This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement N. 681647)
Future neutrino physics will require measurements of absolute neutrino cross sections at the GeV scale with 1% precision.

Leading source of uncertainty in cross-section measurement: neutrino flux → dominated by the uncertainty on the simulation of the beamline and the hadro production data.

Measure the number of leptons that are produced in a decay tunnel: one-to-one relationship between the lepton that you produce and the neutrino.

ENUBET: $K^+ \rightarrow \pi^0 e^+ \nu_e$
Design optimized to reach a 1% systematic error on measurement of the flux and of the cross-sections of the electron neutrino

Two main steps:
- layout of the π/K focusing and transport system with suitable proton extraction schemes
- special instrumented beamline capable of performing positron monitoring from decays of K in a ν beam decay tunnel at single particle level

Positrons from: $K^+ \rightarrow \pi^0 \ e^+ \ \nu_e$
Muons from: $K^+ \rightarrow \mu^+ \ \nu_\mu, \ K^+ \rightarrow \pi^0 \ \mu^+ \ \nu_\mu$

Muon monitoring: $\pi^+ \rightarrow \mu^+ \ \nu_\mu$
ENUBET beamline

Requirements:

- Use of conventional magnet field and apertures (normal-conducting, aperture < 40cm)
- Keep under control level of background transported to the tunnel
- Small beam size: non decaying particles should exit the decay pipe without hitting the walls
- Maximize number of $K^+$ at tunnel entrance
- Minimize total length of the transferline (~20 m) to reduce kaon decay losses

Focusing system: a quadrupole triplet before the bending magnet
Reference momentum 8.5 GeV, 10% momentum bite
One quadrupole triplet, two bending dipoles (14.8° bending)
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ENUBET beamline

Larger bending angle w.r.t. original proposal (single dipole beamline)
- increased length
- better collimated beam
- reduced backgrounds

- Optics: optimized with TRANSPORT
- Particle transport and interaction: full simulation with G4Beamline
- FLUKA: doses and n shielding, target (Be, graphite)
- In progress: GEANT4 (systematics)
Horn-based beamline - “burst slow extraction”

Magnetic horn placed between the target and the quadrupoles, pulsed with large currents (2-10 ms pulse, 180 kA at 10 Hz)

“Burst slow extraction”: small bursts of 10 ms, repeated with a frequency of 10Hz during the flat top of the accelerator.

Tested at the SPS at CERN in 2018: 20 ms achieved

Today:
- Simulation → 2-10 ms
  → to be tested after LS2 (2022)
- Reoptimization of the horn geometry: conductor and currents

Static focusing option: single resonant slow extraction → less challenging (no need synchronise proton extraction with current pulsing)
Particle yields

The horn-based option allows ~ x5 faster statistics, but the static transferline offers several advantages:

- No need for fast-cycling horn
- Strong reduction of the rate (pile-up) in the instrumented decay tunnel
- Monitor $\mu$ after the dump at % level (flux of $\nu_\mu$ from $\pi$)

Initial estimates were ~ x4 too conservative wrt present simulations $\rightarrow$ configuration still under optimization

<table>
<thead>
<tr>
<th>Focusing system</th>
<th>$\pi/\rho_{ot}$ ($10^{-3}$)</th>
<th>$K/\rho_{ot}$ ($10^{-3}$)</th>
<th>Extraction length</th>
<th>$\pi/cycle$ ($10^{10}$)</th>
<th>$K/cycle$ ($10^{10}$)</th>
<th>Proposal (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn</td>
<td>97</td>
<td>7.9</td>
<td>2 ms</td>
<td>438</td>
<td>36</td>
<td>$\times 2$</td>
</tr>
<tr>
<td>Static</td>
<td>19</td>
<td>1.4</td>
<td>2 s</td>
<td>85</td>
<td>6.2</td>
<td>$\times 4$</td>
</tr>
</tbody>
</table>

To be updated with the new beamline

(*) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155
**Instrumented decay tunnel**

**Calorimeter**

→ Longitudinal segmentation (three radial layers, plastic scintillator + iron absorber)
→ $e^+ / \pi^+ / \mu$ separation

**Light readout system**

SiPMs on top of the calorimeter, above a borated polyethylene shield

Lateral light readout system: WLS fibers running along the edges of the tiles → reduced (x18) neutron damage the SiPMs

**Photon veto**

Plastic scintillator tiles arranged in doublets forming inner rings → $\pi^0$ rejection

September 2018 @ CERN-PS: response to MIP, $e$ and $\pi$ tested for a calorimeter prototype and an integrated $t_0$-layer.
Instrumented decay tunnel

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Lateral light readout system: WLS fibers running along the edges of the tiles → reduced (x18) neutron damage the SiPMs

- ENUBET $e^+$ mean angle: 88 mrad
Testbeam results

Energy resolution

- MC
- Data

$\chi^2 / \text{ndf}$ = 18.46 / 3
- Constant Data $6.957 \pm 0.2575$
- Stochastic Data $14.97 \pm 0.3398$

$\chi^2 / \text{ndf}$ = 6.024 / 3
- Constant MC $3.929 \pm 0.1496$
- Stochastic MC $15.97 \pm 0.1153$

$\gamma / E (\%)$

Energy [GeV]

- π energy vs shower depth (planes)
- Energy in scintillator [MeV]
- Plane n.

1 mip/2 mip separation

- tile 1 [n p.e.]
- tile 2 [n p.e.]

SiPMs

Module 3 (3x4x4)
Module 1 (3x2x3)
Module 2 (3x2x3)

September 2018 @ CERN-PS: response to MIP, e and π tested for a calorimeter prototype and an integrated $t_0$-layer
Positron reconstruction

Full GEANT4 simulation of the detector, validated by prototype tests at CERN during 2016-2018.

- particle propagation and decay from transfer line to detector
- hit level detector response
- pile-up effects included

Analysis chain:

- Event builder → identify the seed of the event (LCM with largest energy deposit in inner layer and of E>28 MeV). Cluster neighbour LCM deposits compatible with propagation of shower
- e/π/μ separation → multivariate analysis exploiting 19 variables (energy pattern deposition in calorimeter, event topology, and photon-veto energy deposition)
- e/γ separation → signal on the tiles of the photon veto (0-1-2 mip)

S/N = 2.1
Efficiency: 24% (dominated by geometrical efficiency)
Flux components

Assumption: 500 t neutrino detector located 50 m from the hadron dump
→ $10^4$ fully reconstructed $\nu_e$ CC in about 1.5 y of data taking

Events:
- **80%** directly monitored (positrons in the decay tunnel)
- **10%** from decay in the transfer line (straight section in front of the tagger, pointing to the detector)
  → removable with simulation
- **10%** low energy events from early decays of kaons
  → removable with energy cut.
Muon neutrinos (in progress)

High-Energy: \( K^+ \rightarrow \mu^+ \nu_\mu \), \( K^+ \rightarrow \pi^0 \mu^+ \nu_\mu \) → constrained by the tagger

Low-Energy: \( \pi^+ \rightarrow \mu^+ \nu_\mu \) → constrained by detectors following the hadron dump

\( K^+ \rightarrow \mu^+ \nu_\mu \) Efficiency = 35% S/N = 6.1

\( K^+ \rightarrow \pi^0 \mu^+ \nu_\mu \) Efficiency = 21% S/N = 6.1

- Event builder → identify seed of the event (inner layer LCM with \( E = 5-15 \text{ MeV} \)). Cluster all LCM deposits compatible with muon-track topology and propagation
- \( \mu \)-like background separation → multivariate analysis exploiting 13 variables (energy deposition, track isolation and topology)

\( \pi^+ \rightarrow \mu^+ \nu_\mu \)

Muon stations after hadron dump: pions have a large forward boost, muons from decays exit the tunnel.

Estimation of muon and neutron rates in progress → choice of detector technology
The ENUBET demonstrator

- Length ~ 3m
- Fraction of $\Phi$

Due by 2021, it will allow the containment of shallow angle particles in realistic conditions

Validation: East Area beamline at CERN
Conclusions & next steps

2016 → today:
- Simulation of the beamline
- Tested the “burst” slow extraction scheme at the CERN-SPS
- Feasibility of a purely static focusing system \((10^6 \nu_\mu^{CC}, 10^4 \nu_e^{CC}/y/500 \text{ t})\)
- Positron reconstruction: single particle level monitoring
- Testbeams campaign before LS2

Reduction of the uncertainty in the flux
→ New generation of short-baseline experiments
→ Support from the European Strategy
Conclusions & next steps

- The design phase is over
- The simulations are nearly completed

2020 ✔

Work in progress

- Horn optimization
- Update of flux and spectra with the final beamline
- Establish the final systematic budget

2021 ✔

Construction of the demonstrator
- Full assessment of systematics

2022 ✔

- Test of the demonstrator
Thank you!

http://enubet.pd.infn.it/