The ENUBET monitored neutrino beam

108° Congresso Nazionale della Società Italiana di Fisica

Evgenii Lutsenko
University of Milano Bicocca & MiB INFN
on behalf of ENUBET Collaboration

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ν cross section experiments

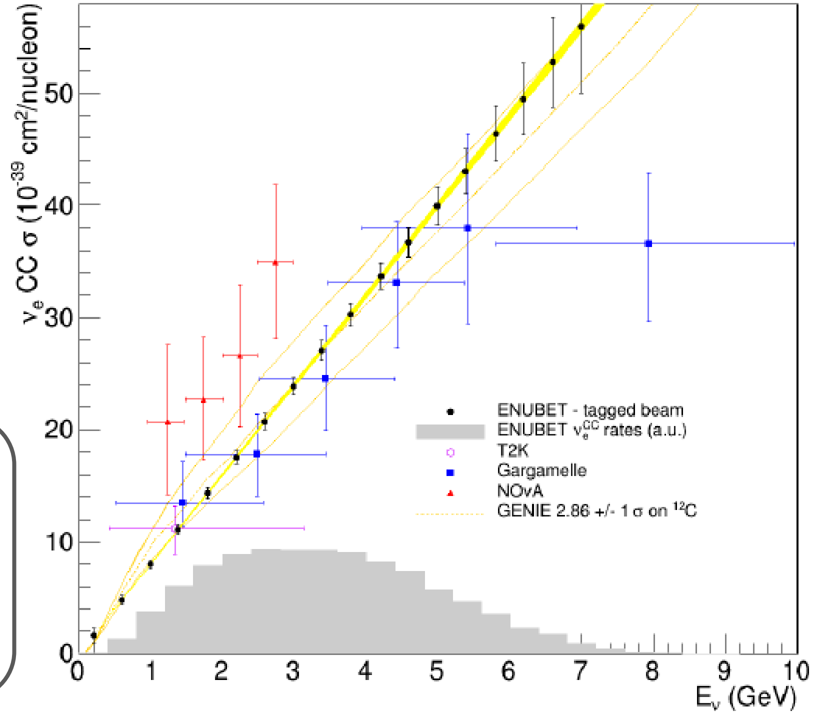
Previous neutrino cross section experiments used pion-based sources, which are mainly **sources of ν_μ**

> To extract the most physics out of DUNE and Hyper-Kamiokande, a complementary programme of precision supporting measurements is needed. NA61 and its upgrade are an important component of this programme for the determination of the neutrino fluxes. A study should be set up to evaluate the possible implementation and impact of a facility (based on the ENUBET or νSTORM concepts) to measure the neutrino cross sections at the percent level. *

The **current ν_e cross section** precision is **O(~20%)** and even the **ν_μ cross section** is known with a precision of **10%**

Present	Future
NOvA	DUNE
T2K	Hyper-K

The dominant systematics of all cross section measurements is the **systematic on the flux**



Future experiments require precision O(1%):

- Lepton CPV
- Mass hierarchy
- PMNS parameters
- Sterile Neutrino

ENUBET physics goal: **overall error** on the flux of the produced neutrinos **<1% level**

→ More precise flux knowledge

*European Strategy for Particle Physics, arXiv_1910.11775

ENUBET

Enhanced NeUtrino BEams from kaon Tagging

Project approved by the European Research Council (ERC)

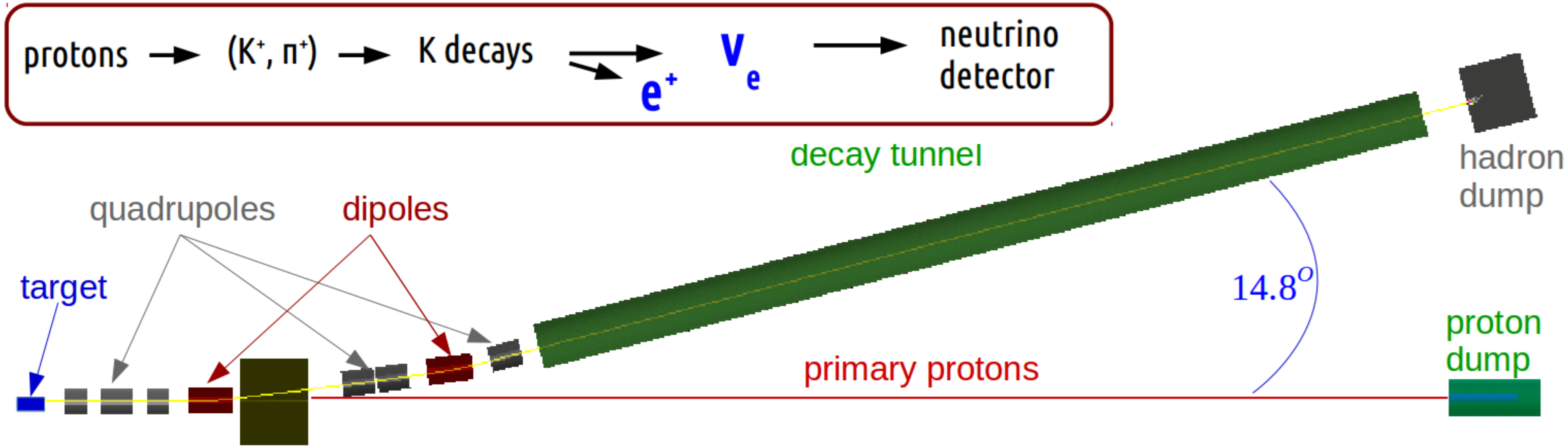
ENUBET is the project for the realization of the first monitored neutrino beam

- precise measurement of the **ν_e flux**
- (NEW!) precise measurement of the **ν_μ** from **two body kaon decay**
- (NEW!) precise measurement of **ν_μ** from **pion decay** (instrumented beam dump)

60 physicists, 13 institutions

Visit our webpage for further info and material!
http://enubet.pd.infn.it

The ENUBET experiment



Large bending angle of 14.8^o:

- better collimated beam + reduced muons background + reduced ν_e from early decays;

Transfer Line:

- optics optimization w/ **TRANSPORT G4Beamline** for particle transport and interactions;
- **FLUKA for irradiation studies, absorbers and rock** volumes included in simulation;
- **optimized graphite target** 70 cm long & 3 cm radius;
- **tungsten foil downstream target** to suppress positron background;
- tungsten alloy **absorber @ tagger entrance** to suppress backgrounds;

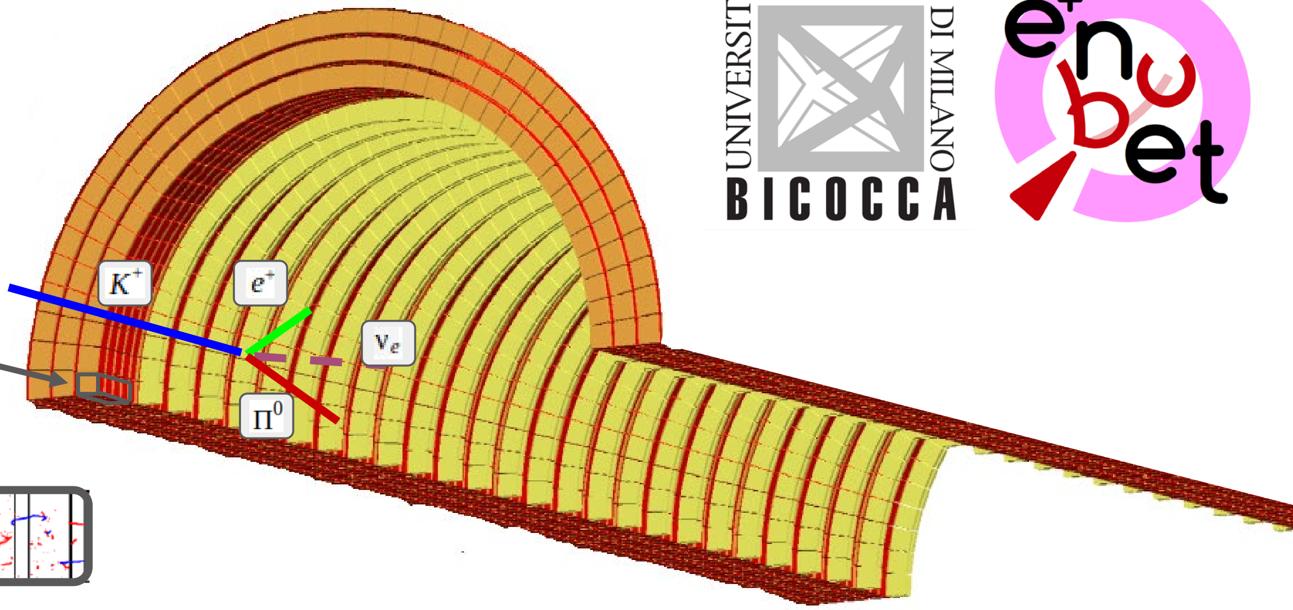
Dumps:

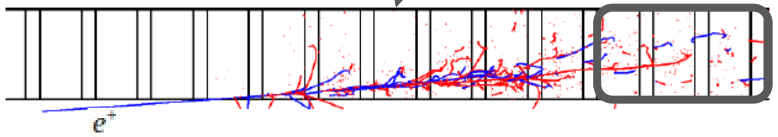
- **Proton dump:** three cylindrical layers (graphite core -> aluminium layer -> iron layer);
- **Hadron dump:** same structure of the proton dump -> allows to reduce backscattering flux in tunnel.

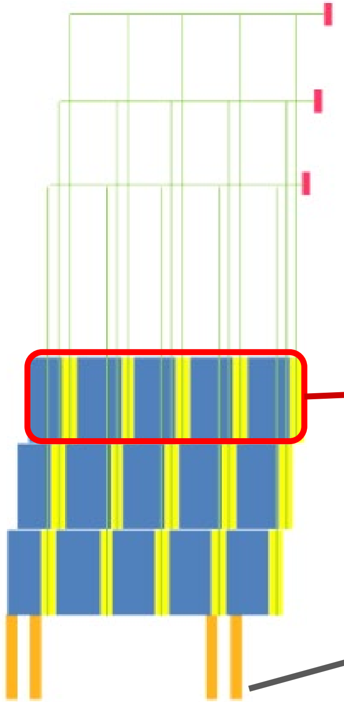
Decay tunnel

Calorimeter
- Lateral Compact Module (LCM)
- Longitudinal segmentation
- WLS-fibers for light collection
- Light readout with SiPMs

Basic unit = LCM
3x3x10cm^3 4.3X_0





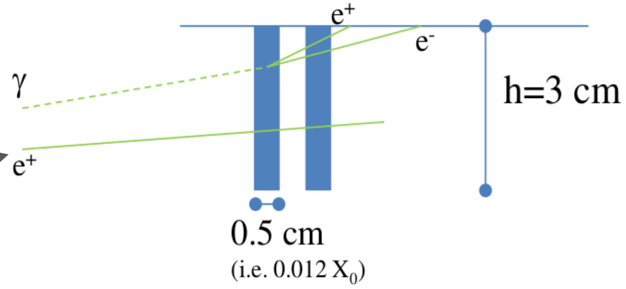


LCM

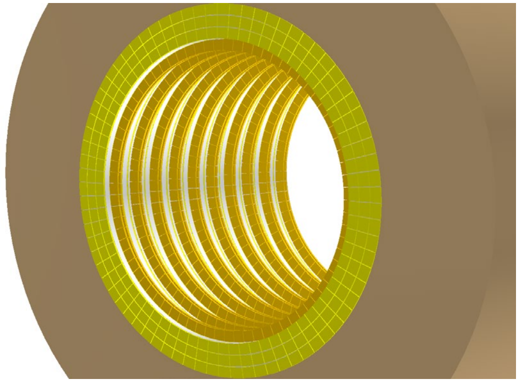
e^+ (signal) topology

π^0 (background) topology

π^+ (background) topology



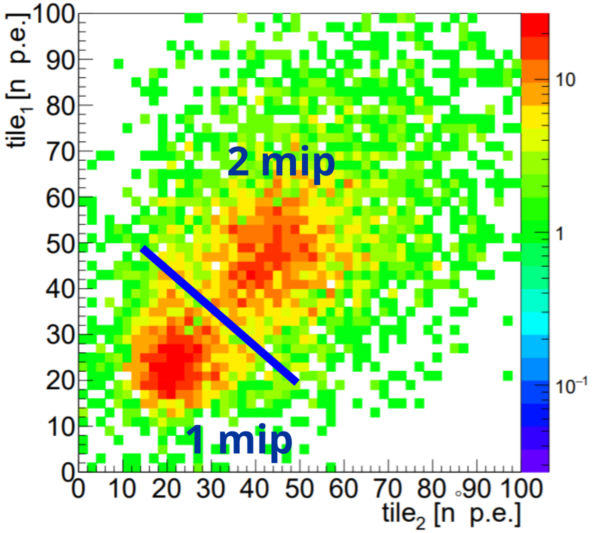
Integrated Photon-veto
- 3x3 cm^2 plastic scintillator pads
- e^+/π^0 separation



Prototypes & tests

- **LCM** is a **sandwich of 5 iron tiles** interleaved with **5 plastic scintillator tiles**
- Each **LCM has 10** 1mm WLS **fibers coupled with SiPM**

Photo from the test-beam 2018 at CERN



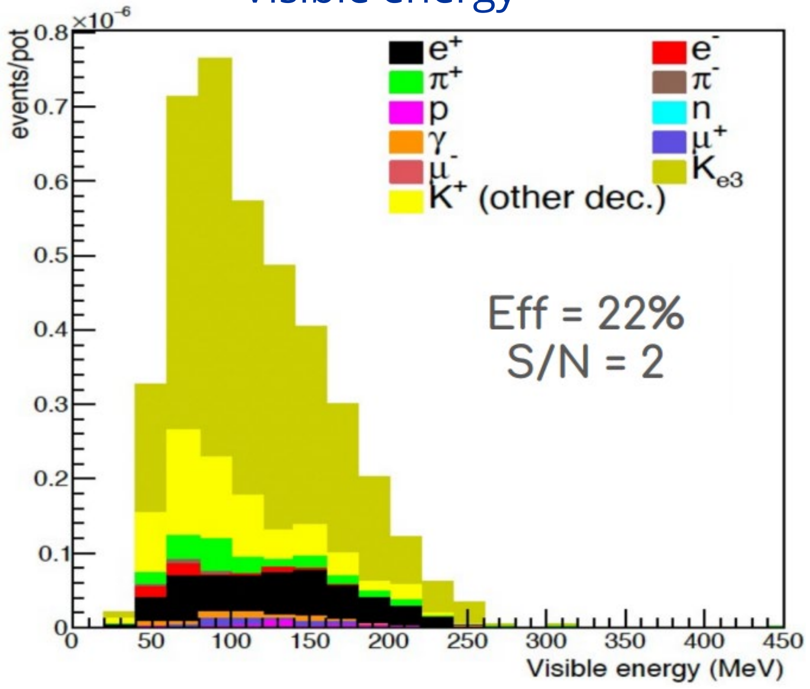
- **Doublets of plastic scintillator tiles** 3x3x0.5 cm^3 mounted below the LCM every 7 cm
- **e^+/ π^0 separation** with precise timing
- Light yield for a **single mip crossing a t_0 tile** → collection of **25 p.e. with time resolution ~400 ps**
- Single t0 tile selects **1-mip signal with ε=87%**

Lepton R&I performance

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);

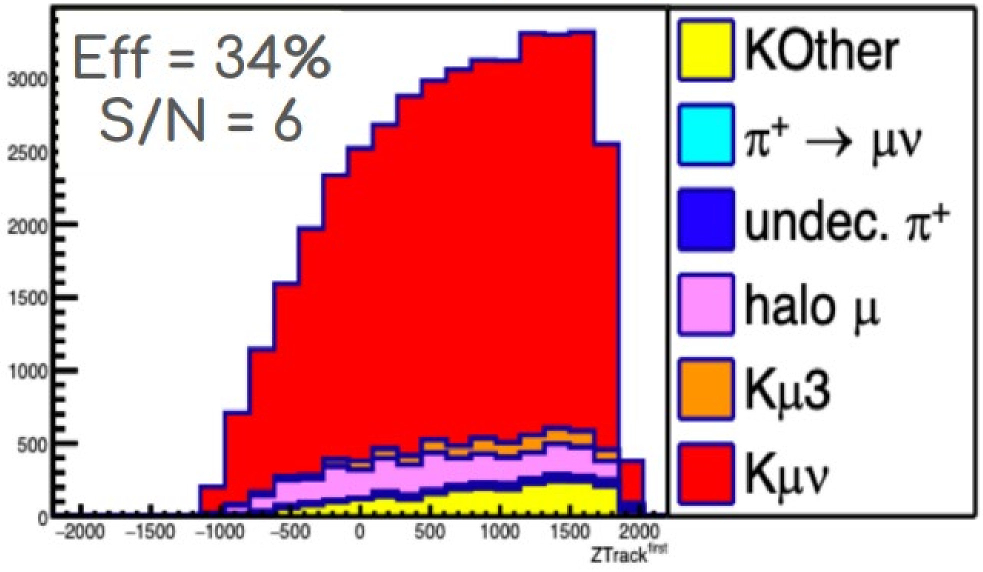
- Large angle **positrons** and **muons** from **K decays** reconstructed searching for patterns in energy depositions in tagger;
- **Signal identification** done using a **Neural Network** trained on a set of discriminating variables.

Visible energy



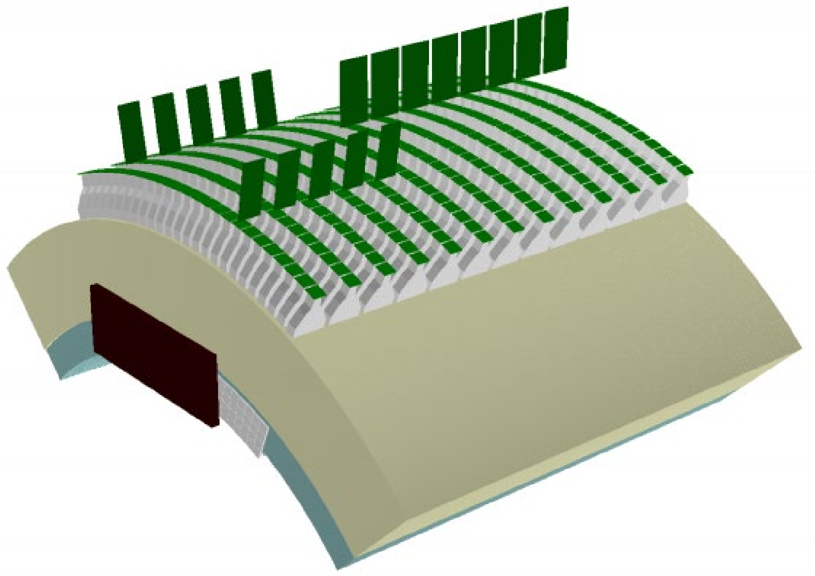
Efficiency ~half geometrical

Tagger impact point

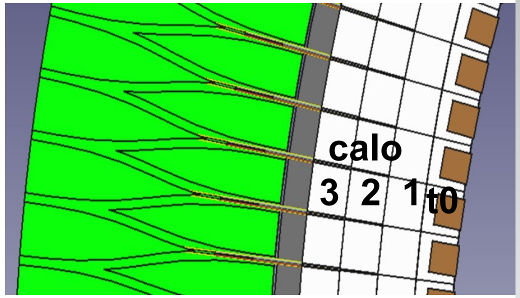


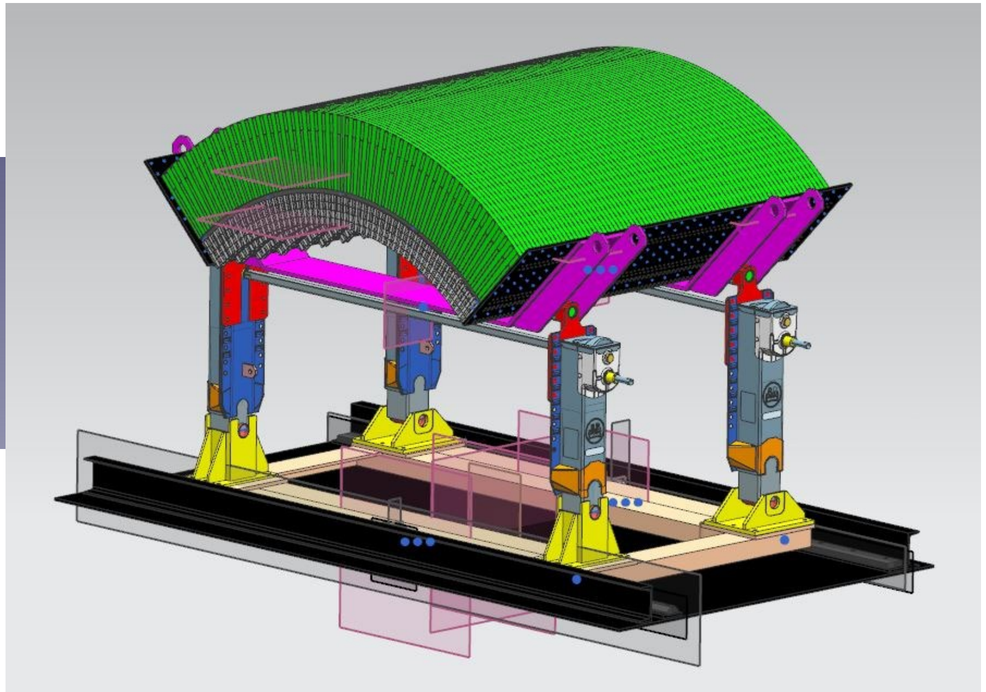
F. Pupilli et al., PoS NEUTEL 2017 (2018) 078

Detector prototype



The **demonstrator** is a **full scale prototype** of the instrumented tunnel but the length is 1.65 m

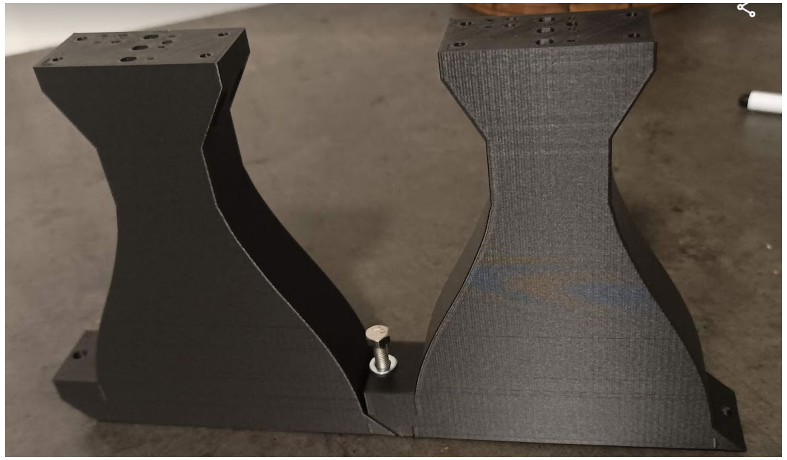


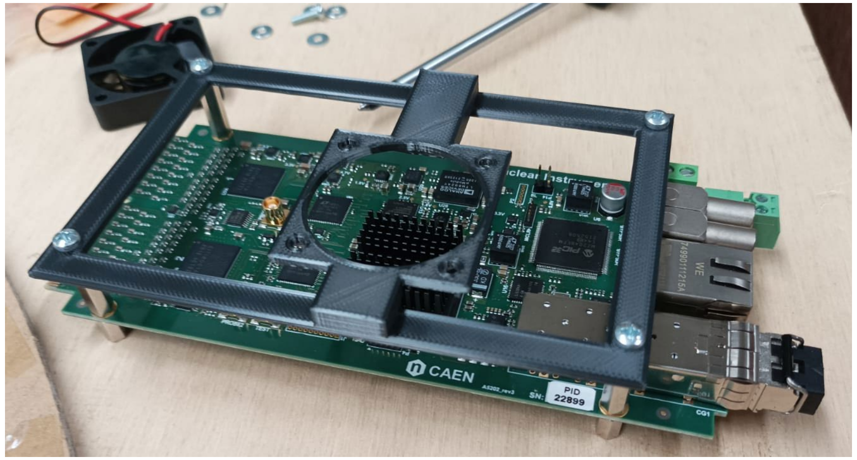


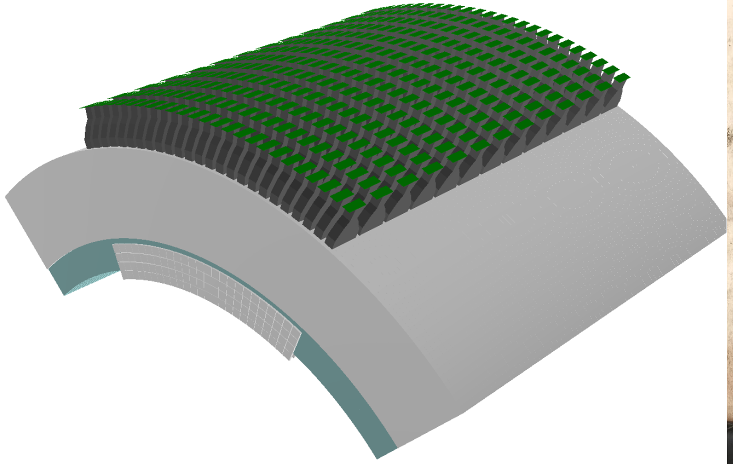
- **Dimensions**: 1.65m x π/2
- **Material**: steel, org. scint., fibers, SiPM
- # **SiPM**: 600
- **Channels**: 600
- **Modular design**: can be extended to a full 2π object
- To demonstrate **performance, scalability** and **cost-effectiveness**

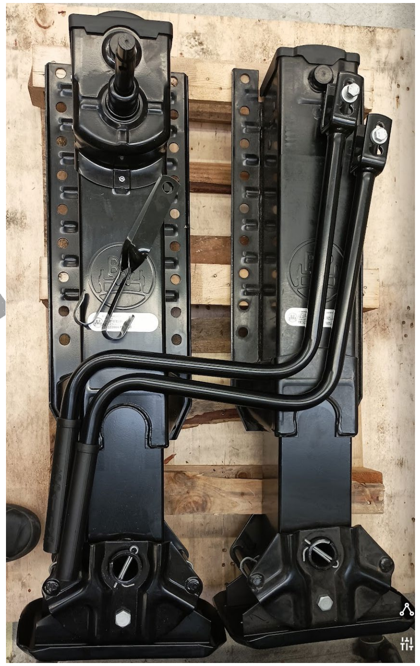
To be tested at CERN in **October 2022**

Detector prototype at INFN-LNL

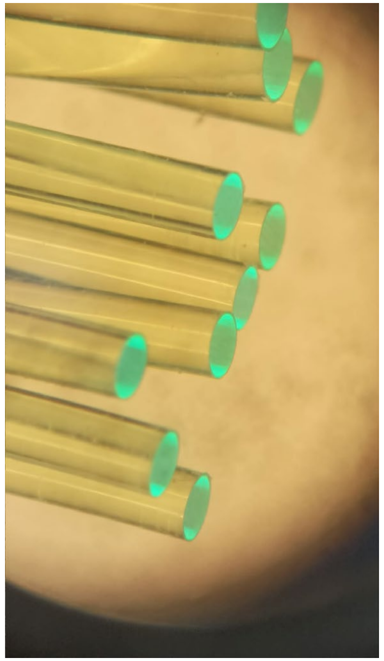
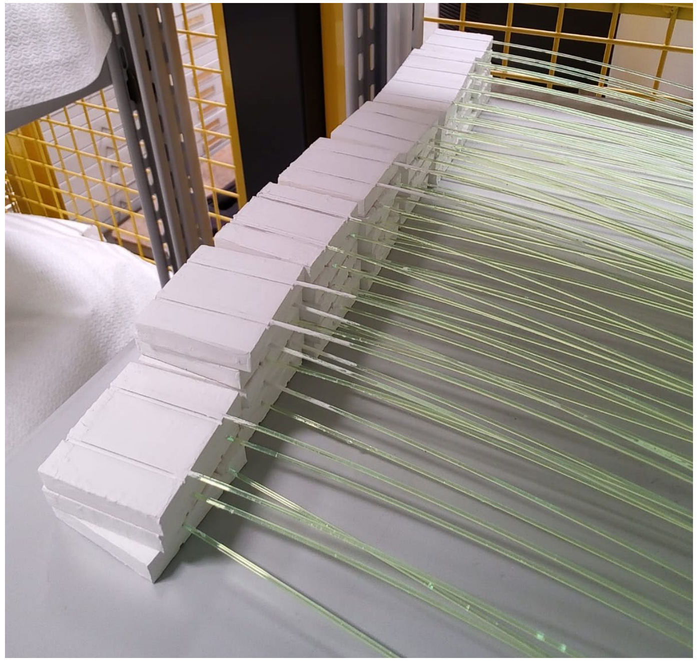
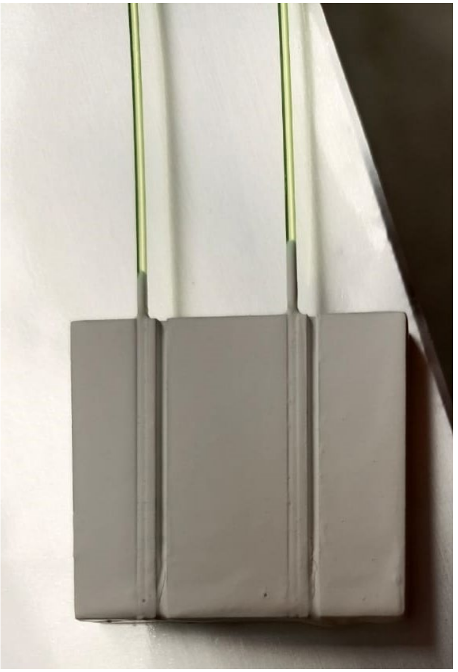


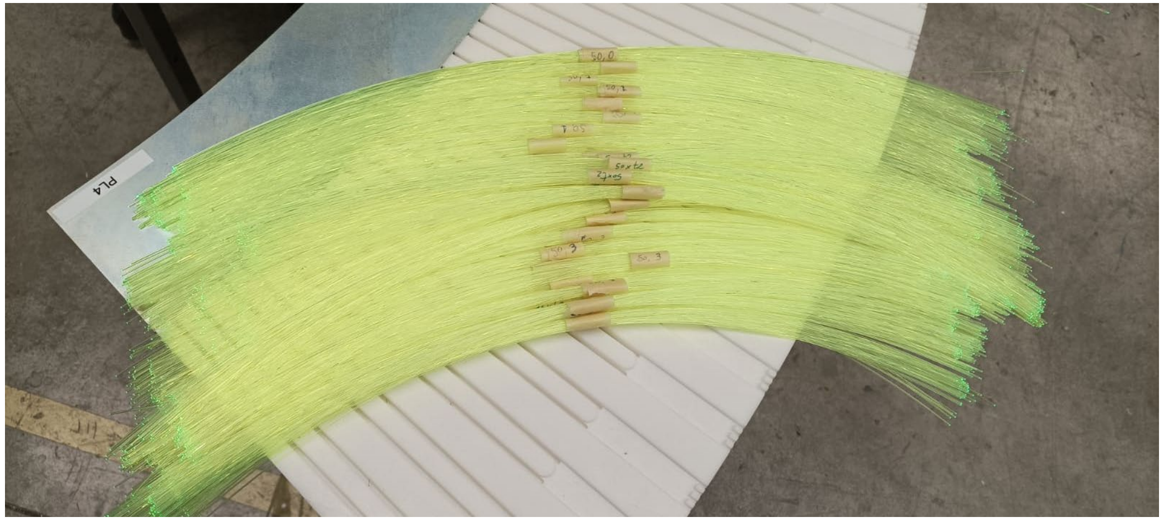
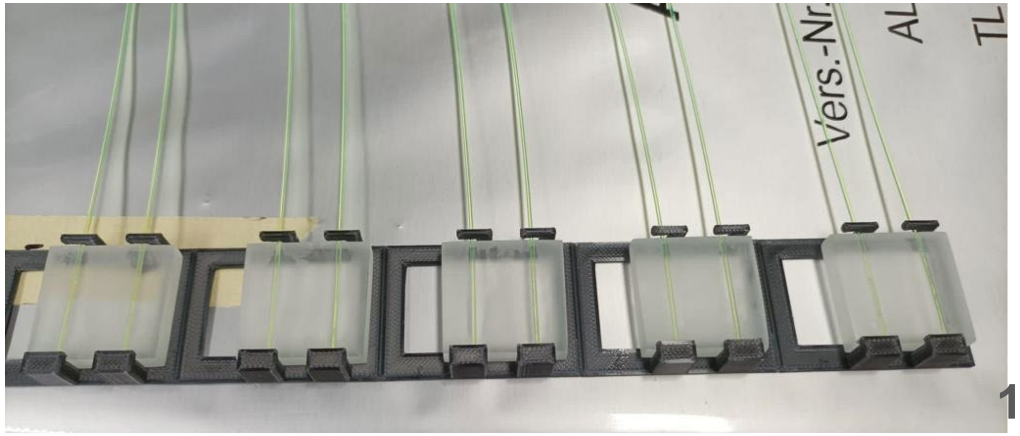






Detector prototype at INFN-LNL

Summary

ENUBET

- **ERC** project started in **2016-2022**;
- CERN experiment (**NP06**) within Neutrino Platform **2019-2024**;
- part of **Physics Beyond Collider** framework

First monitored neutrino beam for ν cross-section **measurements @ O(1%)**

Final design of beam transfer line in place:

- static transfer line: 10^4 **events** in 2/3 years (**@ SPS**)
- optimization of transfer line parameters with dedicated framework in progress

Detector simulation and **PID** studies done:

- developed **full GEANT4 simulation** of calorimeter
- finalizing waveform to fully assess the pile-up effects
- **very good PID** performance achieved

2023-2024 delivery of Conceptual Design Report with physics and costs definition

Experimental proposal expected in 2024

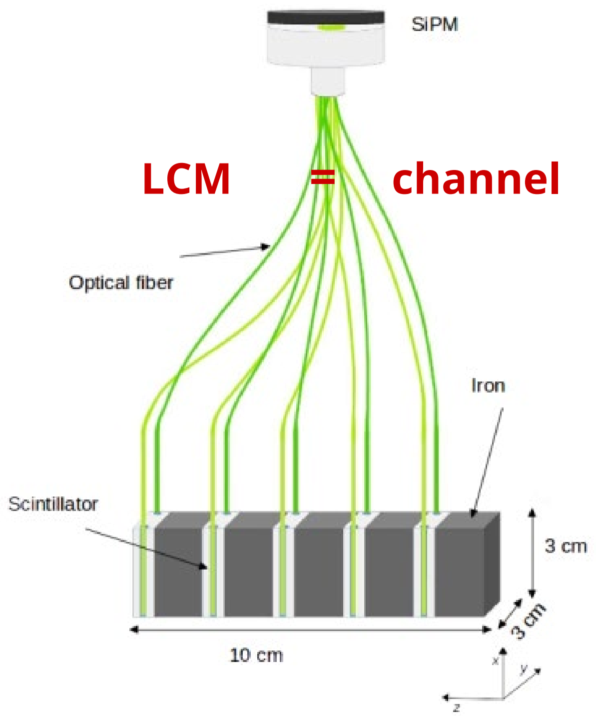
Design of **decay tunnel** instrumentation **finalized**:

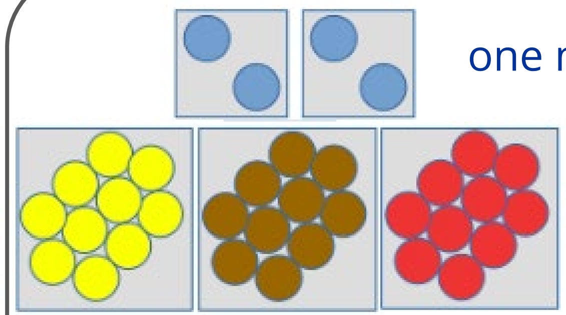
- prototypes test-beams @ CERN: technology validation;
- building **final demonstrator to be tested @ PS East Hall in October 2022**

Thank you
for your attention!

Readout chain

LCM = channel

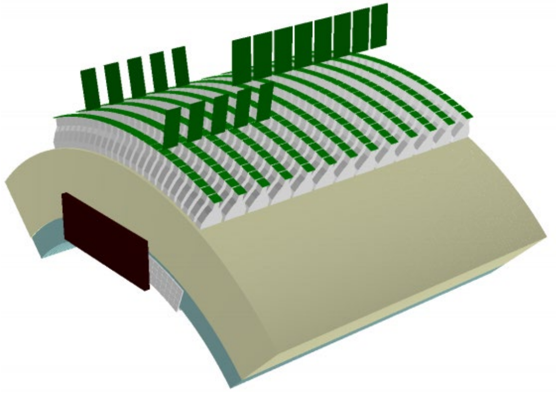




one module of the **t0 layer**

three calorimeter **layers**

1 radial segment = 5 channels

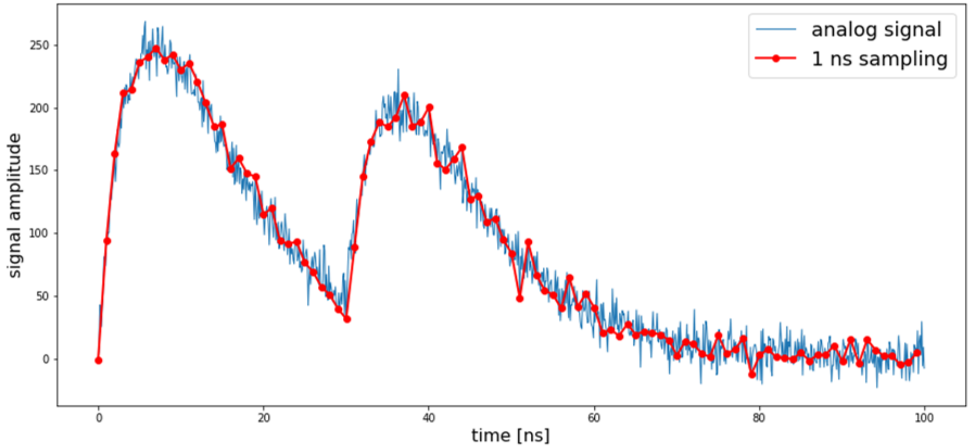


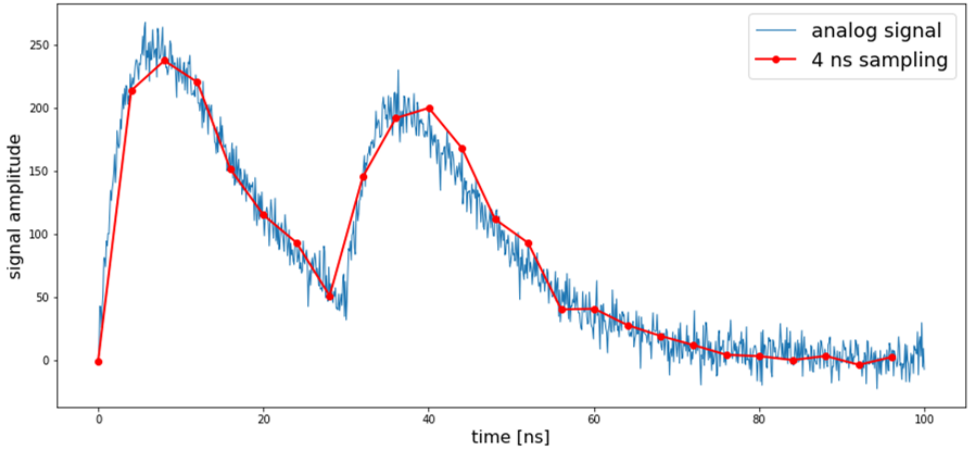
Layer	Number of channels
Photon-veto (t0)	145600
Calorimeter 1 (calo1)	72800
Calorimeter 2 (calo2)	72800
Calorimeter 3 (calo3)	72800

=364000 channels

R&D read-out system

Read-out system includes a large number of steps from SiPM to saved signal
Developed electronics and software for reading the signal from the detector
Possible digitizer **sampling time: 1ns** (1000MS/s), **2 ns** (500MS/s), **4 ns** (250 MS/s)





- Develop a **digitizer** with a **cost-efficiency trade-off**
- Develop an **algorithm for finding** the **amplitude** and absolute **time** of a signal to **compress** the saved **data**
- **Trigger less** data saving

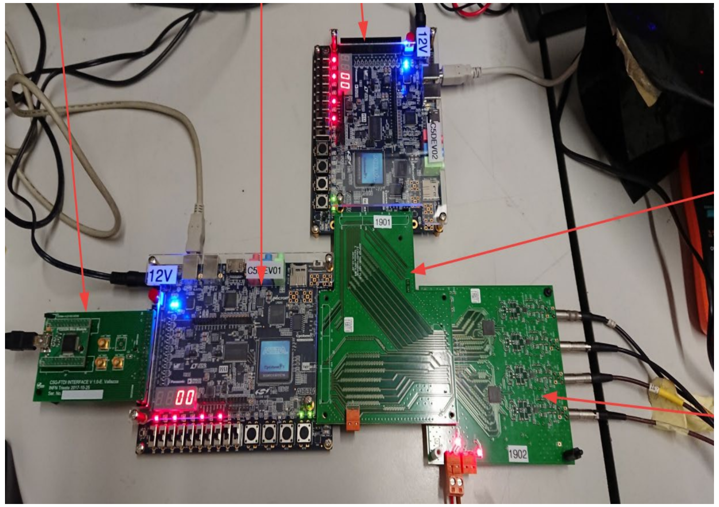
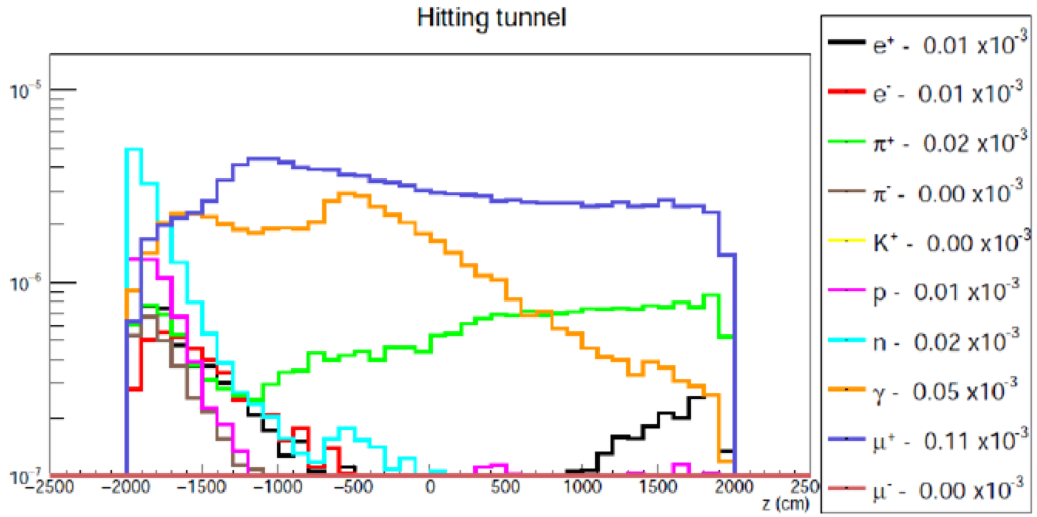
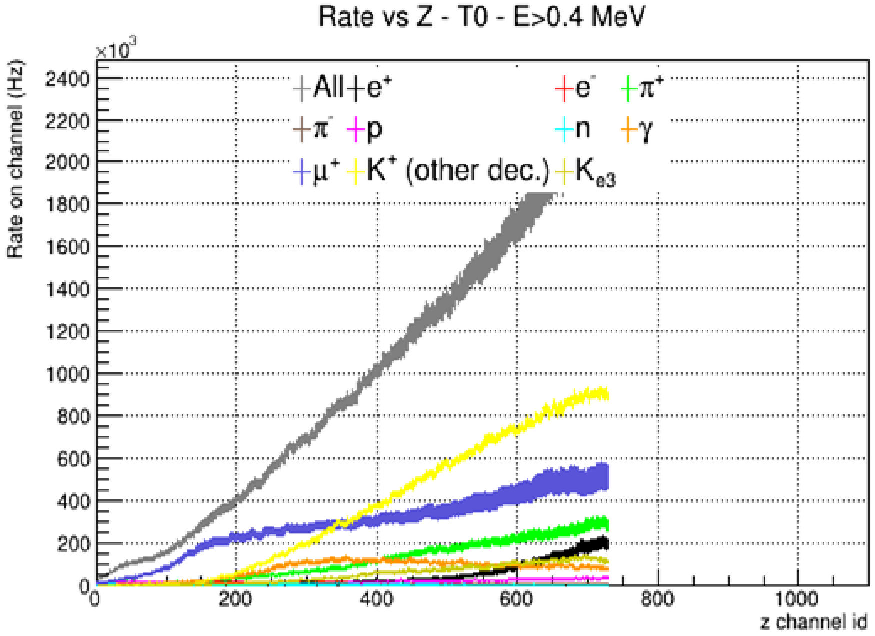


Photo from the INSULAB tests 2021

Particle hit rate





- **not all** the particles will **hit the detector**
- Entrance spectra **peak is 8.5 GeV/c**
- **all K^+ have decayed**
- Different particles have different momentum spectra
- **Muons, photons and pions** have the **highest frequency** of hits

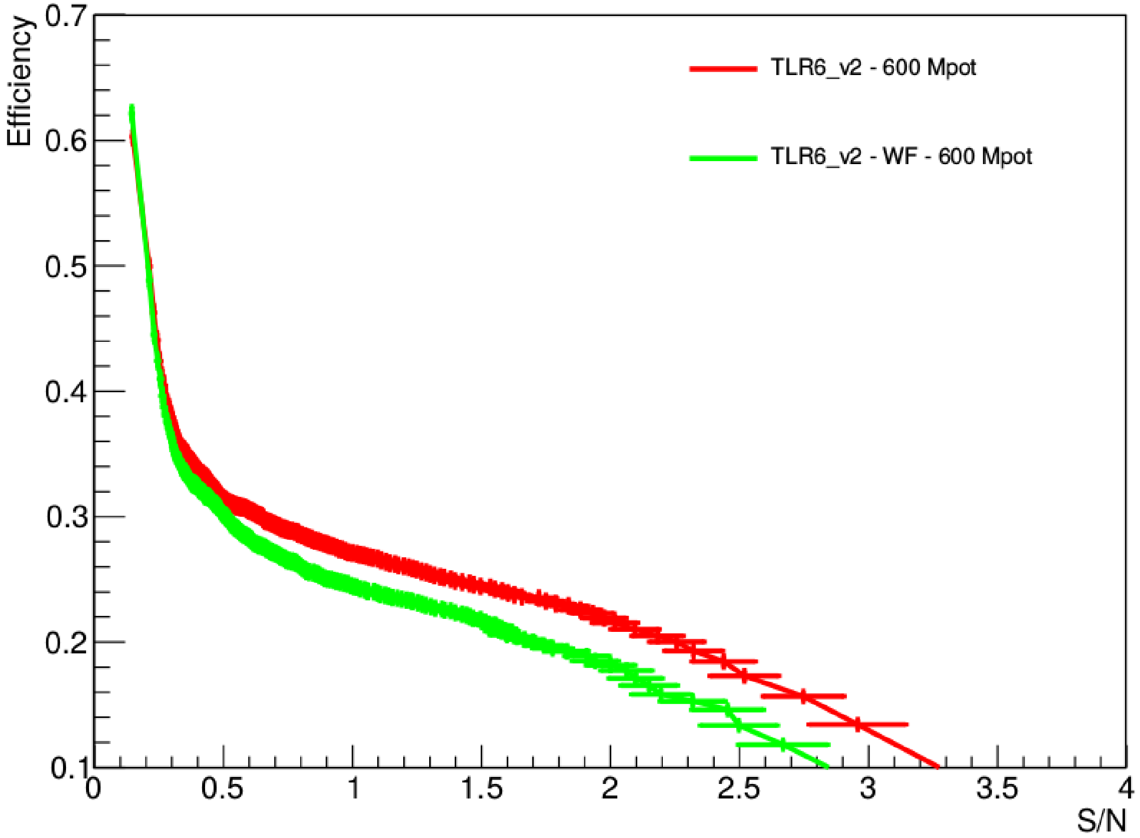
- **Hit rate** on channel **depends on layer**
- On the plots **low-energy cut** (E>0.4 MeV)
- Average **hit rates** on channel are **1.5 MHz**

Pile-up effect

The peak detection algorithm results

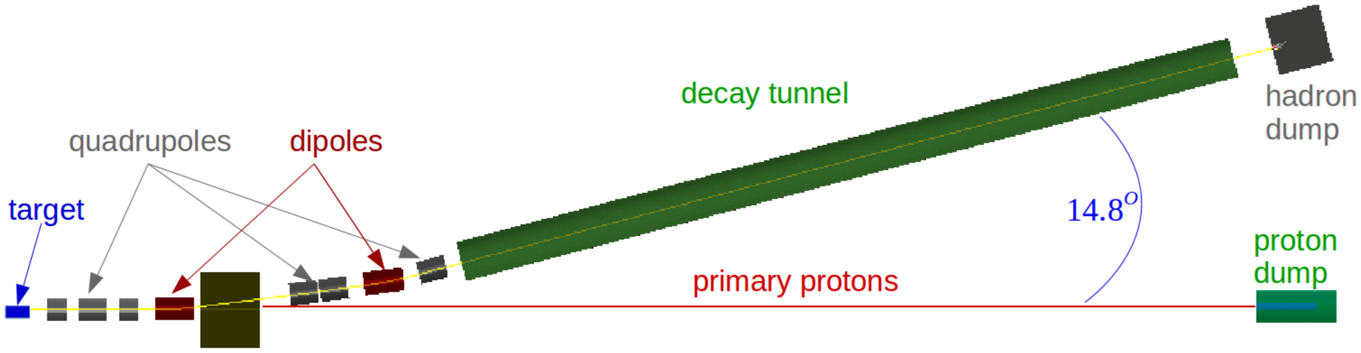
Efficiency as a function of the **signal-to-noise ratio** in the selection of K_{e3} events

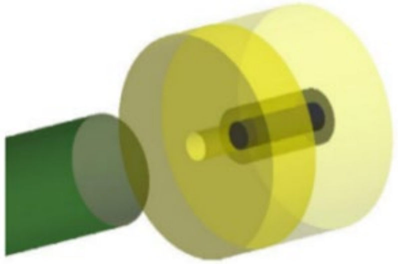
- The **red line** refers to the GEANT4 **simulation energy deposits**
- The **green line** refers to the **detected** by the PD algorithm **energy deposits**

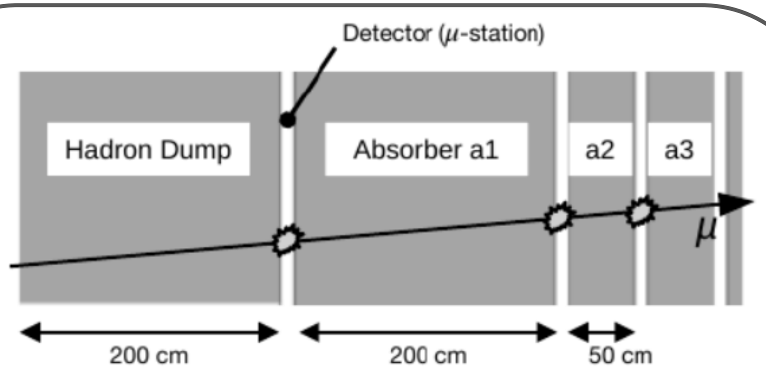


- **Efficiency** is defined as the percentage of the **reconstructed K_{e3} e^+ events**
- **signal** is the reconstructed e^+ events **from** the **K_{e3}** decay
- **noise** is the reconstructed events which are **not K_{e3} positrons**
- The **ENUBET** project **expects** to have an efficiency of **≈22%**
- The **red S/N ≈2.2**
- The **green S/N ≈1.6**

Dumps







Low-E **νμ from π decays** can be constrained by monitoring associated μ → **emitted at a small angle**

→ **go through** the tunnel and the **h-dump**

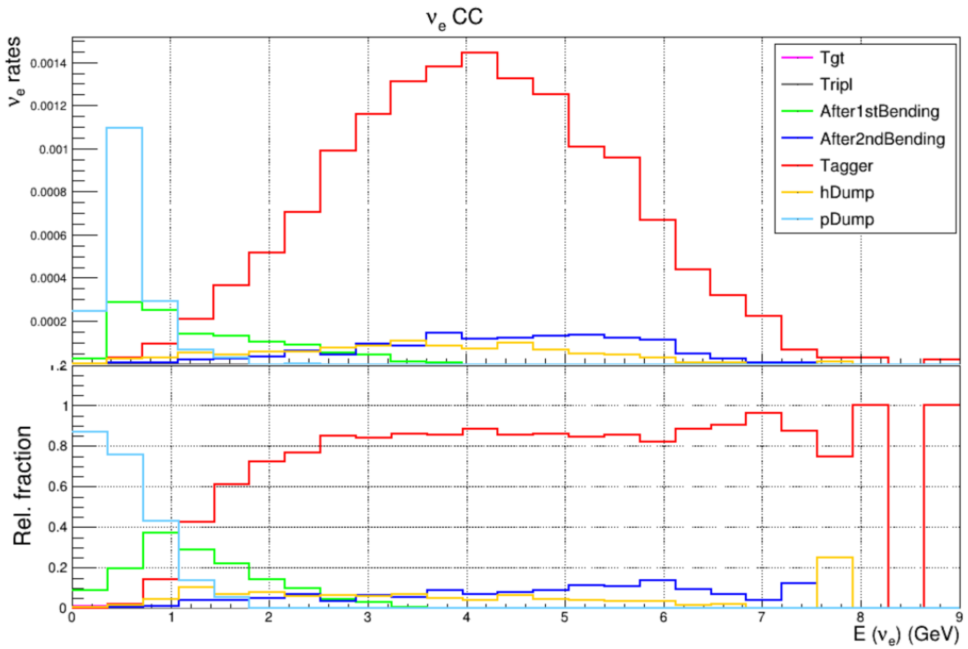
→ **Instrumented h-dump**: detector layers interleaved by the absorber

Hadron dump: graphite core (50 cm d), inside a layer of iron (1 m d), covered by borated concrete (4 m d) + 1 m of borated concrete is placed in front of the hadron dump leaving the opening for the beam

→ **design optimized to reduce the backscattering**

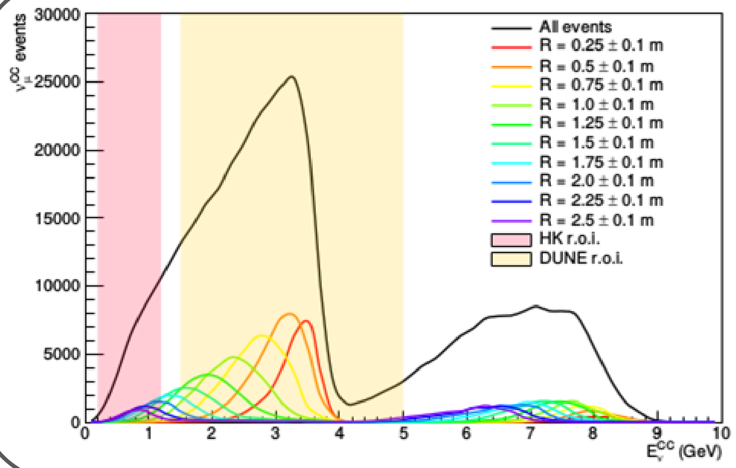
Proton dump: 3 m long graphite core, surrounded by aluminium, covered by iron

Fluxes



- **Nominal SPS 4.5 10^{19} POT/year**
- **500 ton neutrino LAr detector located 50m from the tunnel**

- **10^4 νe CC** in about **2 years**
- **73.5%** of the **total νe flux** generated **inside the tunnel**
- more than **80% above 1 GeV**



Narrow-band Off-axis Technique

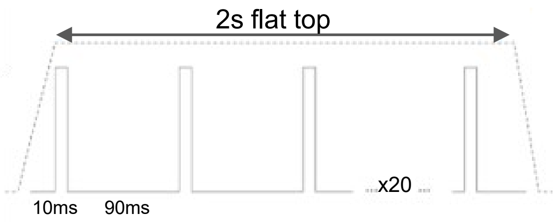
- **Strong correlation** between **Eν** in the detector and the **radial distance** (R) of the interaction **vertex** from the beam axis
- **Total 4 10^5 νμ CC**, assuming 4.5 10^{19} POT
- Loose energy cut enough to **separate π/K** component

Beam line particle yields

2 possibilities:

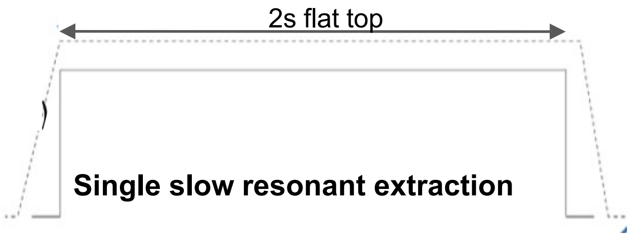
HORN-BASED

20x10ms resonant multiple spills



STATIC-FOCUSING

Continuous long spill



Advantages of the horn(fast) extraction:

- Increase the number of kaons that possible to focus
- Would **take less** to do a measurement (if ENUBET manage to sustain the pile up)

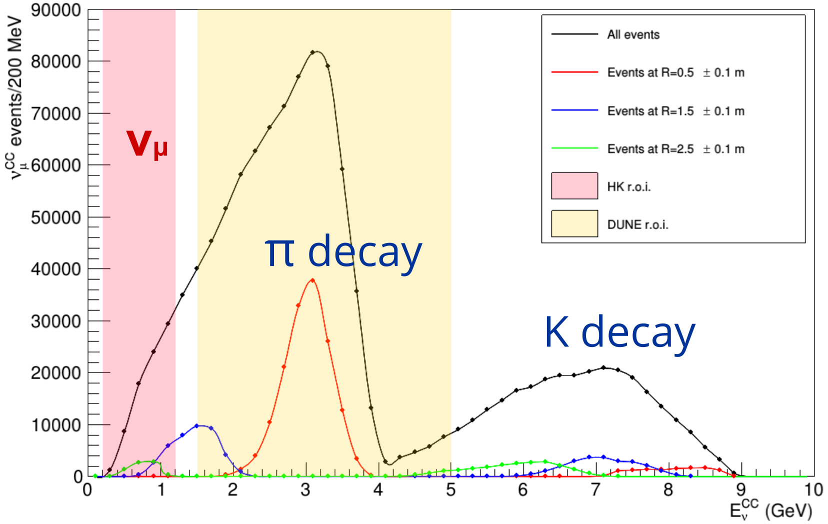
Advantages of the static(slow) extraction:

- No need for fast-cycling horn
- Strong **reduction of the rate** (pile-up) in the instrumented decay tunnel

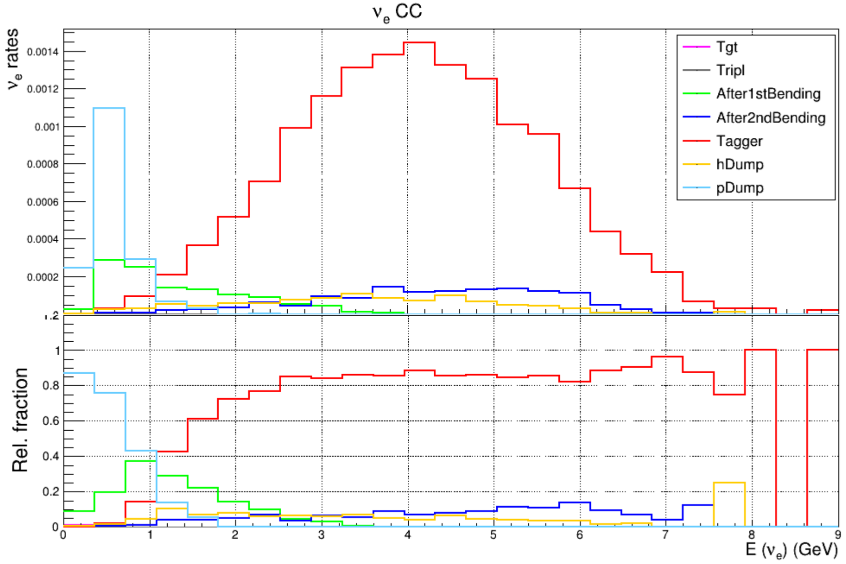
ν_μ *and* ν_e *physics performance*

- **ν_μ** from **K** and **π** are **well separated** in energy;
- Since the momentum bite is <10% and the detector distance is small, there is a strong **correlation** between the **position** of the neutrino vertex and its **energy**
- Technique dubbed "**narrow-band off-axis**"
- **ν_e** and **ν_μ** from **K** are **constrained** by the tagger measurement (K_{e3}, mainly $K_{\mu 2}$);
- Assumption: 500 ton LAr neutrino detector (6x6 m2) @ 50 m from dump

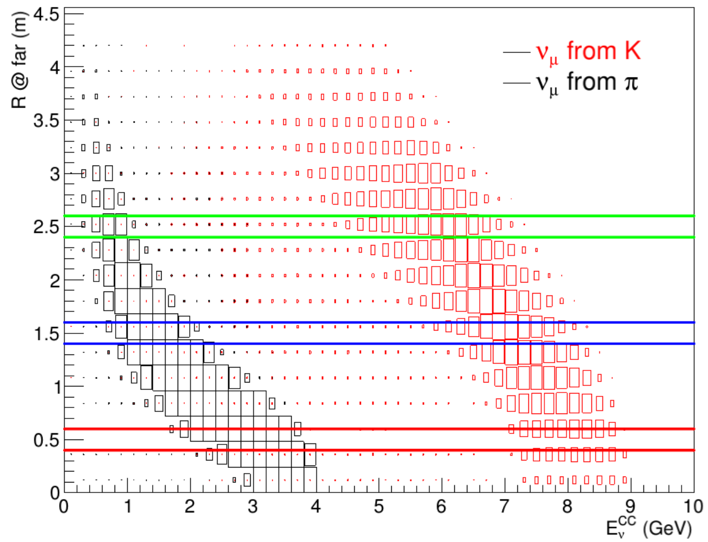
1.2 million ν_μ Charged Current per year

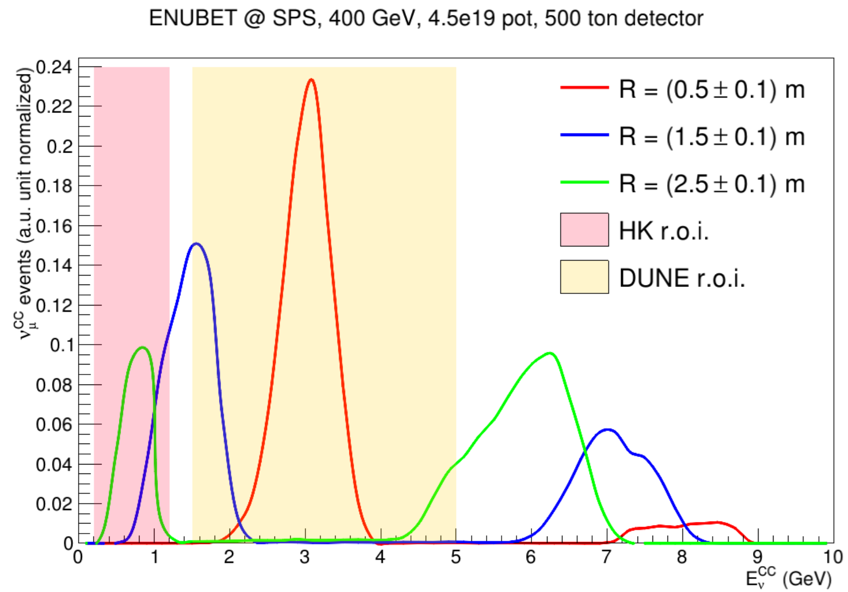


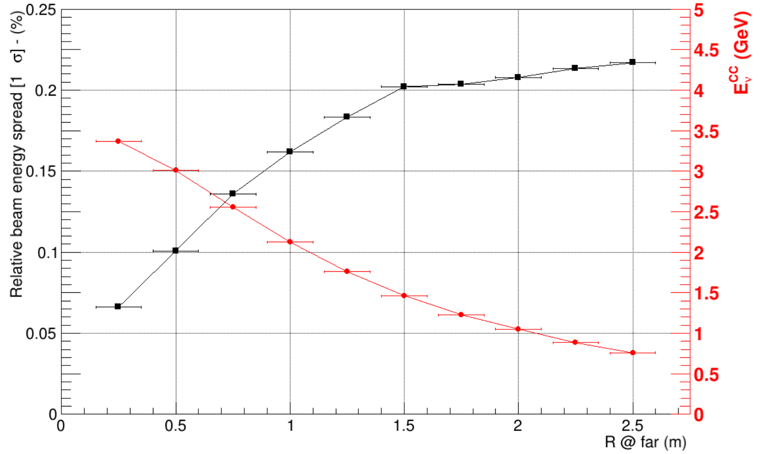
~10000 ν_e Charged Current per year



ν_μ CC events. Narrow band beam







The neutrino E is a function of the distance of the neutrino vertex from the beam axis.

The beam width at fixed R (≡ ν energy resolution for π component) is:

- 8 % for r ~ 50 cm, <Eν>~ 3 GeV
- 22% for r ~ 250 cm, <Eν> ~ 0.7 GeV