The ENUBET neutrino beam

ENUBET is

- a narrow band beam at the GeV scale with a **superior control of the neutrino flux**, flavor and energy of the neutrinos produced at source

It is designed for

- a new generation of short-baseline experiments and a 1% precision measurement of the ν_e and ν_μ **neutrino cross sections**

We present at ICHEP 2018

- the first **end-to-end simulation of the ENUBET beamline**
- the updated physics performance
- the latest results on the design and construction of the beamline instrumentation

F. Terranova (Univ. of Milano-Bicocca and INFN)
on behalf of the ENUBET Collaboration

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).

A narrow-band beam for the precision era of ν physics

Absolute flux of ν_e and ν_μ at the 1% level

↓

Remove the leading source of uncertainty in **neutrino cross section measurement**

Energy of the neutrino known at the 10% level

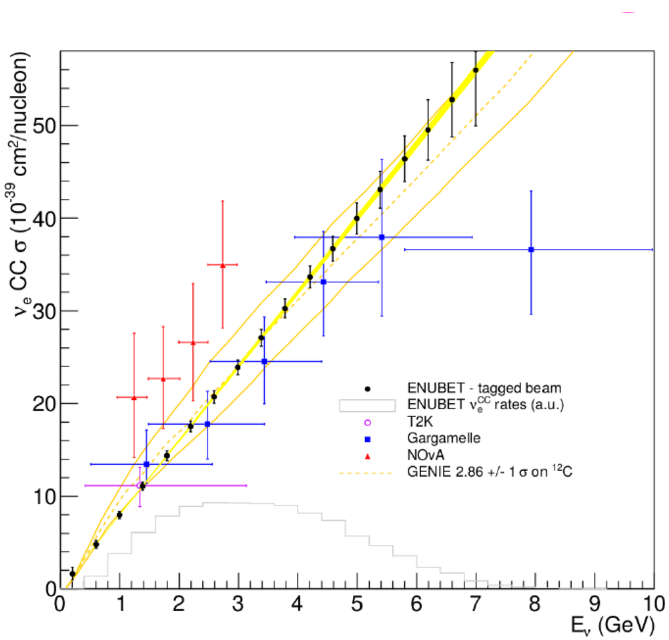
↓

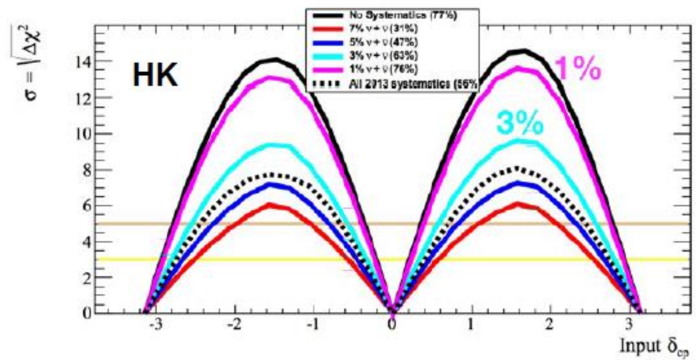
The ideal tool to study neutrino interactions in nuclei

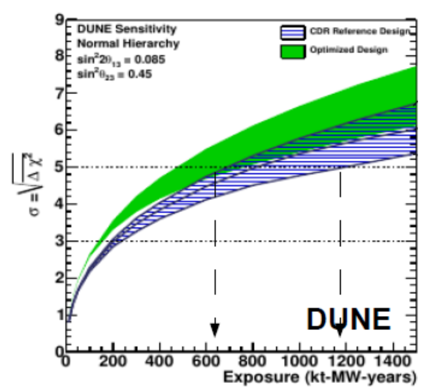
Flavor composition known at the 1% level

↓

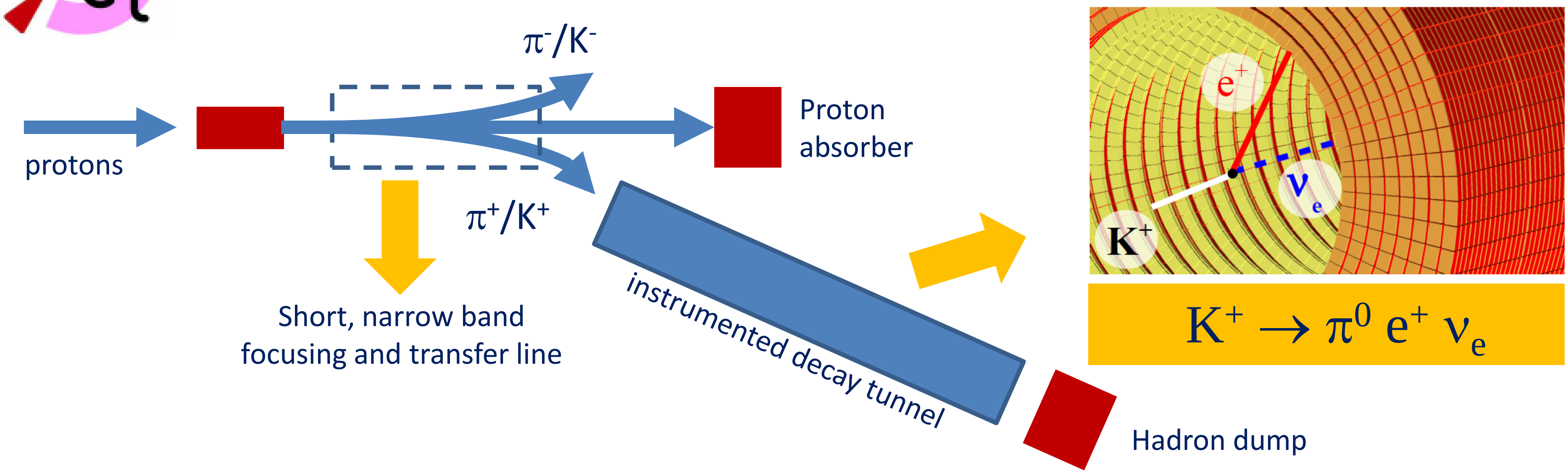
The ideal tool to study NSI and sterile neutrinos at the GeV scale







ENUBET

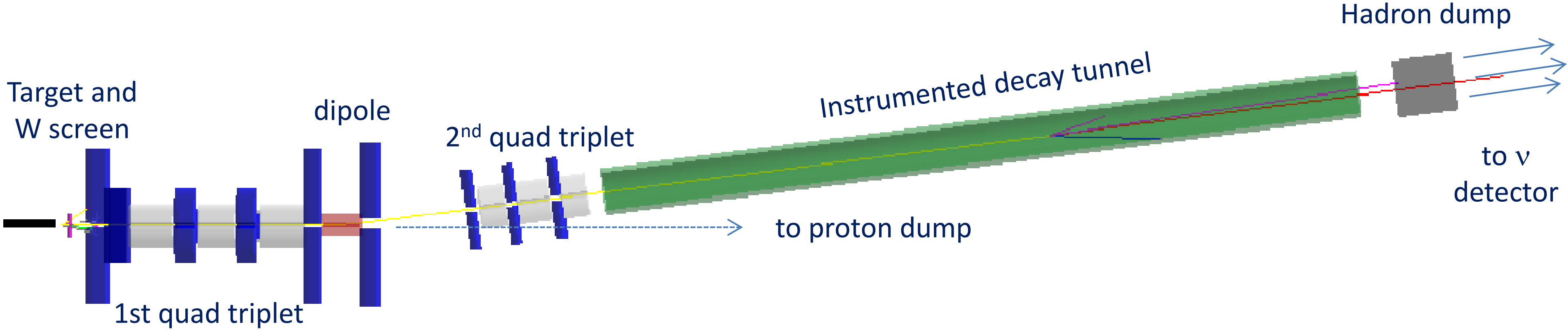


Goal: demonstrate the technical feasibility and physics performance of a neutrino beam where **lepton production at large angles is monitored at single particle level** $\Rightarrow$ direct measurement of the flux

ERC Consolidator Grant. From Jun 2016 to May 2021. PI: A. Longhin

The ENUBET Collaboration: 52 physicists, 11 institutions

The ENUBET beamline



- Proton driver: CERN SPS (400 GeV), Fermilab Main Ring (120 GeV), JPARC (30 GeV)
- Target: 1 m Be, graphite target. FLUKA 2011 (+check with hadro-production data)
- 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:
  - Optics: optimized with TRANSPORT to a 10% momentum bite
  - Particle transport and interaction: full simulation with G4Beamline
  - All normal-conducting, numerical aperture <40 cm, Two quadrupole triplet, one bending dipole
- Decay tunnel
  - Radius: 1m. Length 40 m [re-optimized after beam envelope determination]
  - Low power hadron dump at the end of the decay tunnel
- Proton dump: position and size under optimization (in progress)

Yields (ref: CERN SPS, 400 GeV)

Focusing system	π/pot (10^{-3})	K/pot (10^{-3})	Extraction lenght	π/cycle (10^{10})	K/cycle (10^{10})	Proposal [c]
Horn	97	7.9	2ms [a]	438	36	x2
No horn	19	1.4	2 s [b]	85	6.2	**x5**

(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle: this extraction scheme is currently under test at CERN
(b) Slow extraction. Detailed performance and losses currently under evaluation at CERN
(c) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

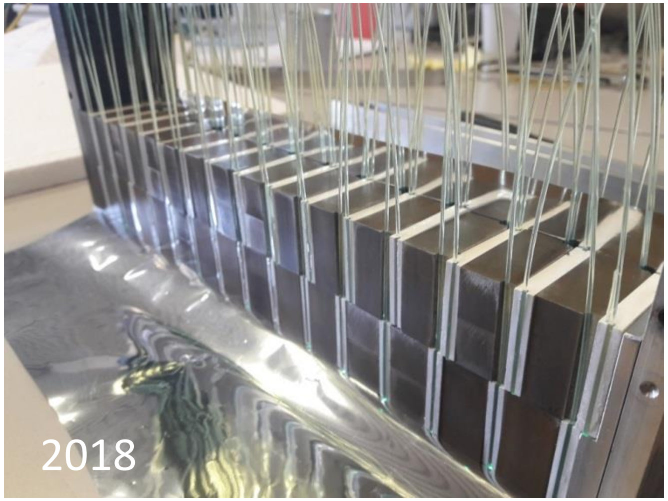
Advantages of the static extraction:

- No need for fast-cycling horn
- Strong reduction of the rate in the instrumented decay tunnel
- Possibility to monitor the muon rate after the dump at 1% level (flux of ν_μ from pion decay) [**NEW: under evaluation**]
- Pave the way to a «tagged neutrino beam», namely a beam where the neutrino interaction at the detector is associated in time with the observation of the lepton from the parent hadron in the decay tunnel

Instrumentation of the decay tunnel

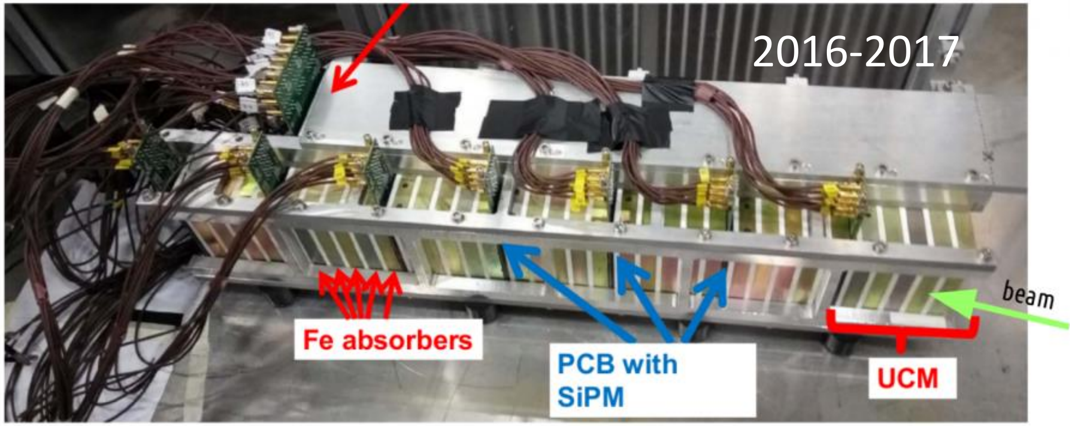
$e^+/\pi^+/\mu$ separation

Longitudinally segmented calorimeters
- 5-layer shashlik option (Proposal)
- 3-layer with lateral readout of light

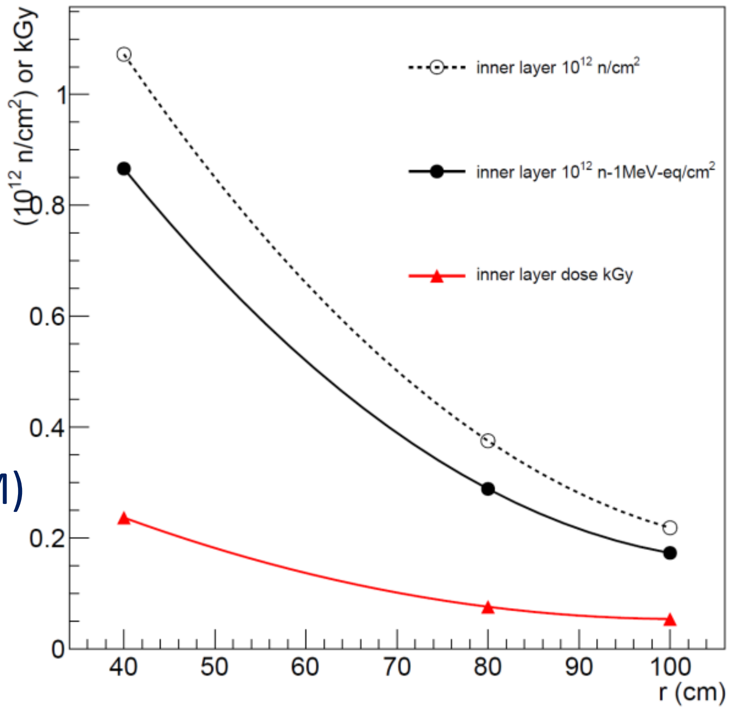


e^+/γ separation

Rings of 3 x 3 cm^2 pads of plastic scintillator located in the innermost part of the calorimeter **(photon veto)**



Full evaluation of doses performed in 2017
Design optimized for these doses
Granularity: 3x3x10 cm^3 «Ultra Compact Modules» (UCM)



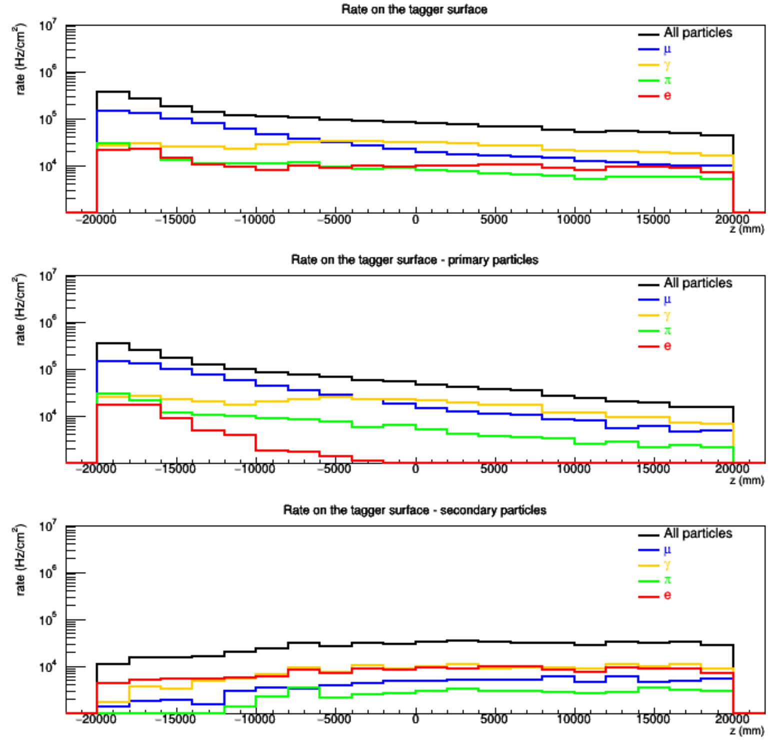
G. Ballerini et al., JINST 13 (2018) P01028

A. Coffani et al., arXiv:1801.06167

Particles in the decay tunnel

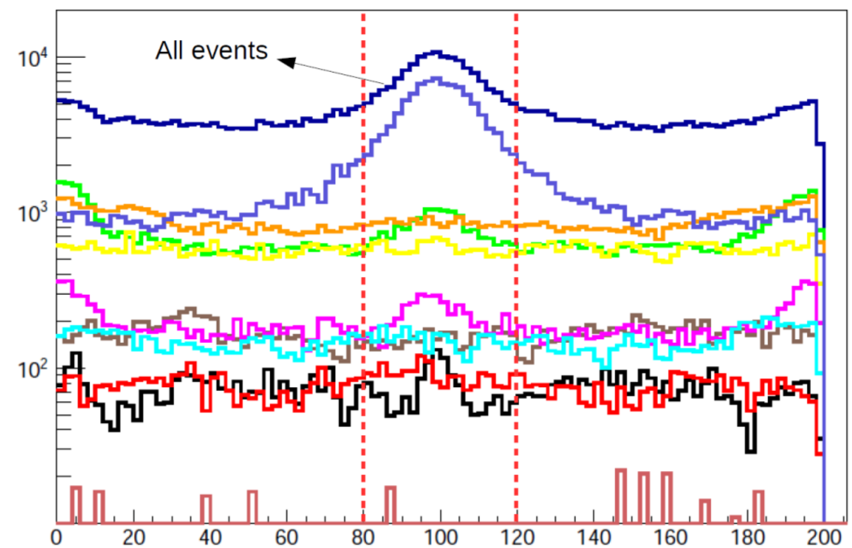
Static focusing system, 4.5 10^{13} pot in 2 s (400 GeV)

Calorimeter 1 m from the axis of the tunnel (ρ_{inner}=1.00 m)
Three radial layers of UCM (ρ_{outer}=1.09 m)

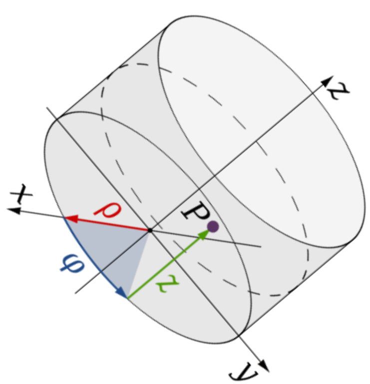


Rate as a function of the longitudinal position z in the tunnel

Rate as a function of the azimuthal angle φ in the tunnel



φ (deg)



Positron identification from K decay

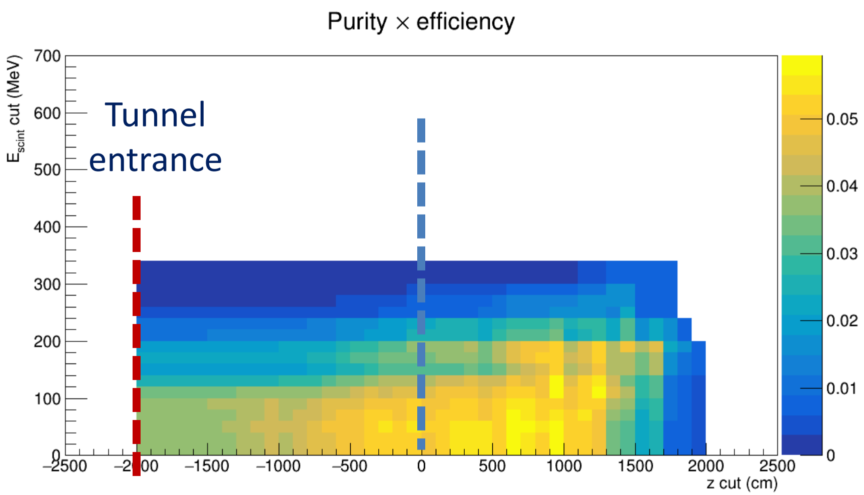
Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018. The simulation include particle propagation and decay, from the transfer line to the detector, hit-level detector response, pile-up effects.

Analysis chain

Event Builder → Identify the seed of the event (UCM with large energy deposit) and link neighboring modules

e/π/μ separation → (**Neural Network**) TMVA multivariate analysis based on 5(+6) variables (pattern of the energy deposition in the calorimeter)

e/γ separation → Signal on the tiles of the photon veto



after E and z-cut

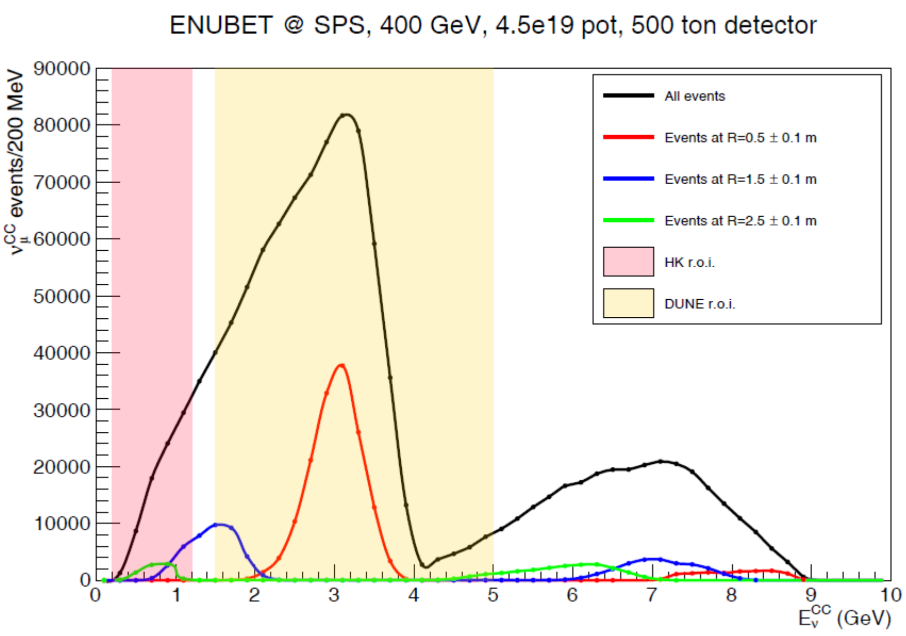
ε_{geom}	**0.36**
ε_{sel}	0.55
ε_{tot}	0.20
purity	0.26
S/N	0.36

S/N: φ-cut → **0.46**

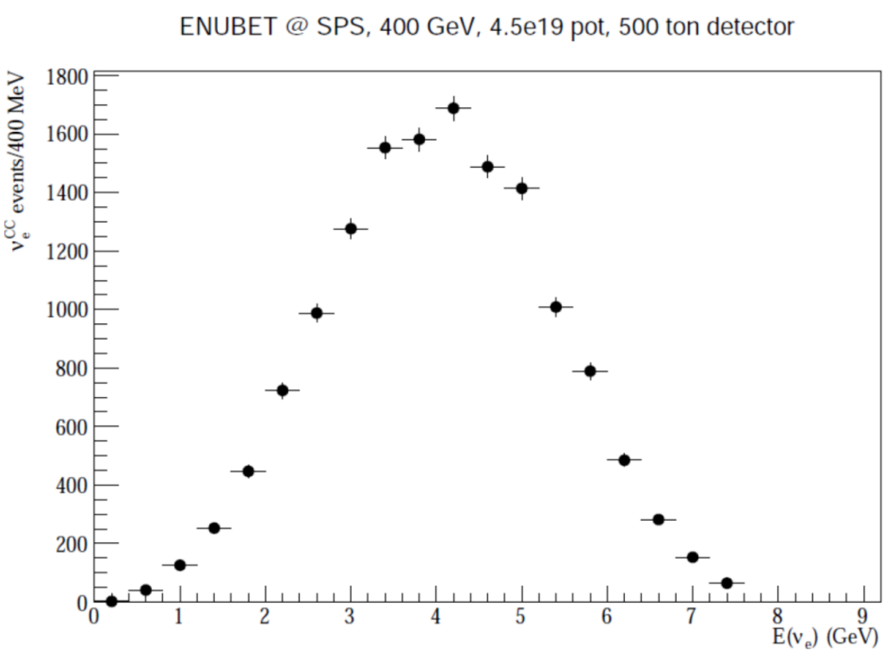
Instrumenting half of the decay tunnel we identify positrons from K decay at single particle level with a S/N = 0.46

Neutrino events per year at the detector

Detector mass: 500 tons (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab)
Baseline (i.e. distance between the detector and the beam dump) : 50 m
Integrated pot: 4.5 10^{19} at SPS (6 months in dedicated mode, ~1 year in shared mode) or, equivalently, 1.5 10^{20} pot at the Fermilab Main Ring.
Warning: detector response not simulated!



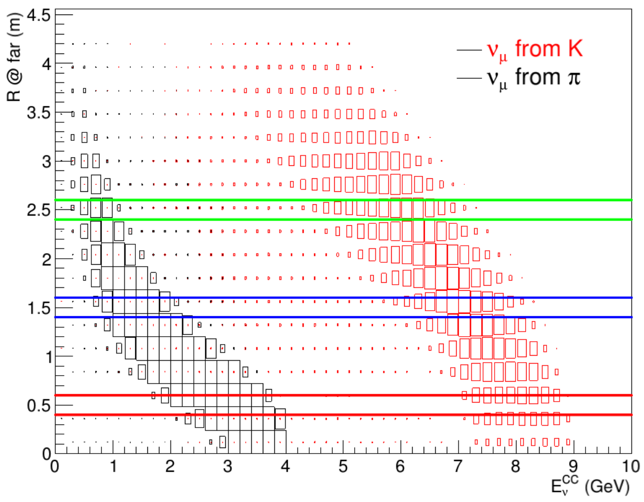
1.2 10^6 ν_μ charged current events per year

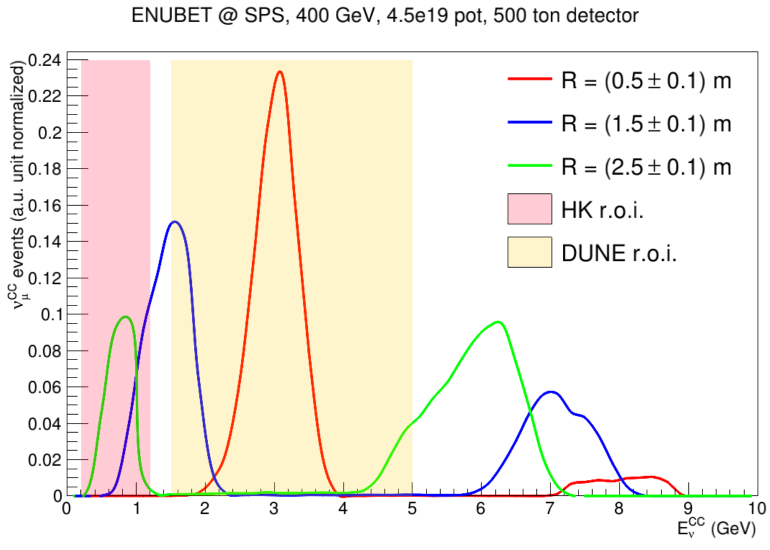


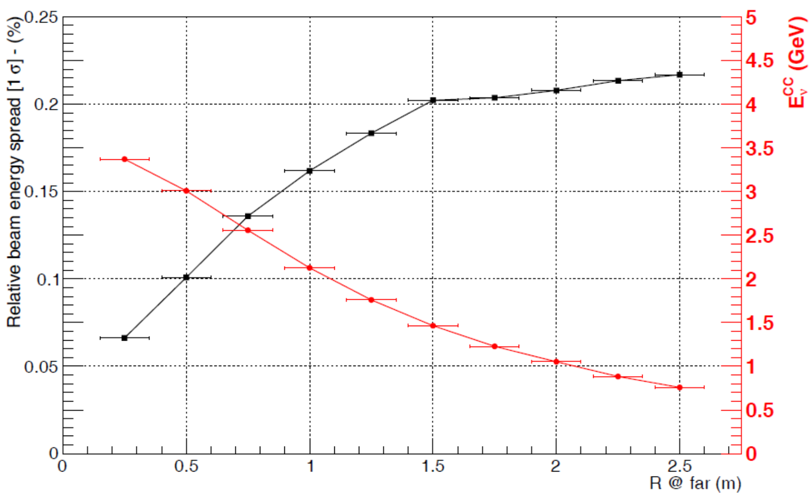
1.4 10^4 ν_e charged current events per year

ν_μ CC events at the ENUBET narrow band beam

The neutrino energy is a function of the distance of the neutrino vertex from the beam axis (R). The beam width at fixed R (≡ neutrino energy resolution at source) is 8-22%







Conclusions

- ENUBET is a narrow band beam with a high precision monitoring of the flux at source (1%), neutrino energy (20% at 1 GeV $\rightarrow$ 8% at 4 GeV) and flavor composition (1%)
- In the last year, we
  - provided the first **end-to-end simulation** of the beamline
  - proved the feasibility of a **purely static focusing system** (10^6 ν_μ CC per year, 10^4 ν_e CC per year with a 500 ton detector)
  - identified the best options for the instrumentation of the decay tunnel (shashlik and lateral readout: final decision in 2019)
  - completed the **full simulation of the positron reconstruction**: the results confirm that monitoring at the single particle level can be performed with S/N = 0.5
- We are proceeding toward the Conceptual Design (2021) that will include the full assessment of the systematics, the monitoring of the other decay modes of K and of pions, the outline of the physics performance for cross-section measurement and cost estimates

The ENUBET technique is very promising and the results we got in the last twelve months exceeded our expectations.

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