Updates on the design of the ENUBET monitored neutrino beam

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on behalf of the ENUBET Collaboration
Overview

Accelerator neutrino beams

Particle accelerators are used to generate a controlled neutrino flux. Unlike other neutrino sources:

- Control of neutrino energy
- Control of source-detector distance

Typical neutrino energies of 1-20 GeV
Typical source-detector distances of 1-100 km

Main neutrino production channel:

\[ p + A \rightarrow \pi^\pm + X \]

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu \]

Accelerator neutrino beams: limitations

Neutrino flux estimation for conventional neutrino beams is a complex task:
- Extensive simulations
- Dedicated hadro-production data
- Short baseline flux measurements
- Muon monitoring at the beam dump

Leading to an overall flux uncertainty of ~ O(10%)

Solving open problems in $\nu$-physics:
- Considerable increase of precision required
- Different solutions actively investigated

One possible approach: monitored neutrino beams
Overview

The ENUBET project: Enhanced NeUtrino BEams from kaon Tagging

ERC grant 2016-2022
CERN Neutrino Platform experiment
NP06/ENUBET
The ENUBET Collaboration: 60 Physicists, 12 Institutions

Goal:

Design of a monitored neutrino beam

Reduction of neutrino flux systematics at the 1% level (additional: energy at 10%)

Opening for high precision cross section measurement (1%)

Concept of monitored neutrino beam:

- Decay tunnel fully instrumented
- Direct estimation of neutrino flux from production vertex particles
- Bypassing high uncertainty hadro-production based flux estimation
The ENUBET project

- Beamline (baseline option): **narrow band** beam at **8.5 GeV/c** secondaries with a **5-10% momentum bite**

[*] **K_{e3} (K^+ \rightarrow \pi^0 e^+ \nu_e) main source of positrons** at the decay tunnel walls: possibility of **direct estimation of \nu_e flux**

- **new**

  - Muons at decay tunnel mainly from **K_{\mu2} (K^+ \rightarrow \mu^+ \nu_\mu) and K_{\mu3}: increased precision on \nu_{\mu K} and \nu_e flux**

  - **new**

    - Additional information on \nu_{\mu \pi} from muon monitors along hadron dump (range-meter)

[*] A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155
The ENUBET project

- Beamline (baseline option): **narrow band** beam at **8.5 GeV/c** secondaries with a **5-10% momentum bite**

  - **Narrow-Band Off-Axis (NBOA) technique** [*]

    - Full energy separation of $\nu_{\mu K}$ and $\nu_{\mu \pi}$ components
    - Direct angle-momentum correlations from two-body decays

Estimation of neutrino energy from impact radius @detector

*F. Acerbi et al., CERN-SPSC-2021-013*
The ENUBET project

Beamline design and simulation

Assessment of systematics and performance

Next slides: new developments in different WPs

Detector development and characterization
The ENUBET beamline

Baseline option: **fully static beamline**

- Target and hadro-production: FLUKA ✓
- Transfer line:
  - optics optimization: TRANSPORT ✓
  - tracking & background: G4Beamline/G4 ✓
  - doses & neutron shielding: FLUKA ✓
  - systematics: GEANT4 [in progress]
- Neutron shielding added at hadron dump ✓
- Proton dump will require further eng. studies

CERN-SPS good candidate
(400 GeV p+)

**Static** = slow extraction of a few seconds required by pile-up constraints (differently from majority of nu-beams)
Results from recent target optimiz. (70 cm graphite rod): new beamline version with x2 Kaon flux wrt previous and x1.5 less e+ bkg

Assuming 500 ton neutrino detector at 50 m and CERN-SPS as driver:

10^4 ν_eCC in ~2 years of data taking (preliminary)

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<th>π/pot (10^-3)</th>
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@SPS

Static advantages:
✓ cost effective
✓ stable operation
✓ low rate

But:
potential flux increase from magnetic horn also appealing
Proton extraction studies

Dedicated slow extraction studies at CERN-SPS: [*]

horn-compatible slow extraction

- From experimental campaign:
  - Implemented new pulsed slow extraction (burst-mode)
  - Optimized in operation down to 10 ms pulses @10 Hz

- From simulations:
  - 3-10 ms range of pulse lengths

General extraction method: could be used for other applications (e.g. cosmic veto)

[*] M.Pari, PhD Thesis (2020)
Magnetic horn

Previous proton extraction results open for a horn option:

- Developed simulation model of horn based on GEANT4
- Genetic algorithm used for optimization of horn geometry (> 10 par)
- Hardware constraints enforced
- Developed fully automatic optimization framework
- First candidates available
Magnetic horn

First results from standalone (i.e. first quad) horn optimization point to dedicated study on horn-beamline option:

- Development of horn-beamline currently on-going (based on FLUKA, G4, MADX) in parallel to the nominal static option

- Standalone gain factor \( \sim 3 \) reached with horn optimization, BUT

- Phase space very different: significant design changes required

new INCONEL target
Further optimization

Optimization framework developed for the horn upgraded to be fully generic:

- Application to fine tune beamline collimators for baseline static option
- First results promising: significant bkg reduction (preliminary & ongoing)

Main bkg particles suppressed

Signal not strongly affected

Optimized section
The current ENUBET beamline generates neutrinos peaked in the DUNE region of interest (~4 GeV):

- Study on development of multi-momentum beamline currently ongoing in collaboration with CERN
- Goal is modifiable energy range so to cover full range of interest (HK R.o.I. included)

G4beamline model of multi-momentum beamline using existing CERN magnets geometries

Promising first estimations of K+ fluxes, background studies are ongoing
Instrumentation of decay tunnel [*]

- After dedicated studies (simulations, prototyping, test beams):
  
  ➔ **Chosen final design**: compact scintillating sampling calorimeters (4.3 radiation lengths) will be used to instrument the ~40m decay tunnel (3 layers). One internal layer of photon veto (scintillator doublet)

  ➔ Lateral readout to SiPM via bundled WLS fibers (space for shielding: factor 18 dose reduction)

  ➔ Custom DAQ under development

[*] JINST 15(2020)08, P08001; JINST 14 (2019) 02, P02029; NIM A 956(2020)163379
A prototype of the tagger is under construction for a final experimental validation at CERN-PS in 2022:

**Prototype for exp. validation**

**Final prototype: started design and assembly TB@PS 2022**

**Goal:** proof of principle of the ENUBET detector design and concept.
Detector performance & systematics

Production using full beamline simulation (G4/G4beamline/FLUKA)

Complete simulation of ENUBET tagger detector (G4)

Waveform generation (SiPM) simulation: energy and time reconstruction

Energy deposition vs time for each sub-module

Event reconstruction algorithm
Full simulation chain for waveform generation and analysis is near completion:

- Digitized electrical signal generated from G4 input
- Different peak detection algorithms developed and tested for energy and time reconstruction
- Model also used to set boundaries on tunnel event rate and digitizer sampling time
Event reconstruction

Energy clusters deposited in each sub-module used to reconstruct an event:

- Two main signals for ENUBET: positrons from Ke3, muons from Kmu2/3

- Basic discrimination idea: use tagger granularity to separate EM showers / Hadronic showers / MIP + photon veto

...
More in detail:

→ 15 parameters neural network trained over pure samples.

→ Reconstruction performance in terms of Signal to Noise ratio (S/N) and efficiency can be computed against input G4 information

→ Main results:

For **muons**:

S/N: 6.1
Efficiency: 34%
(dominated by geometrical)

For **positrons**:

S/N: 2.1
Efficiency: 24%
(dominated by geometrical)
Conclusions and next steps

- Main design phase of ENUBET terminated:
  - Simulations nearly completed and detector technology frozen
  - Satisfactory performance confirmed from simulations and data taking
  - A final demonstrator of the tagger will be built and tested at the renovated CERN-PS East Area by 2022
- Promising results up to now: project on schedule, prototype assembly started
- The final systematics on the neutrino fluxes (electron and muon) are under evaluation and will be released by 2021

- Studies of non-baseline options proceed as planned, pointing to promising results and potential improvements:
  - Successful development of pulsed slow extraction and horn design option could further increase nu-flux
  - Genetic optimization on the static beamline for S/N increase
  - Studies on a multi-momentum beamline for different nu-energy currently ongoing

Updated fluxes and spectra with these final beamlines by 2022
Thank you for your attention
Backup
ENUBET: reach
A tolerable pile-up level at tagger (˂ 500 kHz/cm²):
fast extraction of protons impractical  →  slow extraction required

10 ms bursts at 10 Hz
Nominal SE

Two possible slow-extraction schemes compatible:
- Static (standard)
- Pulsed (novel)

Could allow operation of magnetic horn: significant increase in flux.
Effect of horn on beam

Phase space after target

Phase space after horn

Drift (evolution)

Horn (effect)
Launch G4 jobs

Wait for jobs to finish

Run FOM computing code

Merge FOM to population

Log results in optimization database

Run genetic algorithm to compute next horn population

Generate initial population of horns (LHS grid)

Data processing C++ tools

Python utilities lib

Python optimization manager script

G4 simulation (C++)

Jobs settings and submit bash script

Python GA lib