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The ENUBET neutrino cross section experiment and plans at CERN

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ENUBET has pioneered a novel technique to control the neutrino flux and flavor composition with percent-level precision. This successful R&D effort has paved the way for a new generation of cross-section experiments designed to meet the precision requirements of current neutrino oscillation studies. In this talk, we will summarize ENUBET's key achievements and outline the plans for its implementation at CERN

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1. ENUBET: the first monitored neutrino beam

The study of neutrino oscillations has made remarkable progress over the past two decades, driven by the discovery of large neutrino mixing angles and advancements in the intensity of accelerator-based neutrino beams. The next generation of neutrino oscillation experiments, particularly DUNE and HyperKamiokande, is poised to achieve unprecedented precision in probing the lepton Yukawa sector of the Standard Model. These experiments are expected to be the first in this field to transition from being limited by statistical uncertainties to being dominated by systematic uncertainties.

The primary source of systematic uncertainties in neutrino oscillation experiments arises from the limited understanding of neutrino cross-sections at the GeV scale. Current theoretical models and data-driven phenomenological approaches fail to reproduce experimental data with a precision better than 10%, primarily due to insufficient knowledge of nuclear effects in neutrino-nucleus interactions [1]. Additionally, the normalization of cross-sections is not fixed with a precision better than ~10%. The (short-baseline) experiments designed to measure cross-sections cannot determine the neutrino flux at the source at the percent level, which is mandatory for a proper cross-section normalization.

ENUBET was designed to support a new generation of short-baseline cross-section experiments by providing a neutrino source with a flux controlled to 1% precision. Additionally, it enables the a priori measurement of neutrino energy for each produced neutrino with a 10% precision. This effectively makes ENUBET equivalent to a 10%-level monochromatic neutrino beam with a flux normalization controlled at the 1% level. The implementation of this technique would mark a breakthrough in experimental physics, as it provides the necessary precision to study neutrino-nucleus interactions with the same level of accuracy as electron-nucleus interactions.

Flux normalization in ENUBET is achieved in a straightforward and robust manner. Neutrinos are produced by the decay in flight of mesons, and the number of charged leptons generated in the decay tunnel directly corresponds to the number of neutrinos exiting the tunnel. Furthermore, the flavor of the charged lepton uniquely determines the neutrino flavor due to flavor conservation at the production vertex. The innovative approach of identifying charged leptons at the single-particle level by instrumenting the decay tunnel was introduced in 2015, enabling unprecedented precision in flux normalization. Neutrino beams equipped with such instrumentation are referred to as 'monitored neutrino beams' [2].

From 2016 to 2023, the NP06/ENUBET Collaboration conducted an extensive R&D program to address the technical challenges of monitored neutrino beams. The key milestones and achievements of this program are summarized below:

- **2016–2018:** ENUBET identified the optimal instrumentation for monitoring positrons from kaon decays, the primary source of ν_e for short-baseline experiments. This instrumentation was validated at the prototype level [3, 4], and the complete analysis chain for positron identification—from detector response to event reconstruction and particle identification—was successfully simulated.
- **2019–2021:** NP06/ENUBET demonstrated that a monitored neutrino beam with sufficient intensity could be achieved without requiring a magnetic horn, thus utilizing a slow proton

extraction. This breakthrough reduced the instantaneous particle rate at the tunnel instrumentation by approximately 50-fold and enabled the monitoring of all neutrino flavors by detecting muons from π and K decays as well as positrons from K decays.

- **2021–2023:** ENUBET completed the full design of a hornless neutrino beamline, including beam optics, tertiary interactions, radiation doses, and flux predictions at the neutrino detector (a 500-ton target mass located 50 m downstream of the decay tunnel). In 2022-23, the ENUBET Demonstrator—a 1.65-meter-long subsection of the instrumented tunnel with 90° angular coverage (instead of the full 360°)—was constructed and tested at the CERN East Area with charged particle beams to validate the instrumentation's performance under realistic conditions [5].

The ENUBET beamline [6] utilizes 400 GeV protons extracted from the CERN SPS in a 2-second long spill. The protons strike a 70 cm long (3 cm radius) graphite target optimized for maximum meson production at $p = 8.5$ GeV/c, based on detailed FLUKA simulations. The beamline consists of a quadrupole triplet followed by a bending dipole, a pair of quadrupoles, another identical bending dipole, and a final quadrupole. The two dipoles are existing CERN magnets capable of operating up to 1.8 T, with a field length of 2.038 m and an aperture of 300 mm. The optics was optimized using TRANSPORT and then implemented in G4Beamline to evaluate meson transport under realistic conditions, including tertiary interactions.

The radiation doses at beamline components and in the decay tunnel, calculated with FLUKA, are within acceptable limits for all materials, including the first quadrupole. At the hottest point of the quadrupole closest to the target, the dose is <300 kGy for 10^{20} protons-on-target (pot).

The tunnel instrumentation features a modular sampling calorimeter (iron-scintillator), with light read out by SiPMs via WLS fibers. The SiPMs are housed in the outermost section of the calorimeter and shielded by a borated polyethylene layer. Plastic scintillator tiles are installed in the innermost section to veto photons and provide an absolute time reference for events with a precision of 400 ps.

Particle identification is performed using an event builder that clusters hits from the calorimeter and photon veto. A neural network is then employed to classify events as candidate positrons from kaon decay or candidate muons from pion and kaon decays. The primary background arises from halo muons or pion interactions. The particle identification algorithms achieve an efficiency of 35.6% (21%) with a signal-to-noise ratio of 5.2 (2) for muons (positrons) originating from kaon decays. In 2024, ENUBET demonstrated that this level of monitoring is sufficient to reduce the flux systematic uncertainty to below 1%. To validate this, we conducted a systematic assessment similar to the one performed by current experiments (e.g., T2K) using the multi-universe method and hadroproduction data resembling a potential future measurement campaign for the ENUBET target (specifically, we used the NA56/SPY data taken at the CERN PS in 1996). As a result, the systematic uncertainty decreases from 10% to 1% when positron data are included, and it can be further reduced using muon data, which is currently being investigated.

Assuming a proton intensity of 4.5×10^{19} pot/year at the SPS, a total of 10^4 ν_e charged current (CC) interactions in the detector, caused by neutrinos produced from kaon decays within the tunnel volume, can be achieved in 2.3 years. The number of ν_μ interactions is significantly higher (2.1×10^5

from kaon decays) due to the larger branching ratio of $K \to \mu\nu$. An even larger number of ν_μ CC interactions (5.2×10^5) originate from pion decays, with the muons being monitored by a dedicated instrumented hadron dump currently being developed by the PIMENT (Picosecond Micromegas for ENUBET) Collaboration at CEA, France. By exploiting the two-body kinematics of the $K \to \mu\nu$ and $\pi \to \mu\nu$ decays, the neutrino energy can be determined a priori from the neutrino production angle or, equivalently, from the interaction vertex in the neutrino detector. For each ν_μ, the energy is known a priori with a precision of about 10% in the energy region of interest for DUNE.

2. Implementation at CERN

Thanks to the outstanding success of ENUBET's R&D, the realization of a monitored neutrino beam at CERN is currently under evaluation. In 2024, CERN overcame the main limitation of the original ENUBET beamline by reducing the number of pot required to approximately 1×10^{19} pot, which can be collected over five years [8]. This achievement demonstrates that a short-baseline neutrino beam at CERN can be hosted without interfering with the existing CERN fixed-target program, including SHIP. The new beamline (SBN@PBC), developed as part of the CERN Physics Beyond Collider initiative, benefits from the NuTAG collaboration's findings and is capable of tracking mesons along the beamline [7]. This capability further improves the neutrino energy resolution by tracking the parent meson and associating it with the corresponding neutrino observed in the detector. The optimization and performance of SBN@PBC are currently under evaluation, and results will be submitted for the 2025 Update of the European Strategy for Particle Physics.

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