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 and NuSTORM heading to the experiment proposal

F. Terranova

University of Milano-Bicocca & INFN Milano-Bicocca

Neutrino beam "instrumentation" for the decade to come

The precision era of neutrino oscillation physics: beams are the ideal source due to the high level of control

Neutrino oscillation still to be established

Focus on **high-intensity** beam

Beam diagnostics ancillary to beam power

Flux and flavor composition known at 20-30% level

Neutrino energy measured by the neutrino detector final states

Experiments limited by systematic uncertainties since 2020

Focus on high-precision beam

Flux and flavor composition known at 10% level:

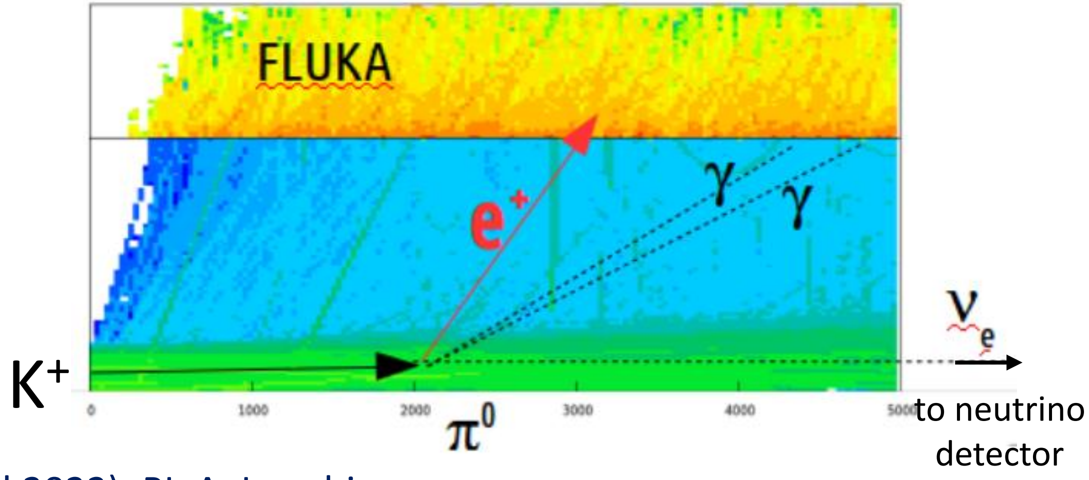
Neutrino energy measured by the neutrino detector final states

Dominant contribution to cross section experiments. Cross sections, in turn, are the dominant systematics of DUNE and HyperK

What is ENUBET?

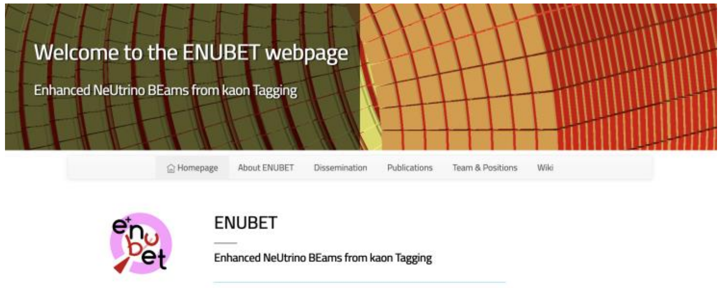
ENUBET is the project for the realization of the first monitored neutrino beam.

"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:

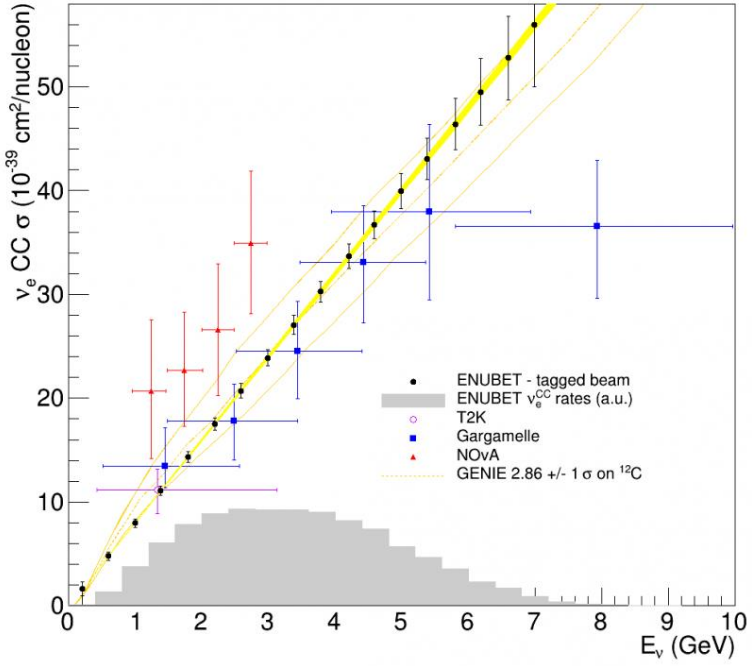
- test the 3-neutrino paradigm;
- determine the mass hierarchy;
- test CP asymmetry in the lepton sector;

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

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

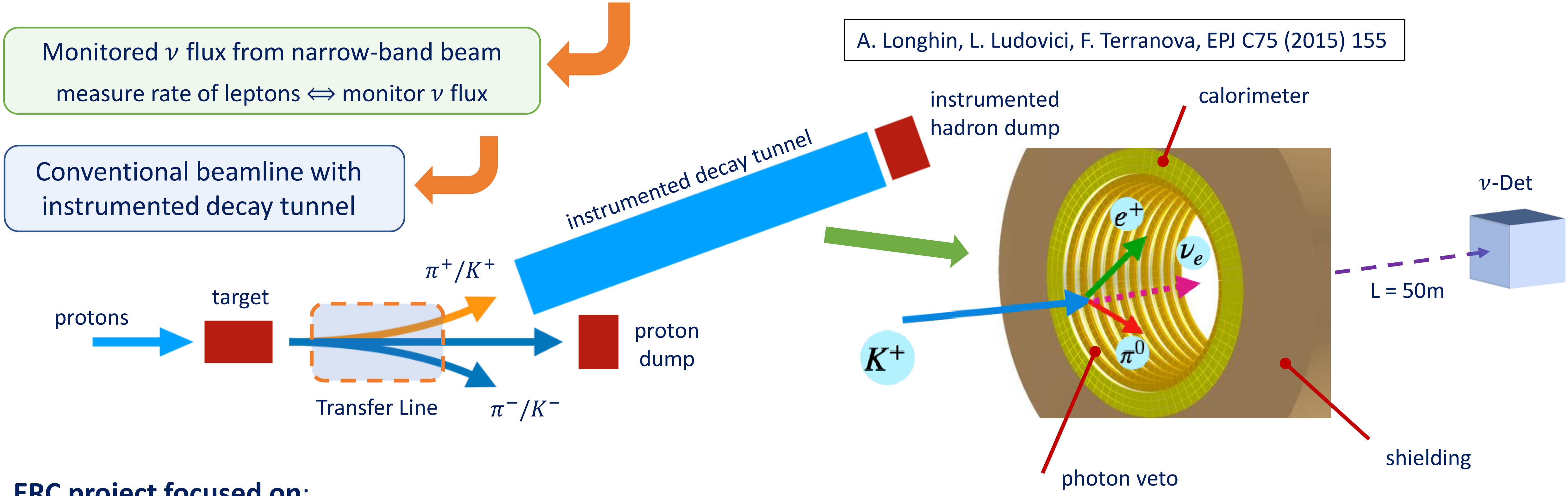
- neutrino cross-section and flavor composition at 1% precision level;
- neutrino energy at 10% precision level;

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?



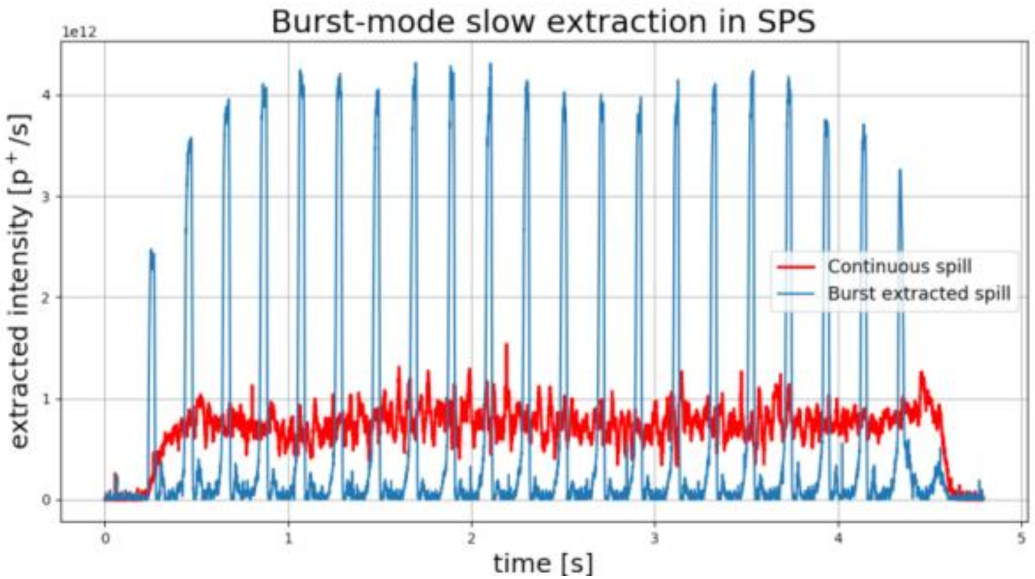
- **ERC project focused on**:
  measure positrons (instrumented decay tunnel) from K_{e3} $\Longrightarrow$ determination of ν_e flux;
- **As CERN NP06 project**:
  extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ $\Longrightarrow$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



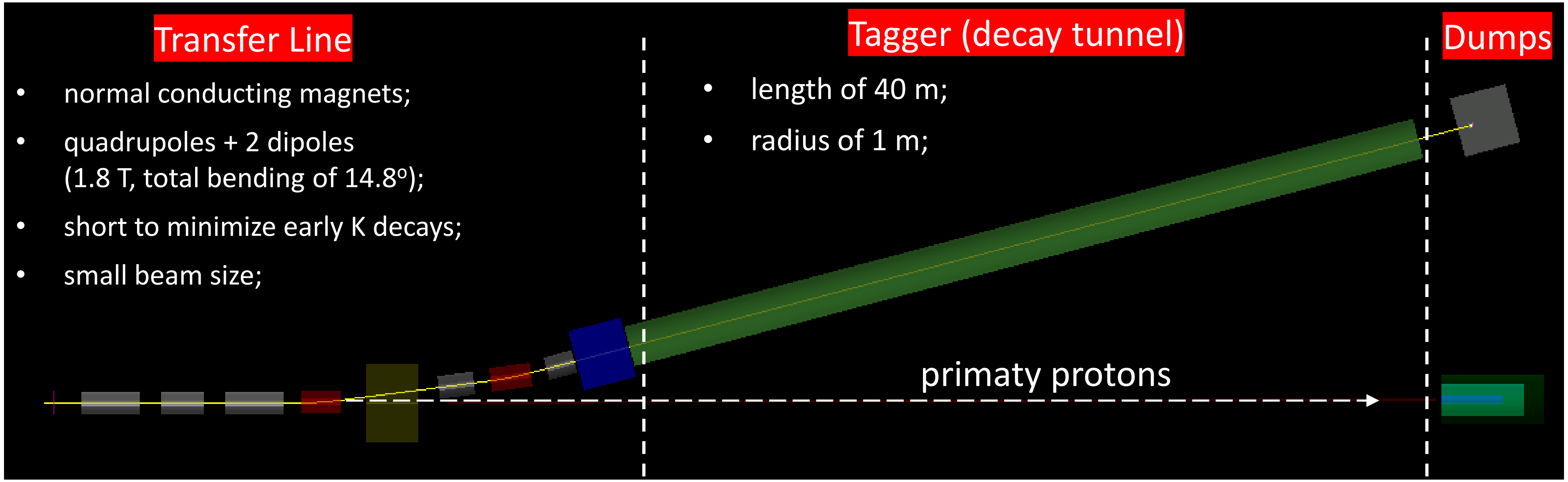
First demonstration of this proton extraction scheme in 2018 at CERN-SPS

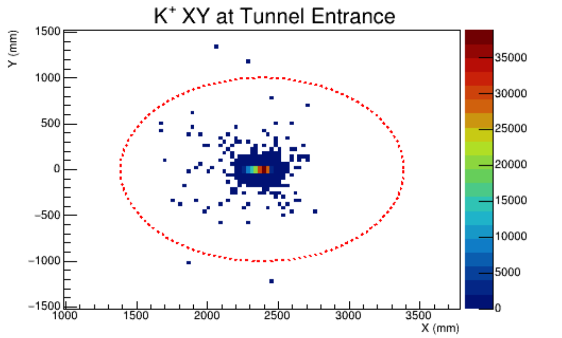
M. Pari, M. A Fraser et al, IPAC2019

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 14.8º:
- 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;

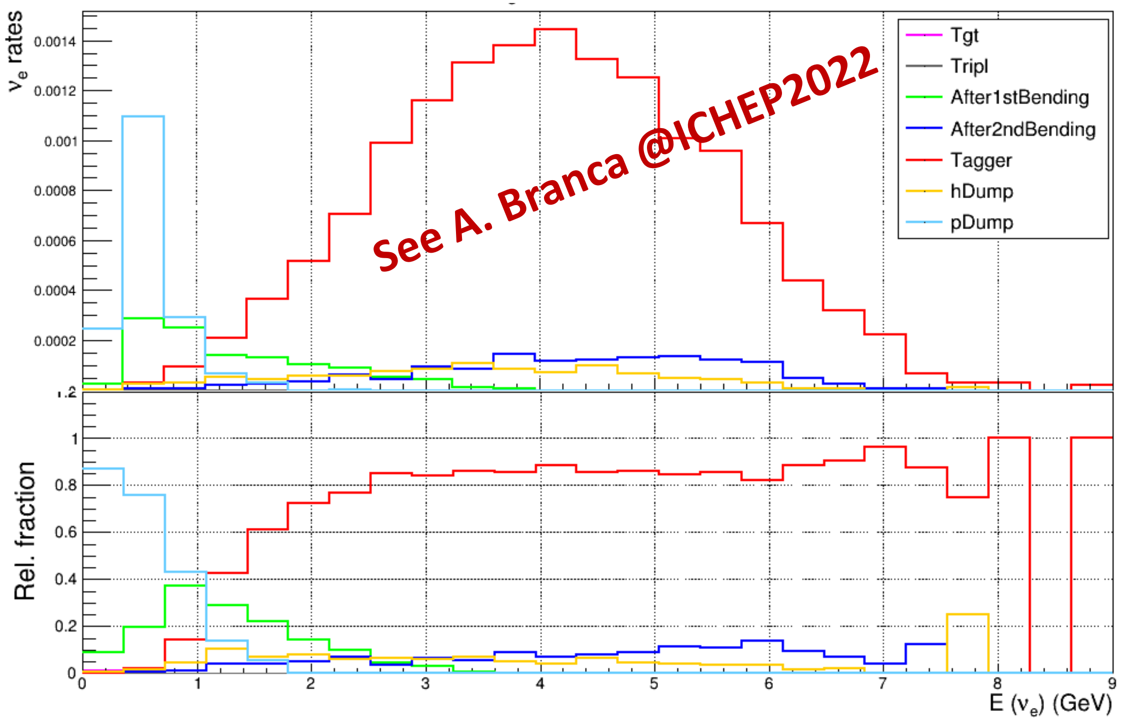
assessment of the nu flux systematics

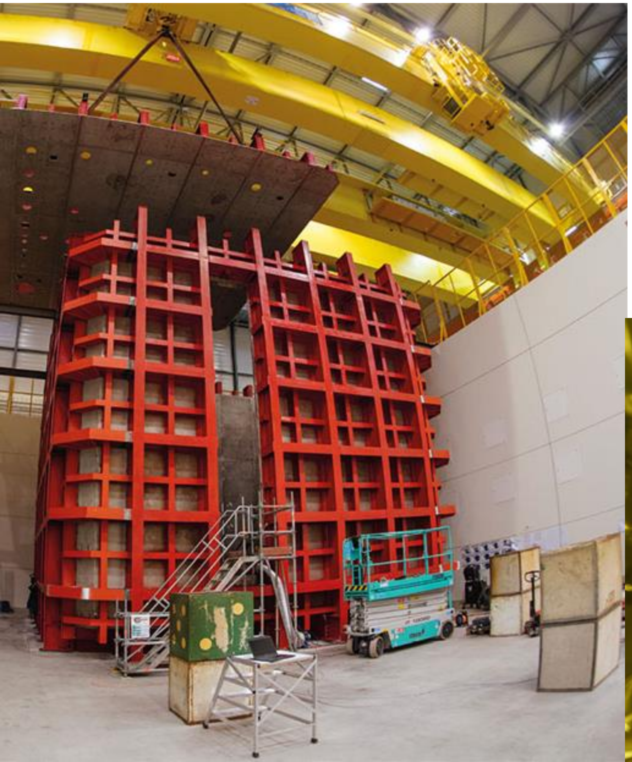
ν_e^{CC} energy distribution @ detector

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

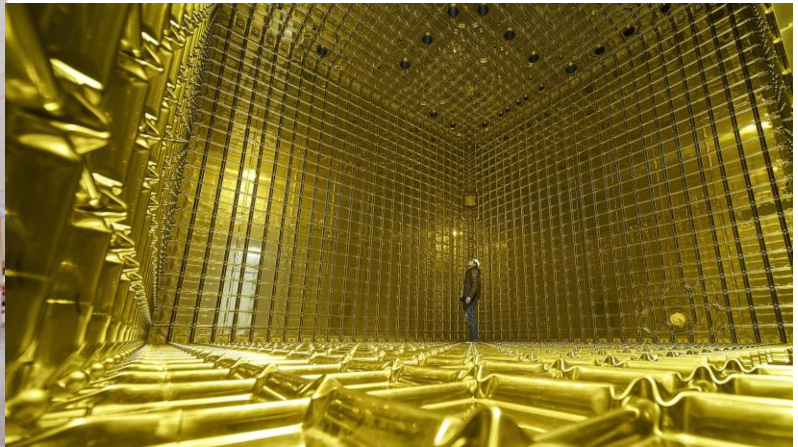
- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 tonne detector @ 50 m from tunnel end;

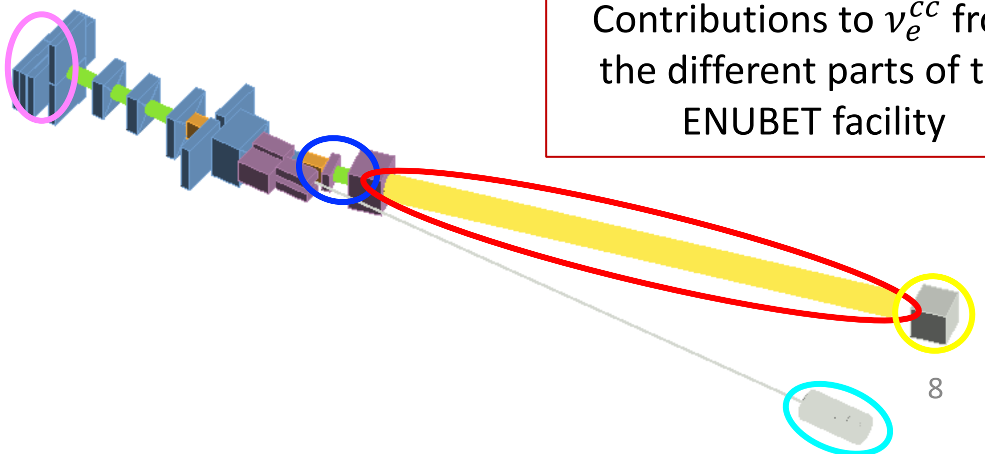
ν_e CC spectra





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;

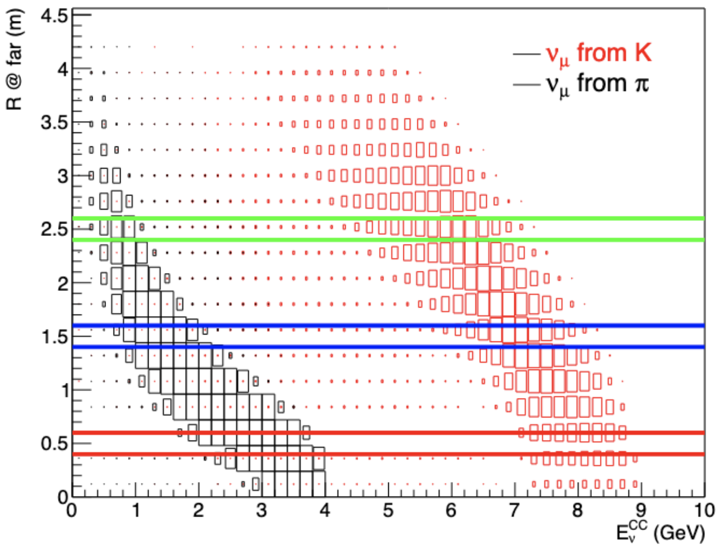
F. Acerbi et al., CERN-SPSC-2018-034

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

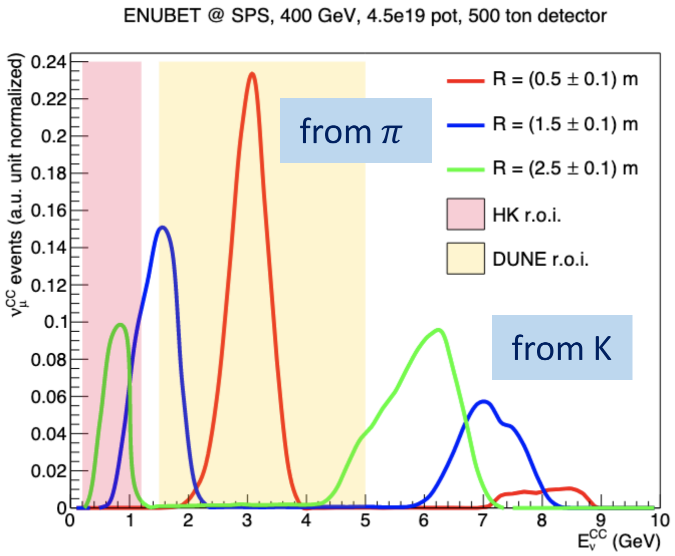
8-25% E_ν resolution from π in the DUNE energy range

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

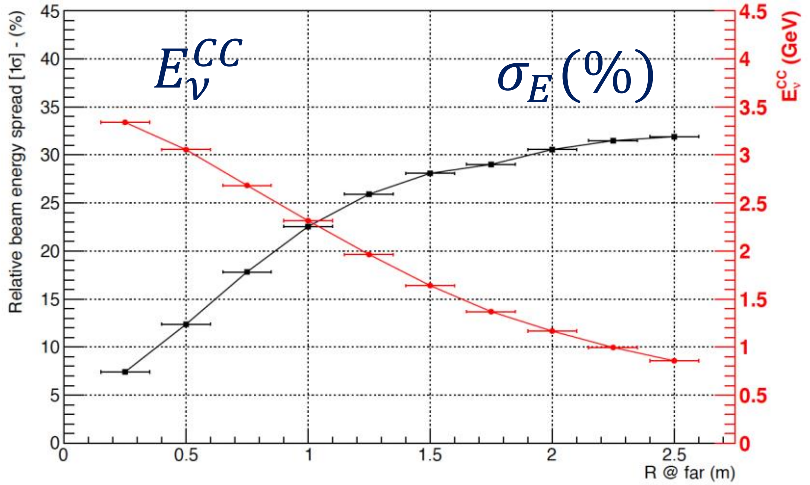
- ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



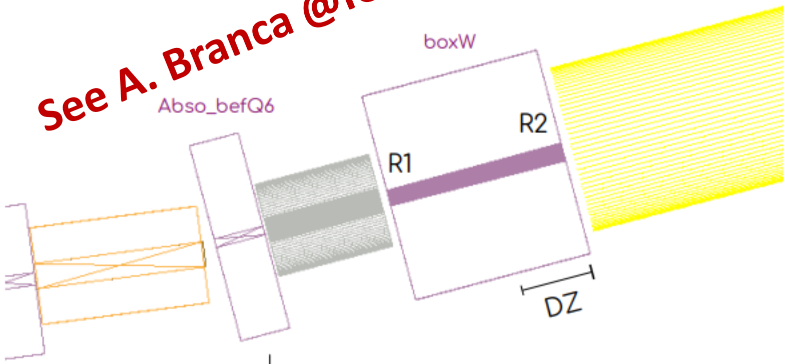
π/K populations well separated

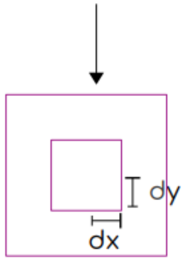


from pion peaks at different R

The ENUBET beamline: optimization studies

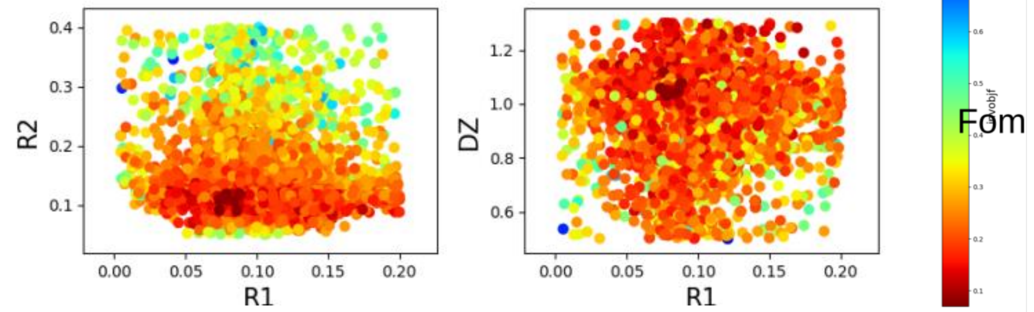
See A. Branca @ICHEP2022





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:

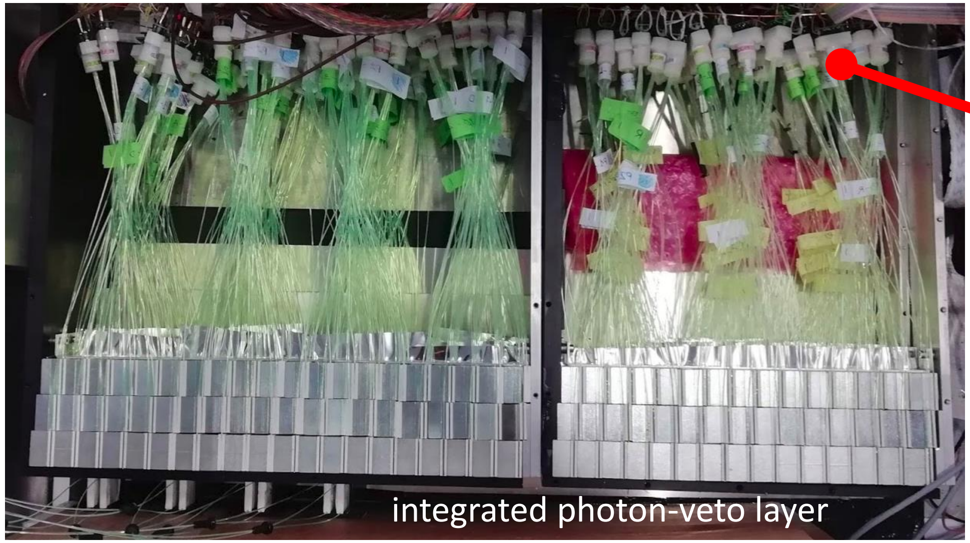
- **Goal**: further improvement of the π/K flux at tunnel entrance while keeping background level low;
- **Strategy**: scan parameters space of beamline to maximize FOM;
- **Tools**: full facility implemented in Geant4 -> controll with external cards all parameters -> systematic optimization with developed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

Preliminary

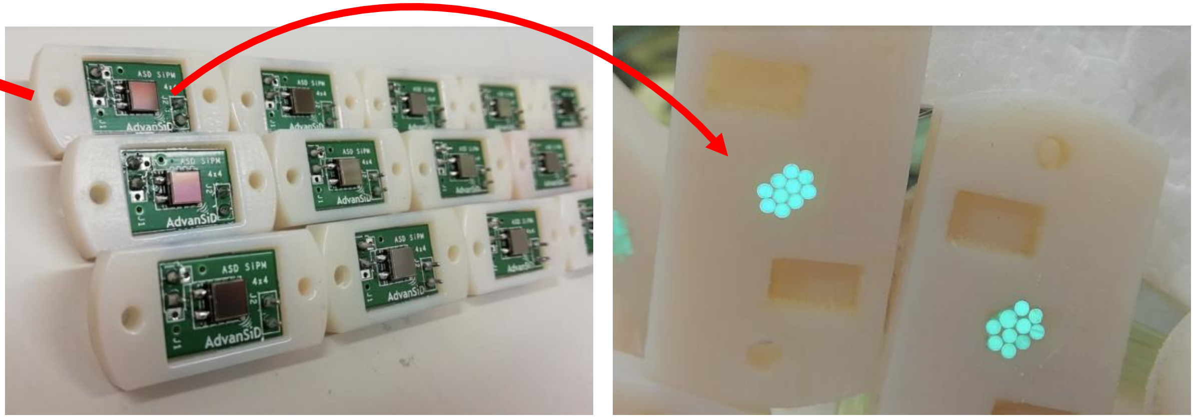
- About 28% gain in flux -> 2.4 years to collect 10^4 ν_e^{CC};
- Reduced backgrounds, but similar to signal shapes -> next step: improve FOM definition (include sgn/bkg distributions);

Decay tunnel instrumentation prototype & tests

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



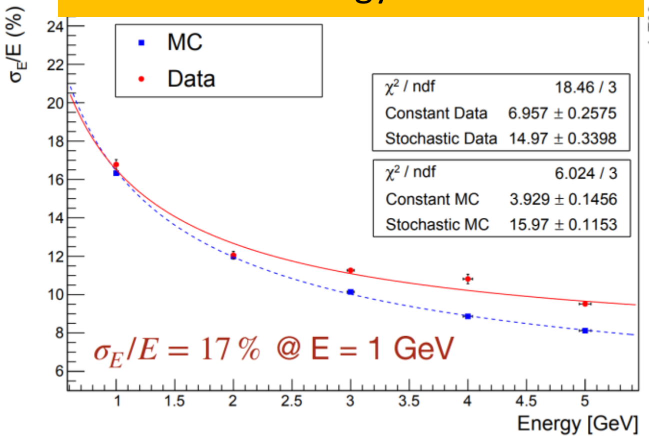
Large SiPM area (4x4 mm^2) for 10 WLS readout (1 LCM)



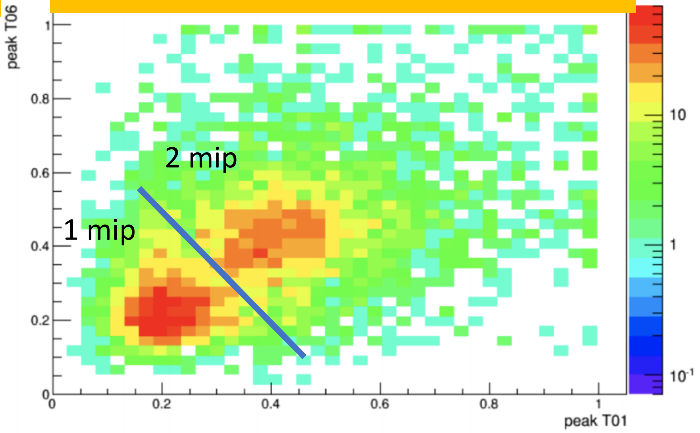
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

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

Electron energy resolution



1mip/2mip separation



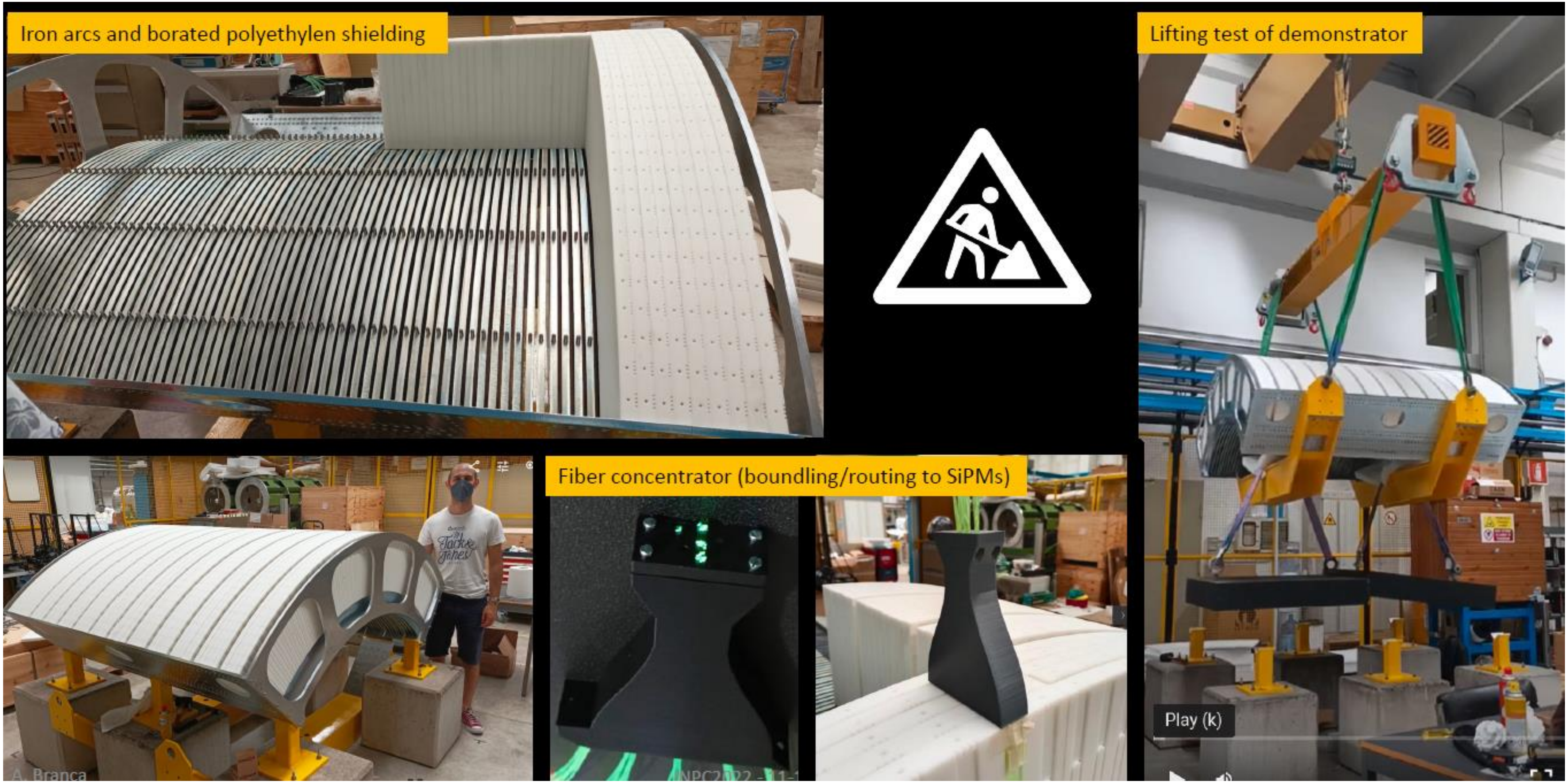
Status of calorimeter:

- ✓ 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

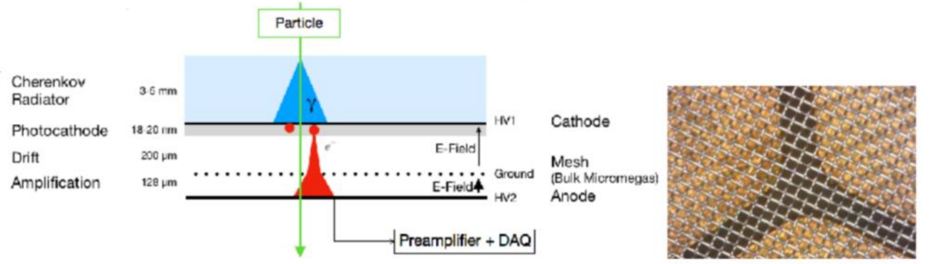
The ENUBET demonstrator



Lepton reconstruction and identification:

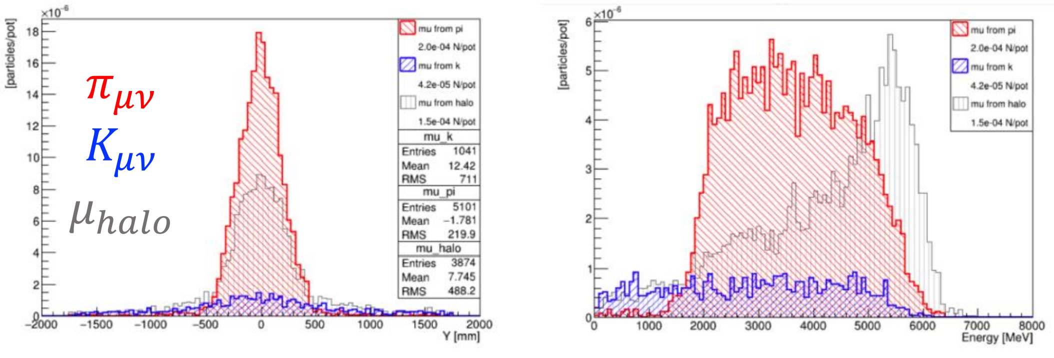
$\pi_{\mu 2}$ muon reconstruction to constrain low-energy ν_μ

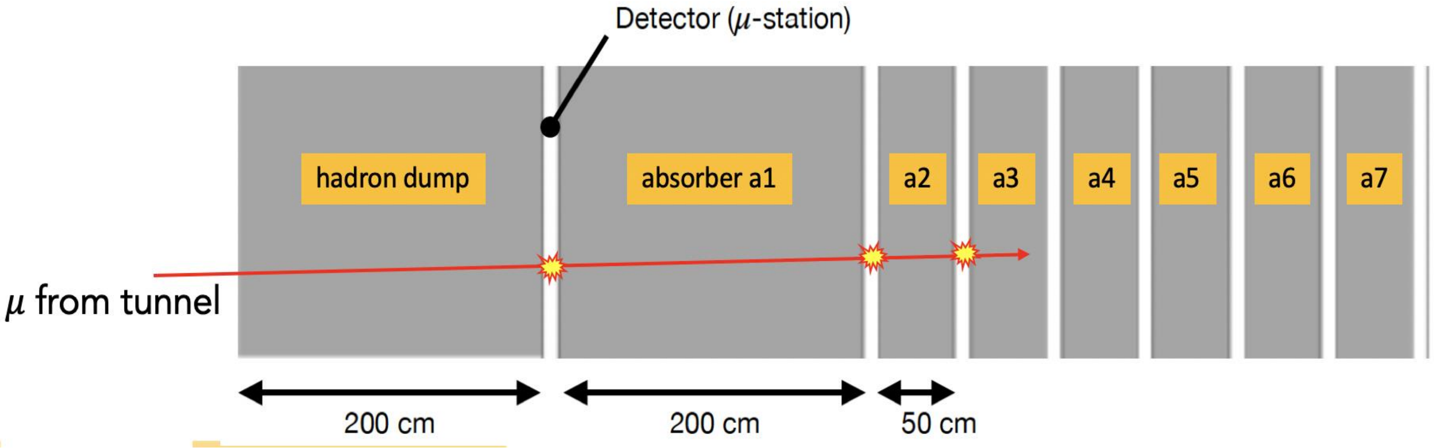
✓ **Low angle muons**: out of tagger acceptance, need muon stations after hadron dump



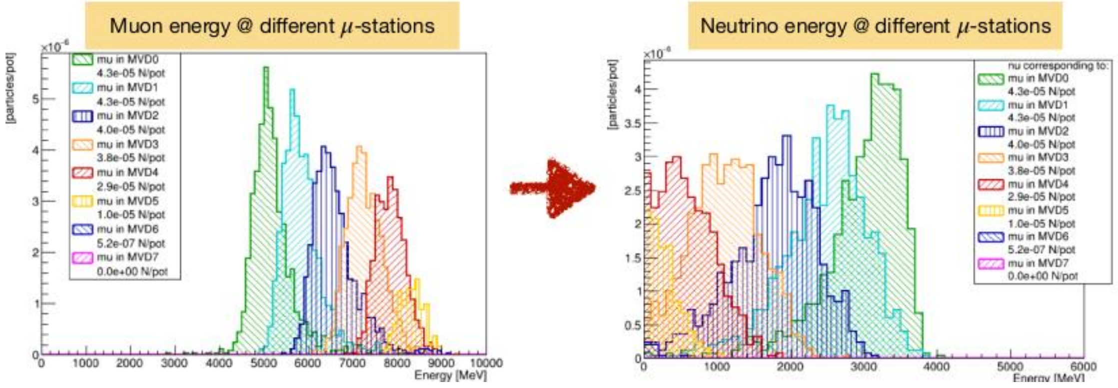
Possible candidates: fast Micromega detectors with Cherenkov radiators (PIMENT)

Exploit differences in distributions to disentangle components





Hottest detector (upstream station): cope with ~2 MHz/cm^2 muon rate and ~10^{12} 1 MeV-n$_{eq}$/cm^2



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;

Systematics: punch through, non uniformity, efficiency, halo-μ;

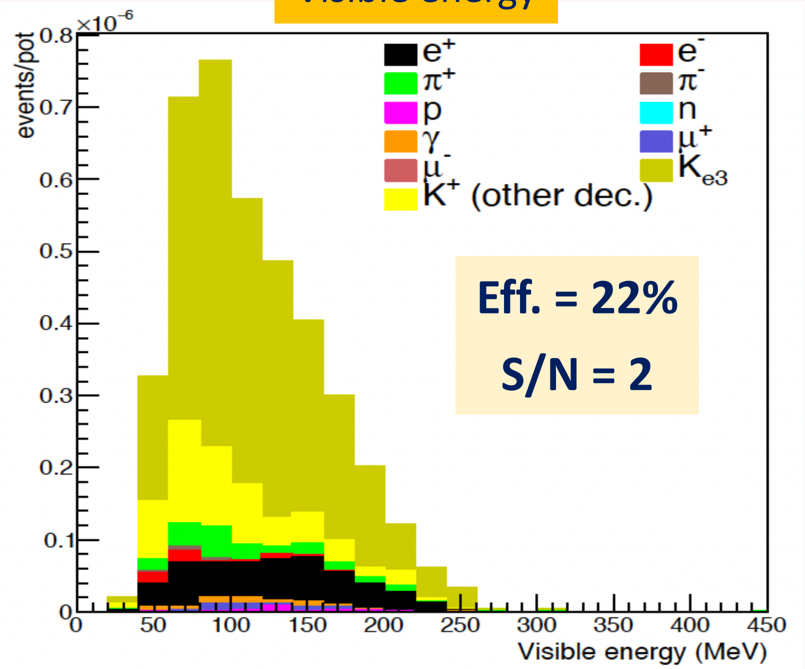
Lepton reconstruction and identification performance

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



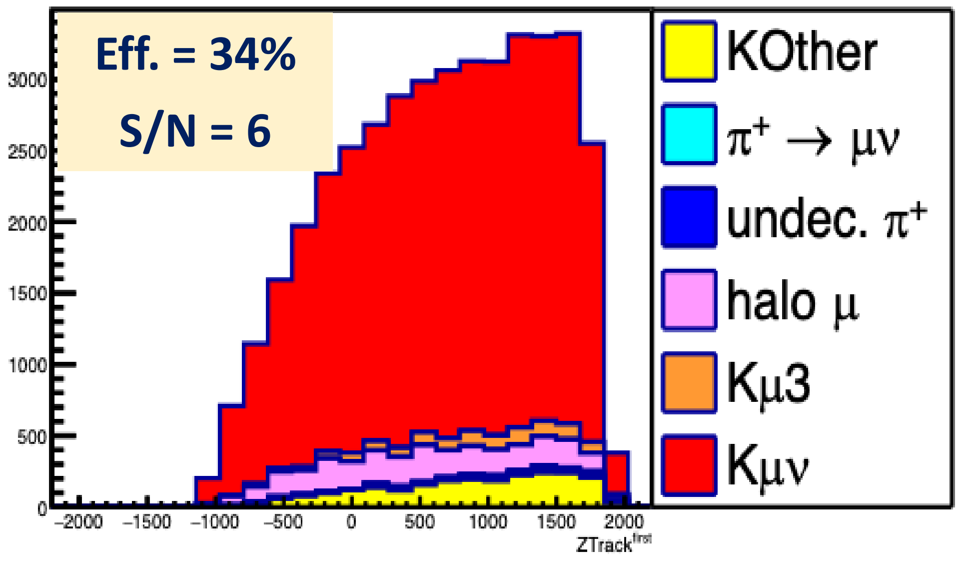
Eff. = 22%

S/N = 2

Efficiency ~half geometrical

$K_{\mu 2}$ muons -> constrain ν_μ

Tagger impact point



Eff. = 34%

S/N = 6

Efficiency ~half geometrical

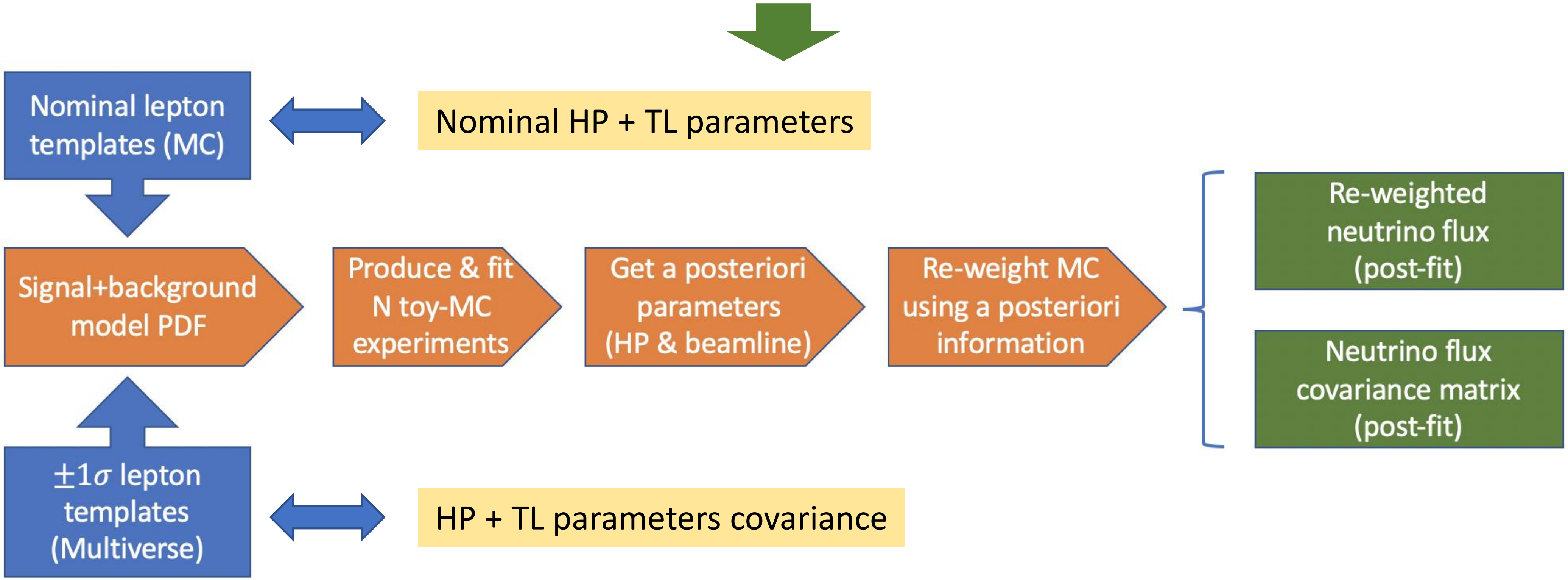
K_{e3} BR $\sim 5\%$ and K make $\sim 5-10\%$ of beam composition

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;



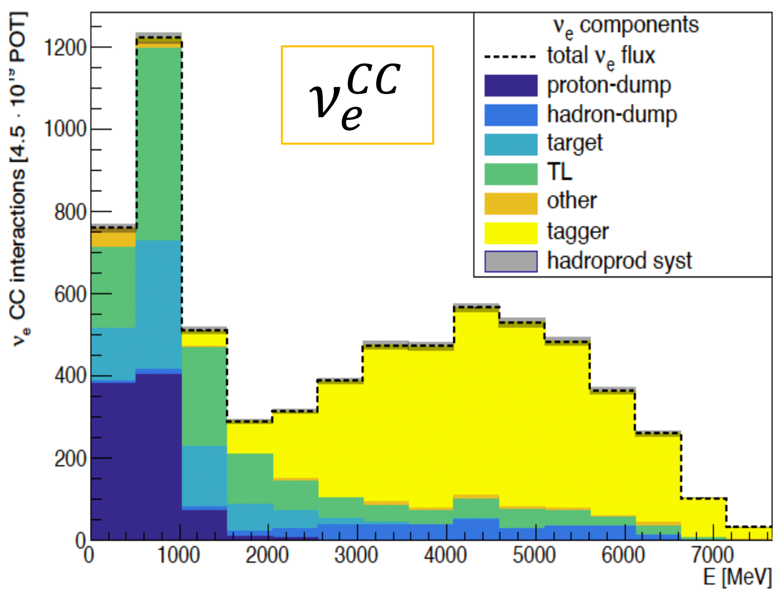
Used hadro-production data from NA56/SPY experiment to:

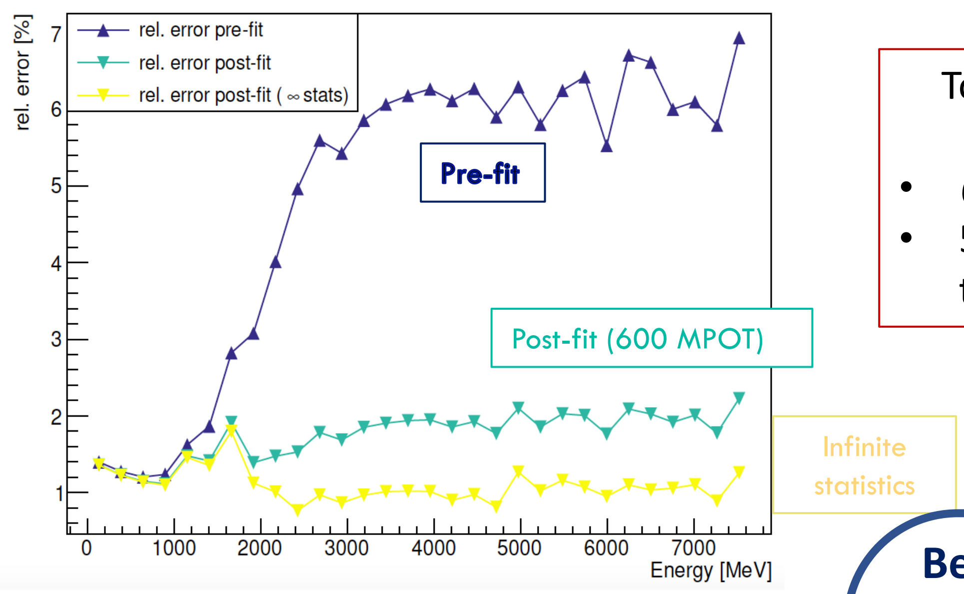
- Reweight MC lepton templates and get their nominal distribution;
- Compute lepton templates variations using multi-universe method;

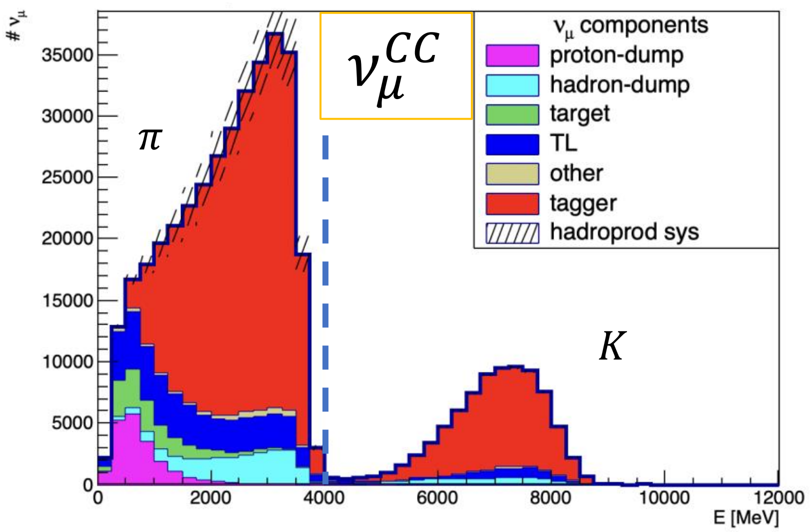
ν-Flux: impact of hadro-production systematics

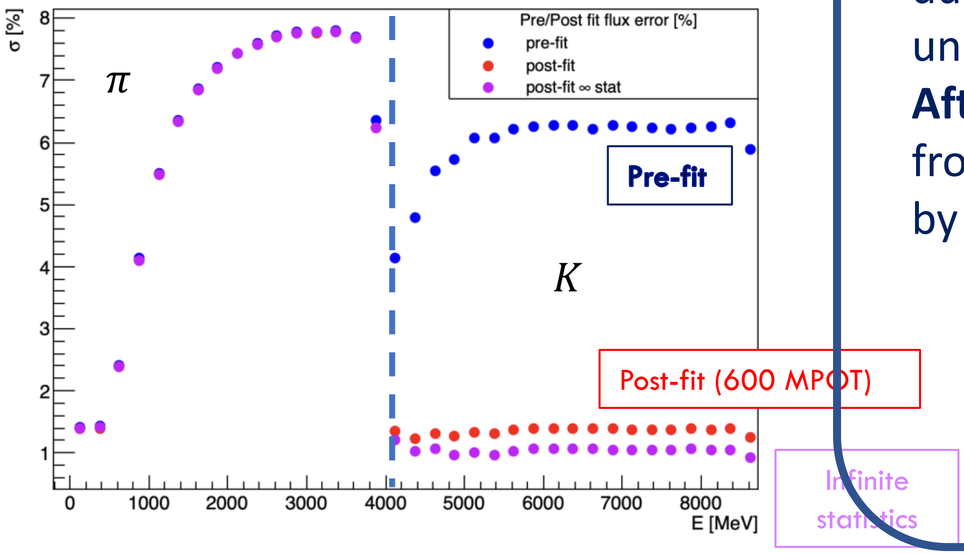
Neutrino interaction rates @ detector

Pre & Post fit relative errors on rates









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;

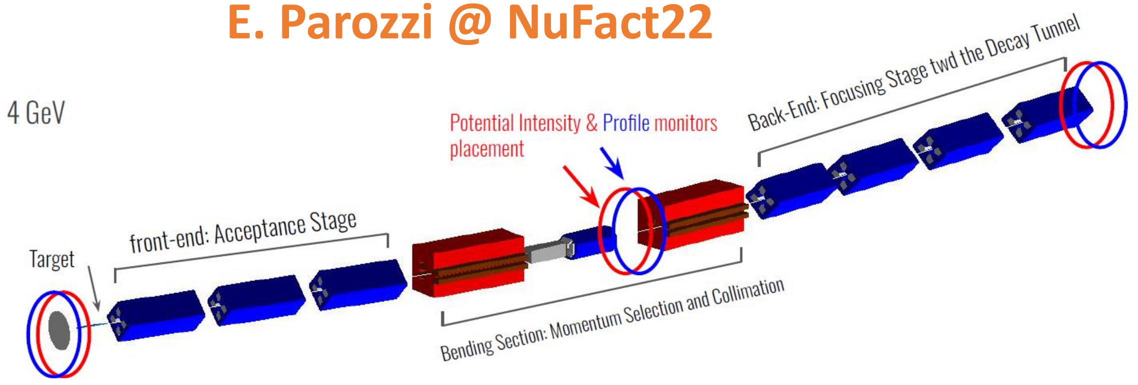
Achieved ENUBET goal of 1% systematics from monitoring lepton rates

A "low-energy" (<1 GeV) monitored neutrino beam

Multi-momentum beamline @ CERN

A CERN-based beamline with multiple runs at 4,6,8 GeV/c secondary momenta: increase the statistics in the region of interest of HyperK. ν_μ from pion decay (high statistics), ne from kaon decay (low statistics)

E. Parozzi @ NuFact22



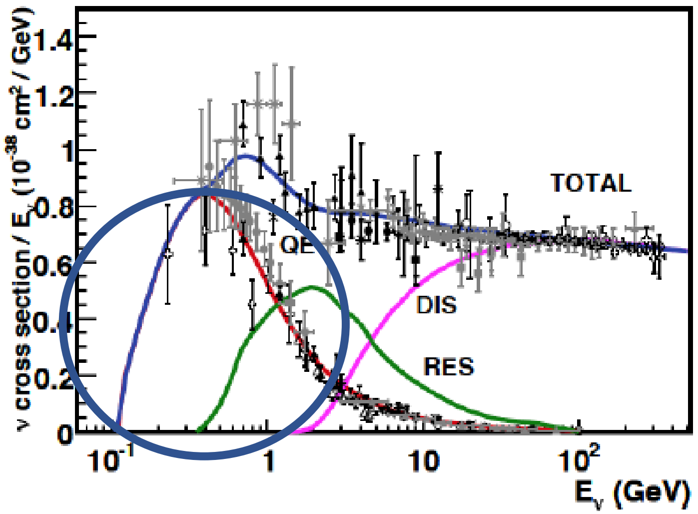
A monitored neutrino beam at ESS (ESSnuSB+)

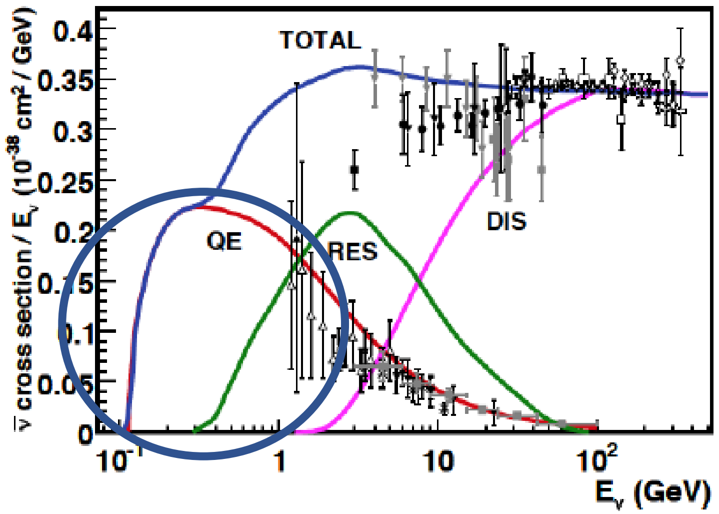
[approved R&D project by EU INFRADEV in July 2022 – 2023-26] **See T. Tolba's talk**

Address specifically the region below 1 GeV

- ν_μ from pion decay ($\pi \to \mu\, \nu_\mu$)
- ν_e from decay in flight of muons

$$\pi \to \mu\, \nu_\mu \to e\, \nu_\mu\, \nu_e\, \nu_\mu$$





Can we build a monitored neutrino beam (without relying on kaons) at the European Spallation Source?

Cool but… are you serious about building ENUBET at CERN?

Yes, we are ☺

- The concept is technically mature and there are no showstoppers
- The "natural" window for construction is Long Shutdown 3 to commence data taking (2 years only!) in 2029
- It gives new life to the Neutrino Platform facilities and, in particular, ProtoDUNE-SP and ProtoDUNE-VD, that will provide the systematic reduction programme for DUNE in parallel with the DUNE data taking
- It may leverage additional detectors located in EHN1 for specific cross section measurements of relevance for HyperK

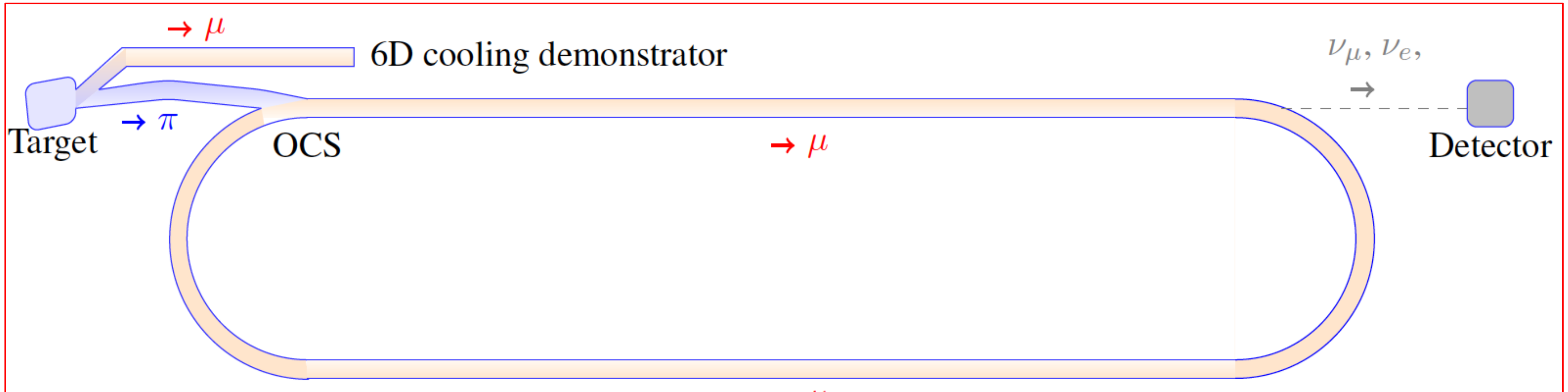
CERN has been responsive to this potential opportunity

- The ENUBET implementation at the CERN North Area **will be studied in 2023-24 by CERN in the framework of Physics Beyond Collider to deliver a proposal to the SPSC in 2025**

- We need to address:
  - Proton economics (we need 9 10^{19} pot at 400 GeV)
  - Irradiation and shielding in the north area
  - Use of existing magnets and dedicated beam components
  - Costs! Costs! Costs!
  - Complete assessment of physics performance with (at least) ProtoDUNE-SP

Addressing the main limitation of monitored beams: nuSTORM

ENUBET is a conventional beam! We will always be limited by the ne statistics! Neutrinos from muon storage rings are the most straightforward step beyond ENUBET



nuSTORM, arXiv:2203.07545

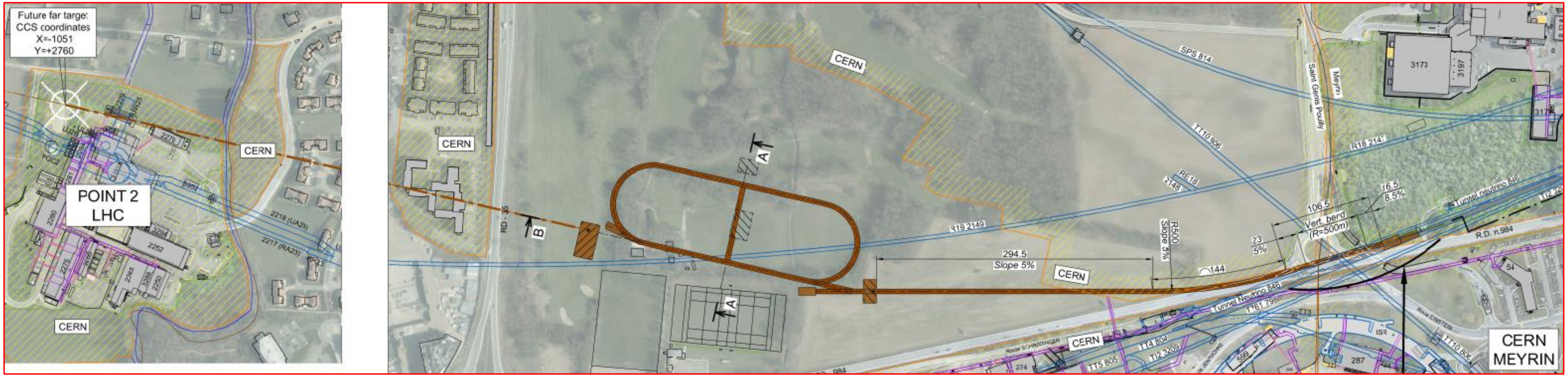
- ✓ %-level *electron* and muon neutrino cross-sections
- ✓ Neutrino energy scan; spectrum at each point precisely known
- ✓ Exquisitely sensitive BSM & sterile neutrino searches
- ✓ Serve as muon accelerator test bed

NuSTORM: toward the experiment proposal

nuSTORM is a mature project and R&D has commenced well before ENUBET!
A full proposal was put forward for FNAL in 2013 [arXiv:1308.6822] and a significant R&D was carried out for target, pion capture, muon accumulator, and the physics performance (cross sections, sterile neutrinos, NSI)

The focus of the activities are the CERN implementation and (more recently) the implementation at ESS (LEnuSTORM) – **See T. Tolba's talk**

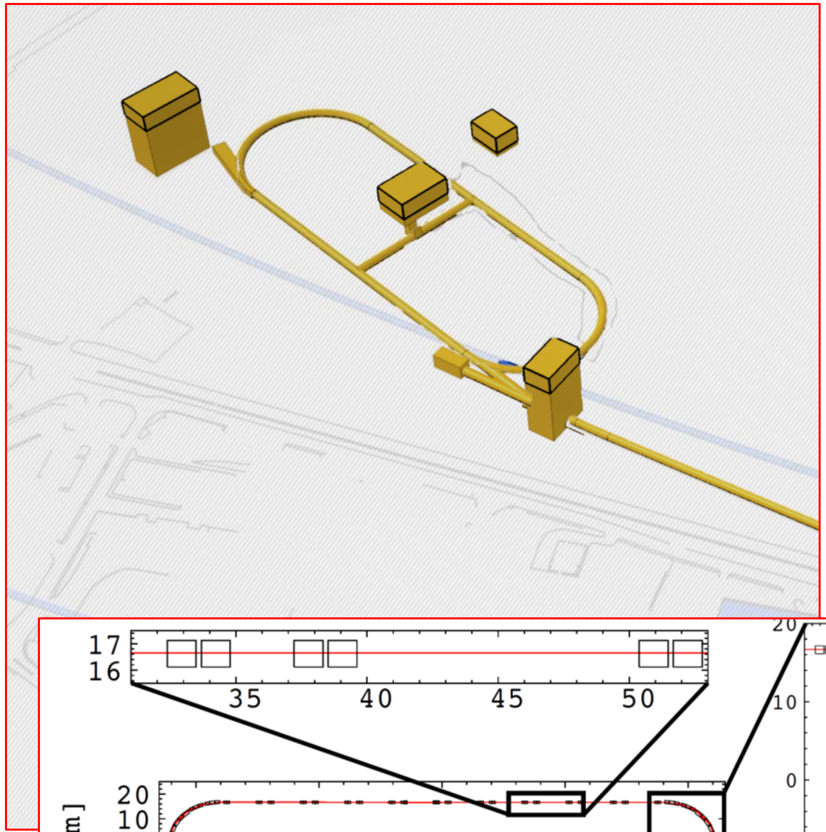
CERN-PBC-REPORT-2019-003
DOI:10.17181/CERN.FQTB.O8QN

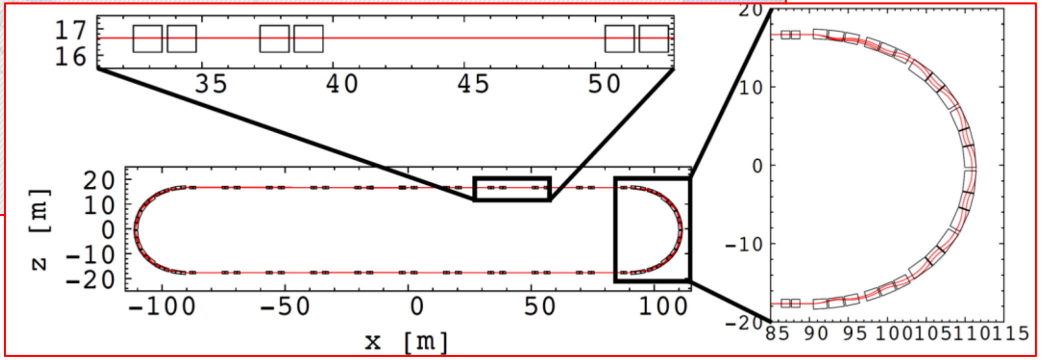


NuSTORM @ CERN (see K. Long@ICHEP2022)

Table 1: Key parameters of the SPS beam required to serve nuSTORM.

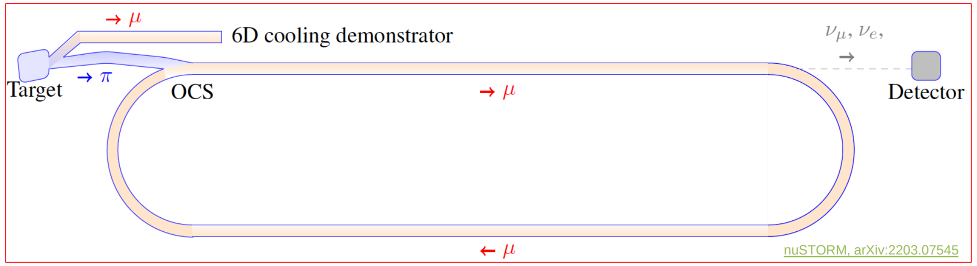
Momentum	100 GeV/c
Beam Intensity per cycle	4 ◊ 10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4 ◊ 10^{19}
Total PoT in 5 year's data taking	2 ◊ 10^{20}
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance (1 ǂ)	8 mm.mrad
Max. normalised vertical emittance (1 ǂ)	5 mm.mrad
Number of extractions per cycle	2
Interval between extractions	50 ms
Duration per extraction	10.5 μs
Number of bunches per extraction	2100
Bunch length (4 ǂ)	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p)	2 ◊ 10^{-4}

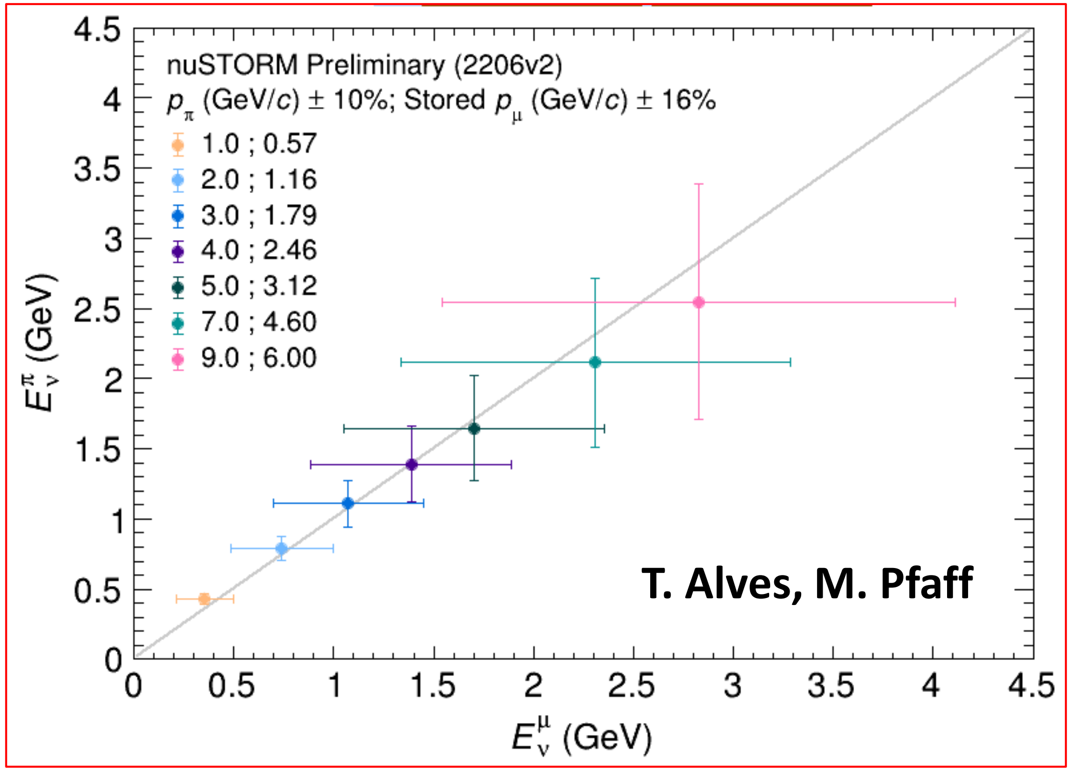




End-to-end simulation for (re)optimisation

- "nuSIM" under development to: **P. Kyberd et al**
  - Simulate facility "from target to detector":
    - Pragmatic approach:
      - Fast simulation, parametric approach
      - Full tracking using G4 based code; "BDSIM"

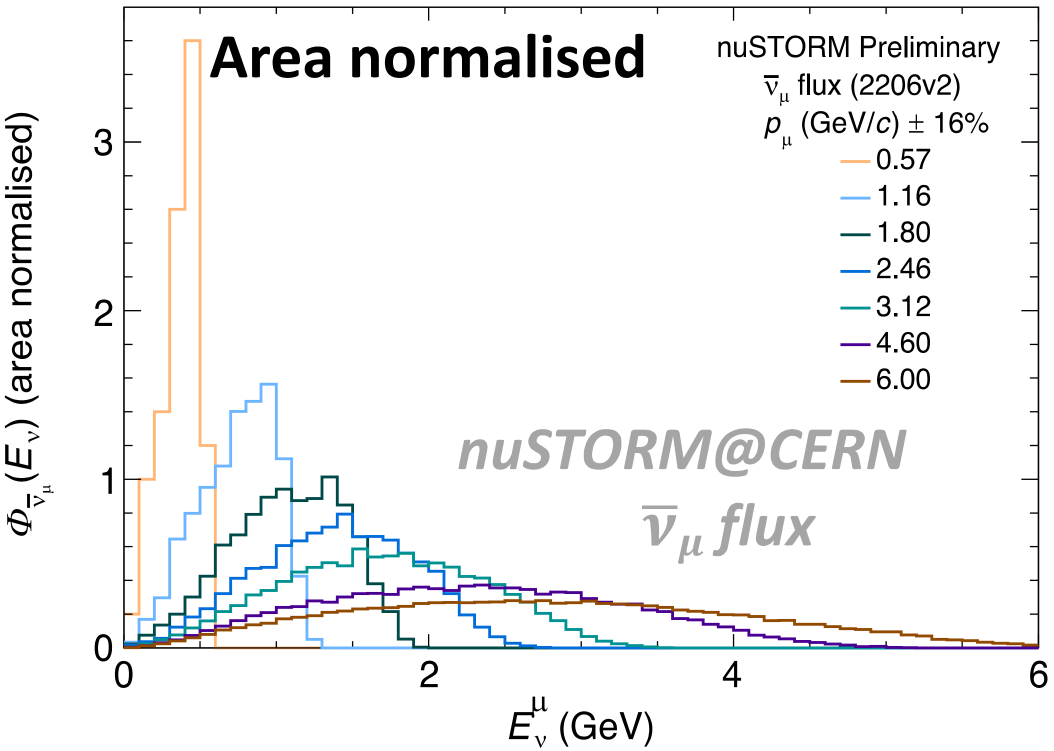


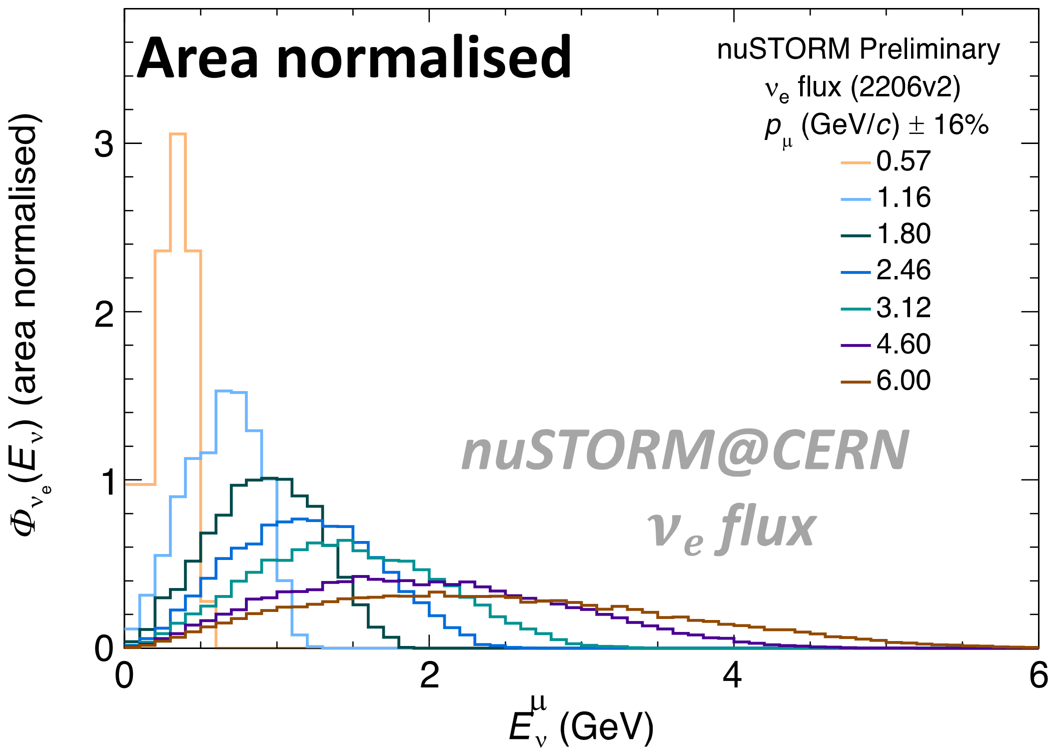


- Neutrino energy scan:
  - –"Pion flash" in first pass
  - –Subsequently neutrinos from muon decay
    - Spectrum determined by accelerator tune

NuSTORM @ CERN: flux estimation

nuSTORM, arXiv:2203.07545



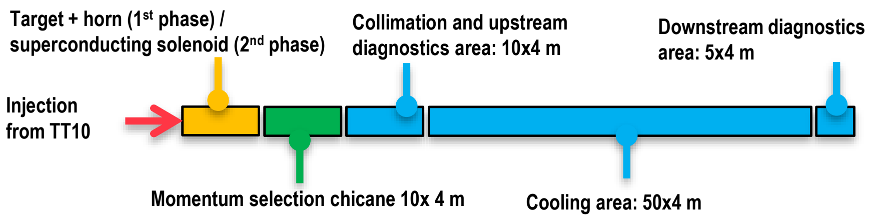


- Oscillation-relevant energy regime
  - Hyper-K: 0.6 GeV
  - DUNE.   : 2.4 GeV
- Set by stored-muon momentum

- Unique opportunity:
  - E_ν-scan measurements
- Accelerator "tune" gives fine control
  - E.g. optimise flux shape (or spread) by adjusting the ring acceptance

Conceptual layout

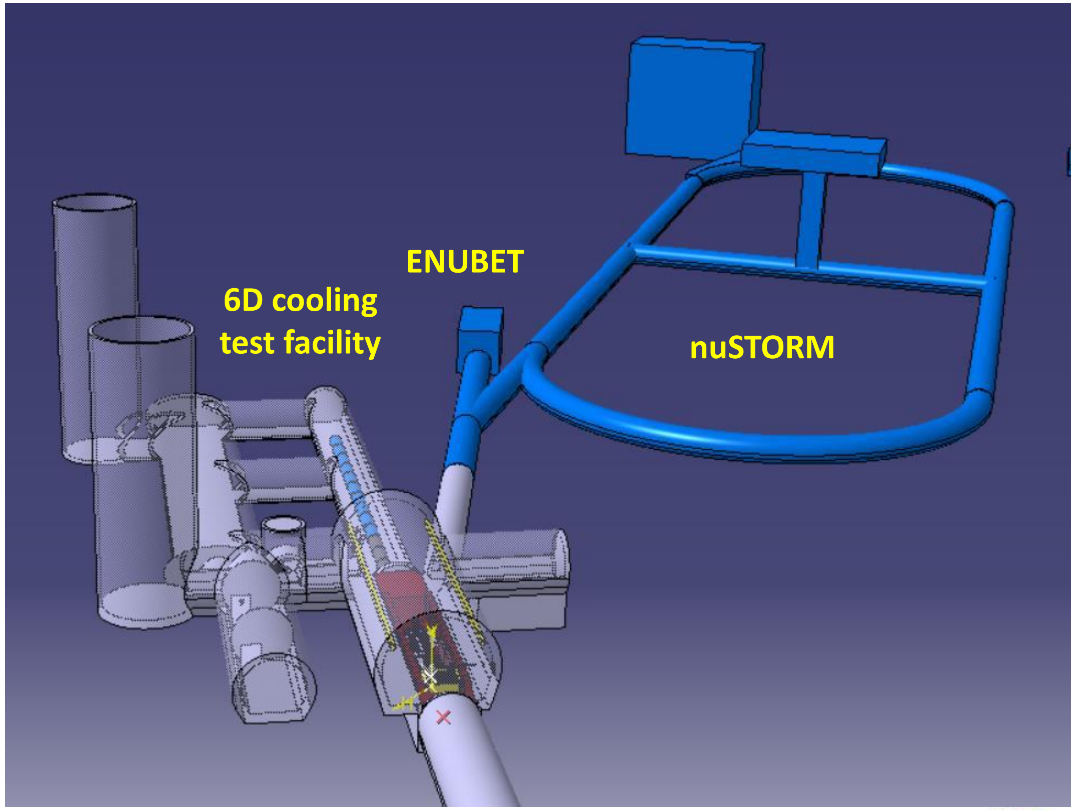
Under discussion!



MUC Demonstrator

- The Facility is flexible enough to accommodate other experiments.
- nuSTORM and potentially ENUBET could be branched from the MUC Demonstrator Facility.
- The same target complex would be used profiting from its shielding and general target systems infrastructure, utilities, and accesses.
- The double deflection of the beamline could reduce radiation streaming towards the nuSTORM ring.
- Synergies between experiments would reduce costs on both sides.
- Is the 26 GeV/c beam from the PS appropriate for these two experiments?

Under study



Conclusions

- The ENUBET ERC project and NP06/ENUBET have been a major success and the concept of monitored neutrino beams is now mature
- We want (seriously!) to propose **a neutrino beam at CERN in operation in 2029**, which uses ENUBET as beamline and (at least) ProtoDUNE-SP as detector
- 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
- A site dependent (CERN) study was already carried out for nuSTORM and **provides a solid ground for a muon-based neutrino beam**
- ENUBET and nuSTORM are working together to address:
  - Physics performance
  - Common infrastructures
  - And possibly a staged implementation