http://enubet.pd.infn.it

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).

Status of NP06/ENUBET

ERC consolidator grant (2016-2022) – P.I. A. Longhin

Since 2019 **CERN Neutrino Platform Experiment**

F. Pupilli
(INFN)

nuSTORM meeting as part of the iMC discussion of demonstrator facilities

25/03/2021

on behalf of the

ENUBET Collaboration: 60 physicists, 12 institutions

New beams for the precision era of ν physics

- Future long baseline projects (DUNE/HK) require a much better knowledge of ν cross sections
- BSM studies (sterile neutrinos, NSI) can be boosted by a better knowledge of the ν flux

High-precision beams

Flux at 1% level measured in a direct way

↓

Remove the leading uncertainty in x-sec measurements

Neutrino energy known at 10-20% level at source

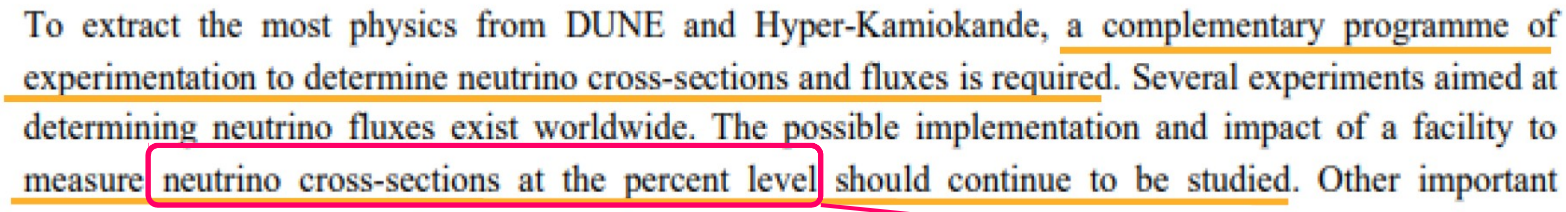
↓

Bypass uncertainties in final state reconsutruction

Flavor composition known at 1% level

↓

Precision study of exotics



To extract the most physics from DUNE 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. Other important

European Strategy for Particle Physics Deliberation document (pag. 5)

Explicit reference to **ENUBET** and nuSTORM

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

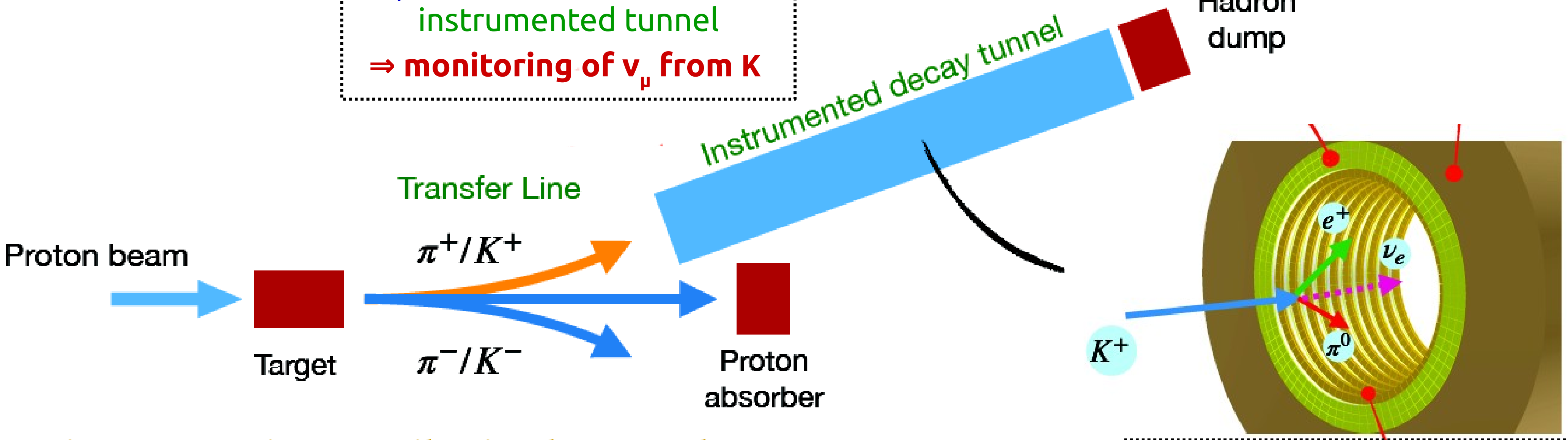
ENUBET: the first monitored neutrino beam

Monitored ν beams

Measure rate of leptons ⇔ monitor ν flux

NEW! (2020)
$K_{\mu\nu}$ muons measured in the instrumented tunnel
⇒ monitoring of ν_μ from K

NEW! (2020)
muons measured by a range meter in the hadron dump
⇒ monitoring of ν_μ from π



K_{e3} positrons measured in the instrumented tunnel
⇒ monitoring of ν_e

Main systematics contribution bypassed:

- Hadron production, beamline geometry and focusing, POT

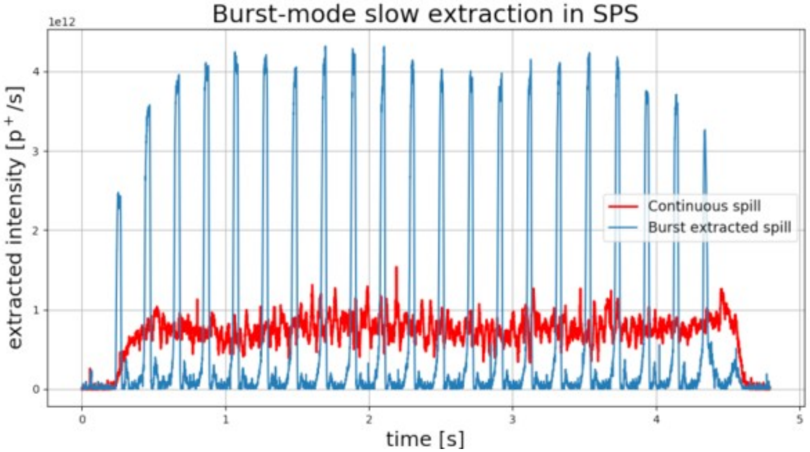
Requirements:

- ✓ Sustainable rate at the instrumentation → Slow proton extraction
- ✓ Highly collimated beam
- ✓ Cost effective detectors to identify muons and positrons

Focusing and extraction schemes

Horn focusing

- Larger meson yield
- Requires a "burst-mode slow extraction"



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

- ✓ Successfully tested @ SPS in 2018
- ✓ Same integrated POT as for continuous spill
- ✓ MAD-X simulation in 2019: **2-10 ms extractions** in the flat top
- ✓ Final tests @ SPS in 2022

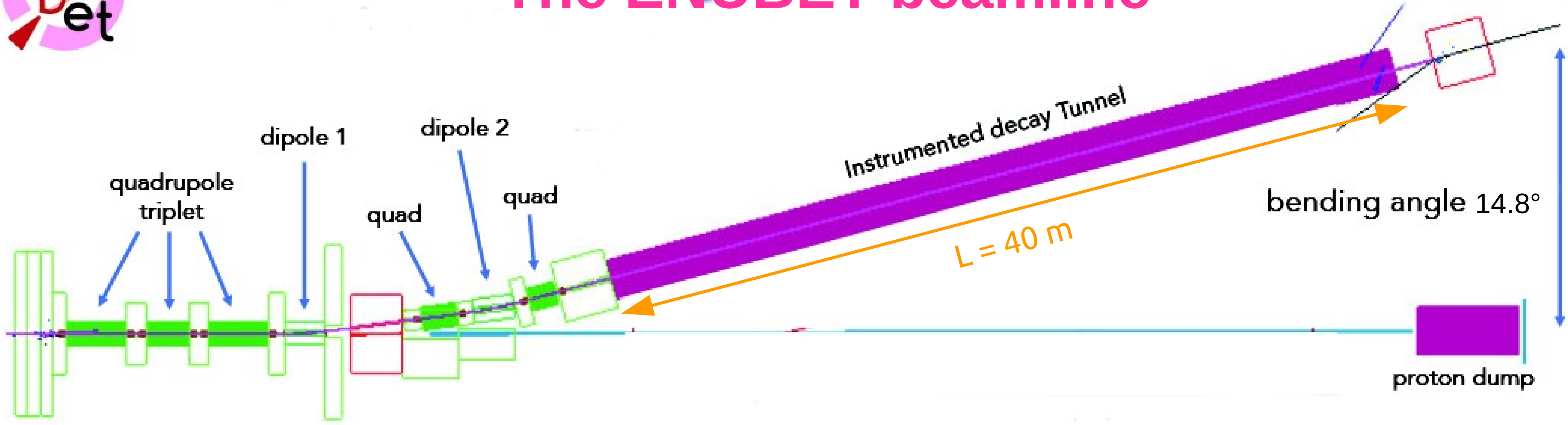
- In parallel, horn shape and current optimization in a broad phase space with genetic algorithms

Static focusing **(2 sec extraction length)**

- No horn needed → Reduce length and complexity of the beamline
- Reducion of rates → Mitigation of pile-up effects in the instrumeted tunnel
- Allows muon monitoring in the hadron dump at per-cent level → flux of ν_μ from pions
- Pave the way for time-tagged neutrino beams → time correlation of the interacted neutrino with the associated lepton in the tunnel

2020 important result: even with static focusing 10^4 ν_e^{CC} interactions in ~2 years

The ENUBET beamline



Double dipole beamline [8.5 GeV/c ±10%]

Cons:

✗ transfer line length

Pros:

✔ better collimation

✔ reduced backgrounds (positrons & forward going muons): better PID in tunnel

✔ reduced not-tagged neutrino contamination

Development status

- Target simulation: **done**
- Proton dump: **done**, but engineerind studies needed
- Hadron dump: **done** (including n shielding)
- Transfer line:
  - ➔ TRANSPORT/G4Beamline for optics and background shielding): **done**
  - ➔ FLUKA for doses and n shielding: **~done**
  - GEANT4 for systematic assessment: in progress

Particle rates and pile-up studies

Double dipole beamline with **slow extraction (2 s)**:

- Maximum total rate of about 2 MHz/ch

Rates breakdown along the decay tunnel:

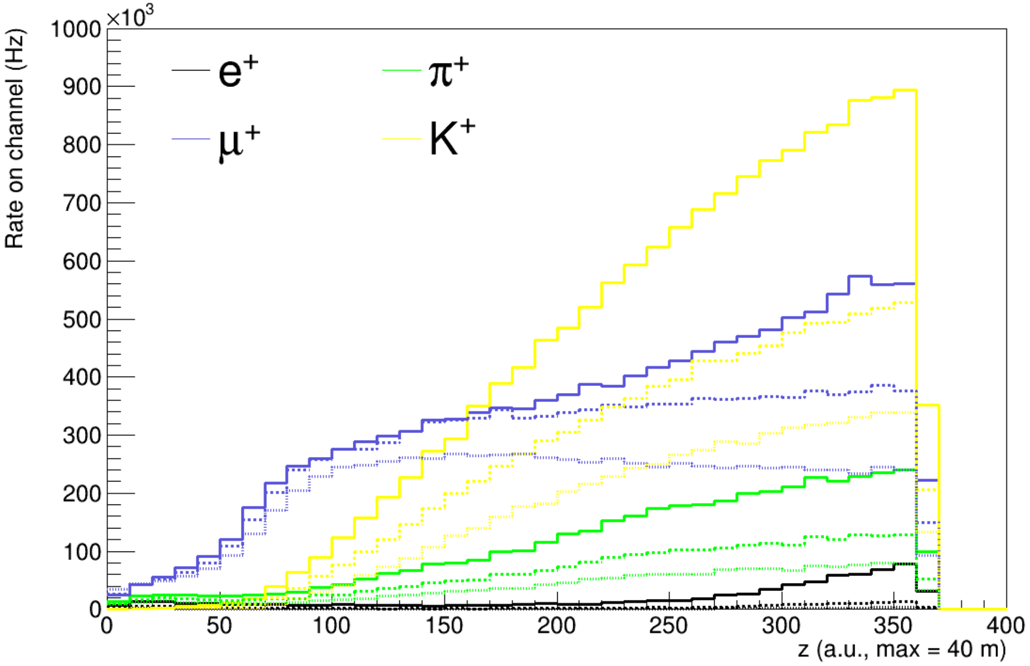
- **Kaon** decay products dominate at high Z;
- **Muons** almost uniform (except the first meters)
- Uncollimated **pions** and **positrons** towards the end of the tunnel

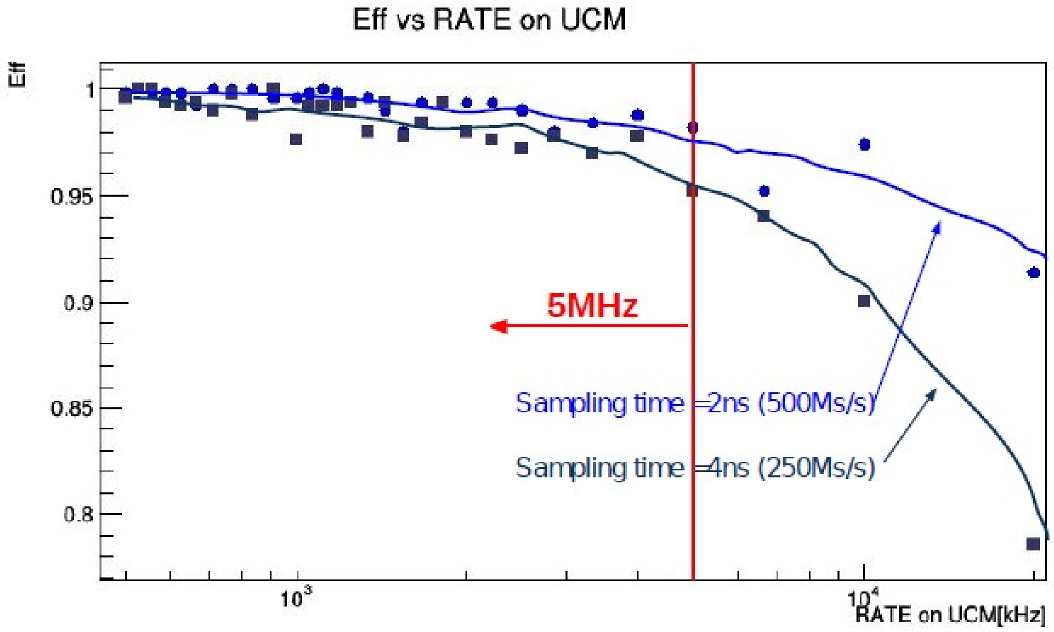
Pile-up studies through WF simulation implemented

Preliminary results show:

- Detection efficiency loss <5% up to 5 MHz
- 250 Ms/s could still be a suitable sampling time

To be updated with the new transfer line yields





The instrumented decay tunnel (I)

Requirements:

- Allow **$e^+/\pi^{\pm,0}$ separation** in the GeV energy region
- **Suppress** background from **beam halo** (μ, γ, non collimated hadrons)
- Sustain O(MHz) rate and **suppress pile-up effects** (recovery time ≤ 20 ns)
- **Doses**: $<10^{10}$ n/cm^2 at SiPMs, 0.1Gy at scintillator

Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Lateral light readout with WLS+SiPM

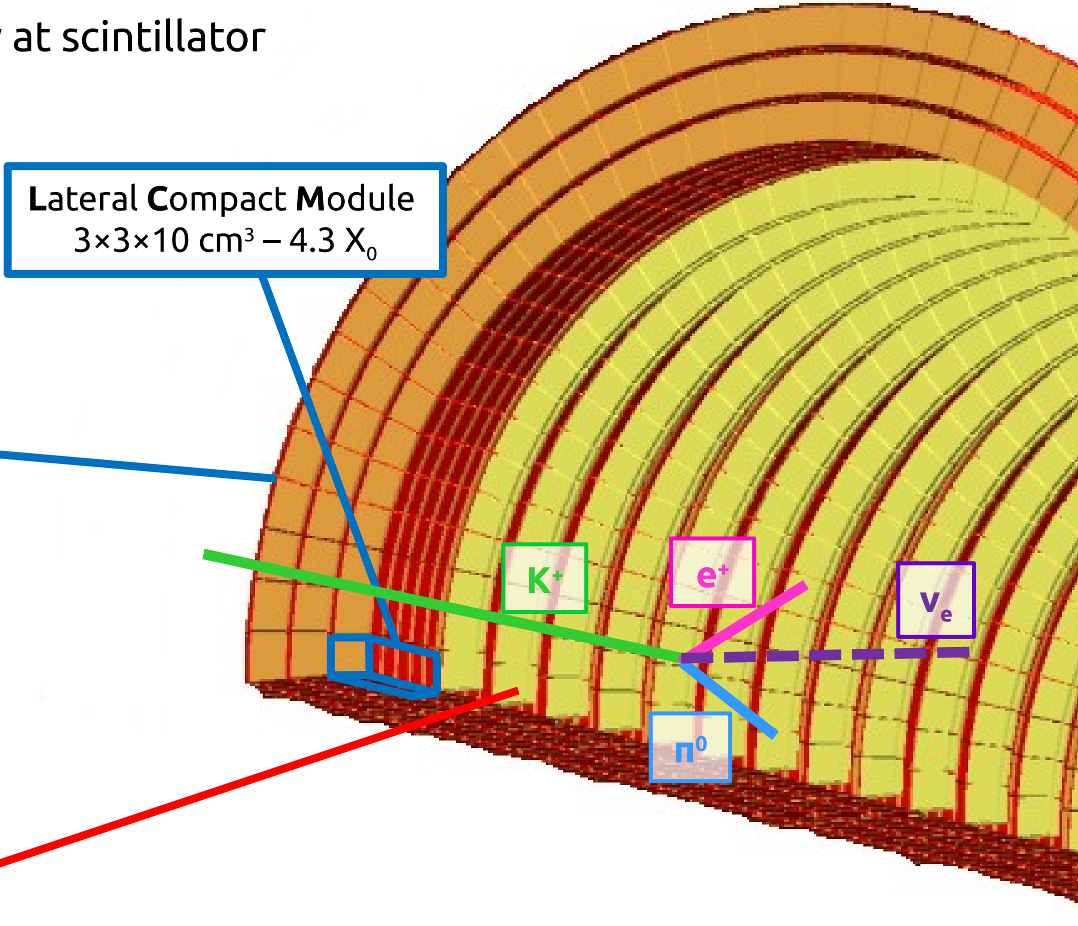
→ $e^+/\pi^\pm/\mu$ separation

Integrated photon veto (t0-layer)

Plastic scintillators

Rings of 3×3 cm^2 pads readout by SiPM

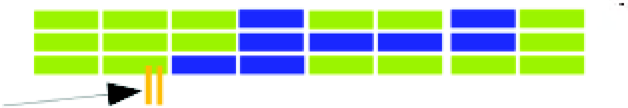
→ π^0/γ rejection



Lateral **C**ompact **M**odule
3×3×10 cm^3 – 4.3 X_0

e^+ (signal) topology

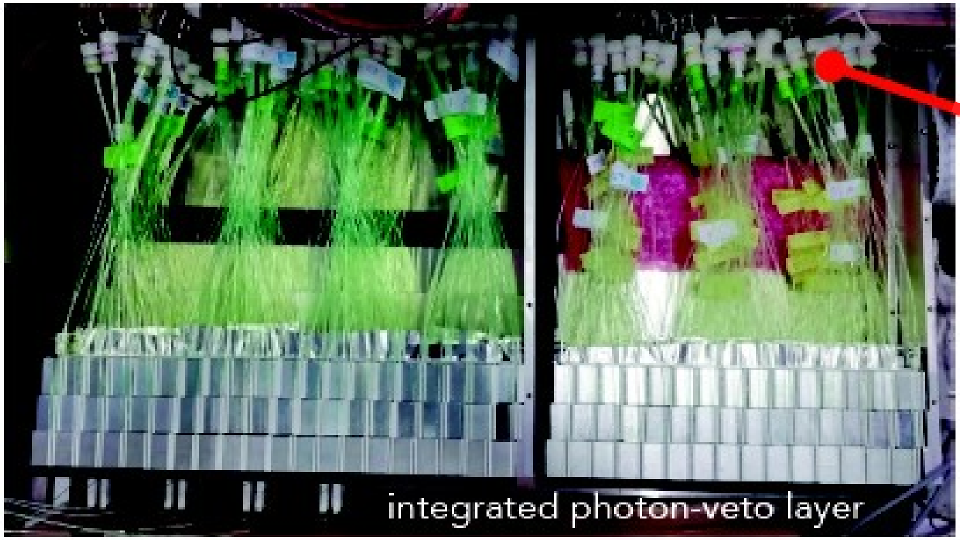
π^0 (background) topology



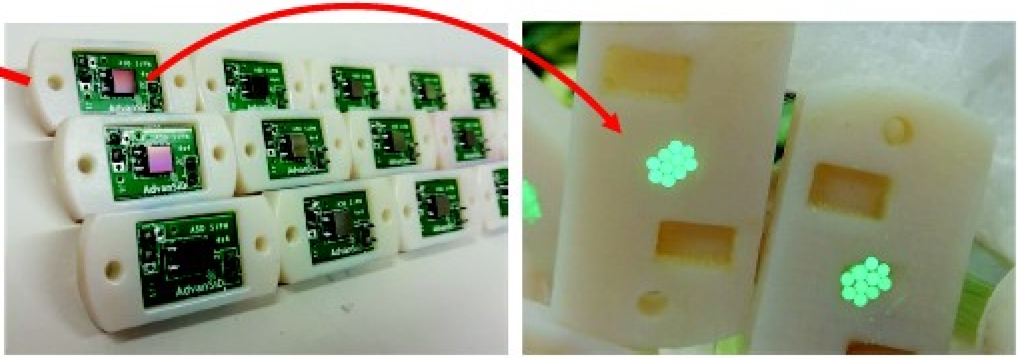
π^+ (background) topology

The instrumented decay tunnel (II)

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



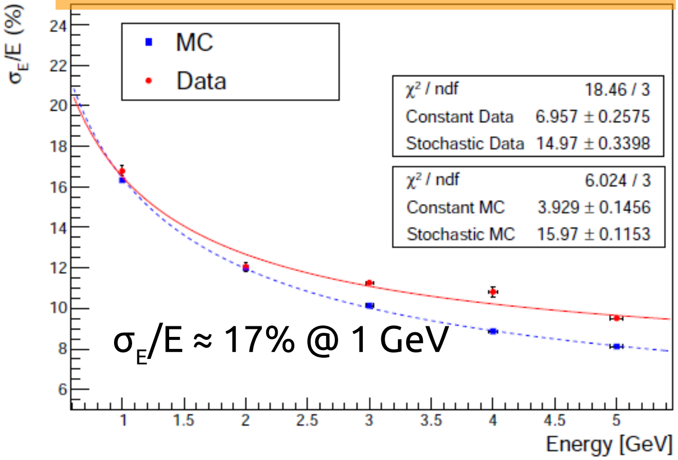
Large area (4x4 mm^2) SiPM for 10 WLS (one LCM)



SiPM installed outside calorimeter, above shielding: reduce neutron radiation damage

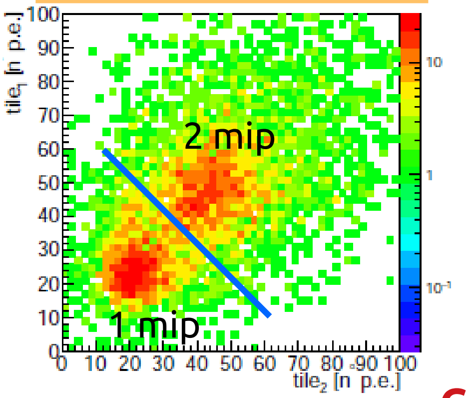
Tested during 2018 test-beam runs @ CERN PS-T9

Electron energy resolution



$\sigma_E/E \approx 17\%$ @ 1 GeV

Photon veto



Status of prototyping:

- ✓ Lateral readout calorimeter prototype successfully tested
- ✓ Photon veto tested
- ✓ Custom digitizer: in progress

Choice of technology finalized and cost-effetive!

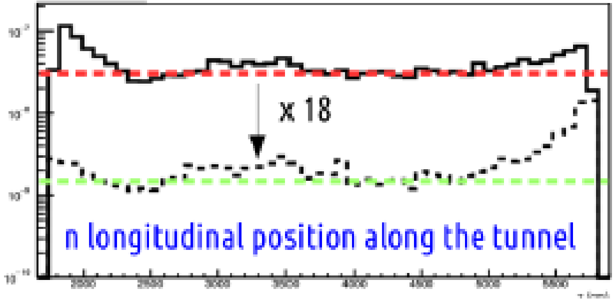
F. Acerbi et al, JINST (2020), 15(8), P08001

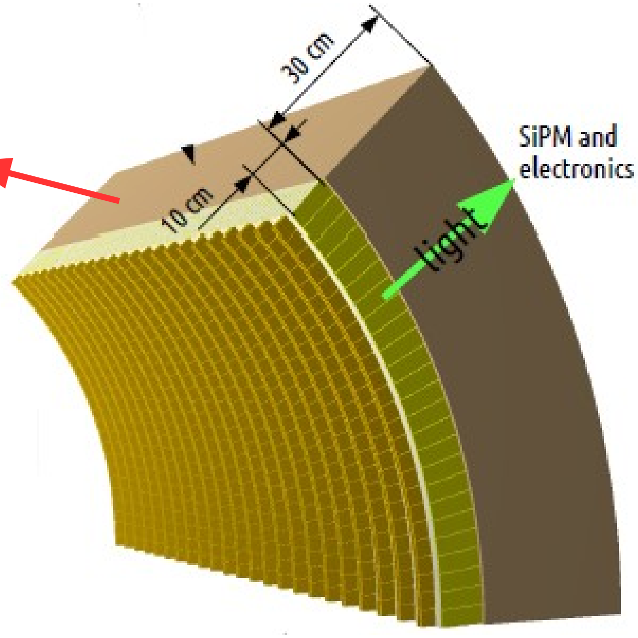
The tagger demonstrator

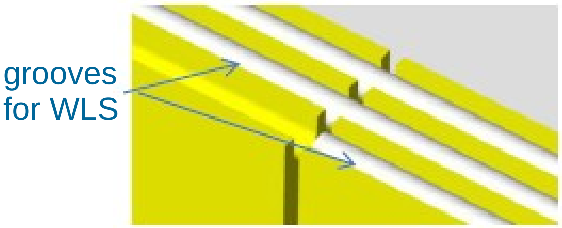
Larger scale prototype:

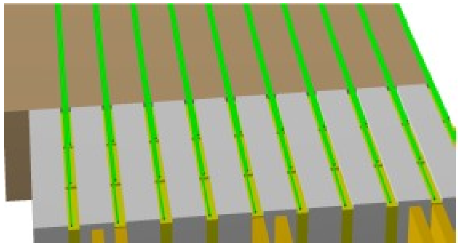
- 1.7 m long
- 45° coverage in φ
- To be tested @ CERN PS-T9 in 2022
- Demonstrate physics, scalability and cost effectiveness

30 cm borated polyethylene
→ ~ **x18 neutron reduction**
Add safety margin for SiPM



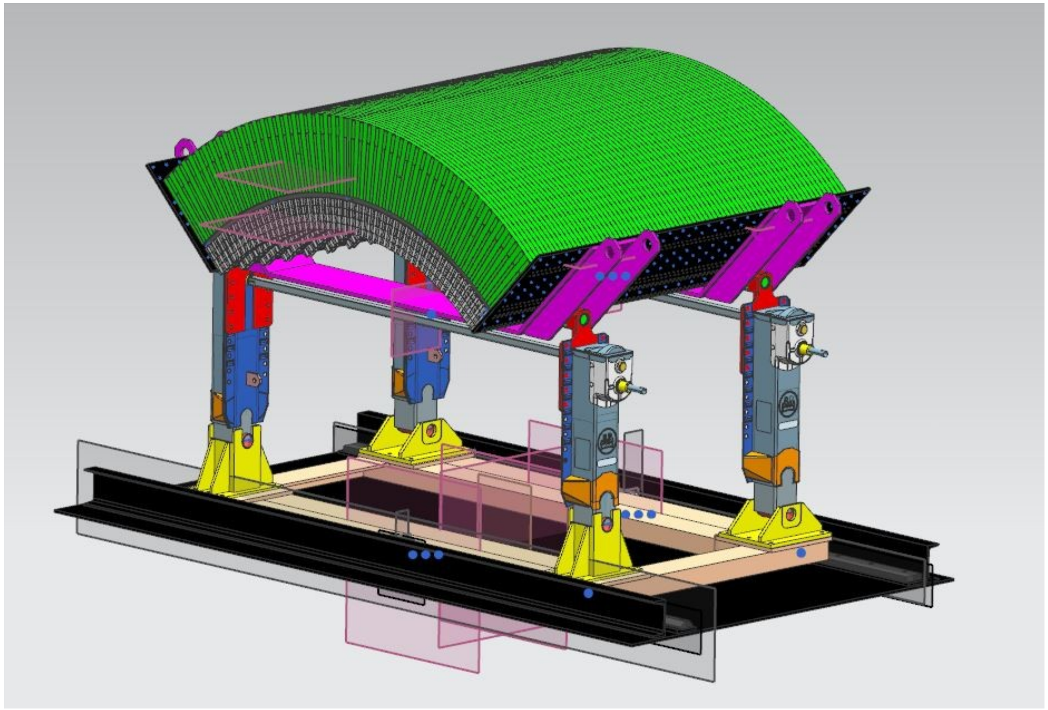






WLS will be **staggered** on the side of scint tiles to collect light from different layers

- SiPMs and readout out of tunnel, accessible for maintainance



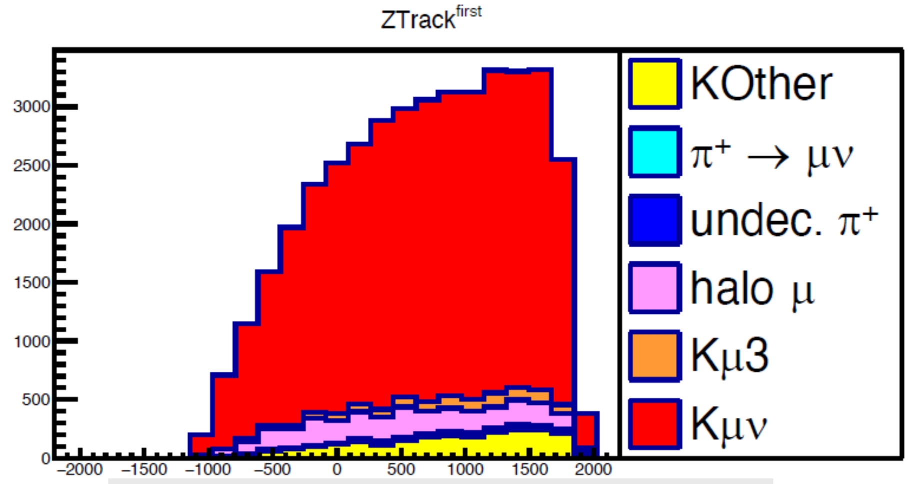
Lepton identification (II)

Full GEANT4 simulation of the detector: validated by prototype tests @ CERN; hit-level detector response; pile-up effects included (waveform treatment in progress)

- Large angle muons and positrons from kaon decays identified exploiting the energy pattern in the tagger
- Event selection based on 19 variables for positrons (13 for muons) employed by a Neural Network

Muons from $K_{\mu2}$ ($\sim\nu_\mu$)

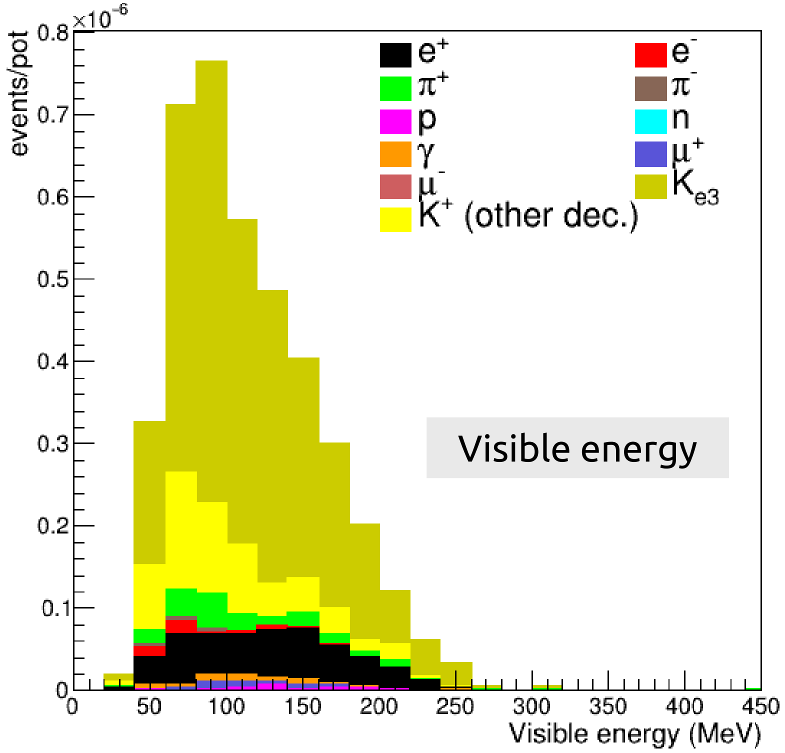
S/N = 6
Efficiency: 33% (~ half geom.)



Longitudinal position along tunnel

Positrons from K_{e3} ($\sim\nu_e$)

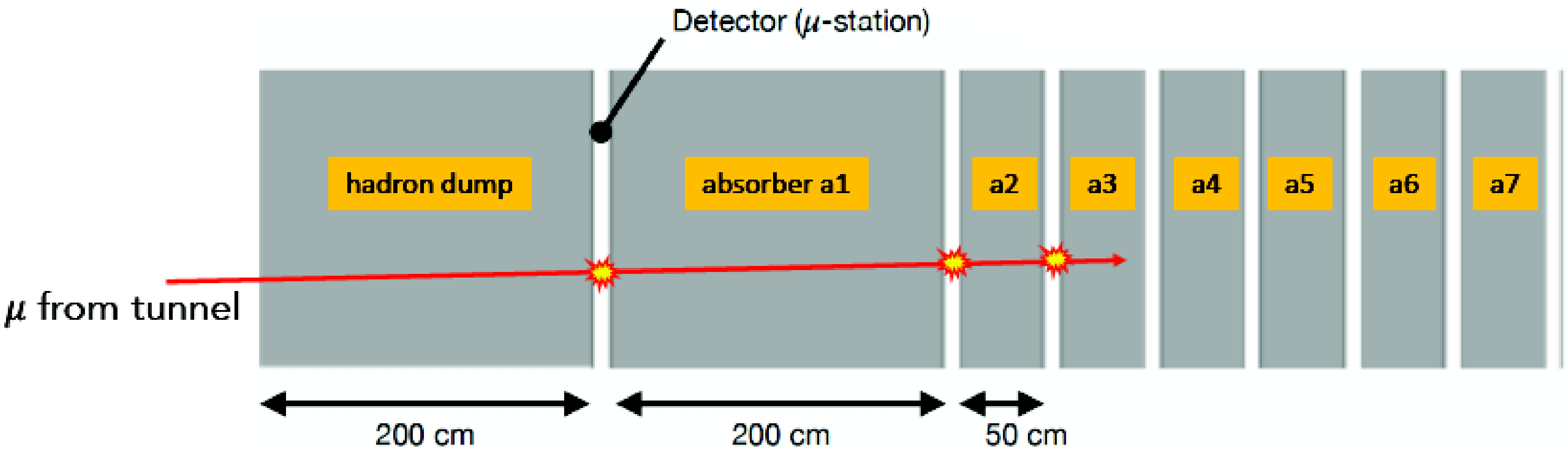
S/N = 2
Efficiency: 22% (~ half geom.)

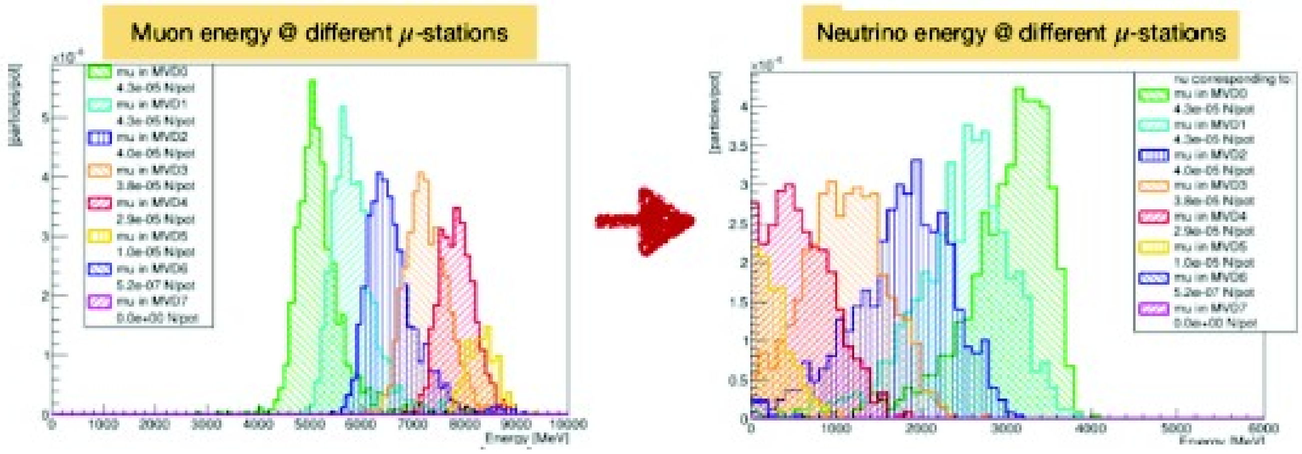


Lepton identification (II)

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

Low angle muons, out of tagger acceptance → need muon stations after the hadron dump





Work in progress

Exploit:

- Correlation btw number of transversed stations (μ energy from range-out) and ν energy;
- Difference in distribution to disentangle signal from halo-muons

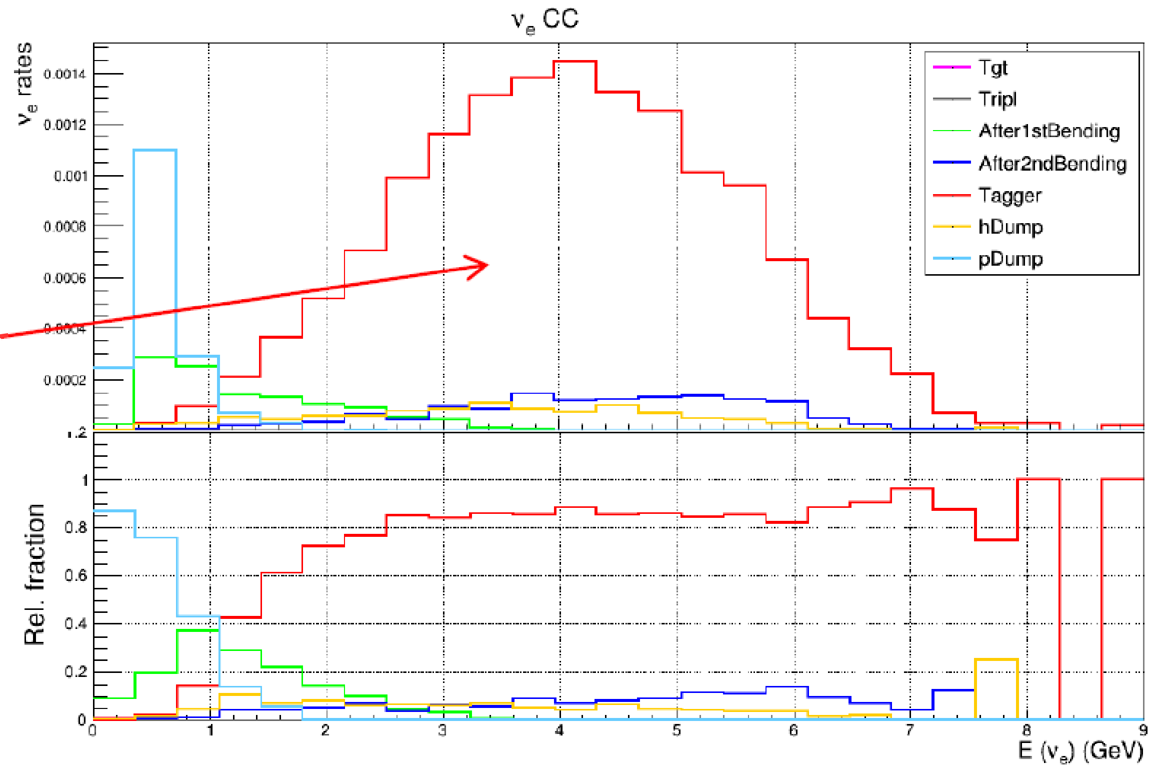
Detector technology to be assessed

Max μ rate: 1 MHz/cm^2

Physics performance: ν_e

Assumption: 500 ton LAr neutrino detector (6x6 m^2) @ 50 m from dump

10^4 ν_e^{CC} interactions in ~2y of data taking without horn!!



- Taggable component:

80% monitored by measuring positrons in the decay tunnel

- Non-taggable component 1:

5-10% low-E n from p-dump

Can be removed with energy cut

- Non-taggable component 2:

10% from decays in the transfer line

Physics performance: ν_μ

Constrain on flux:

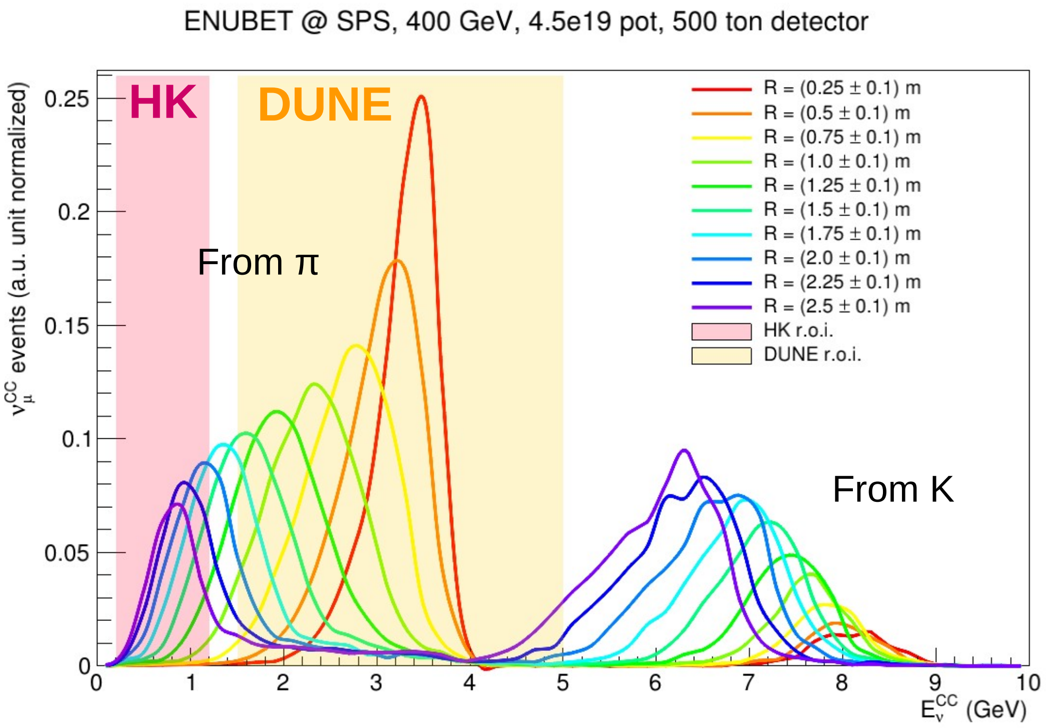
- Muons from π monitored by the range-meter (low energy part of the ν flux)
- Muons from $K_{\mu 2}$ monitored in the instumented tunnel (high energy part)

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

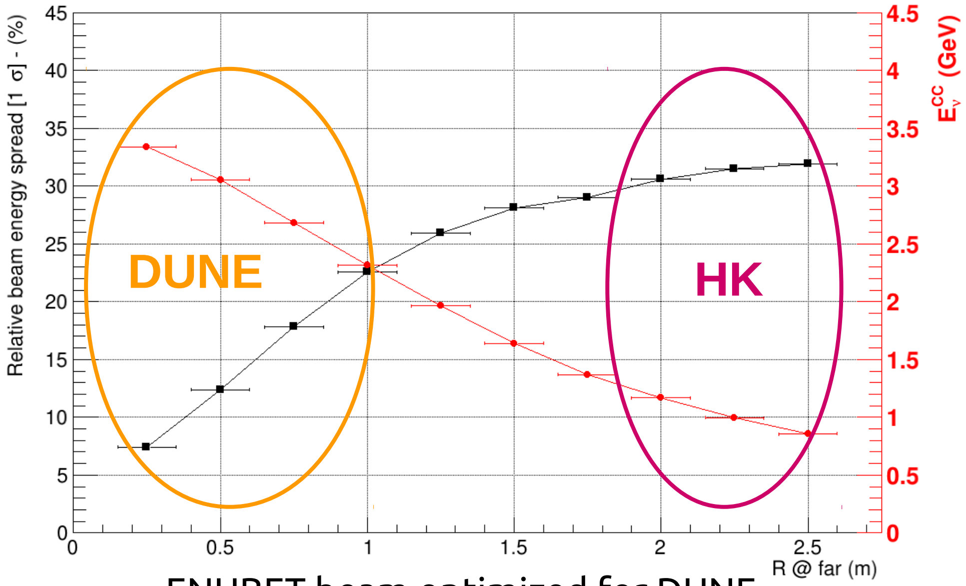
Constrain on energy:

- Since the momentum bite is <10% and the detector distance is small, strong correlation between the position of the neutrino vertex and its energy
- Technique dubbed "**narrow-band off-axis**" *
- ν energy available on a event-by event basis without relying on the reconstruction of the final state in ν_μ^{CC} interactions

About $8\text{x}10^5$ ν_μ^{CC} interactions in ~2 years



Width of π peaks ≈ E resolution



ENUBET beam optimized for DUNE

nuSTORM/ENUBET – p beam requirements

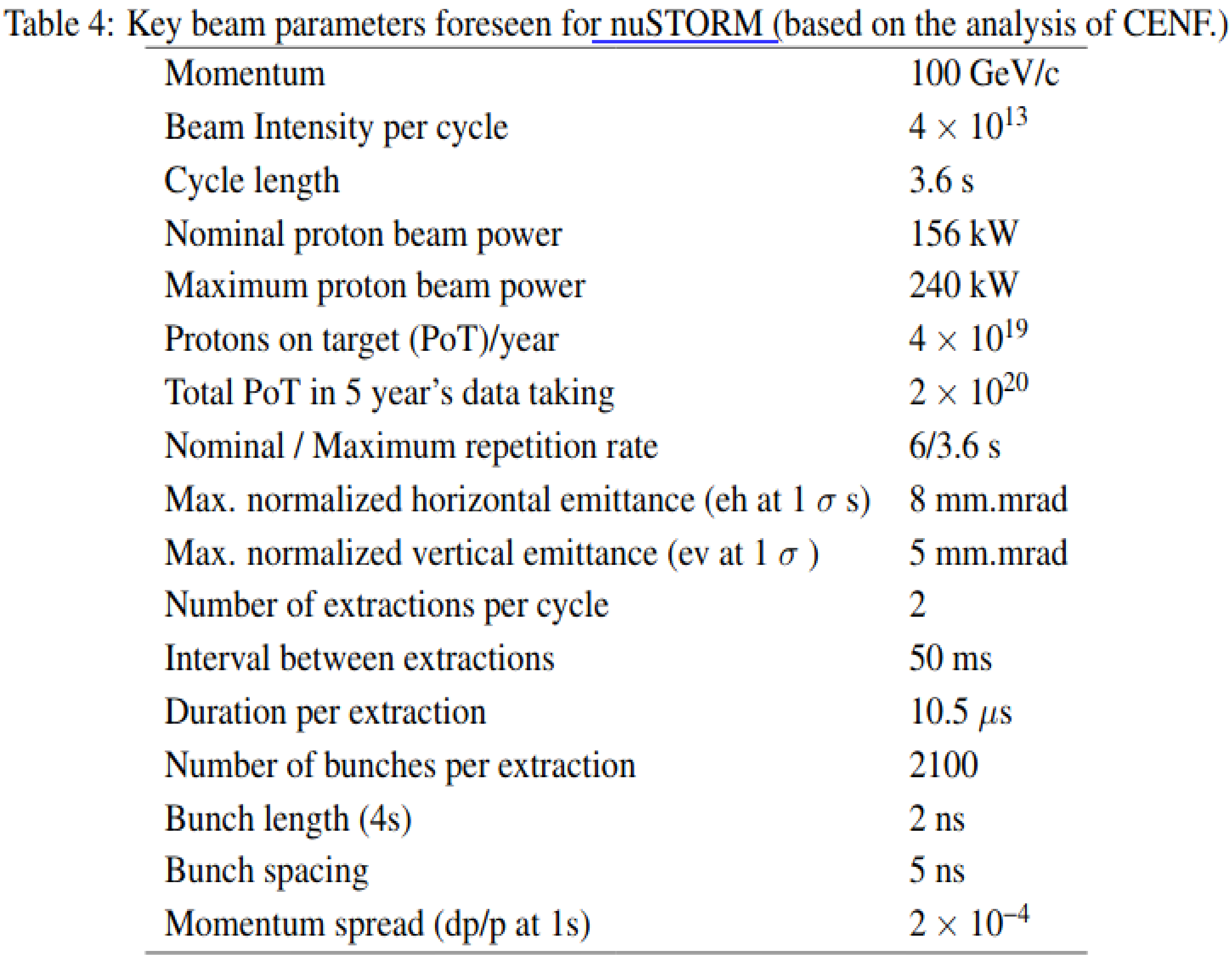
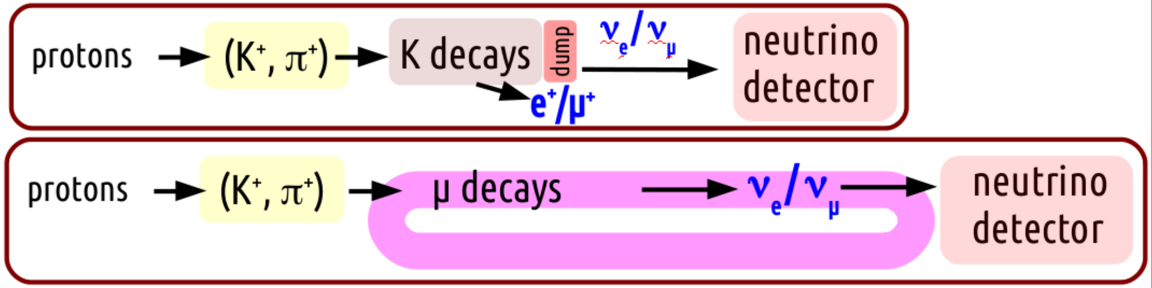


Table 4: Key beam parameters foreseen for nuSTORM (based on the analysis of CENF.)

		ENUBET
Momentum	100 GeV/c	100-400 GeV/c
Beam Intensity per cycle	4×10^{13}	$4.5\text{x}10^{13}$ (@ 400 GeV/c)
Cycle length	3.6 s	24 s
Nominal proton beam power	156 kW	120 kW
Maximum proton beam power	240 kW	
Protons on target (PoT)/year	4×10^{19}	$4\text{x}10^{19}$ pot/y
Total PoT in 5 year's data taking	2×10^{20}	~$9\text{x}10^{19}$ (in 2 y)
Nominal / Maximum repetition rate	6/3.6 s	2 s (slow)
Max. normalized horizontal emittance (eh at 1 σ s)	8 mm.mrad	
Max. normalized vertical emittance (ev at 1 σ)	5 mm.mrad	
Number of extractions per cycle	2	1 (slow) [10 (horn)]
Interval between extractions	50 ms	- (slow) [100 ms (horn)]
Duration per extraction	10.5 μs	2-4 ms (slow) [2-5 ms (h)]
Number of bunches per extraction	2100	
Bunch length (4s)	2 ns	
Bunch spacing	5 ns	
Momentum spread (dp/p at 1s)	2×10^{-4}	

nuSTORM & ENUBET



protons → (K^+, π^+) → K decays → dump → ν_e/ν_μ → neutrino detector

K decays → e^+/μ^+

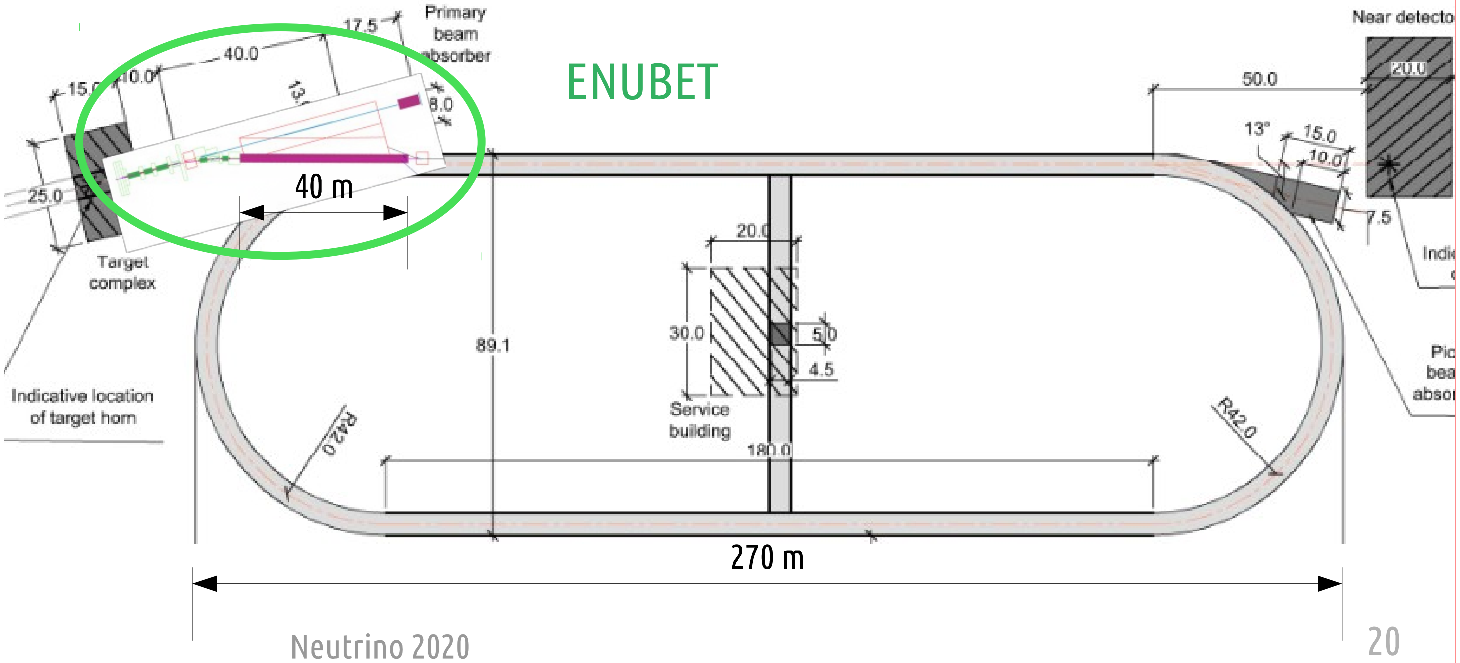
protons → (K^+, π^+) → μ decays → ν_e/ν_μ → neutrino detector

	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section of the ring (180 m).	No. Muons are kept: the most interesting flux parents.	Fast, 100 GeV	Yes, similar	> 300 m from target (ring straight section)

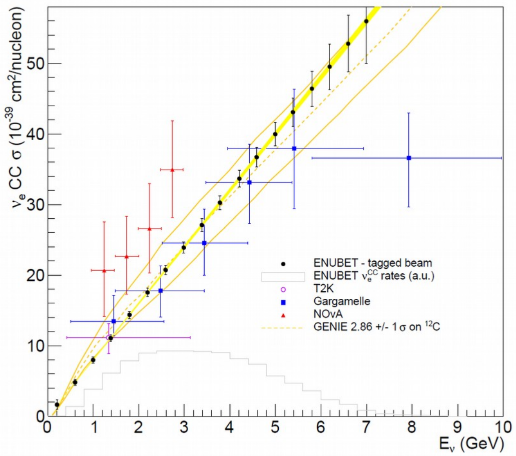
- Different concepts, budget, geometries

BUT...

- Common ground for synergies and joint studies on:
  - ✓ Target station
  - ✓ P-dump
  - ✓ Horn+first part of TL
  - ✓ Civil infrastructures



Summary and outlook



The ENUBET design reached a mature stage:

- Full design and simulation of the transfer line
- Demonstrated the feasibility of a purely static focusing (0.5x10^4 ν_e^{CC}/y/500 t)
- Tested "bursted" slow extraction → Horn option still alive and kicking

- Full simulation of lepton monitoring with adequate S/N
- Preliminary studies for $\pi_{\mu\nu}$ monitoring
- Detector prototyping over → moving to the construction of the tagger demonstrator
- Flux systematics assessment in progress (using an approach à la T2K with ENUBET observables as additional priors to the fit)

Synergies with nuSTORM:

- first steps in the framework of Physics Beyond Collider
- Synergies in the study of the p-dump, target station, horn, first section of the transfer line
- Surveys on shared civil infrastructure could be important to assess and reduce costs