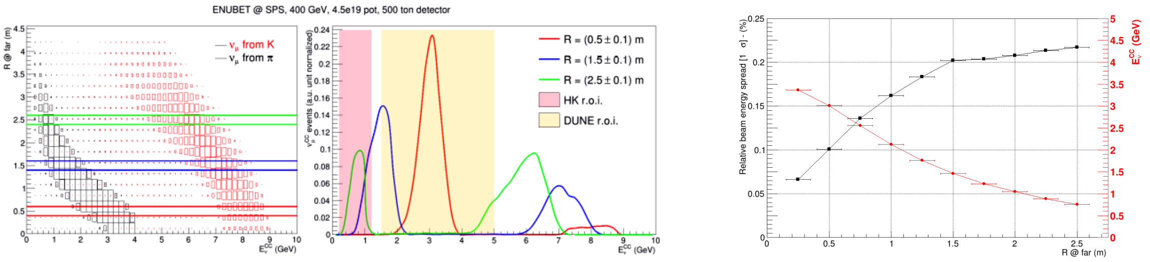
3. The detector and the physics performance

The ENUBET decay tunnel is instrumented along the walls with a calorimeter that offers e/π/μ separation capabilities: the basic unit, called LCM (Lateral Compact Module), is a sandwich of 5 steel tiles (3×3×1.5 cm^2) interleaved with 5 plastic scintillator tiles (3×3×0.5 cm^2). Each LCM has 10 wavelength shifting fibers coupled with SiPM with an active area of 4×4 mm^2. Overall three radial layers of LCM are foreseen as well as a photon veto made of plastic scintillator tiles arranged in doublets forming inner rings (3×3×0.5 cm^2) and mounted below the LCM with a time resolution of ~400 ps for π^0 rejection and timing.

A full GEANT4 simulation reproduces the detectors in the decay tunnel and particle identification is performed by the energy pattern in the modules and by the photon veto allowing the monitoring of positrons and muons from kaon decays, and therefore of the ν_e and ν_μ fluxes, while muon stations after the hadron dump are used to measure muons from pion decays to constrain the low energy ν_μ spectrum. The analysis starts from the event builder that clusters energy deposits compatible in space and time with same decay, then the e/μ/π/γ separation is performed using a TMVA neural network. For the K_{e3} monitoring ENUBET has reached a S/N=2 with an efficiency of 22%, and a S/N=6 has been achieved for muons from kaon decays with 34% efficiency.

Thanks to the narrow band of the beam and the finite transverse dimension of the neutrino detector there is a strong correlation between the neutrino energy in the detector and the radial distance (R) of the interaction vertex from the beam axis. This allows to use the so-called *narrow-band off-axis technique* [3] to provide the neutrino energy on event-by-event basis without relying on final state particles in ν_μCC interactions. The neutrino energy as a function of R is shown in

Fig 4a, the incoming neutrino energy can be determined with a precision given by the pion peak width of the spectrum at a fixed R. It ranges from 8% for R~50 cm at E_ν ~3.5 GeV to 22% for R~250 cm at E_ν ~0.7 GeV (see Fig. 4b).



(a) Neutrino energy and ν_μ^{CC} events at the ENUBET neutrino detector as a function of the distance of the neutrino vertex from the beam axis (R).

(b) Energy resolution (black) and mean neutrino energy (red) as a function of R.

Figure 4

4. Enubet prototype test results and the demonstrator

A prototype of 84 LCM was tested in 2018 at CERN PS-T9 [4], reaching containmnent of em showers up to 5 GeV and an energy resolution σ_E/E=17% at 1 GeV. The photon-veto was also tested reaching 1-mip/2-mip separation with 1-mip signal detection effiiency ϵ=87% and background (2-mip like) rejection efficiency ϵ=89% with 95% purity. ENUBET is now building a detector prototype to demonstrate performance, scalability and cost-effectiveness with a new light readout scheme with frontal light collection. which is safer for injection molding, more uniform and efficient. This demonstrator will be 1.65 m long covering 90° in azimuth corresponding to 12×3 LCMs (75 layers of iron + 75 layers of scintillators) and it will be exposed at CERN in 2022. The design is modular so it can be extended to a full 2π object by joining 4 of these modules. The Conceptual Design Report will be presented at the end of the project in 2022 assessing physics reach and costing.

Acknowledgments

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References

[1] A. Longhin, L. Ludovici and F. Terranova, Eur. Phys. J. C 75 (2015) 155.
A. Berra et al., CERN-SPSC-2016-036, SPSC-EOI-014, Geneva, 2016.

[2] F. Acerbi et al. CERN-SPSC-2020-009, SPSC-SR-268, Geneva, 2020.
F. Acerbi et al. CERN-SPSC-2021-013, SPSC-SR-290, Geneva, 2021.

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

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