NP06/ENUBET Status

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on behalf of the ENUBET Collaboration

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Outline

- ENUBET is the project for the realization of the first monitored neutrino beam. In the next slides:
  - how to reach the purpose of the project;
  - physics performance and status;
  - next steps for 2021-2022;

- ENUBET: ERC Consolidator Grant, June 2016 – May 2021 (now extended to 2022 to overcome COVID difficulties). PI: A. Longhin;

- Since April 2019: ENUBET also a CERN Neutrino Platform Experiment – NP06/ENUBET;

- ENUBET Collaboration: 60 physicists & 12 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna;
Systematics matter!

Future experiments (DUNE & HyperK) are conceived for precision oscillation neutrino measurements:

- test the 3-neutrino paradigm;
- determine the mass hierarchy;
- test CP violation in the lepton sector;

\[ N_{\nu_e}^{FAR} = P_{\nu_\mu \rightarrow \nu_e} \cdot \sigma_{\nu_e} \cdot \Phi_{\nu_\mu}^{FAR} \]

The purpose of ENUBET: design a narrow-band neutrino beam to measure

- neutrino cross-section and flavor composition at 1% precision level;
- energy of the neutrino at 10% precision level;

The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

From the European Strategy for Particle Physics Deliberation document:

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide.
ENUBET: the first monitored neutrino beam

How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?

Monitored $\nu$ beams
measure rate of leptons $\Leftrightarrow$ monitor $\nu$ flux

ERC project focused on: measure positrons (instrumented decay tunnel) from $K_{e3}$ $\Rightarrow$ determination of $\nu_e$ flux;

As CERN NP06 project: extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ $\Rightarrow$ determination of $\nu_\mu$ flux;

Main systematics contributions are bypassed:
• hadron production, beamline geometry & focusing, POT;

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155
New beamline with 2 dipoles

2 dipoles allow a large bending angle (15.2°):
- **cons**: increased length and reduced rates BUT…
- **pros**:
  - better beam containment (collimated);
  - reduced backgrounds (positrons & forward going muons): better PID (next slides);
  - reduced not-tagged neutrino contamination (next slides);

**Beamline development status:**
- **target simulation**: done;
- **proton dump**: done but engineering studies needed;
- **hadron dump**: done including neutron shielding (NEW);
- **transfer line**:
  - TRANSPORT/G4Beamline for the optics and background shielding: done;
  - FLUKA for doses and neutron shielding: done but other studies needed;
  - GEANT4 for systematics assessment: in progress;
Particle rates and pile-up

Double dipole beamline with slow-extraction scheme (2 s):
- maximum total rate of about 500-600 kHz/ch;

Rates breakdown contribution along the decay tunnel:
- Kaons: dominate at high Z;
- muons: almost uniform contribution;
- pions: contribution grows toward the end of tunnel;

Waveform analysis has been developed (NEW):
- pile-up detection efficiency loss < 1% up to ~1 MHz/ch;
- high detection efficiency (> 97%) preserved up to 5 MHz/ch: can cope also with higher rates obtained with horn focusing;
- 250 Ms/s is still a suitable sampling time;
Horn based focusing

Burst mode slow extraction: protons are “squeezed” in time intervals with active horn

- tested at SPS during 2018;
- same integrated POT as for continuous spill;
- no increase in measured losses;
- MAD-X simulation finalized in 2019 to reach 2-10 ms burst length;
- final tests at SPS in 2022 (after LS2);

M. Pari, M. A Fraser et al, IPAC2019

Ongoing re-optimization of the horn for the new beamline:
- current and shape of conductors are being optimized to maximize the flux exploring a large parameter space (genetic algorithm employed, in progress);

Update with the new beamline ongoing

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Preliminary result: a factor 5 in flux increase with horn focusing option

<table>
<thead>
<tr>
<th>Focusing system</th>
<th>$\pi/\text{pot}$ ($10^3$)</th>
<th>$K/\text{pot}$ ($10^3$)</th>
<th>Extraction length</th>
<th>$\pi/\text{cycle}$ ($10^{10}$)</th>
<th>$K/\text{cycle}$ ($10^{10}$)</th>
<th>Proposal</th>
<th>$	imes$</th>
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<tbody>
<tr>
<td>Horn</td>
<td>97</td>
<td>7.9</td>
<td>2 ms ($^{(a)}$)</td>
<td>438</td>
<td>36</td>
<td></td>
<td>2</td>
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<tr>
<td>&quot;static&quot;</td>
<td>19</td>
<td>1.4</td>
<td>2 s</td>
<td>85</td>
<td>6.2</td>
<td></td>
<td>4</td>
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</tbody>
</table>
Electron neutrino flux components

- Contribution dominated by Kaon decays (98.4%): muon contribution small since tunnel short;
- Taggable component: 80% monitored by measuring positron in decay tunnel;
- Not taggable component 1: 10% low energy neutrinos from $K^{0+/-}$ decays in the target region
  - reduced contribution thanks to large bending angle;
  - can be removed with energy cut;
- Not taggable component 2: 10% neutrinos from $K^+$ decays in the straight section in front of the tagger
  - length of beamline collinear with detector reduced at minimum (1 quad)

**assumption**: 500 t detector located 50 m from hadron dump

Reduce uncertainty in the tagged neutrino component (in progress):
- exploit correlation between shape of observed lepton distributions and neutrino energy to build observable templates;
- build model from templates and fit to observed data;
Decay tunnel instrumentation schematics

- A Lateral readout
  - Compact Module LCM

Calorimeter layout

Calorimeter with $e/\pi/\mu$ separation capabilities:
- sampling calorimeter: sandwich of plastic scintillators and iron absorbers;
- three radial layers of LCM;
- longitudinal segmentation;
- WLS-fibers/SiPMs for light collection/readout;

Photon-Veto allows $\pi^0$ rejection and timing:
- plastic scintillator tiles arranged in doublets forming inner rings;
- time resolution of $\sim 400$ ps;

Exploit event topology for PID

- $e^+$ (signal) topology
- $\pi^0$ (background) topology
- $\pi^+$ (background) topology
Decay tunnel instrumentation prototype & tests

Prototype of lateral readout sampling calorimeter built out of LCM with lateral WLS-fibers for light collection

Tested during 2018 test-beams runs @ CERN TS-P9

Electron energy resolution

- $\sigma_E/E = 17\%$ @ $E = 1$ GeV

1 mip/2 mip separation

- $\sigma_E/E = 18.46\%$ for 1 mip
- $\sigma_E/E = 6.02\%$ for 2 mip

Large SiPM area (4x4 cm$^2$) for 10 WLS readout (1 LCM)

SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

Status of calorimeter:
- longitudinally segmented calorimeter prototype successfully tested;
- photon veto successfully tested;
- custom digitizers: in progress;

Choice of technology: finalized and cost-effective!

F. Acerbi et al, JINST (2020), 15(8), P08001
Lepton reconstruction and identification:

$K_{e3}$ positron reconstruction to constrain $\nu_e$

✓ Full GEANT4 simulation of the detector: validated by prototype tests at CERN in 2016-2018; hit-level detector response; pile-up effects included (waveform treatment in progress); event building and PID algorithms (2016-2020);

Analysis chain:

1. **Event builder**: start from event seed and cluster energy deposits compatible in space and time;
2. **$e / \pi / \mu / \gamma$ separation**: multivariate analysis (MLP-NN from TMVA) exploiting 19 variables (energy pattern in calorimeter, event topology, photon-veto);

**Analysis performance**

S/N = 2.1

Efficiency = 24% (~half geometrical)

Better performances for positron PID in the new beamline!

$K_{e3}$ BR $\sim$5% and K make $\sim$5 − 10% of beam composition
Lepton reconstruction and identification: $K_{\mu2,3}$ muon reconstruction to constrain high-energy $\nu_\mu$

✓ **High angle muons**: reconstruction of track in tagger with dedicated event builder and multi variate analysis. Main background from halo muons is identified and can be used as control sample.

Analysis chain:

1. **Event builder**: start from event seed and cluster energy deposits compatible in space and time;

2. $\mu$-like background separation: multivariate analysis (MLP-NN from TMVA) exploiting 13 variables (energy pattern, track isolation and topology);

Analysis performance

$S/N = 6.1$

Efficiency $= 34\% (K_{\mu2})$ & $21\% (K_{\mu3})$ (~half geometrical)

**NEW**: we demonstrate the capability of muon monitoring.
Lepton reconstruction and identification: \( \pi \mu_2 \) muon reconstruction to constrain low-energy \( \nu_\mu \)

- **Low angle muons**: out of tagger acceptance, need muon stations after hadron dump

Exploit:
- correlation between number of traversed stations (muon energy from range-out) and neutrino energy;
- difference in distribution to disentangle signal from halo-muons;

Detector technology: constrained by muon and neutron rates;
Systematics: punch through, non uniformity, efficiency, halo-\( \mu \).
ENUBET demonstrator

- Build prototype (1.7 m long / 45° coverage) to demonstrate performance, scalability and cost-effectiveness;
- Will be tested in the renovated East-Area at the CERN-PS: after LS2 (2021-2022);
Conclusions

ENUBET: a project for the first monitored neutrino beam

Status of the project in very good shape:

- New double-dipole beamline with improved shielding developed;
- Burst mode slow extraction: further optimization developed, final tests after LS2;
- Horn optimization ongoing: preliminary x5 gain in flux;
- Finalized technology for calorimeter: lateral readout calorimeter;
- Positron reconstruction: very good performance with new beamline;
- Constrain also muon neutrino: demonstrated muon monitoring capability;
- Full assessment of systematics on neutrino flux: in progress and will be released by 2021;
- Construction and testing of demonstrator: during 2021-2022;
- Conceptual Design Report by 2022;