The ENUBET project: high precision neutrino flux measurements in conventional neutrino beams

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The problem of flux uncertainty

Indirect technique to estimate neutrino flux (current generation cross-sextion experiment):

• Monitoring of protons on target (pot), horn currents, muons after the beam dump
• Hadro-production data
• Full simulation of beamline, secondary reinteractions etc.

BUT STILL...

Neutrino experiments affected by an intrinsic limitation:
large uncertainty of the overall neutrino flux (∼7-10%) directly reflecting to the cross section measurements.

In addition to the flux uncertainty for $\sigma(\nu_e) \rightarrow$ beam contamination.
$\sigma(\nu_\mu) \leftrightarrow \sigma(\nu_e)$ not simple especially @ low-E (Mc. Farland, 2012)

Poor knowledge of $\sigma(\nu_e)$ can spoil:
the CPV discovery potential
the insight on the underlying physics (standard vs exotic)
Monitored neutrino beams

Kaon-based monitored neutrino beams (A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155) are a very appealing candidate since provide a pure and precise source of $\nu_e$.

Traditional
- Passive decay region
- $\nu_e$ flux relies on ab-initio simulations of the full chain
- Large uncertainties

Monitored
- Fully instrumented
- $\nu_e$ flux prediction = $e^+$ counting ($K^+ \to e^+ \nu_e \pi^0$)
- “By-pass” hadro-production, PoT, beam-line efficiency uncertainties

**ENUBET**, ERC Project (Consolidator Grant, PI A. Longhin, Host Institution: INFN) aims to enable the technology of monitored neutrino beams for the next generation of experiments (technical challenges / physics reach).
The decay tunnel is a harsh environment:
- **particle rates:** > 200 kHz/cm²
- **backgrounds:** pions from K⁺ decays
  → need to veto 98-99 % of them
- **instrument region:** ~ 50 m
- grazing incidence
- significant spread in the initial direction

**e⁺ tagger key points:**
- longitudinal sampling
- perfect homogeneity
  → integrated light-readout

**Photon veto key points:**
- photon identification capabilities
- precise timing of the particles
- Exploit 1 mip – 2 mip separation
Neutrino fluxes in the reference design

The **ENUBET design is optimized** to reach a 1% systematic error on the $\nu_e$ flux and a <1% statistical error for a 500 ton neutrino detector located ~100 m from the hadron dump.

<table>
<thead>
<tr>
<th>Proton Energy</th>
<th>Pot for $10^4 , \nu_e , CC$</th>
<th>Run nominal duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 GeV [JPARC]</td>
<td>$1.0 \times 10^{20}$</td>
<td>~3 months at nominal JPARC intensity</td>
</tr>
<tr>
<td>120 GeV [Fermilab]</td>
<td>$0.24 \times 10^{20}$</td>
<td>~2 months at nominal NuMI intensity</td>
</tr>
<tr>
<td>400 GeV [CERN]</td>
<td>$0.11 \times 10^{20}$</td>
<td>~3 months at nominal CNGS intensity</td>
</tr>
</tbody>
</table>

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The ENUBET design is optimized to reach a 1% systematic error on the $\nu_e$ flux and a <1% statistical error for a 500 ton neutrino detector located ~100 m from the hadron dump.
1) compact calorimeter with longitudinal segmentation

2) integrated γ-veto

(1) Compact shashlik calorimeter (UCM) with longitudinal (4 $X_0$) segmentation.

- 3x3x10 cm$^3$ Fe + scint. modules
- SiPM embedded in the bulk of the calorimeter

(2) Photon Veto Rings of 3 x 3 cm$^2$ pads of plastic scintillator

Separate $e^+$, $\pi^+$, $\mu$

Separate $e^+$, $\gamma$
1) Hadronic + e.m. calorimeter prototype

Test Beam @ T9 - CERN 2016

56 (e.m) + 18 (had) UCM modules → 666 SiPM (FBK)
Prototypes: resolution and $e/\pi$ separation

The obtained results also validate the GEANT4 ENUBET simulation.
Setup shashlik calorimeter (1):
Scintillator: EJ204 scintillator (double thickness)
WLS Fiber: BCF92 MC
14 $X_0$ shashlik calorimeter using plastic
Scintillators: new configuration promising a higher light yield and fast response

Goal:
Study calorimeter response (light collection efficiency, linearity response, energy resolution...)

Setup Photon Veto (2):
Scintillator: 3x3x0.5 cm$^3$ EJ200/EJ204
WLS Fiber: Kuraray Y11 MC / BCF92 MC
SiPM: SenSL

Goal:
Study light collection efficiency
First measure of time resolution
First trial of 1 mip / 2mip separation
Photon veto@ CERN-PS T9 2017

1 mip signal is ~ 20 p.e

Testing 1 mip/2mip separation, exploiting a Delrin cylinder on the beam to enhance the π⁰ production and an iron γ-converter (~ 0.8 X0) for pair production.

Light collection efficiency: > 95%

Timing response: σ ~ 400 ps
Ongoing activities (1)

Irradiation studies

ENUBET works after a transfer line (narrow band beam) and the instrumentation is located only at large angles. BUT still the doses are significant and will drive the final detector choice.

- Neutron and ionizing doses have been studied for a tagger radius of 40, 80 and 100 cm with FLUKA and crosschecked with GEANT4.
- Doses at 1 m radius for $10^4 \nu_e$ CC 0.05 kGy (ionizing dose) $2 \cdot 10^{11}$ neutrons /cm$^2$ (1 MeV equivalent).
- Test irradiation with 1-3 MeV neutrons performed at INFN-LNL CN Van de Graaff on 12-27 June 2017.
- Characterise rad-hard SiPM with 12-15-20 μm cell size (FBK, SensL) up to $10^{11-12}$ 1 MeV-eq n/cm$^2$.
- Test viability of self-calibration with m.i.p.
Ongoing activities (2)

Tests:
• Response of irradiated SiPM (FBK, SenSL)
• Custom digitizers electronics
• photon veto prototypes with plastic scintillators
• recovery time (to cope with pile-up)

Scalable/reproducible technological solutions under study:
• Molded scintillators, water-jet holes machining for absorbers
• Polysiloxane scintillators/powder absorbers
Ongoing activities (3)
Simulation of the decay tunnel

Particles are identified by the energy deposit pattern in the calorimeter modules and in the photon veto using a multivariate analysis.

The clustering of energy deposits ("event builder") is based on position and timing of the signal waveforms in the modules. **Pile up is now fully included.**

![Graph of reconstructed decays](image)

**Composition of the reconstructed sample**

Pile-up effect on Ke3 efficiency seen at nominal rates. Mitigation enlarging the radius: ~ 25 % (~ 50 % purity).
Ongoing Activities (4)

Hadron beamline studies

- A realistic implementation of the beam-line/focusing layout.
- Site-independent. We are considering existing proton driver energies.
- Assess beam-related backgrounds.
- Machine studies of multi-Hz slow resonant extraction at CERN-SPS
Conclusions

• At GeV scale the limited knowledge on the initial flux is the dominant contribution to cross section uncertainties → exploiting the $K^+ \to \pi^0 e^+ \nu_e$ channel (Ke3)

• **ENUBET is investigating this approach** and its application to a new generation of neutrino experiments. enabling a technology to directly monitor neutrino production at source → major breakthrough in experimental neutrino physics.

• The **results** obtained in the first year of the project are **very promising**:
  
  – The Reference Design has been established
  – The detector technology was studied with dedicated prototypes and testbeams, and performance fulfills the expectations
  – The simulation of the decay tunnel is now complete and include particle identification, pile up and assessment of ionizing and non-ionizing doses
  – The work on the beamline simulation and systematics assessment has started