Development of instrumentation for tagged and monitored neutrino beams

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This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (G.A. n. 681647)
Outline

● The ENUBET project
● Status of the positron tagger
● Overview of the R&D and test beam results
● Conclusions and outlooks
The ENUBET Collaboration

Enhanced NeUtrino BEams from kaon Tagging

60 physicist, 12 institutions

P.I A. Longhin
Padova University, INFN
http://enubet.pd.infn.it/
A monitored neutrino beam

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

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

The ENUBET beamline

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

Target
(Be, graphite. **FLUKA**)

Transfer Line
Horn vs Static focusing under study (tested at the **CERN SPS**)
TL kept short, optimized with **TRANSPORT** to a 10% momentum bit centered at 8.5 GeV/c
Particle transport and interaction: full simulation with **G4beamline** and **Geant4**

Design/simulate the layout of the **hadronic beamline**

Transfer Line

~500 T **neutrino detector** 100m from the target.
E.g. :
ICARUS@FNAL, ProtoDUNE@CERN or Water Cher @J-PARC

**50 m instrumented decay tunnel**

**Decay tunnel**
R = 1 m, L = 50 m

**Build/test a demonstrator of the instrumented decay tunnel**
The positron tagger

protons → (K⁺, n²) → K decays → e⁺, νₑ → neutrino detector

K⁺ decay modes

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ⁺νμ</td>
<td>63.55 ± 0.11</td>
</tr>
<tr>
<td>π⁰e⁺νₑ</td>
<td>5.07 ± 0.04</td>
</tr>
<tr>
<td>π⁰μ⁺νμ</td>
<td>3.353 ± 0.034</td>
</tr>
<tr>
<td>π⁺π⁰</td>
<td>20.66 ± 0.08</td>
</tr>
<tr>
<td>π⁺π⁰π⁰</td>
<td>1.761 ± 0.022</td>
</tr>
<tr>
<td>π⁺π⁻π⁰</td>
<td>5.59 ± 0.04</td>
</tr>
</tbody>
</table>

Kₑ₃ → <θₑ⁺> = 88 mrad

Background: μ⁺, π⁺, π⁰
The positron tagger

Sampling **calorimeter** → Longitudinal segmentation
\[ e^+ / \mu^+ / \pi^\pm \] separation

Integrated **photon veto** → scintillator
\[ \pi^0 \] rejection

- **e^- (signal) topology**
- **\( \pi^0 \) (background) topology**
- **\( \pi^+ \) (background) topology**
The positron tagger UCM

Ultra Compact Module
10 cm → 10 $X_0$
Plastic scintillator + iron absorber
Shashlik readout scheme with WLS fibers and integrated SiPMs

SiPM - HD RGB by FBK
1x1 mm$^2$, 12-15-20 $\mu$m cell size

CERN PS, Nov 2016
7x4x2 UCMs
Test beam results

Calorimeter prototype performances
Test-beam data @ CERN-PS T9 line 2016-2017

- Tested response to MIP, e and π
- 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-SiPM coupling (major source of non uniformities)
- Equalizing UCM response with MIPs (MC/data in a good agreement)
- Longitudinal profiles of partially contained π reproduced with MC @ 10% precision

Ballerini et al., JINST 13 (2018) P01028
The positron tagger - Photon veto

$\gamma/e^+$ discrimination (+ timing)

Tests @ CERN-PS T9 line 2016 - 2018
Scintillator (3x3x0.5 cm$^3$) + WLS fiber (30cm) + SiPM
- Light collection efficiency $\rightarrow > 95\%$
- Time resolution $\rightarrow \sigma_t \sim 400$ ps
- 1 mip / 2 mip separation

Charge exchange $\pi^- p \rightarrow n n^0 (\rightarrow \gamma\gamma)$
Trigger: pm1 + veto + pm2
SiPM irradiation

Expected 5-years neutron doses from K decays (FLUKA)

Irradiation campaign @INFN-LNL - July 2017
Van de Graaf CN accelerator
7MV and 5 mA proton current on a Be target
\( p (5 \text{ MeV}) + ^9\text{Be} \rightarrow n + X \)
\( \rightarrow 1-3 \text{ MeV neutrons} \) with fluences up to \( 10^{12}/\text{cm}^2 \) in \( \sim \)hours

Tested 12,15,20 μm (cell size) SiPMs up to \( \sim 2 \times 10^{11} \text{ 1-MeV-eq } n/\text{cm}^2 \)
SiPM irradiation results

- 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 for channel-to-channel intercalibration even after maximum irradiation.

A shashlik calorimeter equipped with irradiated SiPMs later tested at CERN-PS T9 in Oct 2017:
1 cm thick scintillator, 15 μm cell size
1.2 x 10^{11} 1 MeV-eq-n/cm^2
Alternative design: lateral readout

Moving **SiPM + frontend** 30 cm away from the calorimeter bulk

- Borated polyethylene shielding
- FLUKA full simulation, 400 GeV protons.

→ Very good suppression especially below 100 MeV. Factor $\sim 18$ reduction averaging over spectrum.
Lateral readout prototype

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**, easier replacement.
- better **reproducibility** of the WLS-SiPM optical coupling.

Sampling calorimeter with lateral WLS light collection

**May 2018, CERN-PS**

Large area (4x4 mm²) SiPM

*AdvaniSiD ASD-RGB4S-P*
Test beam results and prototype R&D

September 2018 CERN-PS: a module with hadronic cal. for pion containment and integrated t₀-layer

Particle ID

Energy resolution

Efficiency maps

Geant4 simulation
Readout electronics

Development of custom waveform digitizers
8 ch, 14-bit ADC, 500 MS/s
10 ms spill (horn) → 40 MB/spill/UCM

4 ch ADC board already tested and validated
4 amplifiers with gain = 4 (ADA4930 OpAmp)
2 x ADS4249 ADCs (14bit, 250 MS/s)

+ 1 digital interface board

Mid-term plan:
- Final 8-channel waveform digitizer board
- VME interface
2021 - demonstrator construction

- **Length ~ 3 m, fraction of $\varphi \rightarrow 4000$-5000 channels**
- Allows containment of shallow angle particles in **realistic conditions**
- Due by 2021
- Will be tested at the CERN renovated East Area after Long-Shutdown 2
- Demonstrate **physics, scalability** and **cost effectiveness**

Fiber routing optimization to avoid tile staggering
Conclusions and outlooks

ENUBET is demonstrating that a **high precision monitoring** of the flux at source **O(1%)** is feasible.

The **positron tagger** prototyping phase has been concluded:

- test beams campaigns completed before CERN Long Shutdown 2. Particle ID and energy resolution fulfill the requirements
- neutron damage of the sensors assessed
- Lateral readout option → ensures a long lifetime and accessibility of the photosensors
- In-house readout electronics (full waveform digitizer, VME interfaces)

Next steps:

- Full assessment of systematics on the neutrino fluxes (simulation)
- Build the demonstrator prototype of the tagger (2021)
- Conceptual Design Report at the end of the project (2021): physics and costing
- >2021: (likely) propose a full scale experiment implementation supported by a larger international collaboration.