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).

ENUBET: heading toward the experiment proposal

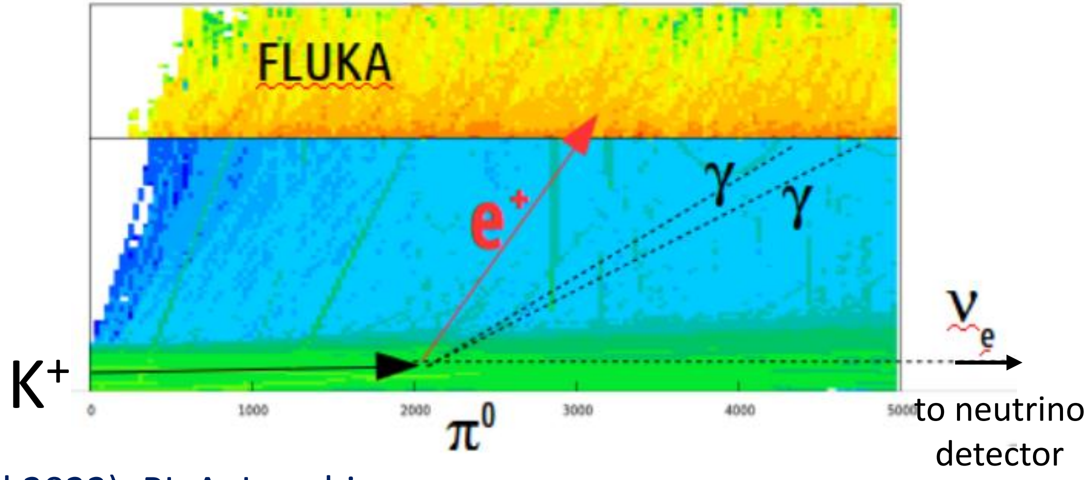
F. Terranova(*) on behalf of the ENUBET Collaboration

(*) University of Milano-Bicocca & INFN Milano-Bicocca

What is ENUBET?

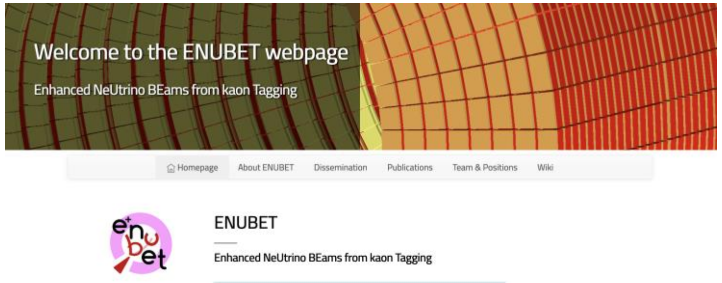
ENUBET is the project for the realization of the first monitored neutrino beam.

“Monitored neutrino beams are beams where diagnostic can directly measure the flux of neutrinos because the experimenters monitor the production of the lepton associated with the neutrino at the single-particle level. “
(Wikipedia)



- ENUBET: ERC Consolidator Grant, June 2016 – May 2021 (COVID: extended to end 2022). PI: A. Longhin;
  - Since April 2019: CERN Neutrino Platform Experiment – NP06/ENUBET – and part of Physics Beyond Colliders;
    - Collaboration: 60 physicists & 13 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna;

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



We are no more in the 20th century: systematics do matter!

Next generation long-baseline experiments (DUNE & HyperK) conceived for precision ν-oscillation measurements:

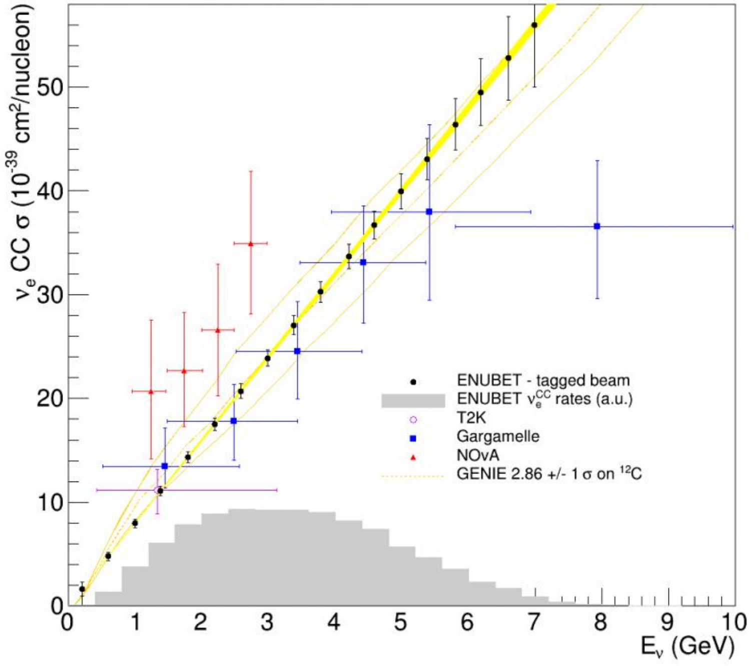
- test the 3-neutrino paradigm;
- determine the mass hierarchy;
- test CP asymmetry in the lepton sector;

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

Very good knowledge needed!

Moreover ν-interaction models would benefit from improved precision on cross-sections measurements

ENUBET impact on σ_{ν_e}



The purpose of ENUBET: design a narrow-band neutrino beam to measure

- neutrino cross-section and flavor composition at 1% precision level;
- neutrino energy at 10% precision level;

From the **European Strategy for Particle Physics Deliberation document**:

To extract the most physics fromDUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

ENUBET: the first monitored neutrino beams

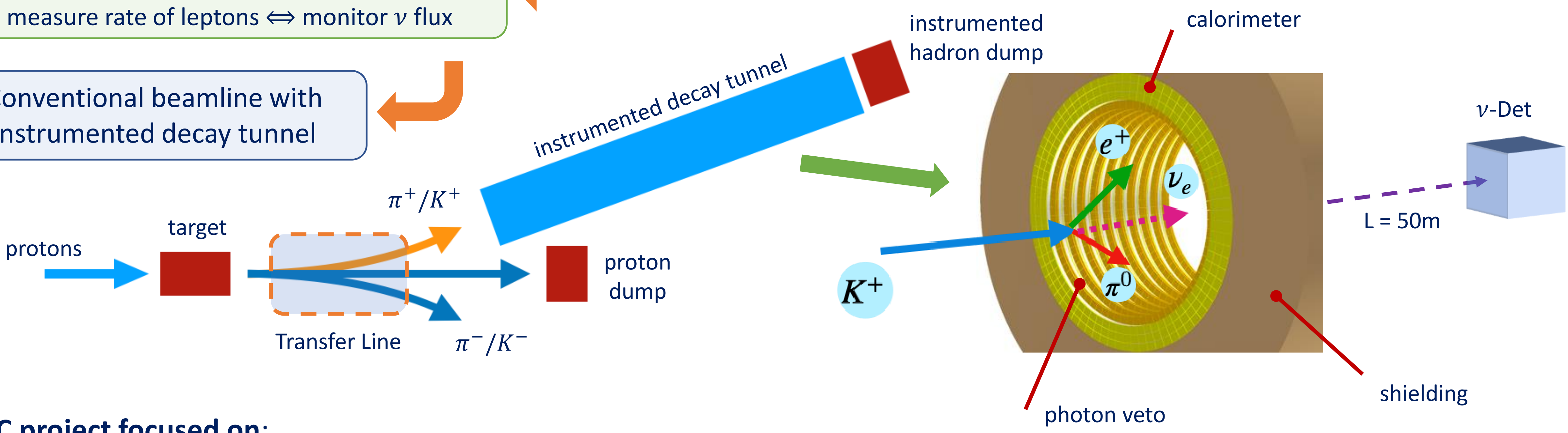
How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?

Monitored ν flux from narrow-band beam

measure rate of leptons $\Leftrightarrow$ monitor ν flux

Conventional beamline with instrumented decay tunnel

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



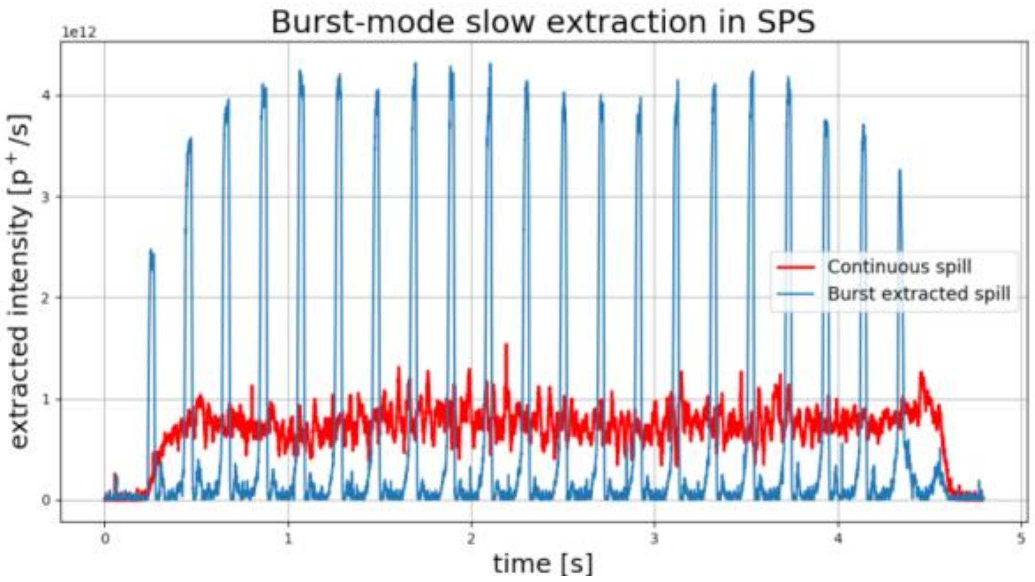
- **ERC project focused on**:
  measure positrons (instrumented decay tunnel) from K_{e3} $\Longrightarrow$ determination of ν_e flux;
- **As CERN NP06 project**:
  extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ $\Longrightarrow$ determination of ν_μ flux;

Main systematics contributions are bypassed: hadron production, beamline geometry & focusing, POT;

The 2020 breakthrough: a high-intensity horn-less neutrino beam

When we first proposed ENUBET, we were aiming at a beam where the leptons in the decay tunnel are produced at **slow rate** because we were afraid of pile-up and saturation of the instrumentation in the tunnel

Original design: a horn pulsed every 100 ms with a 10 ms pulse (“burst proton extraction”)



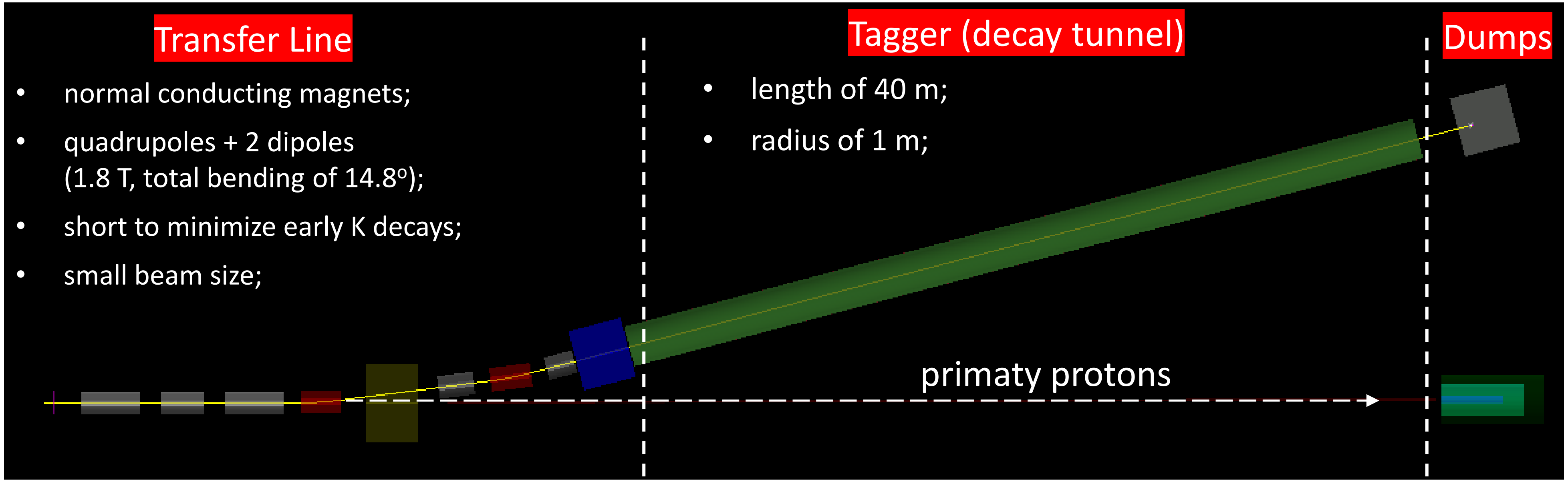
First demonstration of this proton extraction scheme in 2018 at CERN-SPS

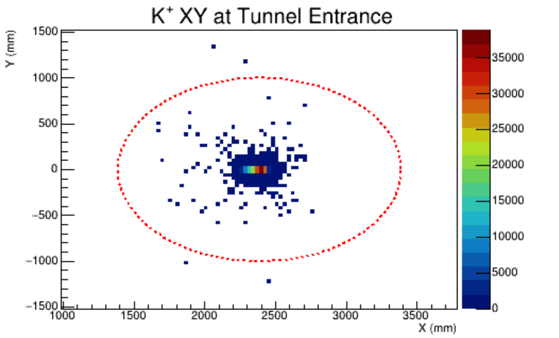
M. Pari, M. A Fraser et al, IPAC2019

2020 design (“static focusing system”): a neutrino beam without a horn where focusing at 8 GeV/c is accomplished by quadrupoles (like e.g. NuTeV but at much lower energy!)

The design was so successful that it achieved a flux that is just 2 times smaller than the corresponding horn-based design but protons are extracted in 2 seconds!! Rates reduced by more than one order of magnitude!

The ENUBET beamline: (details in A. Branca ICHEP2022)





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

~1.5X w.r.t. previous results

Large bending angle of 14.8°:

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

Transfer Line:

- optics optimization w/ **TRANSPORT** (5% momentum bite centered @ 8.5 GeV) **G4Beamline** for particle transport and interactions;
- **FLUKA** for irradiation studies, **absorbers and rock** volumes included in simulation (not shown above);
- **optimized graphite target** 70 cm long & 3 cm radius (dedicated studies, scan geometry and different materials);
- **tungsten foil downstream target** to suppress positron background;
- tungsten alloy **absorber @ tagger entrance** to suppress backgrounds;

Dumps:

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

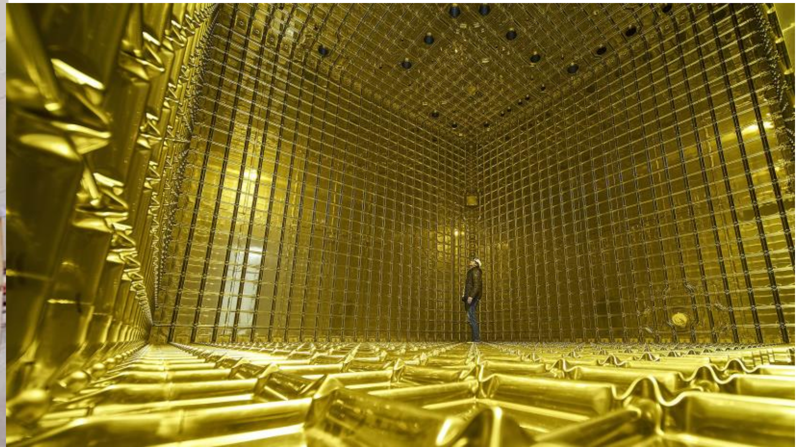
Full facility implemented in GEANT4:
- Controll over all paramaters;
- Access to the paricles histories;

assessment of the nu flux systematics

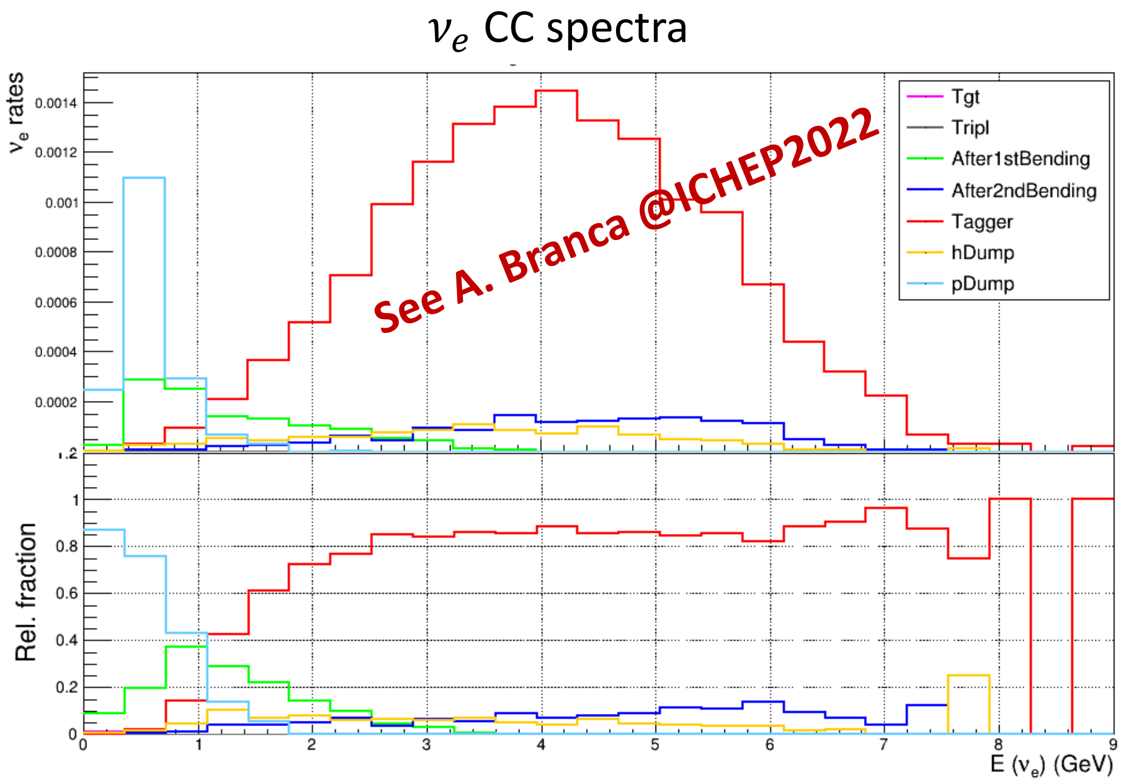
ν_e^{CC} energy distribution @ detector

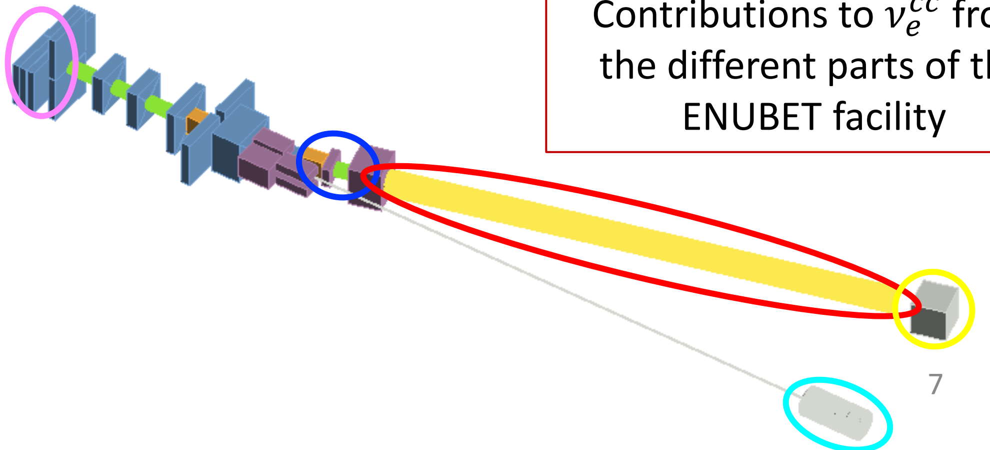
A total ν_e^{CC} statistics of 10^4 events in ~3 years

- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 tonne detector @ 50 m from tunnel end;



ProtoDUNE-SP (NP04)





Contributions to ν_e^{cc} from the different parts of the ENUBET facility

ν_μ^{CC} energy distribution @ detector

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

(E_ν,R) are strongly correlated

E_ν = neutrino energy;

R = radial distance of interaction vertex from beam axis;

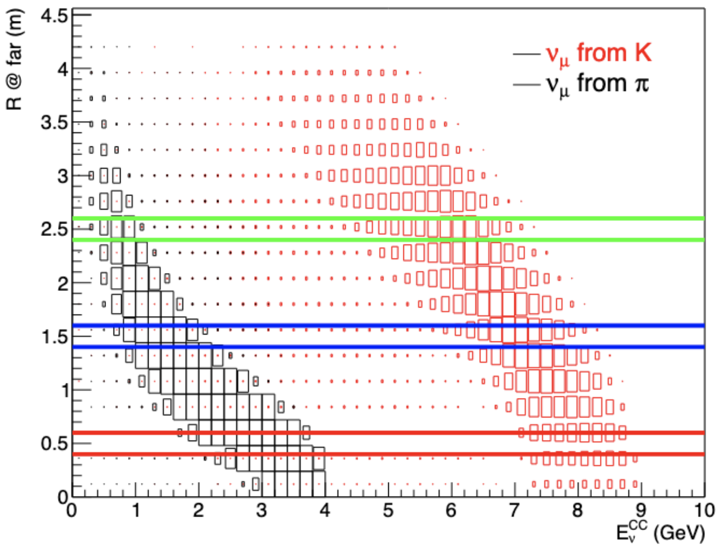
F. Acerbi et al., CERN-SPSC-2018-034

Precise determination of E_ν :
no need to rely on final state particles from ν_μ^{CC} interaction

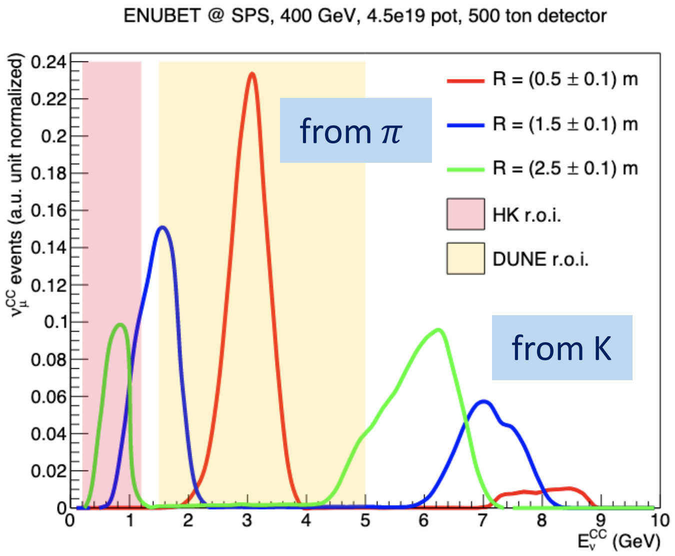
8-25% E_ν resolution from π in the DUNE energy range

30% E_ν resolution from π in HyperK energy range (DUNE optimized TL w/ 8.5 GeV beam):

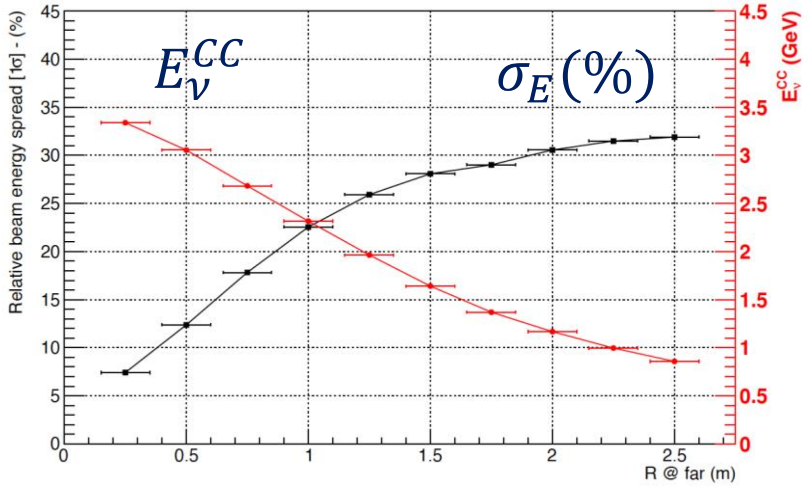
- ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



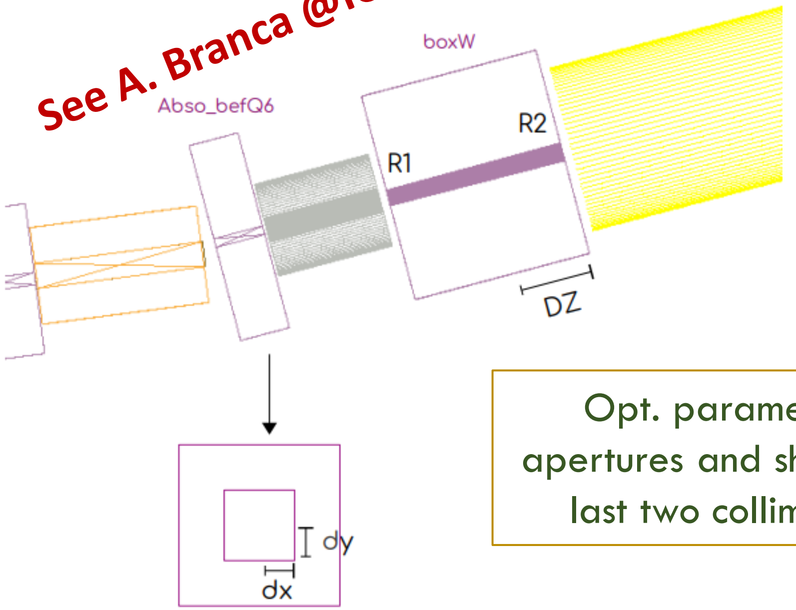
π/K populations well separated



from pion peaks at different R

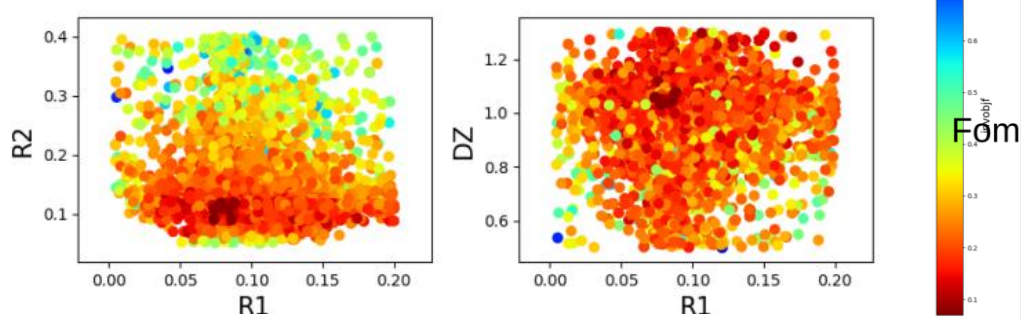
The ENUBET beamline: optimization studies

See A. Branca @ICHEP2022



Opt. parameters: apertures and shapes of last two collimators

FOM dependence on opt. parameters



FOM = signal/background

Signal: π & K @ tagger enterance

Background: e^+& π hitting tunnel walls

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

An optimization campain is ongoing:

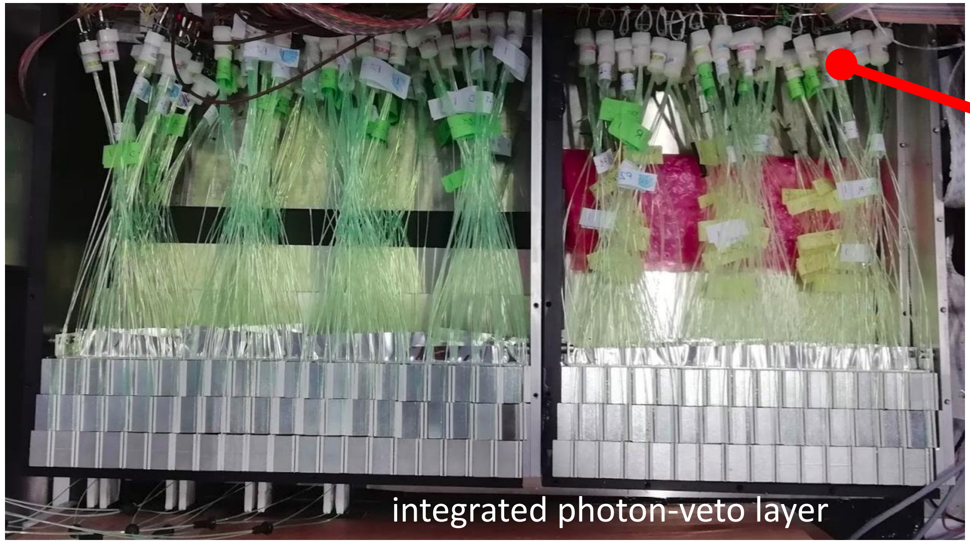
- **Goal**: further improvement of the π/K flux at tunnel entrance while keeping background level low;
- **Strategy**: scan parameters space of beamline to maximize FOM;
- **Tools**: full facility implemented in Geant4 **->** controll with external cards all parameters -> systematic optimization with developed framework based on genetic algorithm;

Preliminary

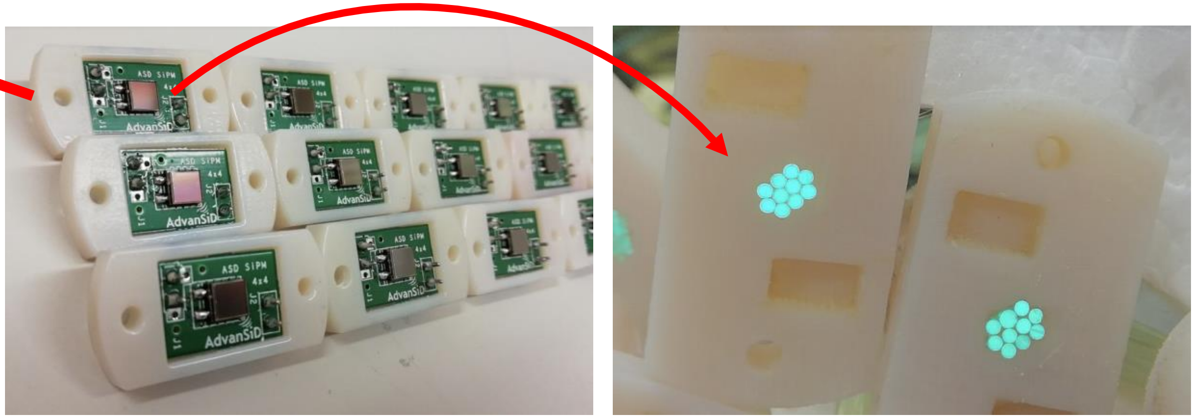
- About 28% gain in flux -> 2.4 years to collect 10^4 ν_e^{CC};
- Reduced backgrounds, but similar to signal shapes -> next step: improve FOM definition (include sgn/bkg distributions);

Decay tunnel instrumentation prototype & tests

Prototype of sampling calorimeter built out of LCM with lateral WLS-fibers for light collection



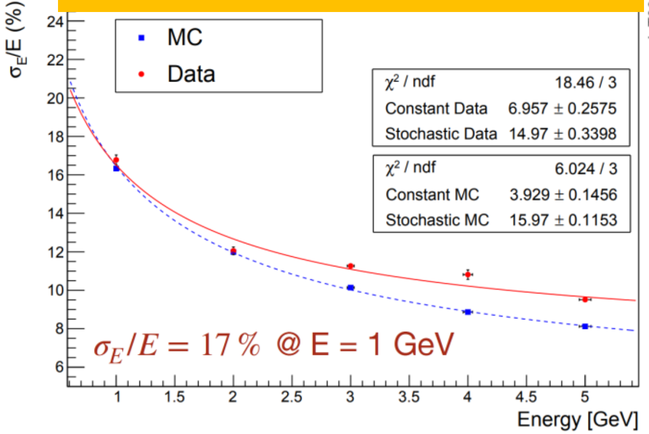
Large SiPM area (4x4 mm^2) for 10 WLS readout (1 LCM)



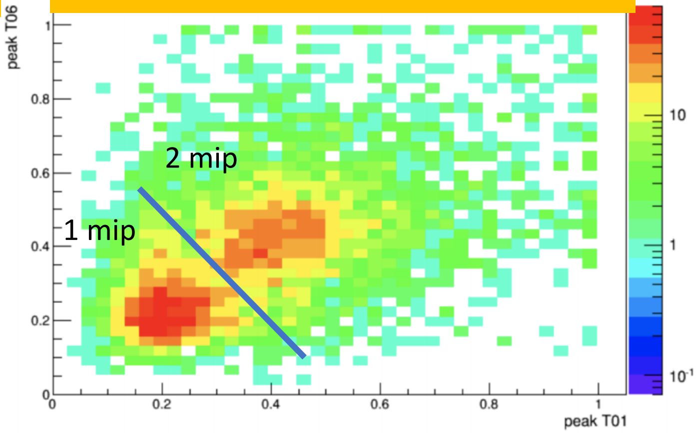
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

Tested during 2018 test-beams runs @ CERN TS-P9

Electron energy resolution



1mip/2mip separation



Status of calorimeter:

- ✓ longitudinally segmented calorimeter prototype successfully tested;
- ✓ photon veto successfully tested;
- ➢ custom digitizers: in progress;

Choise of technology: finalized and cost-effective!

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

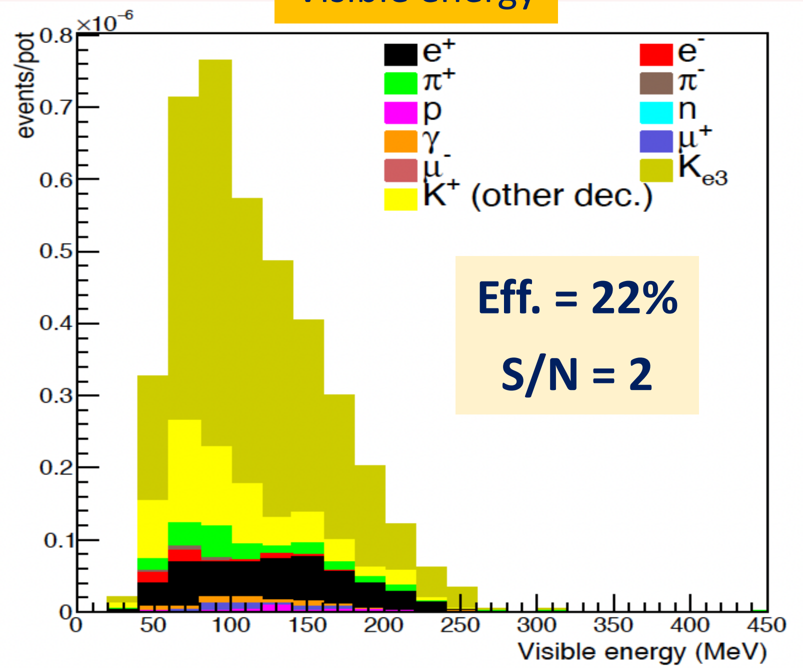
Lepton reconstruction and identification performance

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 kaon decays reconstructed searching for patterns in energy depositions in tagger;
- Signal identification done using a Neural Network trained on a set of discriminating variables;

K_{e3} positrons -> constrain ν_e

Visible energy



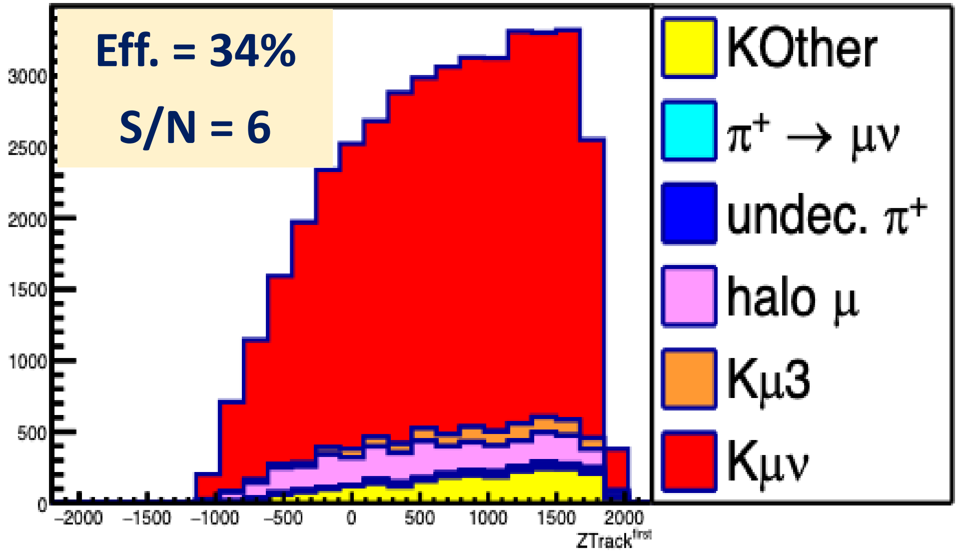
Eff. = 22%

S/N = 2

Efficiency ~half geometrical

$K_{\mu2}$ muons -> constrain ν_μ

Tagger impact point



Eff. = 34%

S/N = 6

Efficiency ~half geometrical

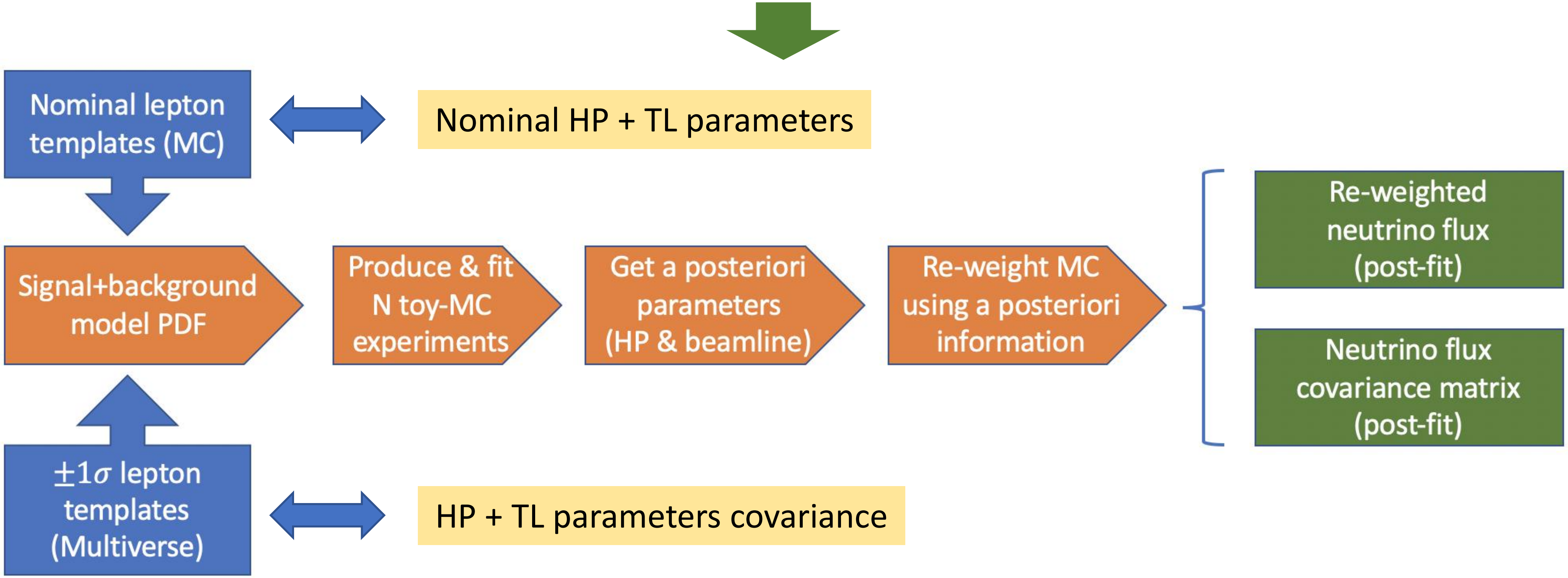
K_{e3} BR $\sim 5\%$ and K make $\sim 5 - 10\%$ of beam composition

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

ν-Flux: assessment of systematics

Monitored ν flux from narrow-band beam: measure rate of leptons ⟺ monitor ν flux

- build a Signal + Background model to fit lepton observables;
- include hadro-production (HP) & transfer line (TL) systematics as nuisances;

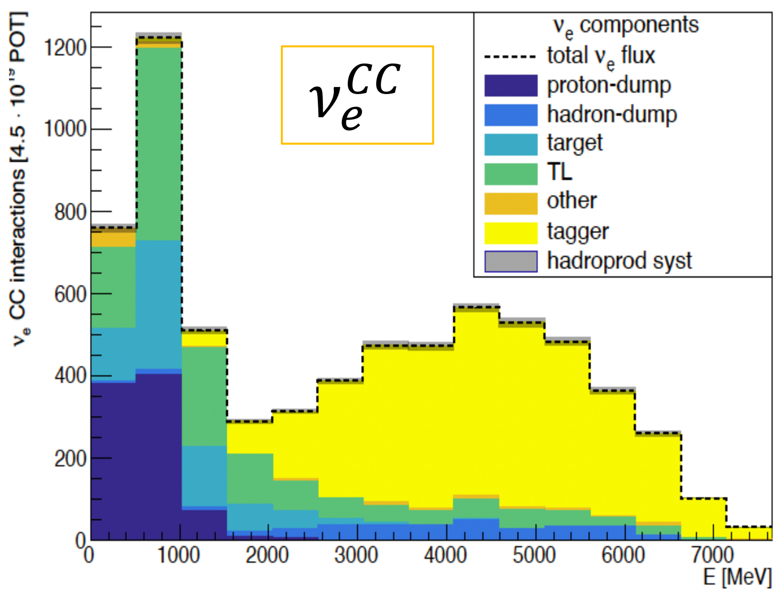


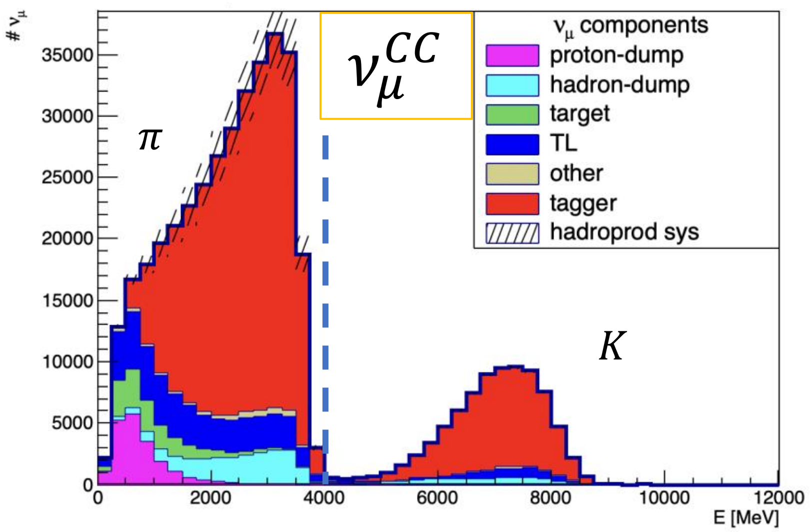
Used hadro-production data from NA56/SPY experiment to:

- Reweight MC lepton templates and get their nominal distribution;
- Compute lepton templates variations using multi-universe method;

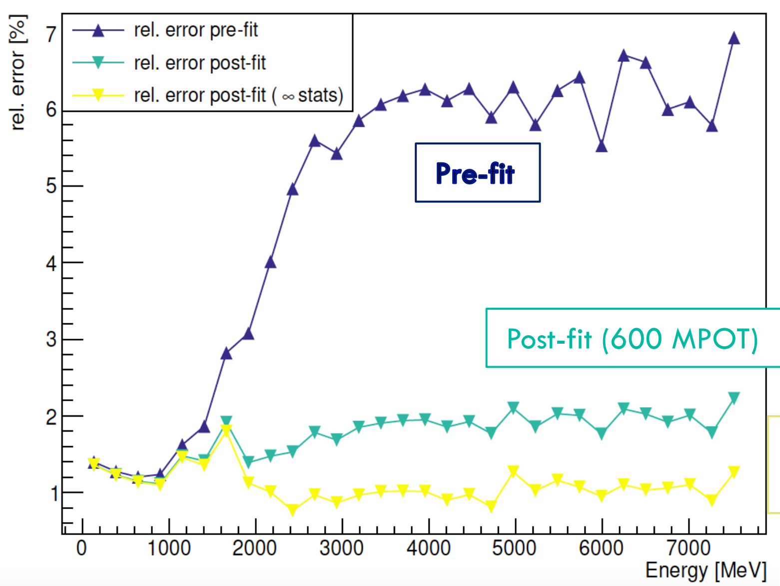
ν-Flux: impact of hadro-production systematics

Neutrino interaction rates @ detector

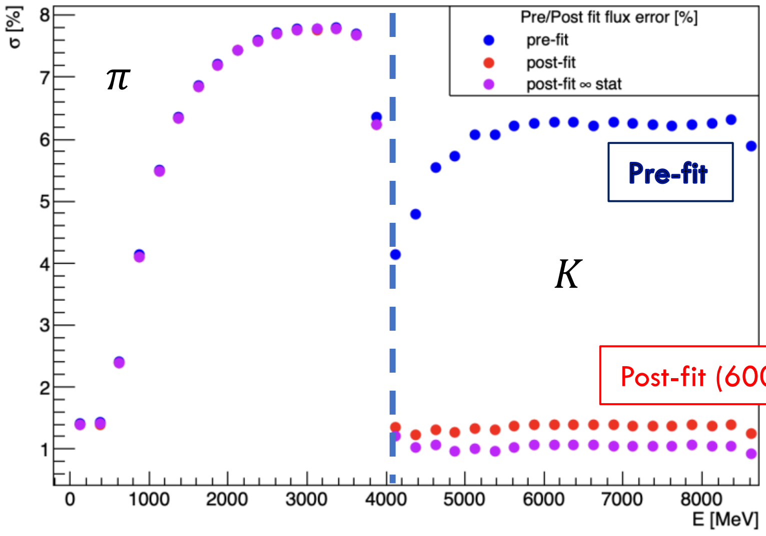




Pre & Post fit relative errors on rates



Infinite statistics



Post-fit (600 MPOT)

Infinite statistics

Total rates in 1 year of data taking

- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 ton detector @ 50 m from tunnel end;

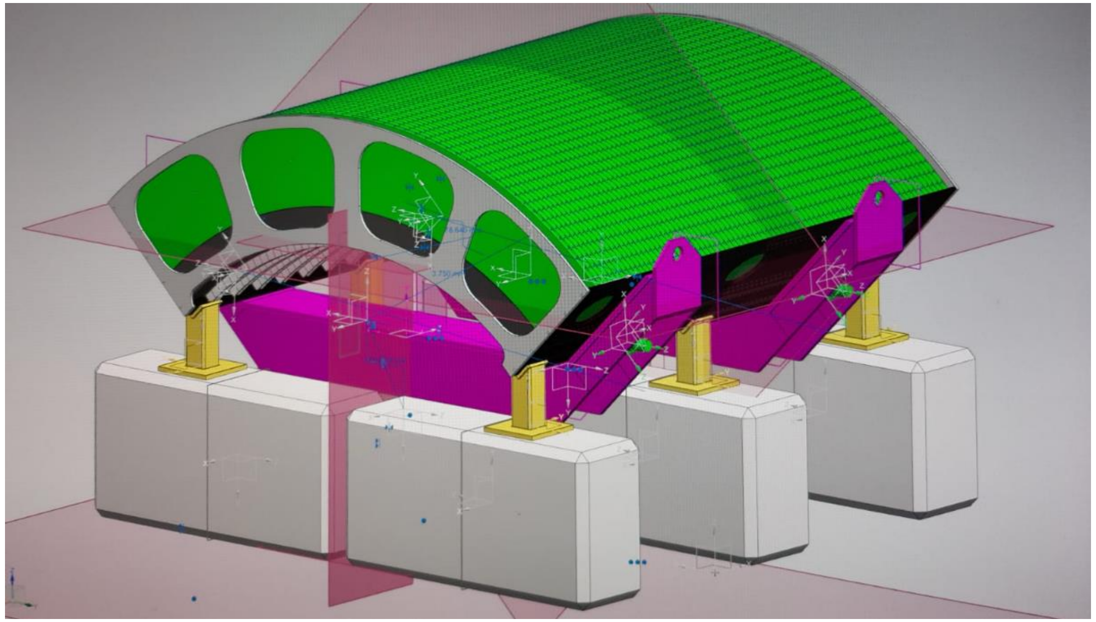
NEW – Mar 2022 !

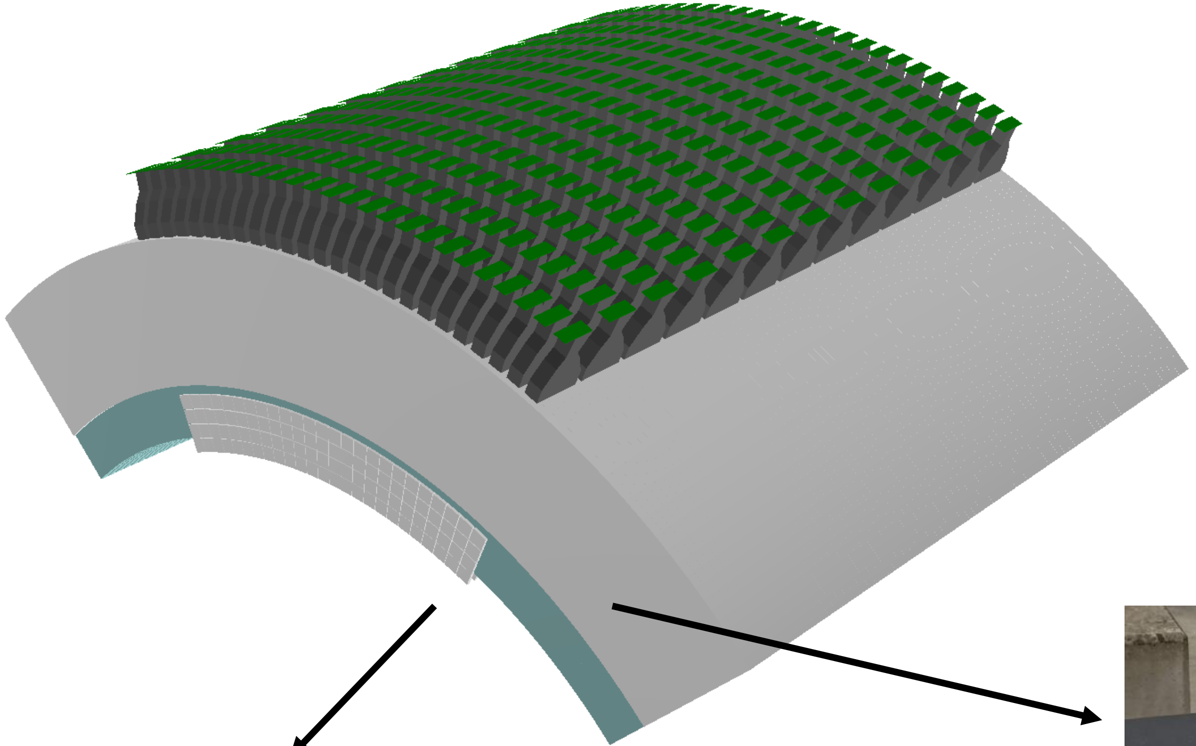
Before constraint: 6% systematics due to hadro-production uncertainties;
After constraint: 1% systematics from fit to lepton rates measured by tagger;

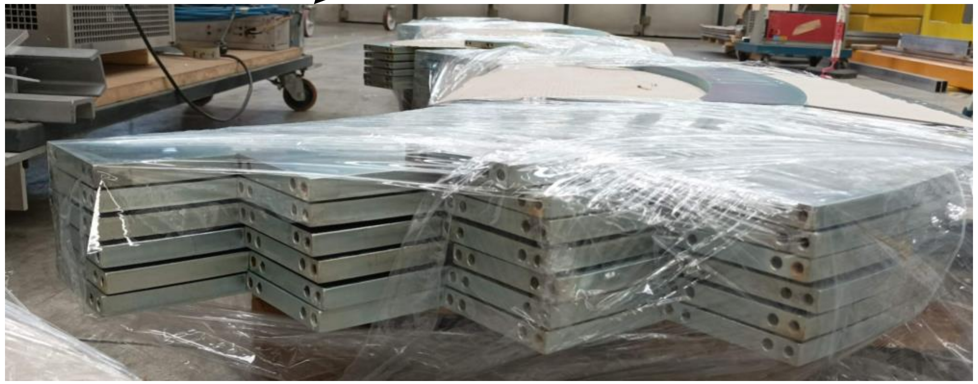
Achieved ENUBET goal of 1% systematics from monitoring lepton rates

The ENUBET demonstrator

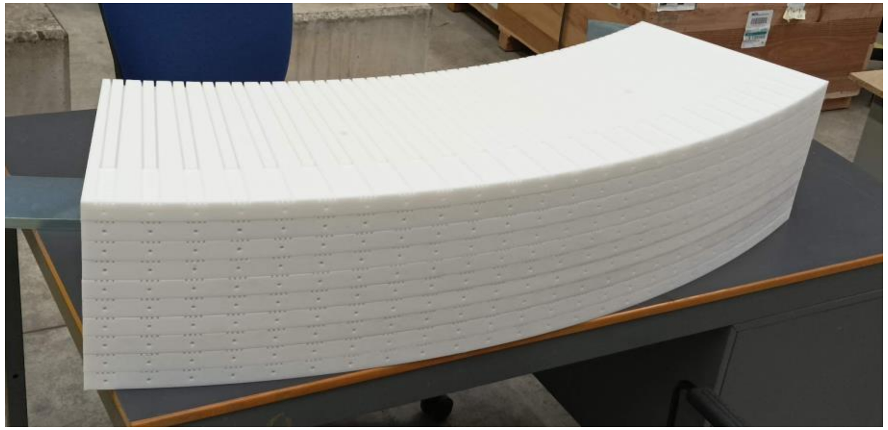
Weight ~7 t







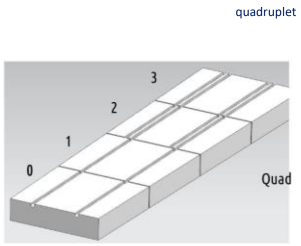
Machined iron for calorimeter absorber layers

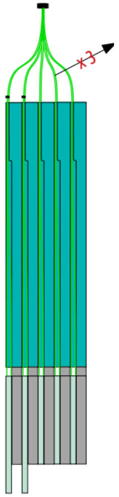


5% Borated Polyethylen arcs

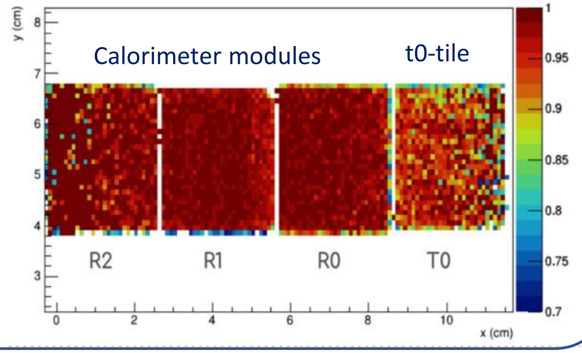
New frontal readout scheme & fibers bundling

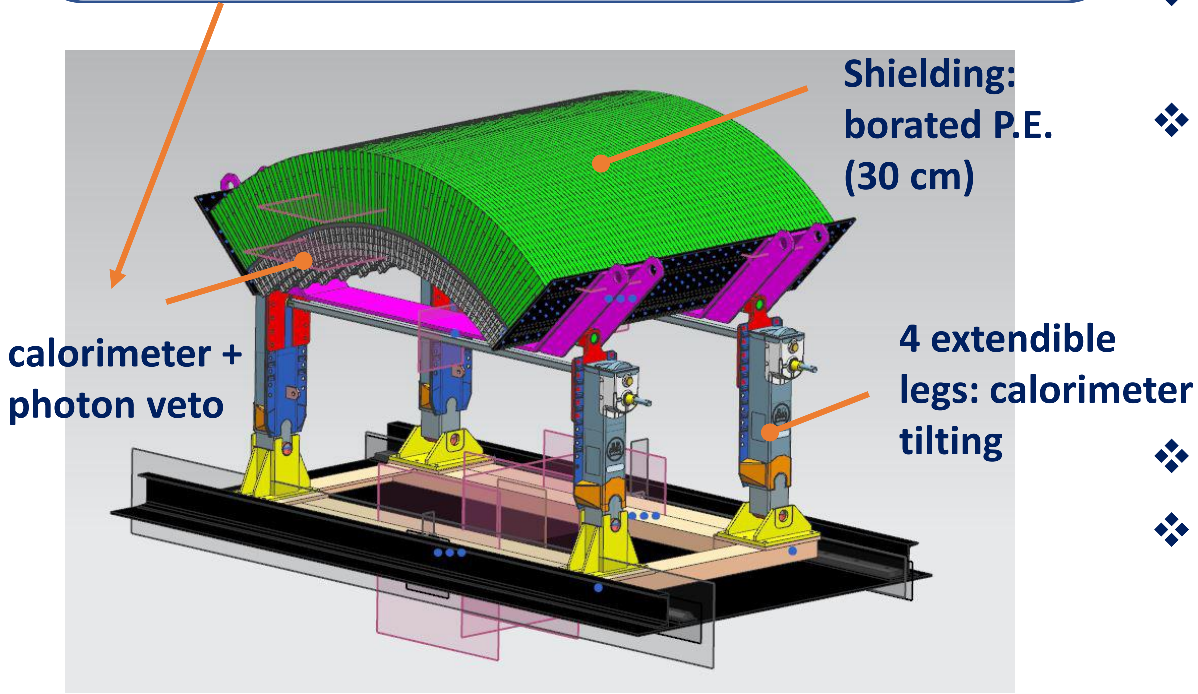
10 WLS fibers (1 LCM) bundled to a 4×4 mm^2 SiPM





Efficiency map from ENUBINO test





- Detector prototype under construction, to demonstrate:
  - Performance / scalability / cost-effectiveness;

Test-beam @ CERN in October 2022

  - 1.65 m longitudinal & 90º in azimuth;
  - 75 layers of: iron (1.5 mm thick) + shintillator (7 mm thick) => 12X3 LCMs;
- central 45º part instrumented: rest is kept for mechanical considerations;
- modular design: can be extended to a full 2π object by joining 4 similar detectors (minimal dead regions);
- new light readout scheme with frontal grooves instead of lateral grooves:
  - driven by large scale scintillator manufacturing: safer production and more uniform light collection;
  - performed GEANT4 optical simulation validation;
- scintillators: produced by SCONIX and milled by local company;
- ENUBINO: pre-demonstrator w/ 3 LCM tested @ CERN in November 2021 to study uniformity and efficiency;

Looking ahead

- Complete our homework (2022-23) [ERC project + NP06/ENUBET]
  - Assessment of sub-dominant systematics
  - Horn-based beam
  - Validation of the demonstrator with the ENUBET custom electronics
  - Publication of the final papers on (1) beamline, (2) multi-momentum beamline, (3) cross section performance and (4) validation of the demonstrator
- Provide a design for the hadron dump and lepton tagging, including the tagged neutrino beams [**ENUBET/PIMENT – see talk from Alexandra Kallitsopoulou**]
- Study the physics performance of an ENUBET-based beam with ProtoDUNE-SP or ICARUS at FNAL [NP06/ENUBET]
- Deliver the Conceptual Design Report using CERN (SPS+ProtoDUNE) as the baseline implementation (2023-24). The site-dependent (CERN) implementation will be carried out by NP06/ENUBET in the framework of Physics Beyond Collider. It includes costs, infrastructures, engineering of the beamline components, beam transport toward the neutrino detector, safety and activation, shielding and decommissioning costs
- We aim at an **experimental proposal** in 2024 to have ENUBET up and running at the beginning of the DUNE and HyperKamiokande data taking.