The NP06/ENUBET project: towards a monitored neutrino beam

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Marta Torti (Univ. and INFN Milano Bicocca)

on behalf of the ENUBET Collaboration

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Enhanced NeUtrino BEams from kaon Tagging

ENUBET goal: demonstrate the technical feasibility and physics performance of a neutrino beam where lepton production at large angle is monitored at single particle level
→ Monitored neutrino beams

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: 62 physicists & 13 institutions; Spokespersons: A. Longhin, F.Terranova; Technical Coordinator: V. Mascagna.

The NP06/ENUBET project

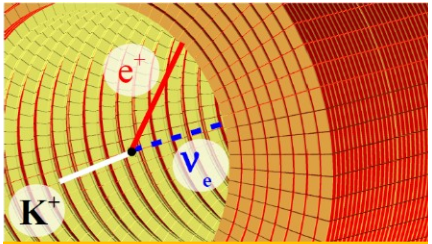
- The uncertainty on the neutrino flux is the main source of systematic error for cross section measurements.
- Need high-precision determination of ν_e and ν_μ cross section at the energy of interest for DUNE and HyperK to reduce substantially the systematics of long-baseline experiments → Increase the sensitivity to oscillation parameters, in particular, the CP violating phase δ .
- The other source of systematic uncertainty for cross section measurements is the reconstruction of the neutrino energy, biased by the inaccurate reconstruction of the final state particles.

- Conventional facility where we monitor the decays in which neutrinos are produced event-by-event.
- "By-pass" uncertainties from hadro-production, beamline effciency, POT.
- Reduce the uncertainty on the flux of ν_e and, possibly, ν_μ below 1%.
- ENUBET is a very narrow band beam (5-10% momentum bite) → Strong correlation between the energy of each ν and its interaction vertex due to kinematics.
- Narrow band off axis technique method → Reconstruction of the energy in the neutrino detector without relying on final state particles.
- Neutrino energy known at 10-20% level → Ideal tool to study neutrino interactions in nuclei.

NP06/ENUBET - Monitored neutrino beam

Monitored ν beam
measure rate of leptons <-> monitor ν flux
A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

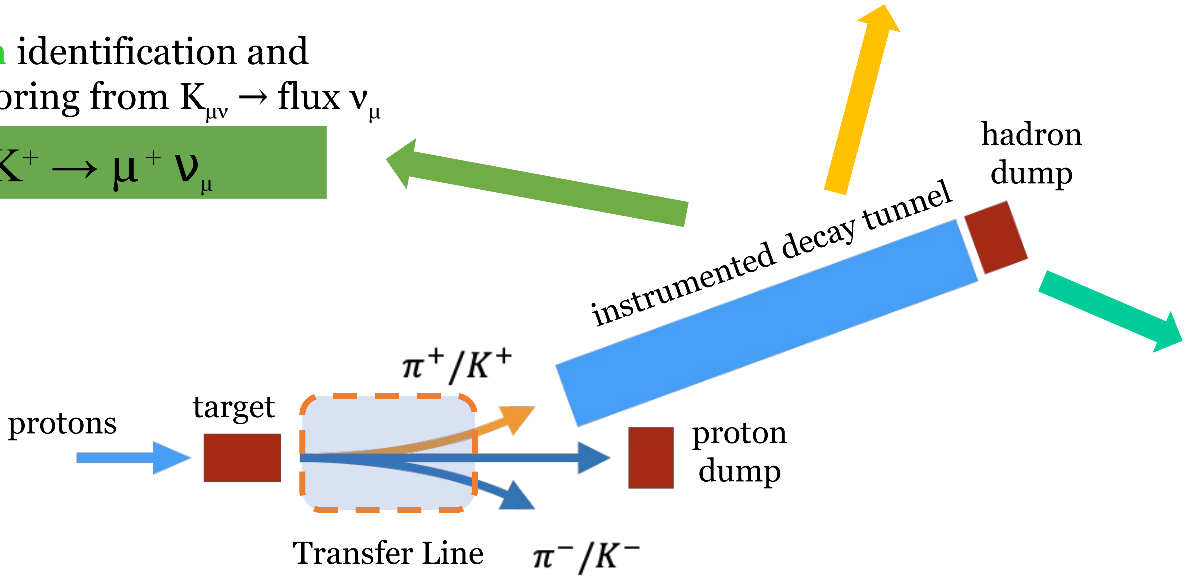
measure **positrons** from $K_{e3} \rightarrow$ flux ν_e



$K^+ \longrightarrow \pi^0 e^+ \nu_e$

Muon identification and monitoring from $K_{\mu\nu} \rightarrow$ flux ν_μ

$K^+ \longrightarrow \mu^+ \nu_\mu$



Muon monitoring at single particle level replacing the hadron dump with a range meter from $\pi_{\mu\nu} \rightarrow$ flux ν_μ

$\pi^+ \longrightarrow \mu^+ \nu_\mu$

Many systematics are bypassed monitoring the leptons in the decay tunnel at single particle level

Beamline and accelerator studies

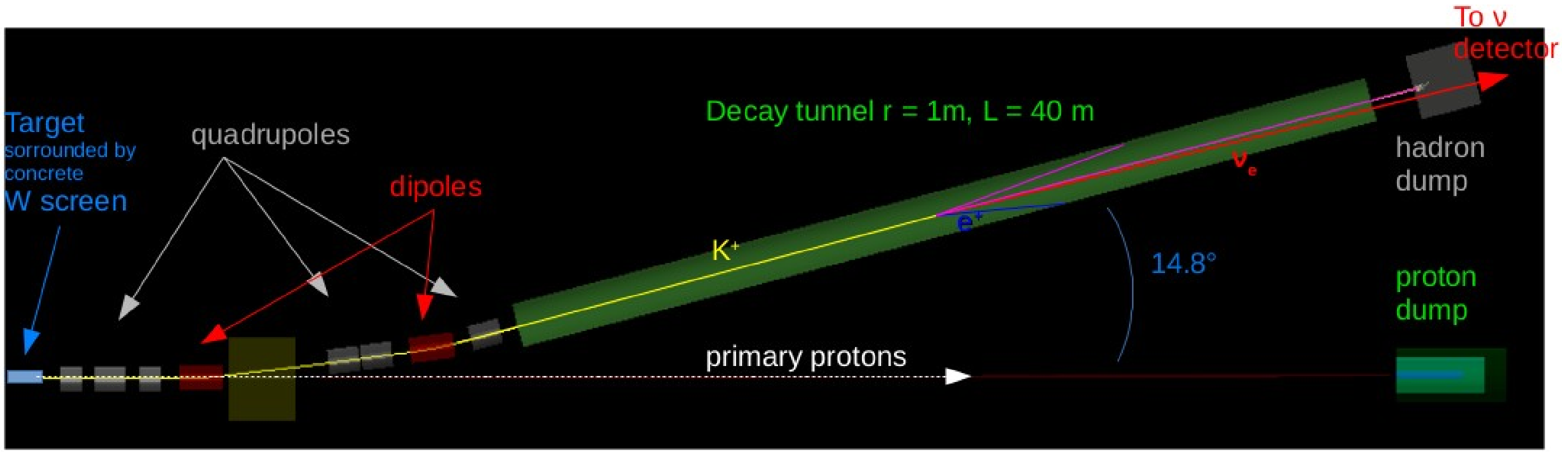
- **Conventional beamline** where the pions and kaons are produced by protons on a fixed target.
  Mean energy of the hadrons selected = 8.5 GeV.

- Selected particles are transported to the decay tunnel that is located off the axis of the proton beam.

- 40 m long **decay tunnel instrumented** with calorimeters along its wall to monitor the leptons → K_{e3} decays become the only source of ν_e : ~ 97% of the overall ν_e flux.
  K_{e3} positrons emitted at large angles → hit the walls of the instrumented tunnel.

- Two possible **focusing** design are pursuing:
  - a purely static system with quadrupoles placed directly downstream the ENUBET target → works with a proton "slow extraction" method;
  - horn-based beamline with a focusing magnetic horn between the target and the transferline → needs a proton "fast extraction" method.

The static ENUBET beamline

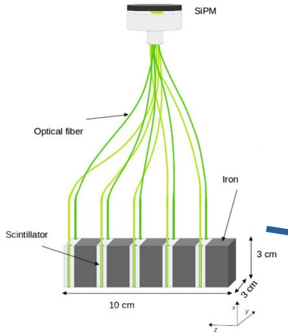


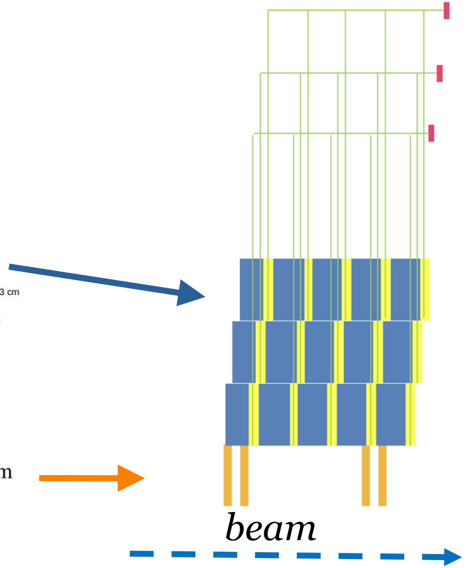
- Proton drivers: CERN (400 GeV), FNAL (120 GeV), J-PARC (30 GeV) .
- Target: Graphite, 70 cm long and with a radius of 3 cm → selected after dedicated studies.
- Positron screen: 10 mm Tungsten foil downstream the target. Get rid of the beam e^+ background in the tagger.
- Transfer line
  - Kept short to minimize early K decays;
  - Small beam size: non-decaying particles must exit the decay tunnel without hitting the tunnel walls;
  - Optics: optimized with TRANSPORT to a 10% momentum bite centered at 8.5 GeV/c.
- Focusing system: normal-conducting magnets (quadrupoles and two bending dipoles). Total bending of the beam w.r.t the primary proton line of 14.8°.
- Particle transport and interaction: full simulation with G4Beamline.
- Hadron dump and Proton dump with cilindrical structure. Engineering studies needed to define them.

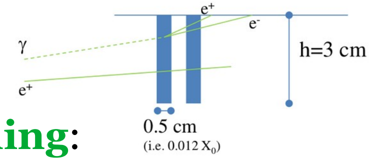
Decay tunnel instrumentation - schematics

Calorimeter with e/π/μ separation capabilities:

- Lateral readout Compact Module (LCM):
  - sandwich of 5 steel tiles (3x3x1.5 cm^2) interleaved with 5 plastic scintillator tiles (3x3x0.5 cm^2);
  - longitudinal segmentation;
  - SiPM active area: 4x4mm^2 , Cell size: 40 μm ;
- three radial layers of LCM.
- Each LCM has 10 WLS (1mm) fibers coupled with SiPM.







Photon-Veto (t_0-layer) allows π^0 rejection and timing:

- plastic scintillator tiles arranged in doublets forming inner rings (3x3x0.5 cm^2 mounted below the LCM);
- time resolution of ~400 ps.

Exploit event topology for PID

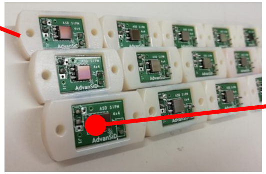
e^+ (signal) topology

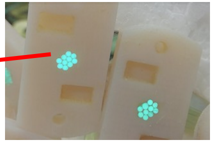
π^0 (background) topology

π^+ (background) topology

Decay tunnel instrumentation – prototype test results

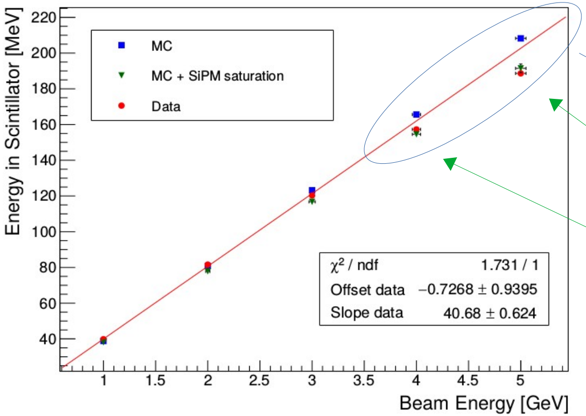
Prototype of 84 LCM tested in 2018 @ CERN PS-T9





Large SiPM area for 10 WLS readout (1 LCM)

- 7 planes on a 3x4 matrix (transverse dim 12x9 cm²) → 30 X_0 , 3.15 λ_0. Containment of em showers up to 5 GeV ;
- Tests with beam of e^- , μ^- and π^- , with momentum [1-5] GeV ;
- Angles tested w.r.t beam direction (mimic K_{e3} positron): 0, 50, 100, 200 mrad.



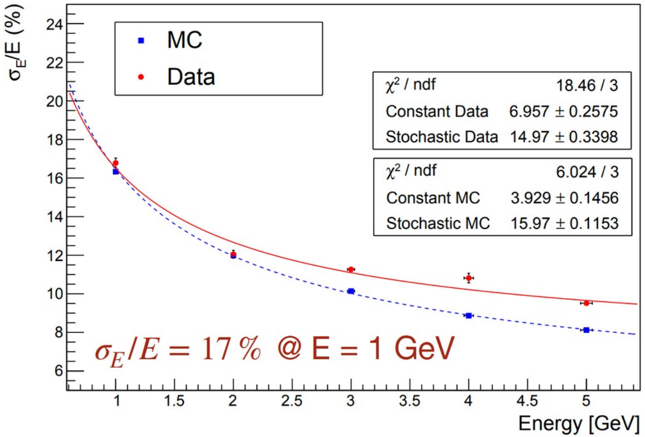
Reconstructed Energy: Data/MC comparison at 100 mrad

SiPM saturation effect ($P_{cross\text{-}talk}$ ~44%)

Dedicated measurment campaign at INFN lab → MC corrected for the effect, accounts for non-linearities

Decay tunnel instrumentation – prototype test results

Energy Resolution at 0 mrad



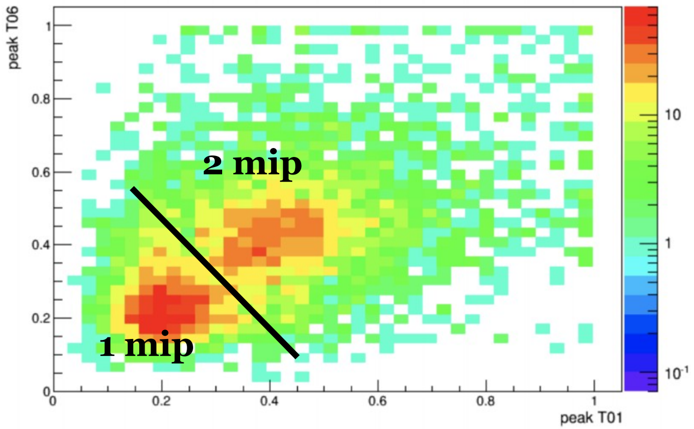
- Fit $\sigma_E/E = S/\sqrt{E(GeV)} \oplus C$;
- 17% energy resolution at 1 GeV ;
- impact point of the particle affects contribution to saturation at higher energies: particles near the edge of the tile are shared between adjacent LCM → lower contribution to saturation than those in the center;
- mean energy deposited by π^- in each plane of the calorimeter from data evaluated and compared to simulation: discrepancy below 10% and comparable to uncertainty due to low-energy hadronic shower simulation.

Photon veto detector

t_0-layer needs: γ ID capability and precise timinig

→ Positrons of K decays in ENUBET cross 5 tiles on average

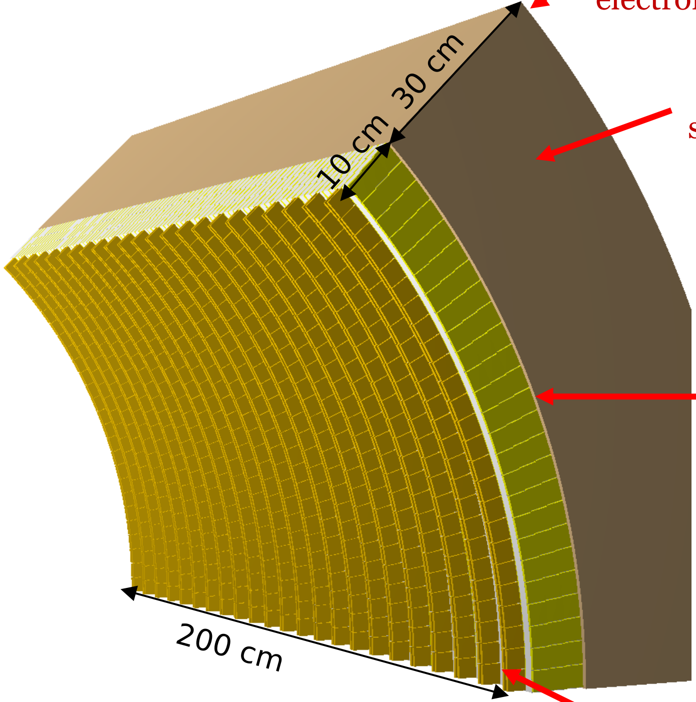
- 1-mip/2-mip separation: 1-mip signal with ε =87%
- Background rejection ε =89% (2-mip like), 95% Purity
- Time resolution ~ 400 ps

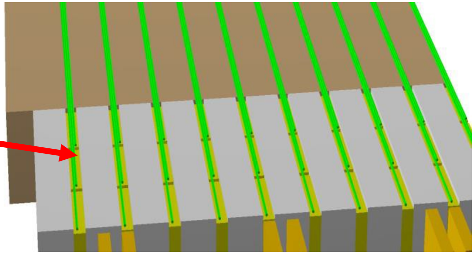


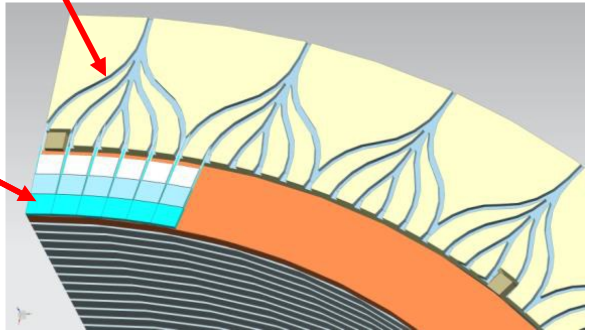
F. Acerbi et al, JINST (2020), 15(8), P08001

The demonstrator

- Build the prototype (1.65 m long and 90° angle coverage) to demonstrate performance, scalability and cost-effectiveness;
- Will be tested at the CERN on 2022.







The demonstrator

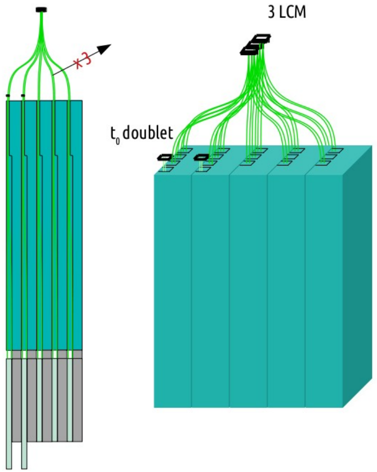
Several activities currently on-going towards the test of the demonstrator.

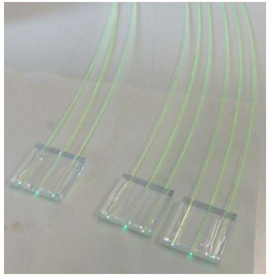
- Large scale production of the scintillators (UNIPLAST Moscow & INR). Total number of scintillator tiles for the demonstrator will be ~10000.

- Improved light readout scheme completely validated by GEANT4 optical simulation → distance between fibers optimized to achieve best possible light collection and uniformity.

- Effciency map measurement of tiles with similar final shape at INFN-Bologna with a cosmic ray tracer.

- **ENUBINO**: pre-demonstrator small prototype = 3 LCMs is being assembled and will be soon characterized with cosmics at INFN-LNL.





Lepton reconstruction and identification

The PID is performed by the energy pattern in the modules and by the photon veto. The event selection is based on 19 variables employed by a Neural Network.

Full GEANT4 simulation reproducing the detectors in the decay tunnel:

Signal in

calorimeter + photon veto

stations after the hadron dump

Monitoring of

- positrons from $K_{e3} \rightarrow \nu_e$
- muons from $K_{\mu 2}$ and $K_{\mu 3} \rightarrow \nu_\mu$

- muons from π decay $\rightarrow$ low-E ν_μ

Lepton reconstruction and identification

K_{e3} positron reconstruction to constrain ν_e

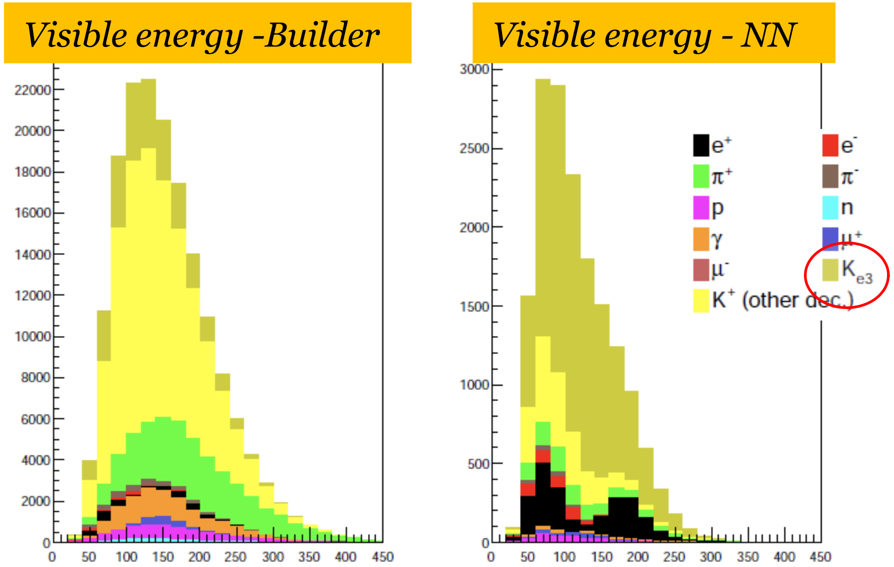
Full GEANT4 simulation of the detector: validated by prototype tests at CERN in 2016-2018; hit-level detector response; pile-up effects included (waveform treatment in progress); event building and PID algorithms (2016-2020).

Analysis chain:

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

2. e/μ/π/γ 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 = 22% (~half of efficiency loss is geometrical)



K_{e3} BR ~5% and K make ~5 − 10% of beam composition

F. Pupilli et al., PoS NEUTEL2017 (2018) 078

Lepton reconstruction and identification

$K_{\mu 2}$ and $K_{\mu 3}$ muon reconstruction to constrain high energy ν_μ

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.

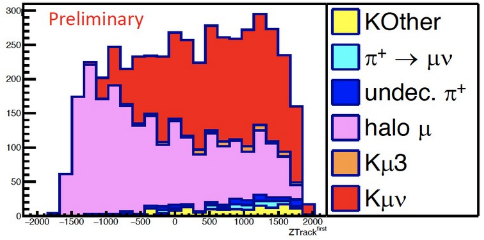
Analysis chain:

1. Event builder: start from event seed and cluster energy deposits compatible, in space and time, with a track from a muon;

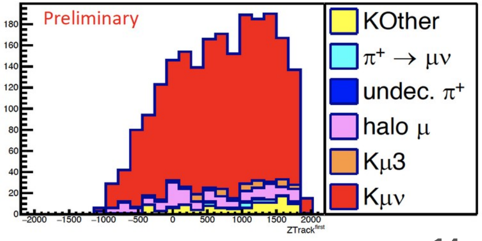
2. μ-like background separation: multivariate analysis (MLP-NN from TMVA) exploiting 13 variables (energy pattern, track isolation and topology);

Analysis performance
S/N = 6
Efficiency = 34% (~half of efficiency loss is geometrical)

Tagger impact point - Builder



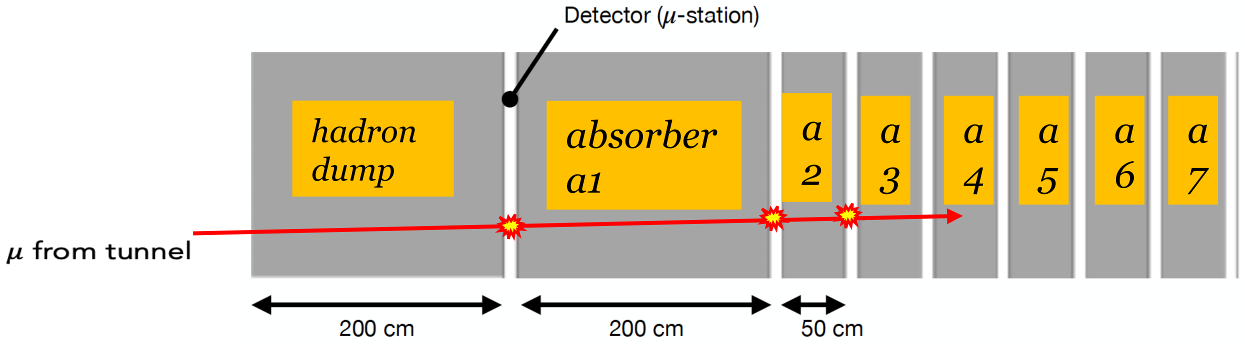
Tagger impact point - NN



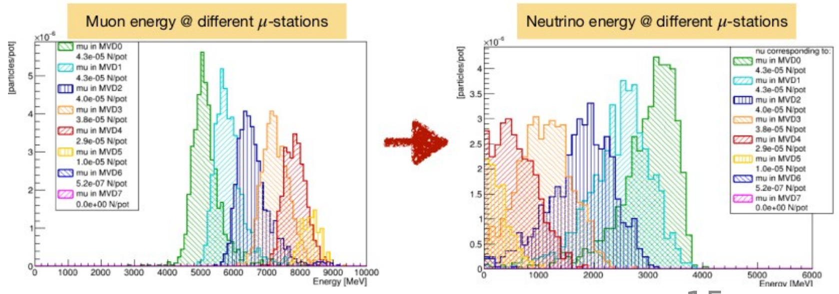
Lepton reconstruction and identification

$\pi_{\mu 2}$ muon reconstruction to constrain low energy ν_μ

Low-E ν_μ from π decays can be constrained by monitoring associated μ emitted at low angle and go through the tunnel and the hadron dump.
Instrumented hadron dump with detector layers interleaved by absorber

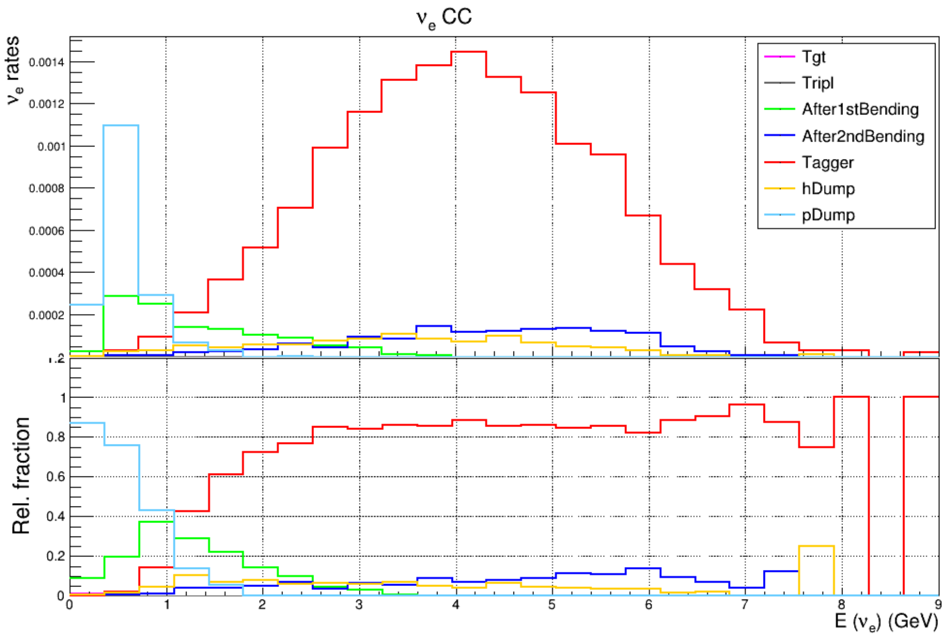


Exploit:
- correlation between number of traversed stations (muon energy from range-out) and neutrino energy;
- difference in distribution to disentangle signal from halo- muons.
- Detector technology: constrained by muon and neutron rates.



Physics performance – ν_e

- At nominal SPS 4.5 10^{19} POT/year 10^4 ν_e CC at a 500 ton neutrino detector located 50 m from the tunnel exit in about 2 years of data taking.
- The neutrinos coming from the decay tunnel are clearly separated in energy from those generated in the proton dump and in the first section of the beamline.



- 73.5% of the total ν_e flux generated inside the tunnel and more than 80% above 1 GeV.
- Below 1 GeV main component is produced in the proton-dump region → further improve the separation against it by optimizing the proton dump position.
- 12% given by the straight section in front of the tagger → corrected for by relying on the simulation.

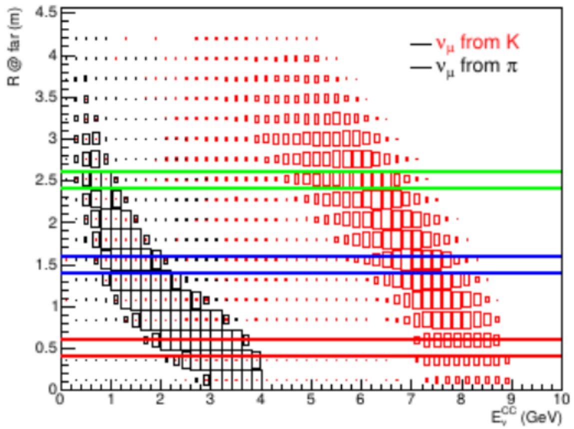
Physics performance – ν_μ

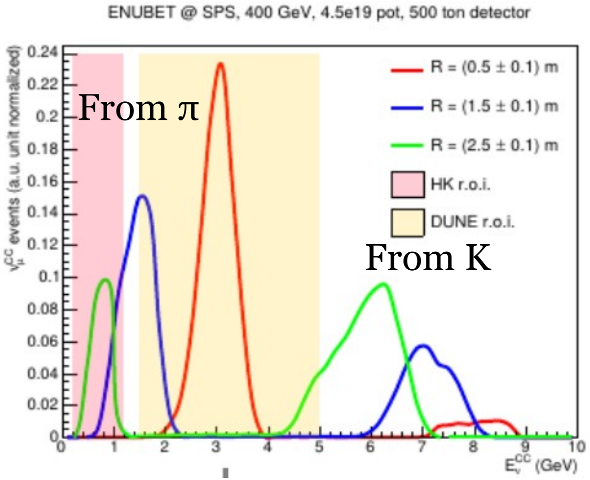
Narrow momentum width of the beam (O(5-10%)) and small neutrino detector distance.

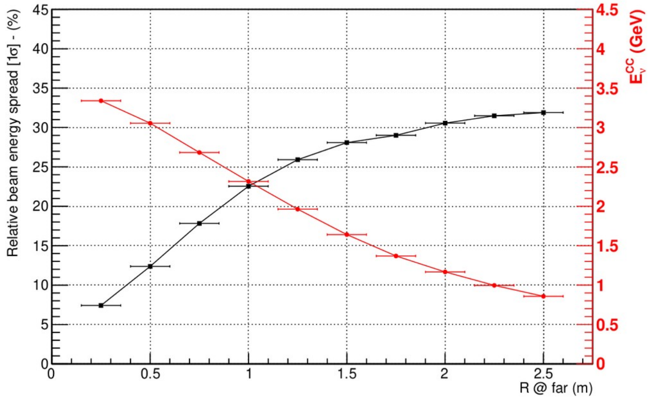
→ Strong correlation between E_ν in the detector and the radial distance (R) of the interaction vertex from the beam axis.

→ **Narrow-band off-axis technique** where the E_ν is provided event-by-event basis without relying on a final state particles in ν_μ CC.

- By selecting interactions in radial windows of ± 10 cm, we collect respective samples of ν_μ CC events.
- Loose energy cut enough to separate π/K component.
- Width of pion peak at different R → estimator of the precision on E_ν .
- 8% to 25% at DUNE energy.







F. Acerbi et al., CERN-SPSC-2018-034

Conclusions

- The ENUBET project is an ERC Consolidator Grant, extended to 2022, and part of the Neutrino Platform experiments at CERN (NP06) that is aiming at the realization of the first monitored neutrino beam.
- ENUBET is on schedule: the design phase is over, the simulation are nearly completed, and we are going to build the demonstrator, that will be tested in 2022 at CERN.
- The physics performance are appealing, but we have to go through for complete studies.
- Conceptual Design Report at the end of the project (2022).

We look forward to seeing ENUBET up and running
in the DUNE/HyperK era!