A high precision narrow-band neutrino beam: the ENUBET project

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The goal of ENUBET is to demonstrate the technical feasibility and physics performance of a neutrino beam where \textit{lepton production at large angles} is monitored at single particle level:

\[
K^+ \rightarrow e^+ \nu_e \pi^0
\]

to tagger
to neutrino detector

Two pillars:
- Build/test a \textbf{demonstrator} of the instrumented decay tunnel
- Design/simulate the layout of the \textbf{hadronic beamline}

Outline
- Beamline simulation
- Experimental validation of detector \textbf{prototypes}
- Updated \textbf{physics performance}

Since 2019, ENUBET is a CERN Neutrino Platform Experiment: NP06/ENUBET

ENUBET Collaboration: 60 physicists, 12 institutions
A narrow-band beam for the precision era of $\nu$ physics

**Absolute flux** of $\nu_e$ and $\nu_\mu$ at the 1% level

Remove the leading source of uncertainty in **neutrino cross section measurement**

**Energy of the neutrino** known at the 10% level

The ideal tool to study neutrino interactions in nuclei

**Flavor composition** known at the 1% level

The ideal tool to study NSI and sterile neutrinos at the GeV scale

- Monitor the decays in which $\nu$ are produced event-by-event
- “By-pass” uncertainties from POT, hadro-production, beamline efficiency
- Fully instrumented decay region $\rightarrow$ $\nu_e$ flux prediction = $e^+$ counting
• **Proton driver:** CERN (400 GeV), FNAL (120 GeV), J-PARC (30 GeV)
• **Target:** Be, graphite target. FLUKA
• **Focusing:**
  • **Horn:** 2 ms pulse, 180 kA, 10 Hz during the flat top [not shown in fig.]
  • **Static focusing system:** a quadrupole triplet before the bending magnet
• **Transfer line**
  • Kept **short** to minimize early K-decays and those of off-momentum mesons out of tagger acceptance (untagged neutrino flux component)
  • Optics: optimized with TRANSPORT to a 10% momentum bite centered at 8.5 GeV/c
  • Particle transport and interaction: full simulation with G4Beamline
  • **Normal-conducting magnets** (numerical aperture<40 cm): Two quadrupole triplets, one (or two) bending dipole
• **Decay tunnel:** $r = 1$ m, $L = 40$ m, low power hadron dump at the end
• **Proton dump:** position and size under optimization
The ENUBET beam line – particle yields

<table>
<thead>
<tr>
<th>Focusing system</th>
<th>π/pot (10⁻³)</th>
<th>K/pot (10⁻³)</th>
<th>Extraction length</th>
<th>π/cycle (10¹⁰)</th>
<th>K/cycle (10¹⁰)</th>
<th>Proposal (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn</td>
<td>97</td>
<td>7.9</td>
<td>2 ms (a)</td>
<td>438</td>
<td>36</td>
<td>x 2</td>
</tr>
<tr>
<td>“static”</td>
<td>19</td>
<td>1.4</td>
<td>2 s</td>
<td>85</td>
<td>6.2</td>
<td>x 4</td>
</tr>
</tbody>
</table>

(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle.
(b) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155.

The horn-based option still allows ~ × 5 more statistics but the static option gained momentum since initial estimates were ~ × 4 too conservative with respect to present simulations!

**Advantages of the static extraction:**

- No need for fast-cycling horn
- Strong **reduction of the rate** (pile-up) in the instrumented decay tunnel
- Pave the way to a “**tagged neutrino beam**” → ν interaction at the detector associated in time with the observation of the lepton from the parent hadron in the decay tunnel (more later)
- Monitor the μ after the dump at % level (**flux of νµ from π**) [**under evaluation**]
The static beamline

G4Beamline simulation for particles at the entrance and exit of the decay tunnel

Particle budget at tagger entrance

\[ \pi^+, p, e^+, \mu^+ \]

Momentum bite (8.5 ± 10%) GeV/c

Divergence of the kaon beam

K\(^+\) at tagger entrance

1 m radius

1 m radius

Spectra at:

tagger entrance

tagger exit

Low energy high angle \( \pi \)

\[ \pi^+ \]

\[ K^+ \]

Loss due to K decays
Beamline studies

Additional static focusing options
Put all inputs/schemes together
→ pindown the best design in terms of physics and technical feasibility

Preliminary

Example: 2 dipoles scheme with an intermediate quadrupole
- improve the quality of the beam in the tagger scheme
- larger bending angle (15.1°) reducing background from muons, less probable for neutrinos produced on the 0° line to reach the detector
**The ENUBET tagger**

**Calorimeter**
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM

$\rightarrow e^+/\pi^\pm/\mu$ separation

**Integrated photon veto**
Plastic scintillators
Rings of $3 \times 3$ cm$^2$ pads

$\rightarrow \pi^0$ rejection

Ultra Compact Module
$3 \times 3 \times 10$ cm$^3$ – 4.3 $X_0$

$\gamma$
$e^+$
$e^-$

$0.5$ cm
(i.e. $0.012$ $X_0$)

$h = 3$ cm

$\nu_e$
$K^+$
$\pi^0$

$\rightarrow e^+$ (signal) topology
$\rightarrow \pi^0$ (background) topology
$\rightarrow \pi^+$ (background) topology
The tagger: shashlik with integrated readout

UCM: ultra compact module.
SiPM and electronics embedded in the shashlik calorimeter

CERN PS test beam Nov 2016
Test beam results with shashlik readout

Calorimeter prototype performance with test-beam data at CERN-PS T9 line 2016-2017

Tested response to mip, e and π

- e.m. energy resolution: $17\%/\sqrt{E}$ (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities
- Equalizing UCM response with mips MC/data already in good agreement
- Longitudinal profiles of partially contained π reproduced by MC at 10% precision

Ballerini et al., JINST 13 (2018) P01028
**Polysiloxane shashlik prototypes**

**Increased resistance to irradiation** (no yellowing), **simpler** (just pouring + reticulation)

A $13X_0$ **shashlik prototype** tested in October 2017 (**first application** in HEP) and May 2018.

15 mm thick scintillators to compensate reduced light yields

WLS-SiPM optical coupling
SiPM irradiation measurements at INFN-LNL and CERN

- At the CN Van de Graaf on July 2017 → 1-3 MeV n with fluences up to $10^{12}$/cm$^2$ in a few hours

A shashlik calorimeter equipped with irradiated SiPMs later tested at CERN-PS T9 in Oct 2017


- By choosing SiPM cell size and scintillator thickness (~light yield) properly, **mip signals remain well separated from the noise even after typical expected irradiation levels**
- Mips can be used from **channel-to-channel intercalibration** even after maximum irradiation.
The tagger: lateral readout option

Light collected from scintillator sides and bundled to a single SiPM reading 10 fibers (1 UCM).

SiPM are not immersed anymore in the hadronic shower → less compact but much reduced neutron damage (larger safety margins), better accessibility, possibility of replacement. Better reproducibility of the WLS-SiPM optical coupling.

Sampling calorimeter with lateral WLS light collection

May 2018, CERN-PS test beam

Large SiPM for 10 WLS 4x4 mm²
Achievable neutron reduction with lateral readout

- 30 cm of borated polyethylene in front of SiPM
- FLUKA full simulation. 400 GeV protons.
- Very good suppression especially below 100 MeV.
- Factor ~18 reduction averaging over spectrum.

Neutron energy

- FLUKA

Si \text{n} damage weight function $\times 10^{-10}$

Neutron longitudinal position along the tunnel
Test beam results with lateral readout option

September 2018 CERN-PS: a module with hadronic calorimeter for pion containment and integrated $t_0$-layer

- Good signal amplitude
- Checking impact of light connection uniformity and reproducibility of WLS-SiPM optical match (In progress).

Efficiency maps

Simulation

Resolution

PID
The tagger demonstrator

- Length ~ 3 m
  - allows the containment of shallow angle particles in realistic conditions
- Fraction of $\phi$
- Due by 2021
The photon veto

At CERN-PS T9 line 2016-2018

- $\gamma$ / $e^+$ discrimination + timing
- scintillator (3 × 3 × 0.5 cm$^3$) + WLS Fiber (40 cm) + SiPM
- light collection efficiency $\rightarrow >95$
- time resolution $\rightarrow \sigma_t \sim 400$ ps
- 1mip/2mip separation

charge exchange: $\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$

Trigger: PM1 + VETO + PM2

- $\pi^-$
- $e^+ e^-$

Input for simulations
**K_{e3} positrons reconstruction**

**Full GEANT4 simulation** of the detector, validated by prototype tests at CERN in 2016-2018. Includes particle **propagation** and **decay**, from the transfer line to the detector, hit-level detector response, **pile-up** effects.

**Analysis chain**

- **Event Builder**: Identify the **seed** of the event (UCM with largest energy deposit in inner layer and > 20 MeV). **Cluster neighboring cells** close in time. **Iterate** on not-yet-clustered cells.
- **e/π/µ separation**: **Multivariate** analysis based on **6 variables** (pattern of the energy deposition in the calorimeter) with TMVA
- **e/γ separation**: Signal on the tiles of the **photon veto** (0-1-2 mip)

**Before tuning of shielding**

Reco level full sim.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε_{geom}</td>
<td>0.36</td>
</tr>
<tr>
<td>ε_{sel}</td>
<td>0.55</td>
</tr>
<tr>
<td>ε_{tot}</td>
<td>0.20</td>
</tr>
<tr>
<td>Purity</td>
<td>0.26</td>
</tr>
<tr>
<td>S/N</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Instrumenting half of the decay tunnel: K_{e3} e^+ at single particle level with a S/N = 0.46
**Neutrino events per year at the detector**

- **Detector mass**: 500 t (e.g. Protodune-SP or DP at CERN, ICARUS at Fermilab, WC at J-PARC)
- **Baseline** (i.e. distance between the detector and the beam dump): 50 m
- $4.5 \times 10^{19}$ pot at SPS (0.5 / 1 y in dedicated/shared mode) or $1.5 \times 10^{20}$ pot at FNAL

- $\nu_\mu$ from K and $\pi$ are **well separated** in energy (narrow band)
- $\nu_e$ and $\nu_\mu$ from K are constrained by the tagger measurement ($K_{e3}$, mainly $K_{\mu2}$).
- $\nu_\mu$ from $\pi$: $\mu$ detectors downstream of the hadron dump (under study)

1.2 million $\nu_\mu$ Charged Current per year

14000 $\nu_e$ Charged Current per year

98.4% from kaons $\mu$ contribution is small (tunnel is “short”)
νµ CC events at the ENUBET narrow band beam

The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.

The beam width at fixed R (≡ ν energy resolution for π component) is:
- 8% for r ~ 50 cm, <Eν> ~ 3 GeV
- 22% for r ~ 250 cm, <Eν> ~ 0.7 GeV

+ 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
Time tagged neutrino beams

- Event time dilution → **Time-tagging**
- **Associating a single neutrino interaction to a tagged e⁺** with a small “accidental coincidence” probability through *time coincidences* $E_\nu$ and flavor of the $\nu$ measured "a priori" event by event. Compare “$E_\nu$ from decay kinematics ” $\leftrightarrow$“$E_\nu$ from $\nu$ interaction products ”

Presently with $2.5 \times 10^{13}$ pot / 2s slow extraction:
- genuine $K_{e3}$ cand. : 80 MHz $\rightarrow$ 1 every $\sim 12$ ns
- background $K_{e3}$ cand. $\sim 2 \times$ $\rightarrow$ 1 cand. every $\sim 4$ ns

With $\delta = 0.5 \oplus 0.5$ ns resolutions: already interesting!
S/N ratio will likely improve with further tuning.

<table>
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<tr>
<th>$\delta t - \Delta/c$</th>
<th>$\delta$</th>
</tr>
</thead>
</table>

$\delta$ = combined t-resolution (e⁺ tagger and $\nu$ detector)

**Time coincidence of** $\nu_e^{CC}$ and e⁺

$|\delta t - \Delta/c| < \delta$

**Diagram:**
- Event time dilution $\rightarrow$ **Time-tagging**
- **Associating a single neutrino interaction to a tagged e⁺** with a small “accidental coincidence” probability through *time coincidences* $E_\nu$ and flavor of the $\nu$ measured "a priori" event by event. Compare “$E_\nu$ from decay kinematics ” $\leftrightarrow$“$E_\nu$ from $\nu$ interaction products ”

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**Diagram:**

\[\delta = \text{combined t-resolution (e⁺ tagger and } \nu \text{ detector)}\]
Conclusions and next steps

ENUBET is a narrow band beam with a high precision monitoring of the flux at source (O(1%)) and control of the $E_\nu$ spectrum (20% at 1 GeV → 8% at 3 GeV)

In the first two and a half years
- first end-to-end simulation of the beamline
- feasibility of a purely static focusing system ($10^6 \nu^CC_{\mu}, 10^4 \nu^CC_{e}/y/500$ t)
- full simulation of $e^+$ reconstruction: single particle level monitoring
- completed the test beams campaign
- strengthened the physics case: → slow extraction + “narrow band off-axis technique”

The ENUBET technique is very promising and the results we got so far exceeded our expectations

2019: freeze light readout technology (shashlik versus “lateral readout”) 
2019: Further tuning of the beamline design (improve current S/N for $e^+$) 
CDR at the end of the project (2021): physics and costing 
Build the demonstrator prototype of the tagger (2021)
Thank you!