Fasci monitorati per la determinazione ad alta precisione del flusso di neutrini: il progetto ENUBET

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IFAE 2019, 8-10 April 2019, Napoli

FLUKA
Neutrino cross sections and flux uncertainties

- **Precise knowledge of** $\sigma(\nu)$ → important for future neutrino oscillation experiments (DUNE, HyperK)

- $\sigma(\nu_\mu)$: remarkable improvement in the last 10 years (MiniBooNE, SCIBooNE, T2K, MINERνA, NOvA...), but still **no absolute measurements below 7-10%**

- $\sigma(\nu_e)$: $\sigma(\nu_\mu) \leftrightarrow \sigma(\nu_e)$ delicate at low energies, no intense/pure source of GeV $\nu_e$ available

Poor knowledge of $\sigma(\nu_e)$ can spoil the CPV discovery potential and the insight on the underlying physics (standard vs exotic, matter vs antimatter)

**Main limiting factor:** systematic uncertainties in the initial flux determination
Monitored neutrino beams

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

Proposed solution

- Monitor the neutrino flux inside the decay tunnel with conventional technologies
- Aim for a $\nu_e$ source pure and precise (1%) from a kaon-based beam

Protons $\rightarrow$ Target ($K^+,\pi^+$) $\rightarrow K_{e3}$ decays $\rightarrow$ $\nu_e$ @ neutrino detector

Measure positrons (emission angle $\approx 88$ mrad) in a FULLY INSTRUMENTED decay region

- “By-pass” uncertainties from POT, hadro-production, beamline efficiency
- $\nu_e$ flux prediction = $e^+$ counting

Improvement of one order of magnitude cross-section measurement @GeV scale

Determine absolute $\nu_e$ flux at neutrino detector with O(1%) precision
The ENUBET beamline

- **Proton driver**: CERN SPS (400 GeV), Fermilab Main Ring (120 GeV), JPARC (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 figure)
  - **Static focusing system**: a quadrupole triplet before the bending magnet
- **Transfer line**:
  - **Kept short (~20 m)** → minimize early K decays and those of off-momentum mesons out of tagger acceptance (untagged neutrino component)
  - **Optics**: reference momentum **8.5 GeV/c ± 10%** (TRANSPORT)
- **Decay tunnel**: L = 40 m, low power hadron dump at the end
- **Proton dump**: position and size under optimization
The ENUBET narrow-band beam

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

IFAE 2019, 8-10 April 2019
The ENUBET beamline: 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>$\pi$/cycle ($10^{10}$)</th>
<th>$K$/cycle ($10^{10}$)</th>
<th>Proposal(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn</td>
<td>77</td>
<td>7.9</td>
<td>2 ms(a)</td>
<td>347</td>
<td>36</td>
<td>x2</td>
</tr>
<tr>
<td>Static</td>
<td>19</td>
<td>1.4</td>
<td>2 s</td>
<td>86</td>
<td>6.3</td>
<td>x4</td>
</tr>
</tbody>
</table>

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

**Horn option** → more efficient in terms of meson yields,
**however**

**Static option** → yields x4 larger wrt preliminary estimates from optic optimization

**PROS:**
- No need for fast-cycling horn
- Strong reduction of the rate in the instrumented decay tunnel
- Monitor muons after the dump at 1% level (→ flux of $\nu_\mu$ from $\pi$) [under evaluation]
- **Possibility to associate in time the $\nu$ interaction at the detector with the observation of the lepton from the parent hadron in the decay tunnel**

**Neutrino tagged beams**
The Tagger

**e^+/\pi^+/\mu^+ separation**

Longitudinally segmented sampling calorimeter

1) compact calorimeter with longitudinal segmentation
2) integrated γ-veto

Plastic scintillator exploiting 1 mip – 2 mip separation

hadronic

em

10 cm = 5 X₀

60 cm

e^+

t₀-layer

K^+

UCM

\pi^0

K^+

\pi^0

e^+

\nu_e

\gamma

\nu_e

\gamma

\nu_e

\gamma

\nu_e

\gamma

\nu_e

h=3 cm

0.5 cm
(i.e. 0.012 X₀)

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Tagger prototypes performances

Two readout schemes, tested at CERN:

**Compact “shashlik”:**
- Compact readout based on SiPMs embedded in calorimeter bulk
- PROS: scalable technology
- CONS: SiPMs exposed to large neutron flux \((10^{11} \text{ 1MeV-eq n/cm}^2)\)

**“Lateral”:**
- Fibers bundled and coupled to SiPMs 40 cm from the bulk of the calorimeter
- PROS: SiPMs less exposed to radiation, more cost-effective
- CONS: less compact
Tagger prototypes performances

Experimental setup @ CERN

Results for the shashlik prototypes:
- ~17%/$\sqrt{E}$ energy resolution
- Good agreement data/MC

Ballerini et al., JINST 13 (2018) P01028

Results for the lateral readout prototypes:
- ~17%/$\sqrt{E}$ energy resolution
- Bigger constant term, probably due to non-uniformity in light collection

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**t_0** layer and irradiation studies

γ/e^+ discrimination (photon-veto)
- light collection efficiency \( \rightarrow \) >95%
- Time resolution \( \rightarrow \) ~400 ps
- First 1mip/2mip separation using photon conversion from \( \pi^0 \) gammas

Irradiation studies
- SiPM irradiated @ LNL-INFN
- Characterization of 12, 15 and 20 \( \mu \)m SiPM cells up to 1.2 \( 10^{11} \) n/cm\(^2\) 1 MeV-eq

Even after max irradiation, electrons & mip remain well separated

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F. Acerbi et al., JINST 14 (2019) P02029
**$K_{e3}$ positron reconstruction**

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

**Analysis chain** [F. Pupilli et al., POS NEUTEL 2017 (2018) 078]

- **Event builder**: identify the seed of the event and cluster neighboring modules
- **$e/\pi/\mu$ separation**: TMVA multivariate analysis based on 6 variables (pattern of the energy deposition in the calorimeter)
- **$e/\gamma$**: signal on the tiles of the photon veto

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<table>
<thead>
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<tbody>
<tr>
<td>$\varepsilon_{\text{geom}}$</td>
<td>0.36</td>
</tr>
<tr>
<td>$\varepsilon_{\text{sel}}$</td>
<td>0.55</td>
</tr>
<tr>
<td>$\varepsilon_{\text{tot}}$</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>
<tr>
<td>S/N $\Phi$ cut</td>
<td>0.46</td>
</tr>
</tbody>
</table>

**Instrumenting half of the decay tunnel:** $K_{e3}$ e$^+$ at single particle level with a S/N = 0.46
Conclusions

ENUBET is a narrow-band beam with 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 2018, the collaboration has:
  → provided the first end-to-end simulation of the beamline
  → proved the feasibility of a purely static focusing system
- **full simulation of the $e^+$ reconstruction**: single particle level monitoring S/N ~0.5
- Completed the beam tests campaign before LS2
  → identified best options for instrumentation (shashlik and lateral readout)
- **Strengthened the physics case**
  → slow extraction + “narrow band”
Backup
The ENUBET narrow-band beam

Neutrino events per year at the detector

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

$\nu_\mu$ 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)
The ENUBET narrow-band beam

$\nu_\mu$ CC events at the ENUBET narrow band beam

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

Initial neutrino energy inferred from the measurement of the neutrino interaction vertex distance with respect to the axis of the decay tunnel.
Machine studies for the horn-based option

Burst-mode slow extraction in SPS

CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard