The ENUBET project

High Precision Neutrino Flux Measurements in Conventional Neutrino Beams

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on behalf of the ENUBET Collaboration

Outline

• The problem of flux uncertainty in conventional beams → monitored beams
• Challenges, goals and recent achievements for ENUBET
• Forthcoming activities and conclusions

NUFACT2017

Uppsala, 25-30 September 2017

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 681647).
Neutrino cross sections and flux uncertainties

• An important ingredient for the success of the future neutrino oscillation experiments is the precise knowledge of $\sigma(\nu)$

  • $\sigma(\nu_\mu)$
    ✓ Remarkable progress in the last 10 years (MiniBooNE, SCIBooNE, T2K, MINERvA, NOvA...)
    ✓ But still no absolute measurements below 7-10%

  • $\sigma(\nu_e)$
    ✓ $\sigma(\nu_\mu) \leftrightarrow \sigma(\nu_e)$ delicate @ low energies
    ✓ Rare and not precise measurements available, despite its relevance for CPV, NSI, sterile
    ✓ No intense/pure source of GeV $\nu_e$ available (using the beam contamination)

• Main limiting factor: syst. uncertainties in the initial flux determination

Flux estimated through a well established but indirect procedure
Monitored neutrino beams

A direct measurement of neutrino fluxes based on conventional technologies

Kaon-based monitored neutrino beams can provide a pure and precise \(O(1\%)\) \(\nu_e\) source:

\[
\text{protons} \rightarrow (K^+, \pi^+) \rightarrow K \text{ decays} \rightarrow \nu_e \rightarrow \text{neutrino detector}
\]

- Monitoring the decays in which \(\nu\) are produced
- Get rid of systematics from PoT, hadro-production, beam-line efficiency

Traditional

- Passive decay region
- \(\nu\) flux relies on ab-initio simulation of the full chain
- Large uncertainties

Monitored

- Fully instrumented decay region
- \(K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow \) large angle \(e^+\)
- \(\nu_e\) flux prediction = \(e^+\) counting
The conceptual design: ENUBET

- **Hadron beamline:** charge selection, focusing, fast transfer of $K^+/\pi^+$
- **Tagger:** real-time, «inclusive» monitoring of K decay products

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**Reference parameters**

- $P_{K,\pi} = 8.5\pm20\% \text{ GeV/c}$
- $\Theta < 3 \text{ mrad}$ over $10\times10 \text{ cm}^2$
- Tagger: $L = 50 \text{ m}, r = 40 \text{ cm}$

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- Thanks to the short decay tunnel, **muon decay** gives a **negligible contribution** to the $\nu_e$ flux that is dominated ($\sim98\%$) by neutrinos coming **from** $K_{e3}$ decays

- Only **kaon decay** products are **measured** in the tagger, since pions and muons decay at small angles

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- **Complete control on $\nu_e$ flux**
- **Tolerable rates / detector irradiation**
  ($< 500 \text{ kHz/cm}^2, < 1 \text{ kGy}$)
ENUBET: Enhanced NeUtrino BEam from kaon Tagging

Project approved by the European Research Council (ERC)
5 years duration (06/2016 – 06/2021)
Overall budget: 2 MEUR

http://enubet.pd.infn.it

Bibliography
- A. Berra et al., NIM A824 (2016), 693
- A. Berra et al., NIM A830 (2016), 345
- CERN-SPSC-2016-036; SPSC-EOI-014

Expression of interest (CERN-SPSC, Oct. 2016)

ERC-Consolidator Grant-2015, n° 681647 (PE2)
P.I: A. Longhin
Host Institution: INFN

41 physicist, 10 institutions:
CERN, IN2P3 (Bordeaux), INFN
(Bari, Bologna, Insubria, Milano-Bicocca, Napoli, Padova, Roma-I)

In the CERN Neutrino Platform (NP03, PLAFOND)
Constraining $\nu$ fluxes

$\nu_e$ flux

✓ $K_{e3}$ (golden sample)
  - $\pi^+/\pi^0$ from $K^+$ can mimic an $e^+$
    $e/\pi$ discrimination through:
    I. **Longitudinal profile** of showers
    II. **Vertex reconstruction** by timing

✓ Non $K_{e3}$ (silver sample): exploitable,
  additional systematics only from K B.R.

$\nu_\mu$ flux

• Kaons well constrained by the tagger
  (both from $K_{e3}$ and hadronic decay rates)

• $\nu_\mu$ from K can be selected at the
  nu_detector using **radius-energy**
  **correlations** → **High precision** $\sigma(\nu_\mu)$
Hadron beam-line scenarios

Baseline choice: magnetic horns focusing

- **Tagger rate limit** (~500 kHz/cm²) reached with ~10^{12} PoT/spill
- **Horn pulsing limit**: t_{\text{impulse}} < O(1-10) ms
- Needs for 10^4 \nu_e^{\text{CC}} in a 500 t v-det at 100 m:
  - ~10^{20} PoT a fraction of a year run at present proton drivers
  - ~10^8 spills challenging/unconventional

Solution: multi-Hz slow resonant extraction + horn pulsing → machine studies at SPS

Alternative choice: static focusing + long extraction

**Cons**: Less efficient focusing (more PoT needed)

**Pros**: Lower rates at the decay tunnel (1 e^+/30 ns)

Event time tagging → coincidences among tagger and v-detector

Single slow resonant extraction

Synergies with SHiP
Horn focusing

- **Realistic implementation** of the beam-line/focusing layout
- **Site independent**. We are considering existing proton driver energies
- **FLUKA/G4Beamline (+ Transport** for optics optimization) simulations in progress
- Assess **beam-related backgrounds**

**Preliminary**

- Momentum at the tagger entrance (MeV)
- Polar angle at the tagger entrance (mrad)
Static focusing

- Used the same simulation machinery as in the horn option (FLUKA + G4Beamline+Transport)
- More promising configuration: Quadrupole triplet + Dipole + Quadrupole triplet
- **Compact beam-line:** ~28 m length

**Preliminary results:** competitive with respect to the horn-based focusing in terms of secondary meson yield (~ 1/4)
Neutrino samples

- Need good e-tagging capabilities, like:
  - ICARUS/μBOONE @ FNAL
  - Proto-DUNE SP/DP @ CERN
  - Water Cerenkov (e.g. E61 @ JPARC)

- Assumed a 500 t LAr det (6×6×10 m³) @ 100 m

<table>
<thead>
<tr>
<th>E_p (GeV)</th>
<th>PoT (10⁲⁰) for 10⁴ ν_e CC (on-axis)</th>
<th>Run duration (w/ nominal int)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.03</td>
<td>~ 0.2 JPARC γ</td>
</tr>
<tr>
<td>120</td>
<td>0.24</td>
<td>~ 0.4 NUMI γ</td>
</tr>
<tr>
<td>400</td>
<td>0.11</td>
<td>~ 0.25 CNGS γ</td>
</tr>
</tbody>
</table>

- Reference design better suited for multi-GeV (e.g. DUNE)
- Hyper-K r.o.i accessible in off-axis configuration, but larger exposures needed
- Studying the possibility to reduce the initial hadron momentum
- Can exploit also ν_μ from π (~10⁵ @ low E), estimating the initial π flux with BCT and K constraint from the tagger → to be investigated
Systematics on the $\nu_e$ flux

**Positron tagging** eliminates the most important contributions. Assessing in detail the **viability of the 1% systematics** on the flux is one of the final goals of ENUBET. Full analysis is being setup profiting from a **detailed simulation** of the beamline, the tagger and inputs from **test beams**.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical error</td>
<td>$&lt;1% \ (10^4 \nu_e^{CC})$</td>
</tr>
<tr>
<td>kaon production yield</td>
<td>irrelevant (positron tag)</td>
</tr>
<tr>
<td>number of integrated PoT</td>
<td>irrelevant (positron tag)</td>
</tr>
<tr>
<td>secondary transport efficiency</td>
<td>irrelevant (positron tag)</td>
</tr>
<tr>
<td>branching ratios</td>
<td>negligible + only enter in bkg estimation</td>
</tr>
<tr>
<td>3-body kinematics and mass</td>
<td>$&lt;0.1%$</td>
</tr>
<tr>
<td>phase space at the entrance</td>
<td>to be checked with low intensity pion runs</td>
</tr>
<tr>
<td>$\nu_e$ from $\mu$-decay</td>
<td>constrain $\mu$ from K by the tagger and $\mu$ from $\pi$ by low intensity runs</td>
</tr>
<tr>
<td>$e/\pi$ separation</td>
<td>being checked directly at test beams</td>
</tr>
</tbody>
</table>
1) **Calorimeter** ("shashlik")
   - Ultra Compact Module (UCM) (Plastic scint. + Fe absorbers)
   - Integrated light readout with SiPM
     \[ \rightarrow e^+/\pi^+/\mu \text{ separation} \]

2) **Integrated γ-veto**
   - Rings of 3×3 cm² pads of plastic scintillator
     \[ \rightarrow \pi^0 \text{ rejection} \]

**Ultra Compact Module**
3×3×10 cm³ – 4.3 \( X_0 \)

**First milestone**: build/test a scalable **demonstrator** consisting of a 3 m long section of the instrumented tunnel by **2021**
Simulation of the decay tunnel and event reconstruction

- **Full GEANT4 simulation** of the instrumented tunnel
- "**Event building**: clustering of energy deposits** based on position and timing of signal waveforms in UCM, with realistic treatment of background (up to 500 kHz/cm²). Pile-up effects fully included
- **Multivariate analysis** exploiting the pattern of the energy deposition in the calorimeter to select e⁺ and simultaneously reject π⁺ and π⁰

Instrumenting the decay tunnel at 1 m radius allow e⁺ ID with ~25% efficiency (~50% purity)
Calorimeter prototype performances with test beam data

- **TB @ CERN-PS T9** beamline (Nov. 16)
- 56 UCM arranged in 7 longitudinal blocks (~30 $X_0$) + had. layer (coarse sampling) at grazing incidence (orientable cradle)
- e/μ tagged with Cherenkov counters and a muon catcher

Data/MC agreement reasonably good already $\rightarrow$ **GEANT4 simulation validated**

A. Berra et al. IEEE TNS 64 (2017) 4

Energy deposit (a.u.)

Preliminary

4 GeV beam at 100 mrad

Data: dots
MC: $\pi^-, \mu^-, e^-$
**Doses and radiation damage**

- **Neutron** and **ionizing doses** have been studied for a tagger radius of 40, 80 and 100 cm with **FLUKA** and cross-checked with **GEANT4**
- Choosing 100 cm allows $\sim 2 \times 10^{11}$ n 1MeV-eq/cm² and $\sim 0.05$ kGy in the innermost layers in the detector lifetime
- **Test irradiation** with **1-3 MeV neutrons** performed at **INFN-LNL CN Van de Graaff** on 12-27 June 2017. Characterization of rad-hard SiPM with 12-15-20 μm cell size (FBK, SensL) through **I-V curves**

**Irr. SiPM tested @ T9**
(July 2017)

Reduction of the gain

**Self-calibration** with m.i.p **still viable**
(increasing scint. thickness)

Preliminary
R&D activities

Intense test beam activity @ CERN-PS T9

• Achieve *recovery time* $\sim 10$ ns (to cope with pile-up)
• Test of *custom digitizers electronics*
• *Photon veto* prototypes with plastic scintillators

• **Scalable/reproducible technological solutions**
  ✓ *water-jet holes* machining for absorbers
  ✓ *Molded scintillators* (a prototype calorimeter tested in July 17 @ T9, analysis on-going)
  ✓ *Polysiloxane scintillators* (a 12 $X_0$ calorimeter will be tested @ T9 in october)

First application in HEP!

**Promising results:**
• High efficiency
• Light yield comparable to plastic scint.
  (w/ $\times 3$ thickness wrt to EJ200)

High rad. hardness
No drilling!
Summary

In about one year ENUBET moved from a conceptual study to a concrete Reference Design

<table>
<thead>
<tr>
<th>Item</th>
<th>baseline option</th>
<th>alternatives</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton extraction</td>
<td>Few ms spills at $O(10)$ Hz during the flat top (2 s)</td>
<td>Single slow extraction</td>
<td>Not tested yet</td>
</tr>
<tr>
<td>Focusing</td>
<td>Horn based</td>
<td>Quadrupole based</td>
<td>Optimization ongoing</td>
</tr>
<tr>
<td>Transfer line</td>
<td>Quad+dipoles</td>
<td></td>
<td>Full simulation ongoing</td>
</tr>
<tr>
<td>Detector for $e/\pi$ separation</td>
<td>Shashlik calorimeter with SiPM readout</td>
<td>Polysiloxane scint.</td>
<td>Full simulation and prototyping ongoing</td>
</tr>
<tr>
<td>Photon veto</td>
<td>Scint. Pads with fiber readout</td>
<td>Direct readout LAPPD</td>
<td>Full simulation and prototyping ongoing</td>
</tr>
<tr>
<td>Particle ID and detector optimization</td>
<td>3×3×10 cm$^3$ UCM</td>
<td>Different radii and granularities</td>
<td>Full simulation and prototyping ongoing</td>
</tr>
<tr>
<td>Systematic assessment</td>
<td>Positron monitoring (Ke$^3$ decay)</td>
<td>Enhanced exploiting other K decay modes</td>
<td>Just started</td>
</tr>
</tbody>
</table>
Conclusions

- **Flux systematics** could be **reduced by one order of magnitude** exploiting $\text{K} \rightarrow \text{e}+ \nu_\text{e} \pi^0$

- In the next 4 years ENUBET will investigate the **feasibility** of this approach and of its application to a new generation of **cross section experiments** at CERN, FNAL or JPARC providing $\sigma(\nu_\text{e})$ at **1%** with a detector of **moderate mass** (500 t)

- The intriguing possibility of a **time-tagged facility** will be also studied

- 1st year of project: a **rich simulation and prototyping program** is giving very **promising results**. Challenging open items ahead. But **no showstoppers** so far