The ENUBET neutrino beam

A. Longhin (Padova University and INFN) on behalf of the ENUBET Collaboration

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ENUBET: 52 physicists, 11 institutions
Monitored beams

Based on conventional technologies, aiming for a 1% precision on the $\nu_e$ flux.

- Monitor (~ inclusively) the decays in which $\nu$ are produced
- “By-pass” hadro-production, PoT, beam-line efficiency uncertainties

- Fully instrumented decay region
  
  $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle $e^+$

- $\nu_e$ flux prediction = $e^+$ counting

Removes the leading source of uncertainty in $\nu$ cross-section measurements.

To get the correct spectra and avoid swamping the instrumentation, needs a collimated momentum selected hadron beam (only decay products in the tagger).

→ Correlations with interaction radius allows an a priori knowledge of the $\nu$ spectra.
Neutrino beams for precision physics: the ERC ENUBET project

The next generation of short baseline experiments for cross-section measurements and for precision $\nu$ physics (e.g. sterile $\nu$ and NSI) should rely on:

✓ a direct measurement of the fluxes
✓ a narrow band beam: energy known a priori from beam width
✓ a beam covering the region of interest from sub- to multi-GeV

The ENUBET facility fulfills simultaneously all these requirements

~ 500 t neutrino detector @ 100 m from the target

e.g. ICARUS@FNAL or ProtoDUNE-SP/DP@CERN
ENUBET goals and highlights

**Goal:** demonstrate the technical feasibility and physics performance of a neutrino beam where *lepton production at large angles is monitored at single particle level.*

**Two pillars:**
- Build and test with data a *demonstrator* of the instrumented decay tunnel
- Design/simulate the layout of the *hadronic beamline*

**Recent achievements**
- *end-to-end simulation* of the hadronic beamline
- Updated *physics performance*
- Experimental results on the beamline instrumentation prototypes
The ENUBET beam line

**Proton driver:** CERN (400 GeV), FNAL (120 GeV), J-PARC (30 GeV)

**Target:** 1 m 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**
- **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**
  - 2 quad triplets (15 cm wide, L < 2 m, B = 4 to 7 T/m)
  - 1 bending dipole (15 cm wide, L = 2 m, B = 1.8 T)

**Decay tunnel**
- **Radius:** 1 m. **Length:** 40 m, low power hadron dump at the end of the decay tunnel

**Proton dump:** position and size under optimization
The ENUBET beam line – particle yields

<table>
<thead>
<tr>
<th>Focusing system</th>
<th>$\pi$/pot $(10^{-3})$</th>
<th>K/pot $(10^{-3})$</th>
<th>Extraction length</th>
<th>n/cycle $(10^{10})$</th>
<th>K/cycle $(10^{10})$</th>
<th>Proposal (c)</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 $^{(b)}$</td>
<td>85</td>
<td>6.2</td>
<td>x 5</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) Slow extraction. Detailed performance and losses currently under evaluation at CERN
(c) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155.

Advantages of the static extraction:
- No need for fast-cycling horn
- Strong reduction of the rate in the instrumented decay tunnel
- Monitor the $\mu$ after the dump at % level ($\text{flux of } v_\mu \text{ from } \pi$) [NEW: under evaluation]
- Pave the way to a “tagged neutrino beam”, namely a beam where the neutrino interaction at the detector is associated in time with the observation of the lepton from the parent hadron in the decay tunnel
The ENUBET beam line: horn-based option

- Machine studies @ SPS are currently on-going:
  
  Preliminary studies Jul/Aug 2018
  CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard

Slow extraction is induced by going to the third integer betatron resonance with a periodic pattern

- Beam bunches in time with horn pulses
- Further studies ➔ understand radiation losses.
  Iterative corrections. Sextupoles: sharper bursts.
Divergence of the kaon beam

K\(^+\) @ tagger entrance

exit

1 m radius

Particle budget @ tagger entrance

\(\pi^+\) \(\rho\) \(e^+\) \(\mu^+\)

Momentum bite

p (MeV/c)

Spectra @ tagger entrance and exit

Low energy high angle \(\pi\)

\(\pi^+\)

\(K^+\)

Loss driven by decays

p (GeV/c)
The static beamline: FLUKA simulation

Assess the specs of **rad-hard upstream focusing quadrupoles**

Optimize shielding to:
- **reduce halos** in the tagger region
- **suppress the decays** of off-momentum mesons **out of tagger acceptance**

**Energy deposition. 400 GeV/c p on target**
The ENUBET tagger

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

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

Integrated photon veto
Plastic scintillators
Rings of $3\times3$ cm$^2$ pads

$\rightarrow \pi^0$ rejection

Ultra Compact Module
$3\times3\times10$ cm$^3$ – $4.3X_0$

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

$10 \text{ cm} = 5 X_0$

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

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

Tested response to MIP, e and $\pi$:

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

Ballerini et al., JINST 13 (2018) P01028
SiPM irradiation studies

SiPM were irradiated at LNL-INFN with 1-3 MeV neutrons in Jun 2017

→ Characterization of 12, 15 and 20 μm SiPM cells up to $1.2 \times 10^{11}$ n/cm$^2$ 1 MeV-eq (max non ionizing dose for $10^4 \nu_e$CC at a 500 t $\nu$ detector)

Expected neutron doses (FLUKA)

Irradiated SiPM tested at CERN in Oct 2017

- Mips can be used from **channel-to-channel intercalibration** even after the maximal irradiation.
- Tests allowed **tuning of scintillator thickness** (or equivalently min p.e. yields) and **compensation with overvoltage** tuning.

Electrons

mip

A. Coffani et al. arXiv:1804.03248
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, safer WLS-SiPM coupling.

Sampling calorimeter with lateral WLS light collection

May 2018, CERN-PS test beam
The Tagger – Detector R&D

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

Resolution, light yield, uniformity, optical coupling to photo-sensors, $e/\pi$ separation. In progress.

Efficiency maps

e- energy resolution
The photon veto – test beam

@ CERN-PS T9 line 2016-2018

- $\gamma / e^+ $ discrimination + timing
  - scintillator (3×3×0.5 cm$^3$) + WLS Fiber + SiPM
  - light collection efficiency $\rightarrow >95\%$
  - time resolution $\sigma \rightarrow ~400\text{ps}$
  - 1mip/2mip separation

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

Trigger: PM1 + VETO + PM2
Particle rates in the tunnel

Static focusing system
4.5 x 10^{13} pot in 2 s (400 GeV)

Calorimeter 1 m from the axis of the tunnel (R_{inner} = 1.00 m)
Three radial layers of UCM (R_{outer} = 1.09 m)

Rate vs longitudinal position in the tunnel

Rate vs the azimuthal angle in the tunnel

The bulk of the muons lies on the dipole bending plane → can be easily removed
**Positron ID from K decay**

**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 large energy deposit) and cluster neighboring modules (in time and space).
- **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.

### Instrumenting half of the decay tunnel:

- **K_{e3} e^+** at single particle level with a S/N = 0.46

### Purity x Efficiency (K_{e3} e^+)

<table>
<thead>
<tr>
<th>Parameter</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>

φ cut = 0.46
Neutrino events per year at the detector

- **Detector mass**: 500 t (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab)
- **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**

**From pions**

\[ \nu_\mu \]

**From kaons**

\[ \nu_\mu \text{ from K and } \pi \text{ are well separated in energy (narrow band)} \]

\[ \nu_e \text{ and } \nu_\mu \text{ from K are constrained by the tagger measurement (} K_{e3}, \text{ mainly } K_{\mu2} \text{).} \]

\[ \nu_\mu \text{ from } \pi: \mu \text{ detectors downstream of the hadron dump (under study)} \]

**1.2 million } \nu_\mu \text{ Charged Current per year**

**14000 } \nu_e \text{ Charged Current per year**

98.4% from kaons \mu \text{ contribution is small (tunnel is “short”)\rightarrow}
$\nu_\mu$ 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 $R$ (\(\equiv\) neutrino energy resolution) for the pion component is

- 8\% for $r \sim 30$ cm, $<E_\nu> \sim 3$ GeV
- 22\% for $r \sim 250$ cm, $<E_\nu> \sim 0.7$ GeV
$\nu_\mu$ 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.
Conclusions

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 $\rightarrow$ 8% at 3 GeV)

2018 has been a special year, we have

- provided the first end-to-end simulation of the beamline (Jul)
- Proved the feasibility of a purely static focusing system ($10^6 v_\mu^{CC}, 10^4 v_\nu^{CC} / y/500$ t)
- full simulation of $e^+$ reconstruction: single particle level monitoring. S/N $\sim$ 0.5
- Tested with machine data the “burst” slow extraction scheme at the CERN-SPS (Aug)
- completed the test beams campaign (Sep) before LS2
  $\rightarrow$ identified best options for instrumentation (shashlik and lateral readout)
- Strengthened the physics case:
  $\rightarrow$ slow extraction + “narrow band off-axis technique”

The ENUBET technique is very promising and the results we got in the last twelve months exceeded our expectations
Next steps

In 2019 we need to:

- decide on the light readout technology for the final demonstrator (shashlik versus “lateral readout”)
- improve the design of the beamline to reduce beam halo contamination (current e+ S/N can be significantly improved)
- re-optimise the tunnel radius to increase geometrical acceptance

Systematic assessment on predicted neutrino fluxes

- Develop new ideas to enhance precision also on $\nu_\mu$
  - from $K_{\mu2}$ with $\mu$ id in the tagger
  - from $\pi$: counting $\mu$ from $\pi$ in hadron-dump (could be feasible with a 2s extraction).

CDR at the end of the project (2021): physics and costing

- Build a demonstrator prototype of the tagger (2021)
ENUBET in the European strategy

The ENUBET mission is to demonstrate the feasibility of the tagged neutrino beam approach at CERN, J-PARC or FNAL (site independent).

Still... the protoDUNE prototypes would be ideal detectors for a future experiment: right mass, timeliness, redundancy from dual baseline, appropriate logistics, an opportunity for a coherent development of the original physics program (reduction of syst. for DUNE-HyperK).
The ENUBET beamline: “static” option

- Proton extraction scheme: Single slow extraction (2-4 s).
- Reference beam: 8.5 GeV/c, 10% momentum bite
- Quadrupoles: 15 cm wide, L < 2 m, B = 4 to 7 T/m
- Dipole: 15 cm wide, L = 2 m, B = 1.8 T → 7.4° bending
- Envelope at tunnel exit 50 × 50 cm (Tunnel radius 1 m)

Optics optimized through TRANSPORT

G4beamline

“full simulation” → efficiencies, backgrounds
The static beamline: FLUKA simulation

Assess the specs of **rad-hard upstream focusing quadrupoles**

Optimize shielding to

- **reduce halos** in the tagger region
- **suppress the decays** of off-momentum mesons **out of tagger acceptance**

E deposition. 400 GeV/c p on target

8.5 GeV/c parallel $\pi^+$
The ENUBET monitored beam

- **Hadron beam-line:** charge selection, focusing, fast transfer of π⁺/K⁺
- **Tagger:** real-time, "inclusive" monitoring of K decay products

> With proper hadron focusing only K decay products are measured in the tagger being emitted at large angles (unlike pion decay products) allowing

> a **complete control** of produced νₑ using e⁺ from Kₑ3 (~98%). Muon decays gives a small contribution thanks to the short tunnel (~50 m).

> **tolerable rates / detector irradiation**

  < 500 kHz/cm², O(~1 kGy)
The Tagger – positron ID from K decay

**Event Builder**
Seed of the event = UCM in first layer with energy deposit > 20 MeV → link neighboring modules with time (1 ns) and position requirements

**e/π separation**
TMVA multivariate analysis based on 5(+6) variables (pattern of the energy deposition in the calorimeter)

**Response to signal and background**

**e/γ separation**
n° rejection: we require 3 layers of t0 before first calorimeter energy deposit compatible with a mip (0.65-1.7 MeV)