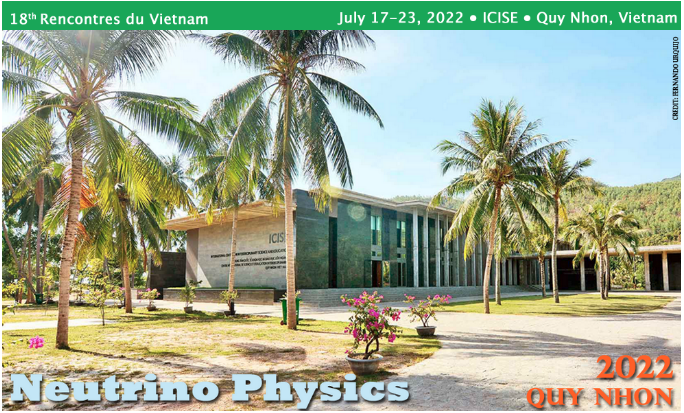
The NP06/ENUBET Project

M. Pari (University and INFN Padova)
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).

Overview

Accelerator neutrino beams

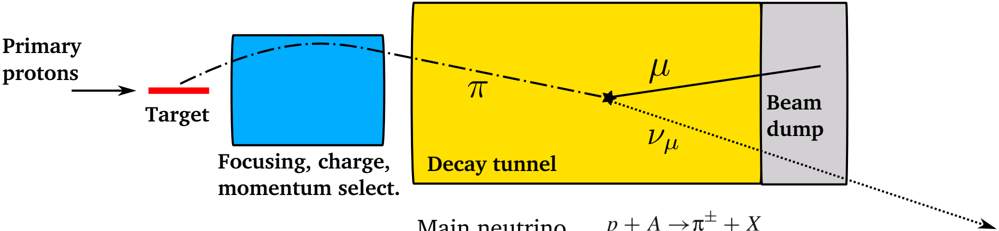
Particle accelerators are used to generate a controlled neutrino flux. Unlike other neutrino sources:

- → Control of neutrino energy
- → Control of source-detector distance

Typical neutrino energies of 1-20 GeV
Typical source-detector distances of 1-100 km

Next generation long-baseline experiments (DUNE, HyperK):

- Neutrino mass hierarchy
- Leptonic CP violation
- Test of 3-neutrino paradigm



Main neutrino production channel:

$$p + A \rightarrow \pi^{\pm} + X$$
$$\hookrightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu/\bar{\nu}_\mu$$

Overview

Accelerator neutrino beams: limitations

Neutrino flux estimation for conventional neutrino beams is a complex task:

- → Extensive simulations
- → Dedicated hadro-production data
- → Short baseline flux measurements
- → Muon monitoring at the beam dump

Leading to an **overall flux uncertainty of ∼ O(10%)**

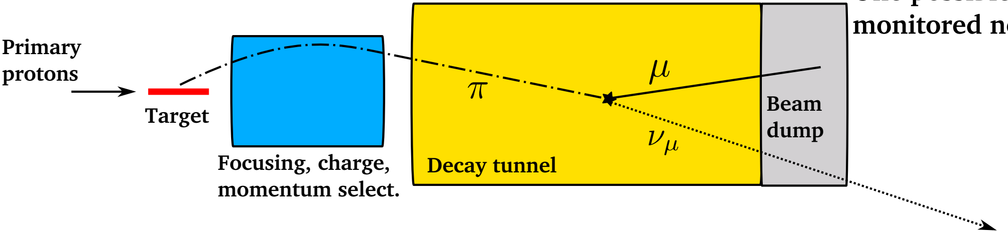
Next generation long-baseline experiments (DUNE, HyperK):

- Neutrino mass hierarchy
- Leptonic CP violation
- Test of 3-neutrino paradigm

Considerable increase of precision required

$$N_{\nu_e} = P_{\nu_\mu \to \nu_e} \cdot \sigma_{\nu_e} \cdot \Phi_{\nu_\mu}$$

One possible approach: monitored neutrino beams



Overview

The ENUBET project: Enhanced NeUtrino BEams from kaon Tagging

ERC grant 2016-2022

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).

CERN Neutrino Platform experiment NP06/ENUBET 2019-2024

The ENUBET Collaboration: 60 Physicists, 13 Institutions

Goal:

Design of a monitored neutrino beam

↓

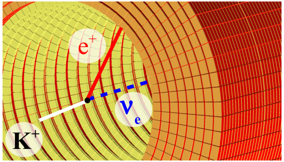
Reduction of neutrino flux systematics at the 1% level (additional: energy at 10%)

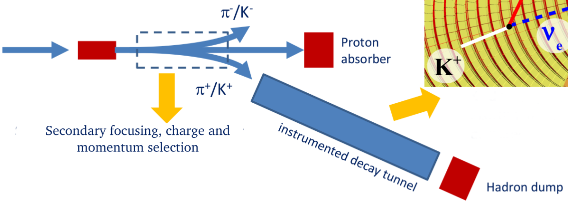
↓

Opening for high precision cross section measurement (1%)

Concept of monitored neutrino beam:

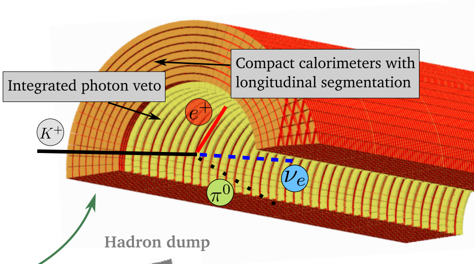
- Decay tunnel fully instrumented
- Direct estimation of neutrino flux from production vertex particles
- Bypassing high uncertainty hadro-production based flux extimation

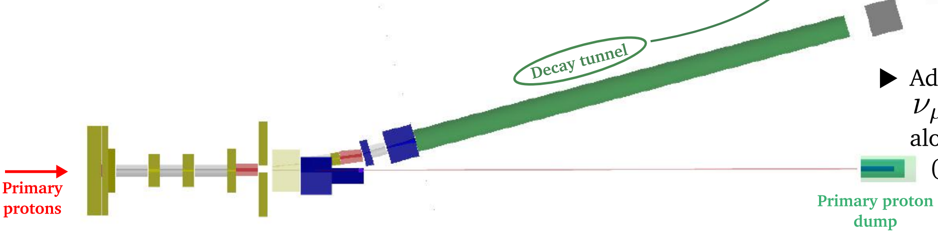




The ENUBET project

- Beamline (baseline option): **narrow band** beam at **8.5 GeV/c** secondaries with a **5-10% momentum bite**
- [*] $\mathbf{K_{e3}}$ $\mathbf{(K^+ \longrightarrow \pi^0\, e^+\, \nu_e)}$ **main source of positrons** at the decay tunnel walls: possibility of **direct estimation of ν_e flux**
- Muons at decay tunnel mainly from $\mathbf{K}_{\mu 2}\,(\mathbf{K}^+ \longrightarrow \mu^+\nu_\mu)$ and $\mathbf{K}_{\mu 3}$: increased precision on $\nu_{\mu_\mathbf{K}}$ and $\nu_\mathbf{e}$ flux





- Additional information on $\nu_{\mu\pi}$ from muon monitors along hadron dump (range-meter)

PIMENT project

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

The ENUBET project

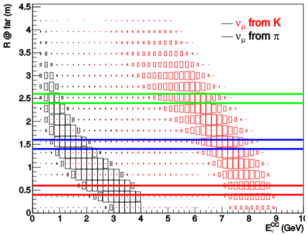
- Beamline (baseline option): **narrow band** beam at **8.5 GeV/c** secondaries with a **5-10% momentum bite**

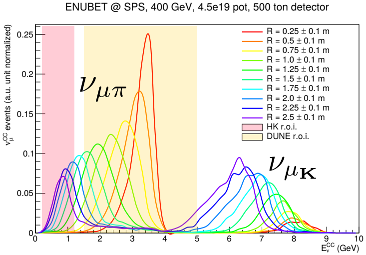
→ **Narrow-Band Off-Axis (NBOA) technique** [*]

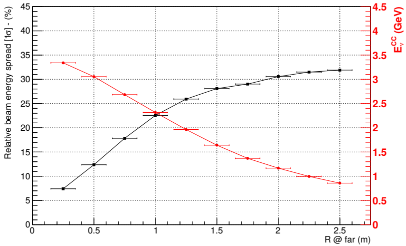
- Full energy separation of ν_{μ_K} and $\nu_{\mu\pi}$ components
- Direct angle-momentum correlations from two-body decays

Current E resolution (from pions)
- 8-25% in DUNE energy range
- 30% in HK energy range (work in progr. for alternative BL)

Estimation of neutrino energy from impact radius @detector

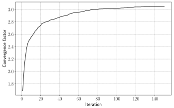


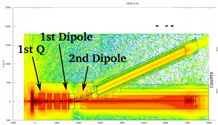


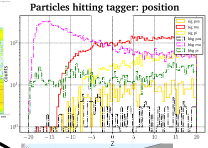


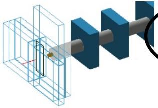
[*] F. Acerbi et al., CERN-SPSC-2021-013

The ENUBET project

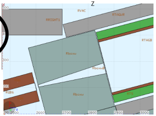


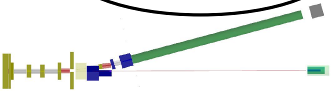


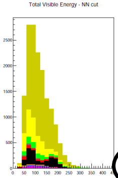


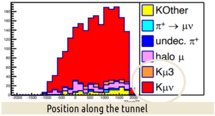


Beamline design and simulation

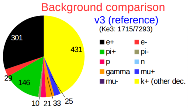


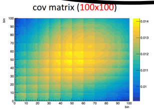


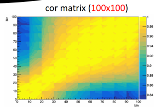


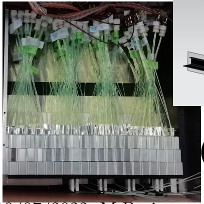


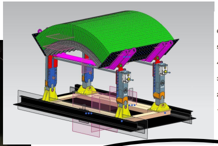
Assessment of systematics and performance

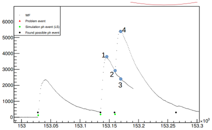




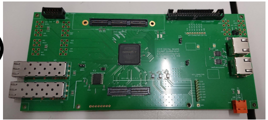








Detector developement and characterization



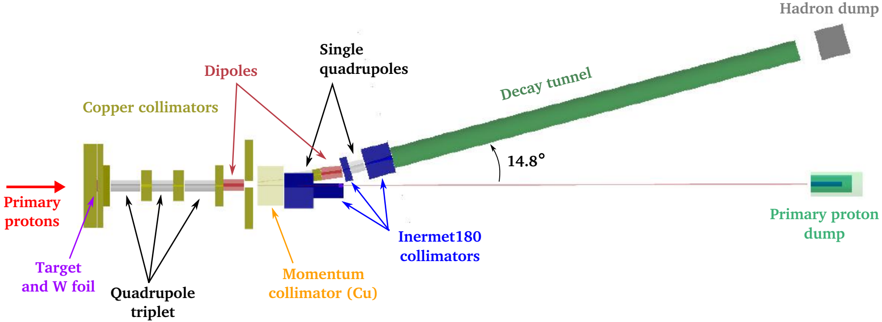
The ENUBET beamline

Fully static beamline

- Target and hadro-production: FLUKA
- Transfer line:
  optics design: TRANSPORT
  tracking & background: G4Beamline/G4
  doses & neutron shielding: FLUKA
  systematics: GEANT4

Static = slow extraction of a few seconds required by pile-up constraints (differently from majority of nu-beams)

CERN-SPS good candidate (400 GeV p+)



Target:

- 70 cm graphite rod w/ 6 cm d

Magnets:

- normal coducting quad & dip
- two 1.8 T dipoles for 14.8 deg total bending angle

Decay tunnel:

- length of 40 m w/ 1 m radius
- borated PE shielding

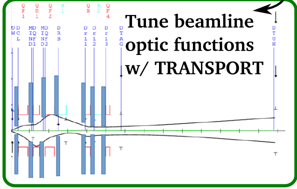
Dumps:

- 3 cylindrical layers proton dump
- same structure for hadron dump (reduced backscattering flux)

Design process:

Iterate

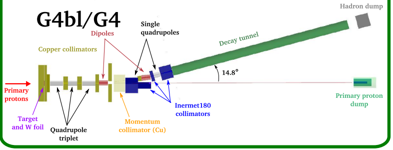
Tune beamline optic functions w/ TRANSPORT

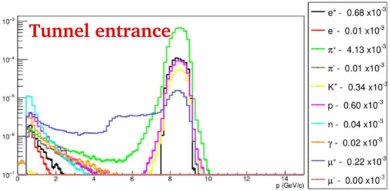


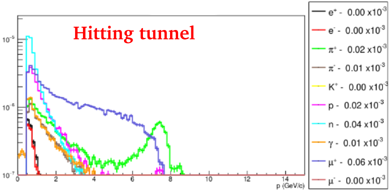
Iterate

Iterate

Implementation and extensive validation with G4bl/G4

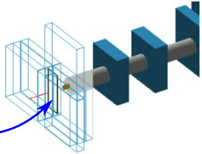


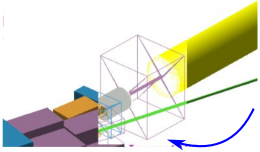




- Full tracking and interaction of beam w/ beamline elements fundamental to assess beamline performance
- Positrons & muons from beamline represents important background, as **ENUBET signals are e^+ and μ^+**
- After several beamline iterations: tight collimation plays an important role. W-positron filter also required

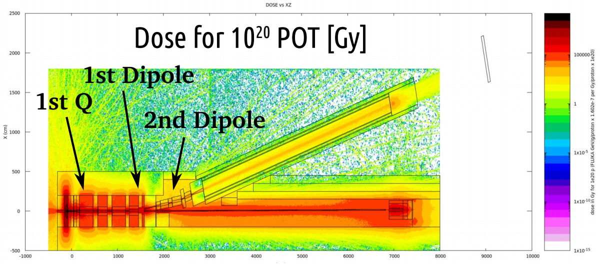
50 mm-thick W foil for target-pos suppression

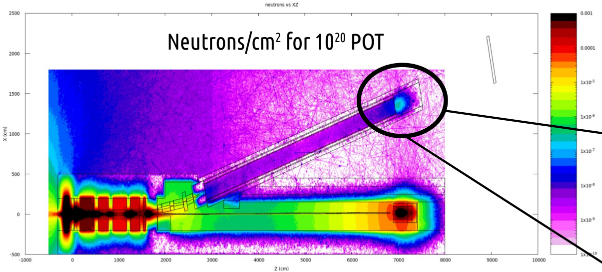




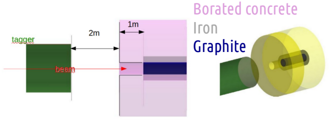
Final pre-tunnel collimator blocks for background & halo suppression

- Irradiation studies of the beamline performed using FLUKA: both charged part. & neutrons
- Hottest point: first collimator & quadrupole is 100-300 kGy
- Layer of borated-PE shielding for SiPMs & electronics: factor 18 dose reduction wrt previous case





After first bending significant reduction of dose to beamline elements (less bkg collinearity, pure nu beam)



The ENUBET beamline

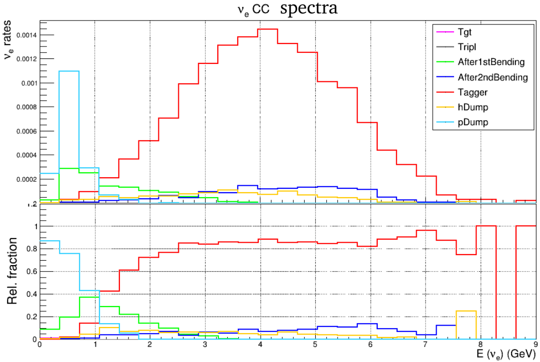
@SPS

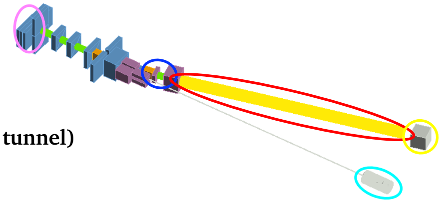
Rates @ Tunnel entrance for 400 GeV POT	
π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
4.13	0.34

~1.5 increase wrt previous results

Assuming 500 ton neutrino detector at 50 m with CERN-SPS as driver and $4.5 \cdot 10^{19}$ POT/y:

10^4 ν_eCC in ~3 years of data taking





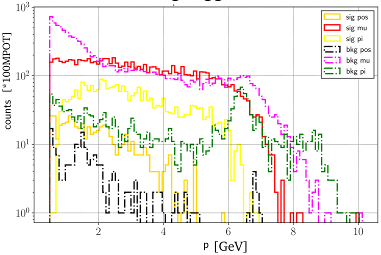
About 80% of total electron enutrino flux is produced by taggable neutrinos (i.e. produced by Ke3 decays in the decay tunnel)

Further beamline optimization

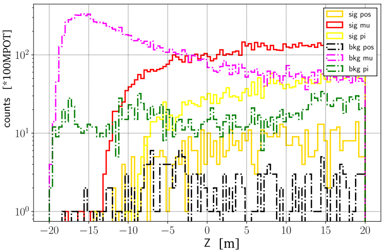
Optimization of signal/noise (S/N) ratio of the beamline is a lengthy process based on full tracking and interaction of particles through all elements and materials:

- → Full GEANT4 beamline model with control over all parameters and access to particle histories and classifications
- → Fully reliant on computing cluster for execution: still ~8h of CPU time and 100s jobs
- → General direction and design guided by analysis of available information on background origin & type
- → Collimation, filtering and shielding very important for background levels @tagger

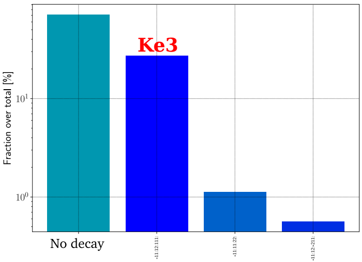
Particles hitting tagger: momentum



Particles hitting tagger: position



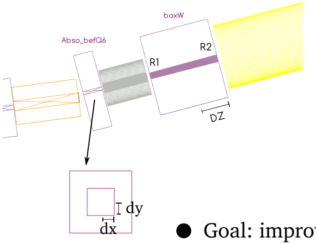
Decay channels of bkg positrons



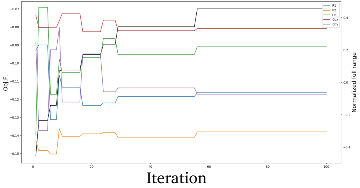
Further beamline optimization

An optimization framework based on a Genetic Algorithm (GA) and running on a computing cluster has been fully developed and applied to the beamline collimation:

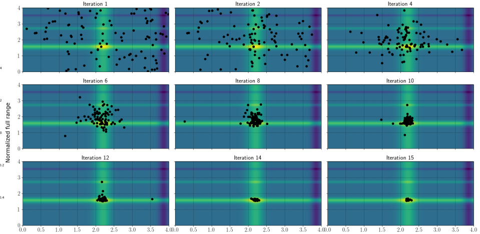
Last two collimators (Inermet180) before decay tunnel: 5 parameters



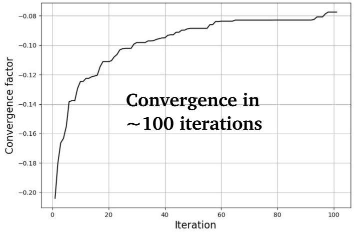
Evolution of best parameters (black: FOM)



Convergence example of 2D problem



- Goal: improvement of S/N ratio
- Figure of Merit (FOM): K+ at tunnel entrance scaled by bkg particles hitting tunnel walls (def. as positrons & pions from beamline and not from tunnel Ke3 events)
- Convercence in ~2 weeks; ~100 beamlines /iteration



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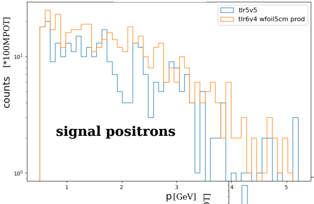
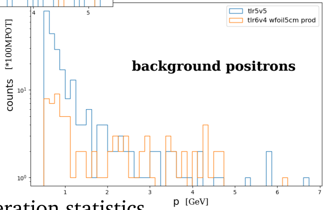




Results (preliminary):

→ **~28% gain in flux**

→ **~2.4 years to $10^4\ \nu_{eCC}$**

Rates @ Tunnel entrance for 400 GeV POT	π^+ [10^{-3}]/POT	K^+ [10^{-3}]/POT
Design	4.13	0.34
Optimized	5.27	0.44

Background hitting tunnel walls	$e^+[10^{-3}]/K^+$	$\pi^+[10^{-3}]/K^+$
Design	7	59
Optimized	2	35

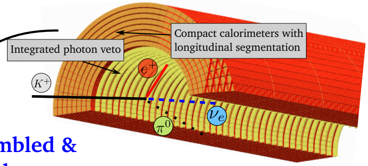
Next steps:

- Boost single iteration statistics
- Improve FOM definition by including info on distributions

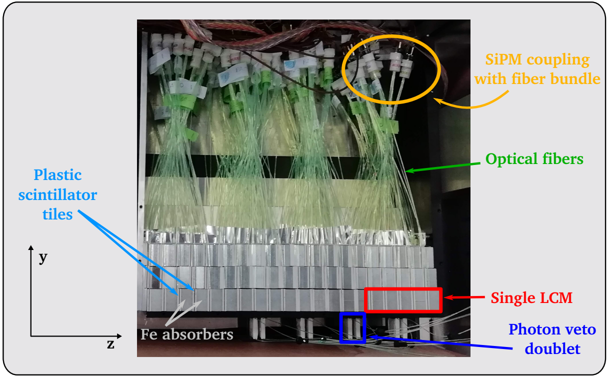
Decay tunnel instrumentation

Instrumentation of decay tunnel [*]

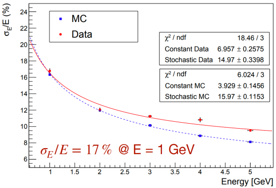
- After dedicated studies (simulations, prototyping, test beams):
  - ⟶ **Chosen final design**: compact scintillating sampling calorimeters (4.3 radiation lengths) will be used to instrument the ∼40m decay tunnel (3 layers). One internal layer of photon veto (scintillator doublet)
  - ⟶ Lateral readout to SiPM via bundled WLS fibers (space for shielding: factor 18 dose reduction)
  - ⟶ Custom DAQ + support with commercial solutions



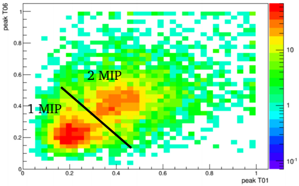
Assembled & tested prototype



Energy resolution (electrons)



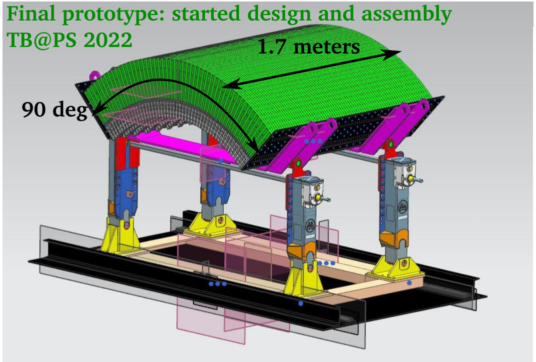
1 MIP/2 MIP separation

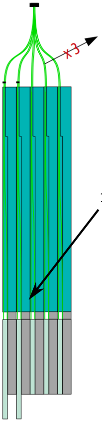


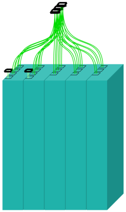
[*] JINST 15(2020)08, P08001; JINST 14 (2019) 02, P02029; NIM A 956(2020)163379

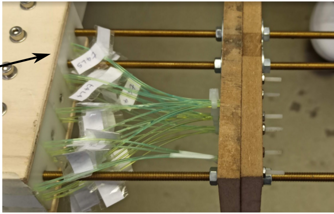
Prototype for exp. validation

A prototype of the tagger is under construction for a final experimental validation at CERN-PS in October 2022:

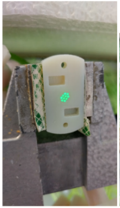








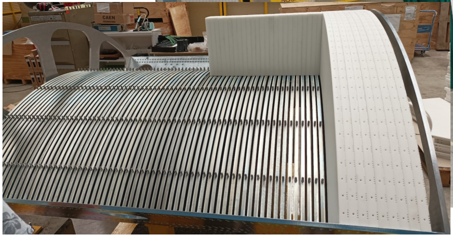
Small prototype ("Enubino") used to test new fiber redout scheme at CERN-PS (2021)

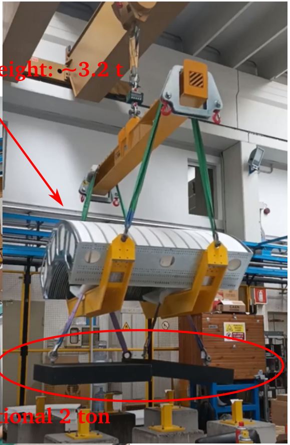


Goal: proof of principle of the ENUBET detector design and concept.

Prototype for exp. validation

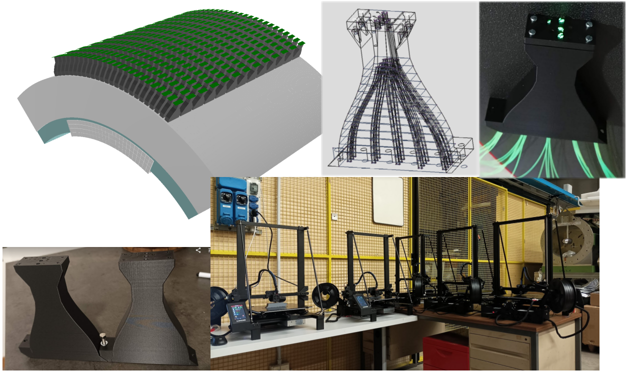
Prototype construction advancing at INFN-LNL laboratories:

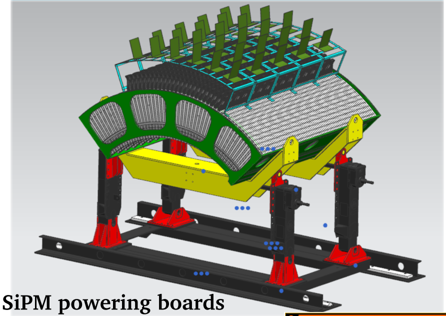




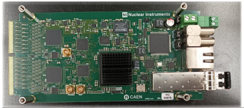
Prototype for exp. validation

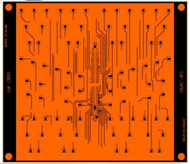
Routers for the optical-fibers produced with a battery of 6 consumer level 3D printers

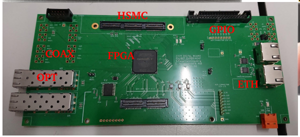


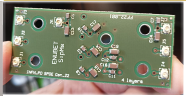


Custom SiPM powering boards in production, custom and commercial FE boards



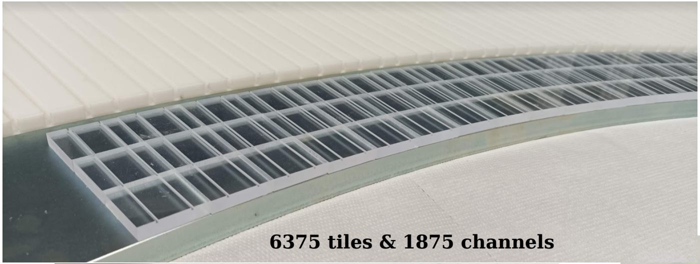


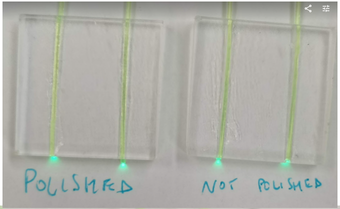


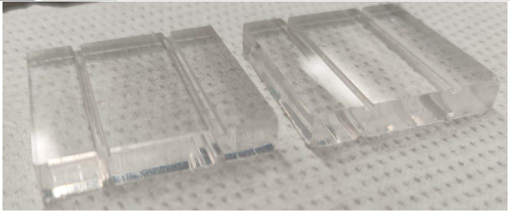


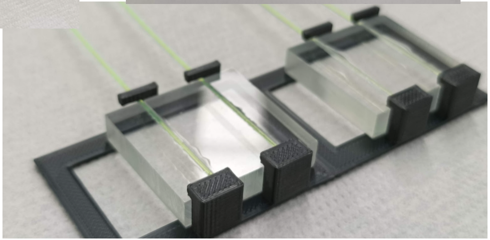
Prototype for exp. validation

Scintillator tiles: lot of manual work required and in progress (polishing, glueing of fibers, painting with diffusive material & more)



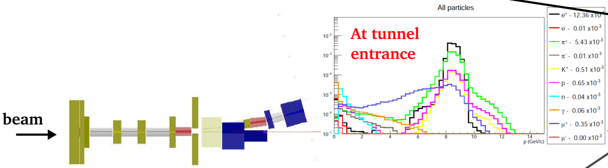




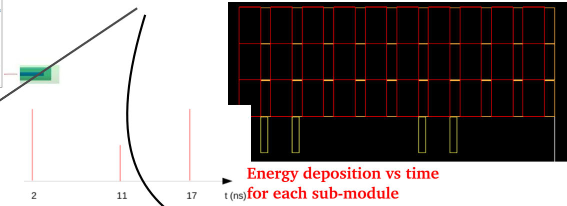


Detector performance & systematics

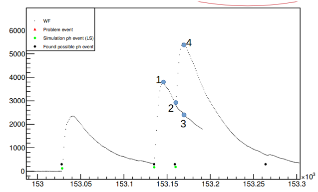
Production using full beamline simulation (G4/G4beamline/FLUKA)



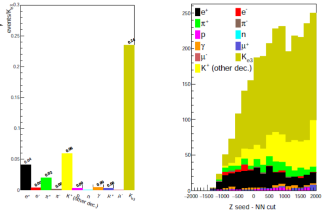
Complete simulation of ENUBET tagger detector (G4)



Waveform generation (SiPM) simulation: energy and time reconstruction



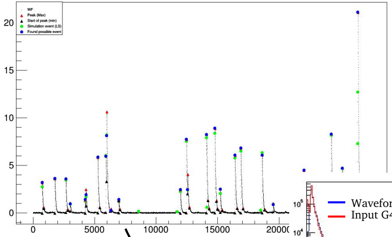
Event reconstruction algorithm

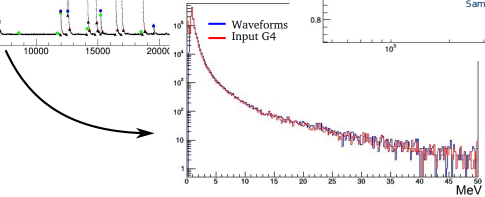


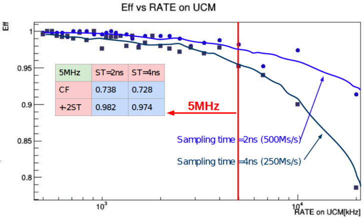
Waveform simulation and reconstruction

Full simulation chain for waveform generation and analysis:

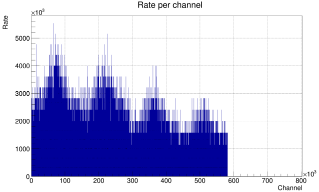
- Digitized electrical signal generated from G4 input
- Different peak detection algorithms developed and tested for energy and time reconstruction
- Model also used to set boundaries on tunnel event rate and digitizer sampling time





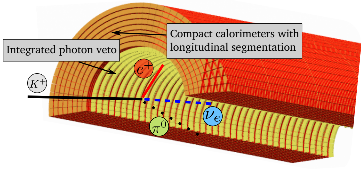


Transfer line and extraction scheme	Hit rate per LCM	detection efficiency
TLR5 slow	1.1 MHz	97.4%
TLR5 fast	10.4 MHz	89.7%
TLR6 slow	2.2 MHz	95.3%



Event reconstruction

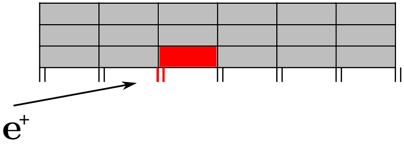
Energy clusters deposited in each sub-module used to reconstruct an event:

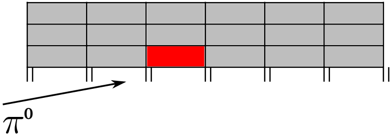


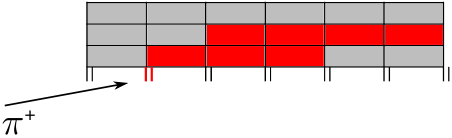
→ Two main signals for ENUBET:

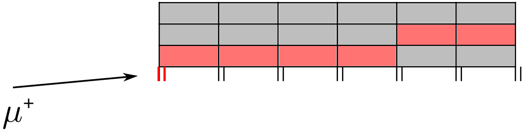
positrons from Ke3 | **muons from Kmu2/3**

→ Basic discrimination idea: use tagger granularity to separate EM showers / Hadronic showers / MIP + photon veto









Event reconstruction

More in detail:

→ 15 parameters neural network trained over pure samples.

→ Reconstruction performance in terms of Signal to Noise ratio (S/N) and efficiency can be computed against input G4 information

For **positrons:**

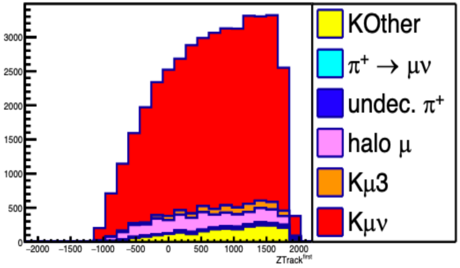
S/N: 2
Efficiency: 22%
(Eff. is ∼half geometrical)

For **muons:**

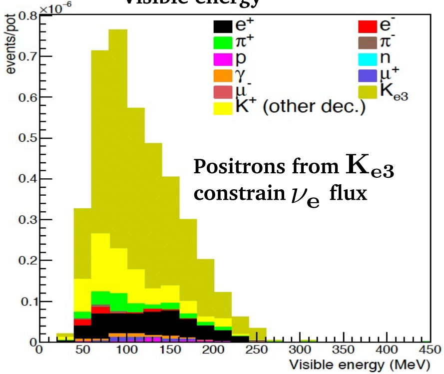
S/N: 6
Efficiency: 34%
(Eff. is ∼half geometrical)

Muons from $K_{\mu 2}$ $K_{\mu 3}$ constrain ν_μ flux

Impact point at tagger



Visible energy



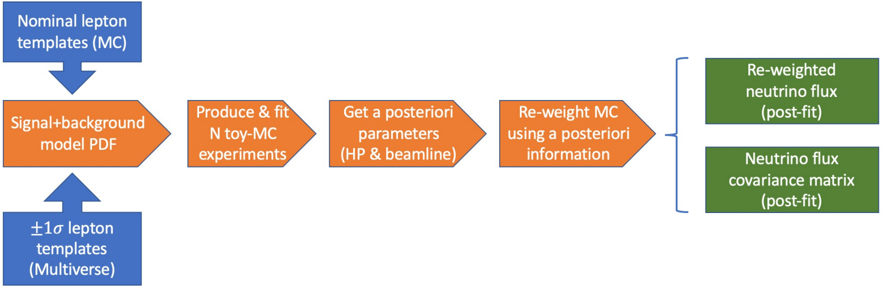
Positrons from K_{e3} constrain ν_e flux

F. Pupilli et al. PoS NuFact2021 (2022) 025

Neutrino flux systematics

In the monitored neutrino beam: measure of leptons @tagger constrains the neutrino flux

- → Build sig + bkg model to fit lepton observables
- → hadro-production (HP) and transfer line (TL) systematics included as nuisances



Hadro production data from NA56/SPY experiment used to:

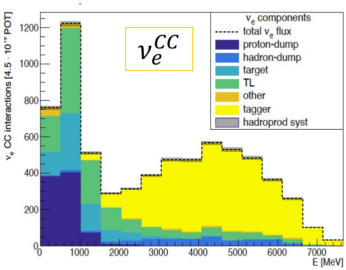
- → Reweight MC lepton templates and get nominal distribution
- → Compute lepton template variations using multi-universe method

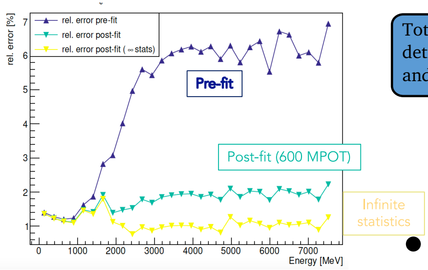
A.Branca et al. PoS NuFact2021 (2022), 030

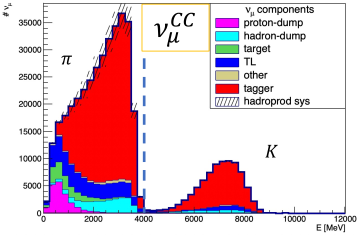
Neutrino flux: impact of HP systematics

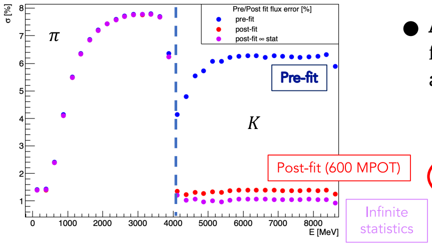
Neutrino interaction rates @ detector

Pre & Post fit relative errors on rates









Total rates assuming 500 ton neutrino detector at 50 m with CERN-SPS as driver and $4.5 \cdot 10^{19}$ POT

- **Before constraint:** **6%** systematics due to HP uncertainties
- **After constraint:** **1%** systematics from fit to lepton rates measured at the tagger

Achieved ENUBET goal of 1% systematics from lepton monitoring!

Conclusions

- Main design phase of ENUBET transfer line terminated, fine tuning in progress:
  - ⟶ Static transfer line: $10^4\,\nu_{\mathbf{e}\mathrm{CC}}$ in 2/3 years data taking (SPS)
  - ⟶ Genetic optimization showing promosing improvements: ongoing
- Design of decay tunnel instrumentation finalized:
  - ⟶ **Final demostrator of the tagger under construction and will be tested at the renovated CERN-PS East Area by 2022**
- Tagger detector simulation and performance assessment:
  - ⟶ Satisfactory PID achieved both for muon and positron reconstruction
  - ⟶ Finalization of waveform simulation and analysis chain
- Systematics on neutrino flux:
  - ⟶ **Achieved 1% systematic goal due to hadro-production w/ lepton monitoring**
  - ⟶ Assessment of systematics due to detector & beamline in progress (sub-leading)

Thank you for your attention