A new generation of cross section experiments in the DUNE/HK era

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IRN Neutrino

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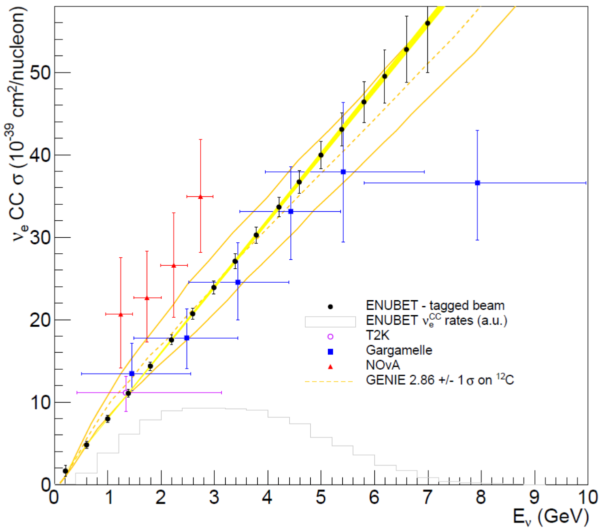


Outline

- The importance of x-sec measurements
- A monitored neutrino beam: **NP06/ENUBET**
- Towards an European dedicated hub

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

Since 2019 Neutrino Platform Experiment

http://enubet.pd.infn.it

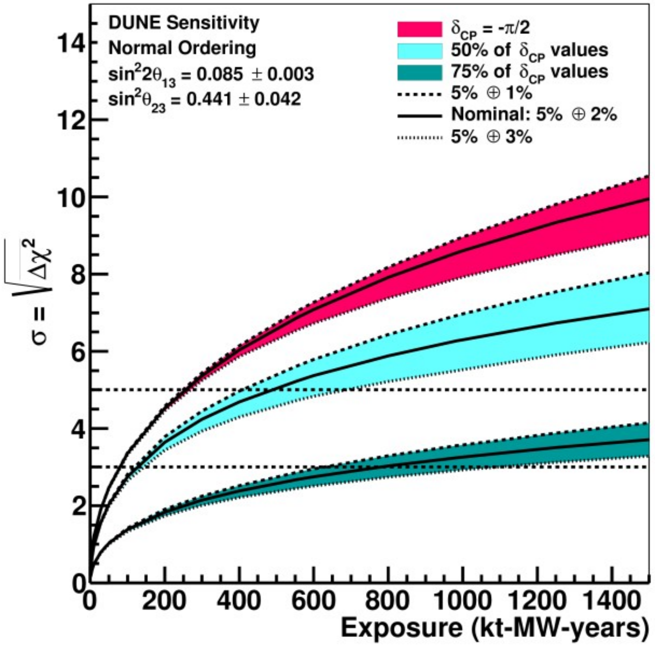
60 physicists
12 institutions

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).

The role of cross sections in the precision era

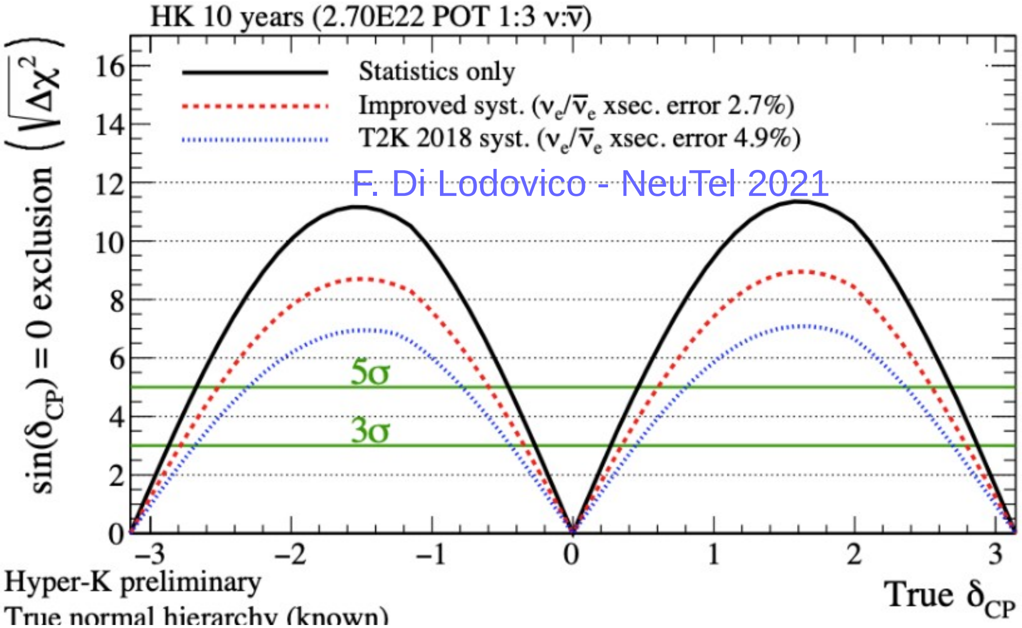
Full exploitation of data from future oscillation programs strongly dependent on the control of **systematics**

- statistics not an issue (large θ_{13}, superbeams, huge mass)



The well konwn **near-to-far ratio** technique **challenged** by the required precision:

- difference in angular acceptance
- large pile-up effects at ND
- different detector technology for the two sites



Fundamental a better knowledge of $\sigma_{\nu\mu}$ and $\sigma_{\nu e}$ (currently know at 25% and 10% level)

Cross section measurement

Modern Near Detectors of LBL projects, dedicated experiments and SBL sterile-ν experiments improved the scenario but a change of paradigm is needed to reach a 1% precision

$$N \sim \int \phi(E)\,\sigma(E)\,\epsilon(E)\,dE$$

- Flux is the largest source of uncertainty
- Mitigation through hadroproduction and detailed simulation
- Difficult to go below 5%

- All terms depends on the energy
- Reconstruction through final state particle kinematics
- Biased by nuclear effects and FSI

- Measure σ x ε for the oscillation program with "replica" detector technologies
- Decouple σ and ε with complementary high efficiency detectors

A dedicated facility with **superior control** on **φ** and **E** and multiple **detector technologies** is highly desirable:

See also the **ESPP Physics Briefbook** arXiv:1910.11775

European Strategy for Particle Physics Deliberation document

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

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

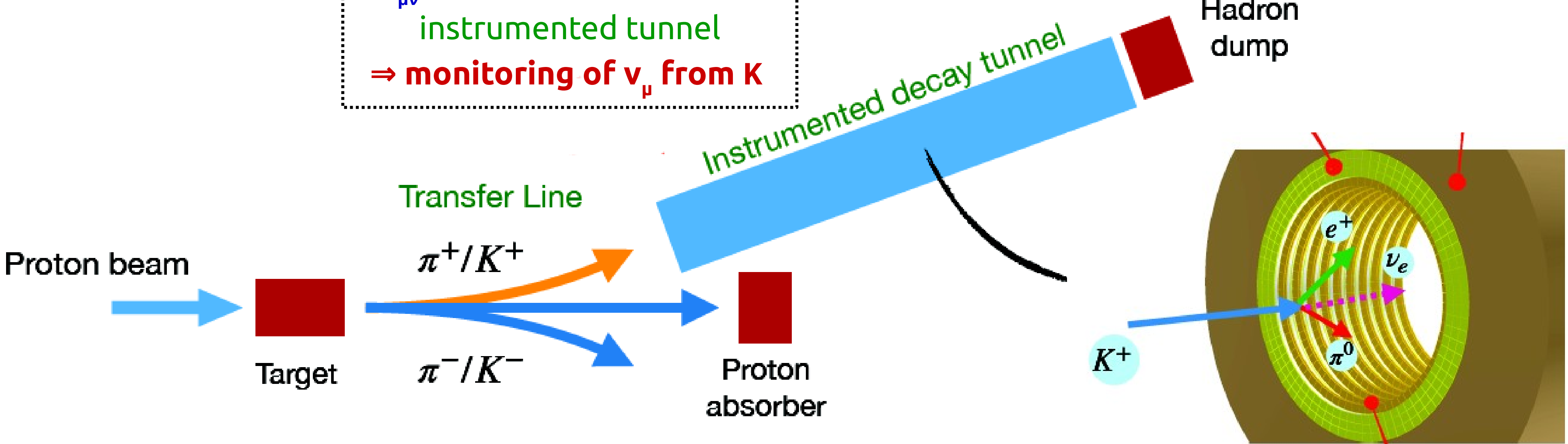
ENUBET: the first monitored neutrino beam

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:

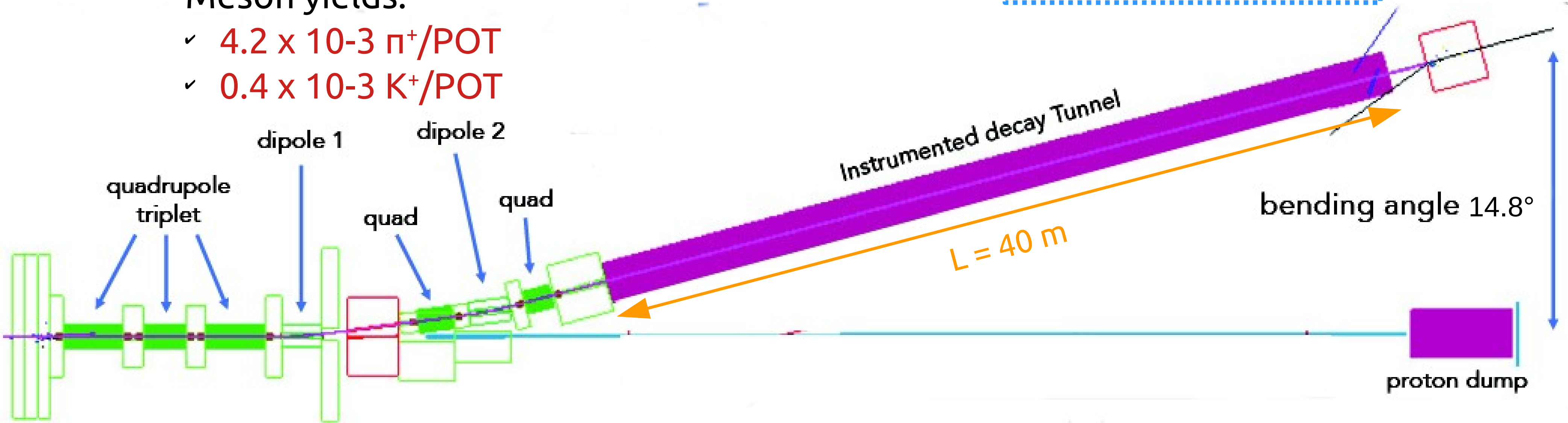
- ✓ Sustainable rate at the instrumentation → Slow proton extraction
- ✓ Highly collimated beam
- ✓ Cost effective detectors to identify muons and positrons

Latest update:
SPSC Annual Report 2021

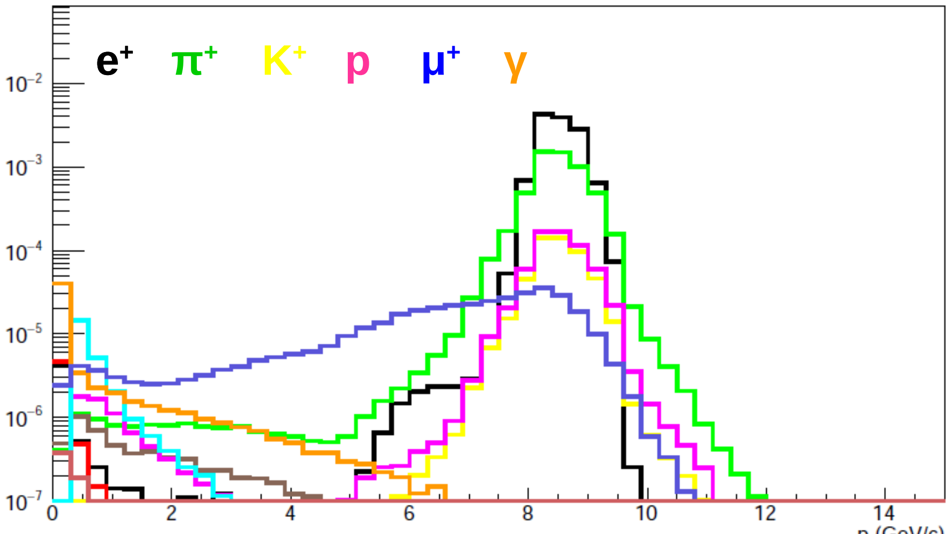
The ENUBET hadron beamline

- Standard warm magnets. Max aperture 15 cm.
- **Momentum bite**: 8.5 ± 10% GeV/c
- Meson yields:
  - ✓ 4.2 x 10-3 π^+/POT
  - ✓ 0.4 x 10-3 K^+/POT

Assuming SPS as proton driver:
4.5x10^{13} POT @ 400 GeV for each extraction



Collimators and shieldings tuned to keep under control backgrounds in the tunnel while retaining large enough meson yields



Static focusing (with 2 s proton extraction)

- Mitigation of pile-up effects in the tunnel
- Muon monitoring at the h-dump at 1% level
  → flux of ν_μ from pions
- Pave the way for time-tagged ν beams:
  → time correlation of the interacted neutrino with the associated lepton in the tunnel

Working in parallel on horn + "bursted" slow extraction

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

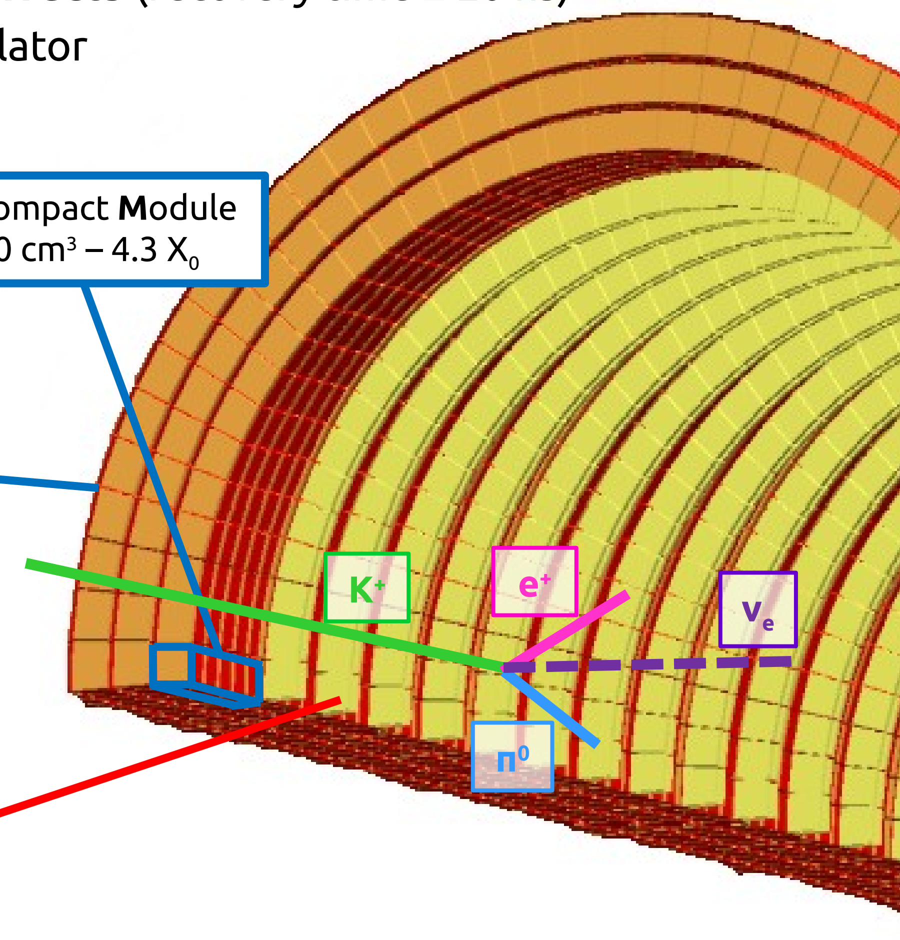
Integrated photon veto (t0-layer)

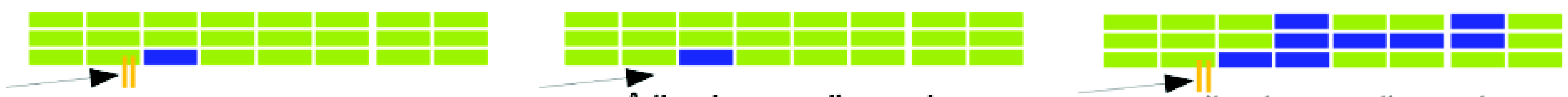
Plastic scintillators

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

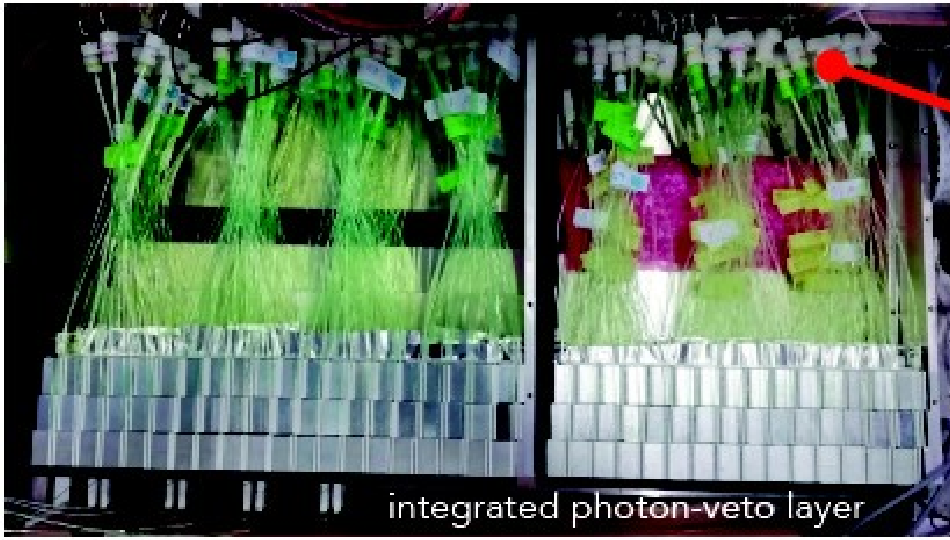




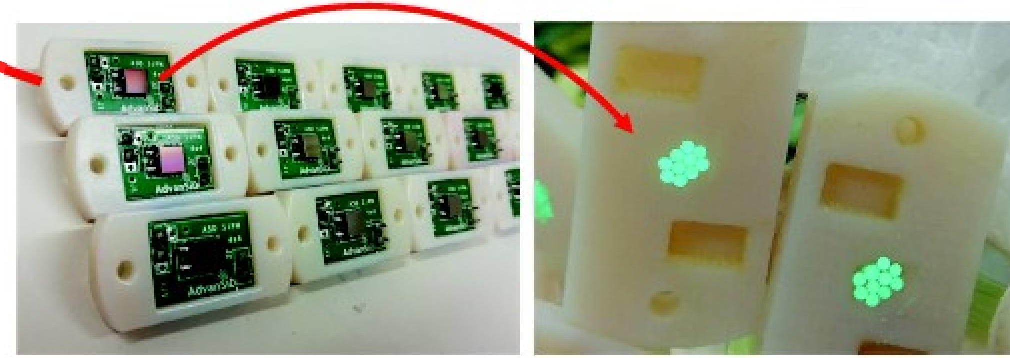
e^+ (signal) topology π^0 (background) topology π^+ (background) topology

The instrumented decay tunnel (II)

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



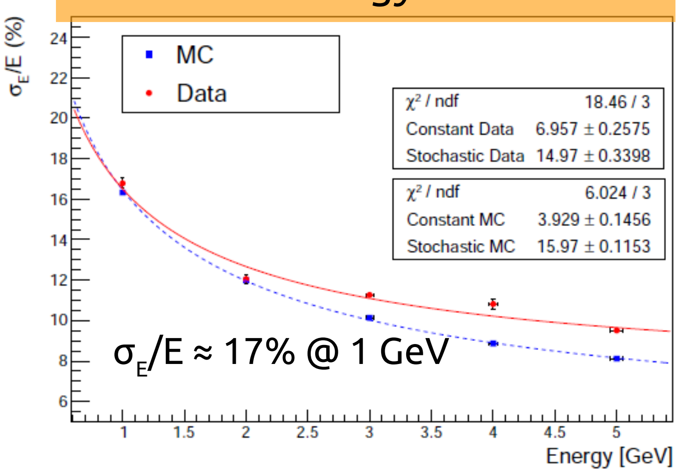
Large area (4x4 mm^2) SiPM for 10 WLS (one LCM)



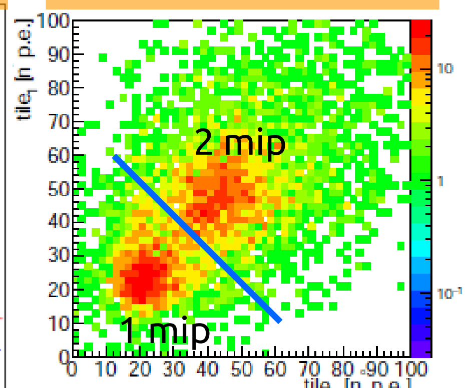
SiPM installed outside calorimeter, above shielding: reduce neutron radiation damage

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

Electron energy resolution



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!

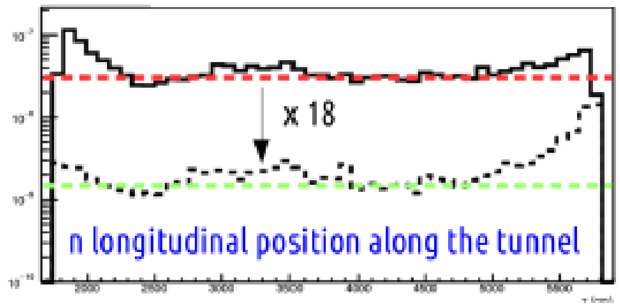
F. Acerbi et al, JINST (2020), 15(8), P08001

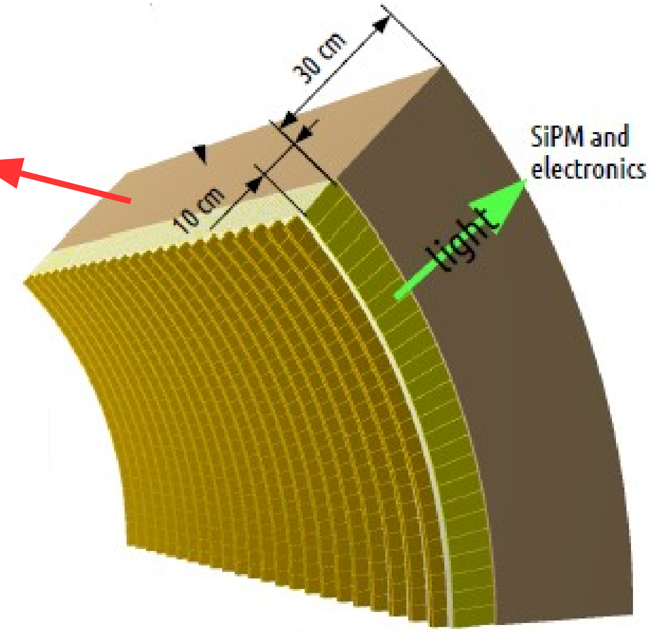
The tagger demonstrator

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

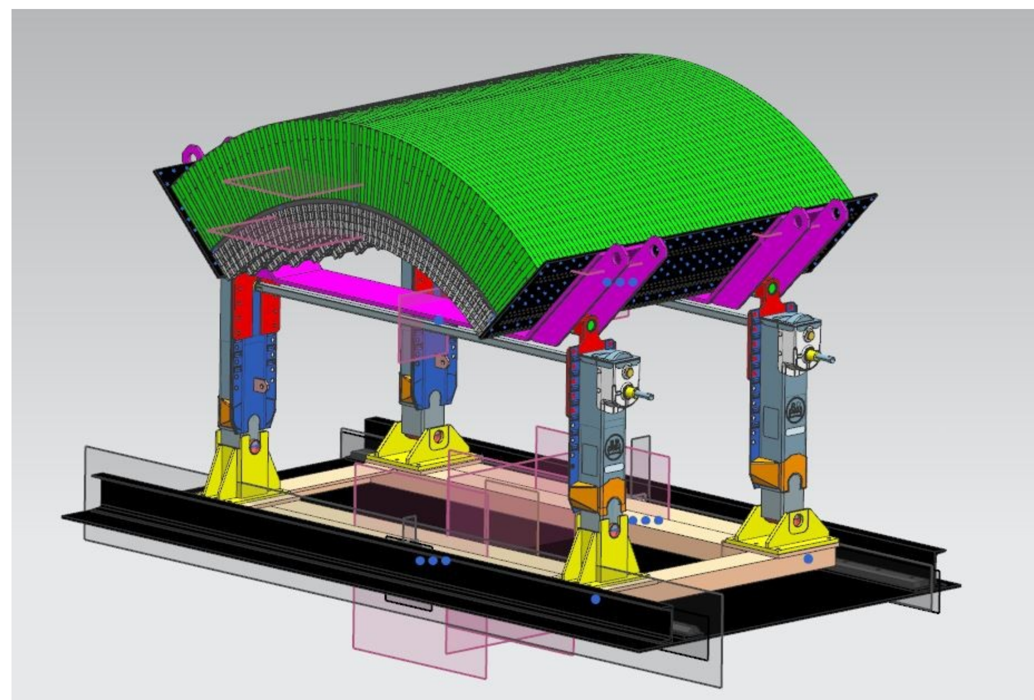
30 cm borated polyethylene
→ ~ **x18 neutron reduction**
Add safety margin for SiPM





WLS collecting light from each module through grooves on the frontal face of scintillator tiles

Custom digitizers
@ 500 MS/s



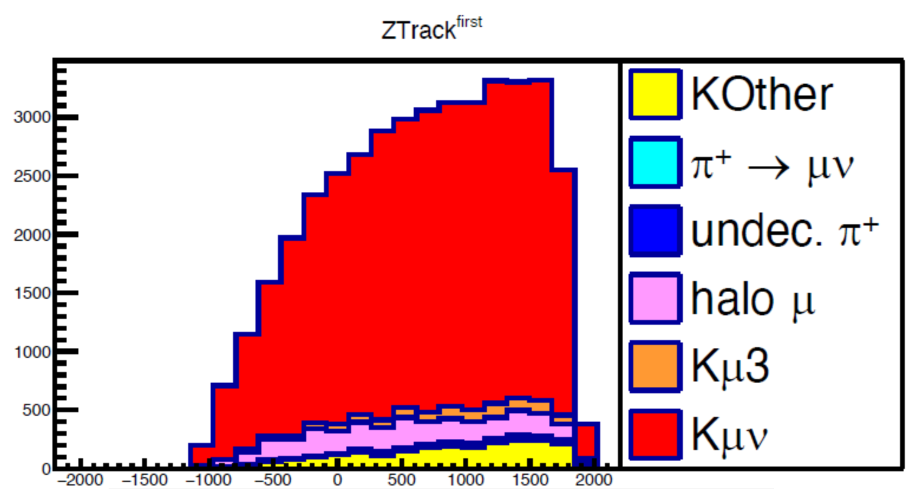
Lepton identification (I)

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

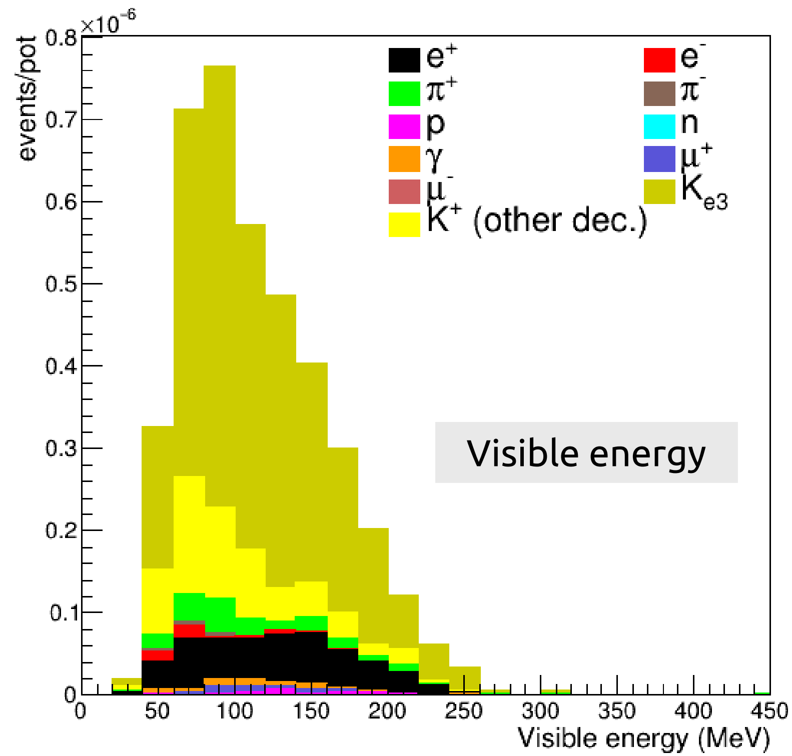
S/N = 6
Efficiency: 33% (~ half geom.)



Longitudinal position along tunnel

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

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

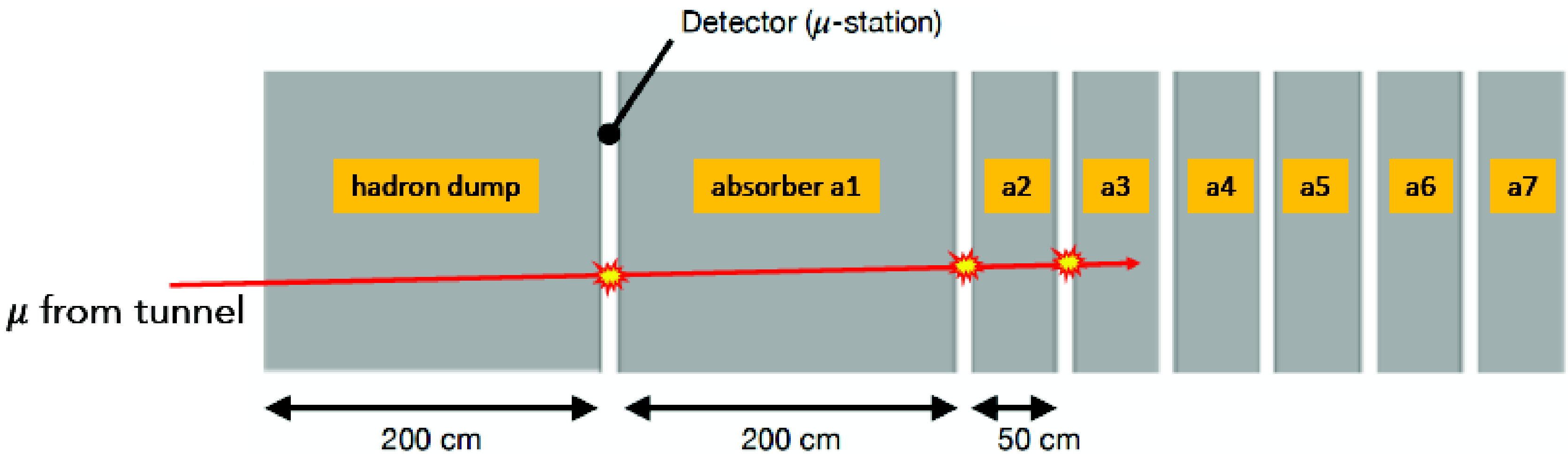


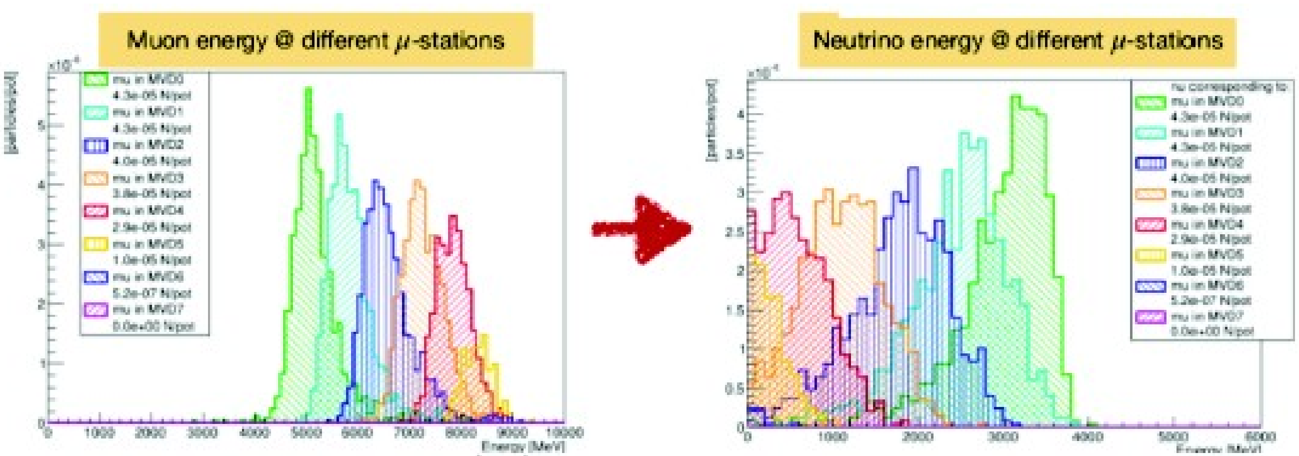
Visible energy

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

ν_e flux

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!!

*assuming 4.5x10^{19} POT/y

- Taggable component:

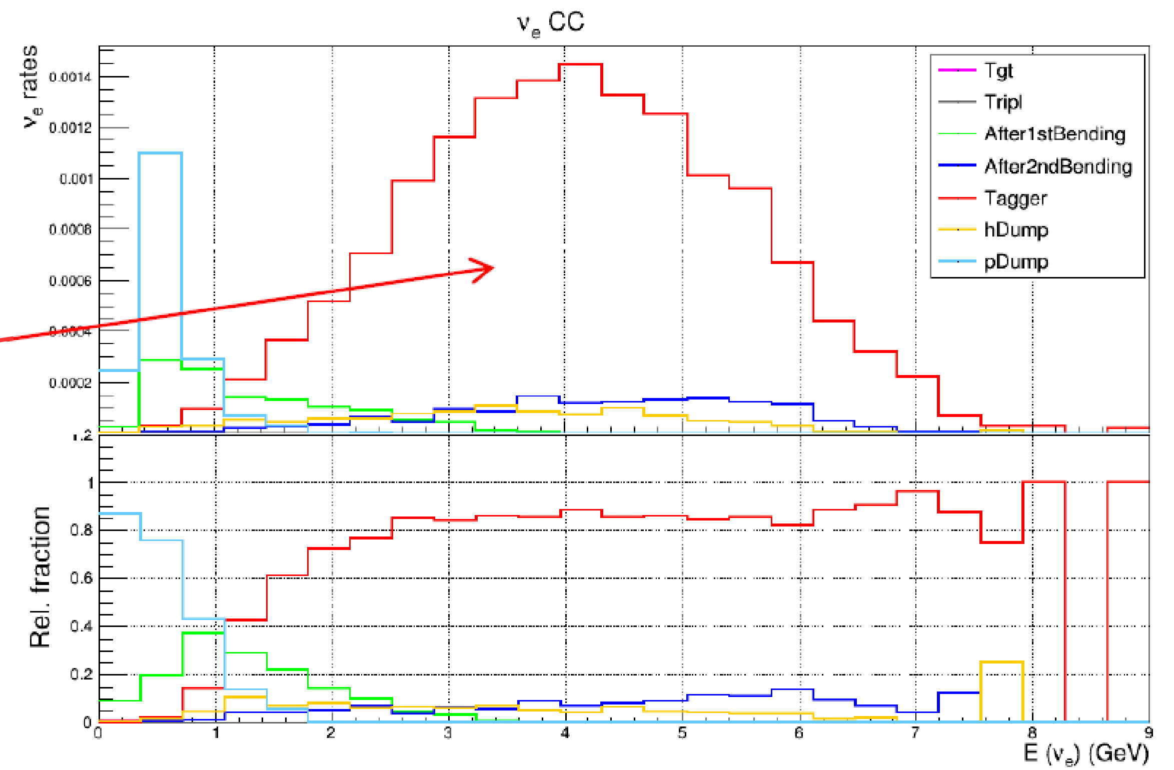
80% monitored by measuring positrons in the decay tunnel

- Non-taggable component 1:

5-10% low-E ν from p-dump
Can be removed with energy cut and tuning the position of the dump

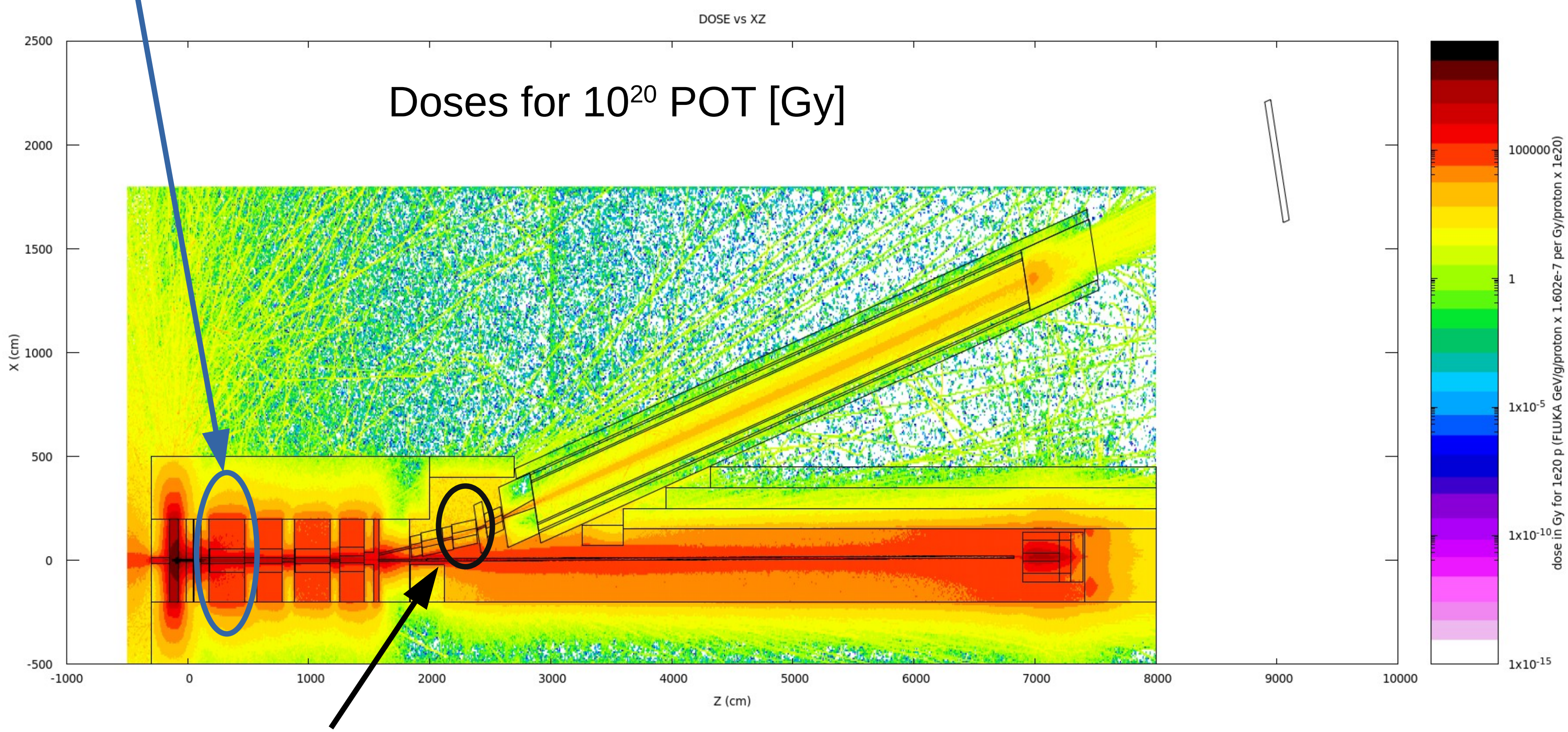
- Non-taggable component 2:

10% from decays after 1st bend/2nd bend



Irradiation studies – add a SC dipole?

- Full FLUKA model of the entire beamline
- The hottest point on the quadrupole closest to the target has a "safe" dose of 100-300 kGy



Doses at the second dipole could allow to place a **Super Conducting magnet**:

- Easily double/triple the bending angle
- Further **reduction** of the non-taggable component from decays in the trasfer line

ν_μ flux

Constrain on flux:

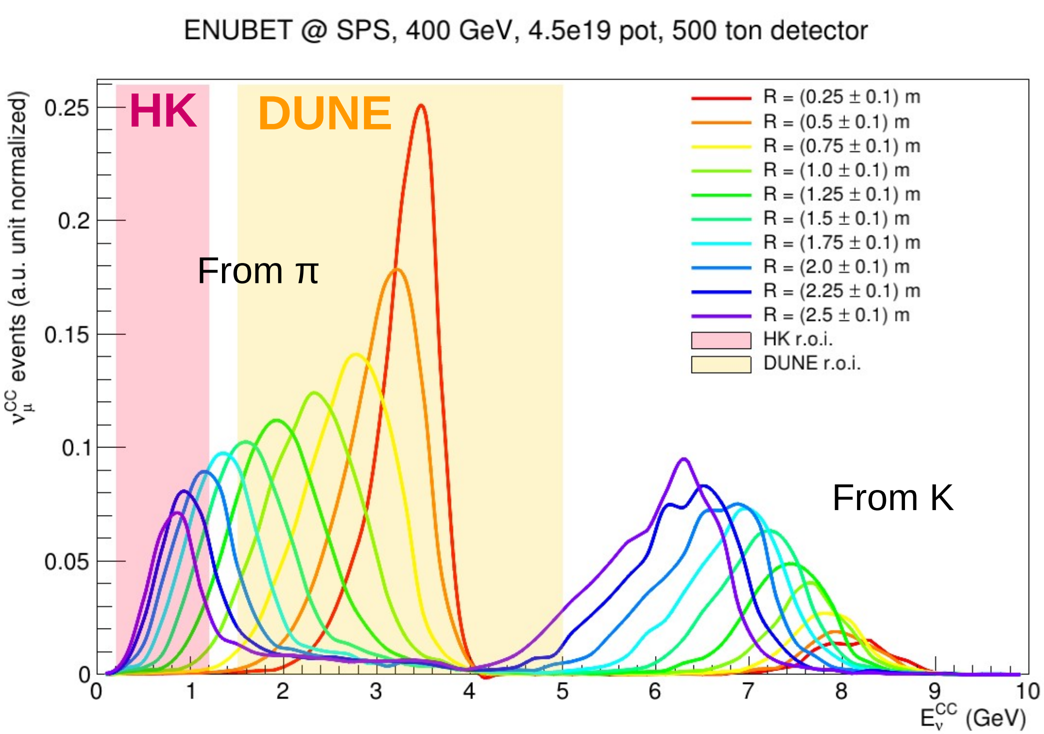
- Muons from π monitored by the range-meter (low energy part of the ν flux)
- Muons from $K_{\mu 2}$ monitored in the instumented tunnel (high energy part)

Constrain on energy:

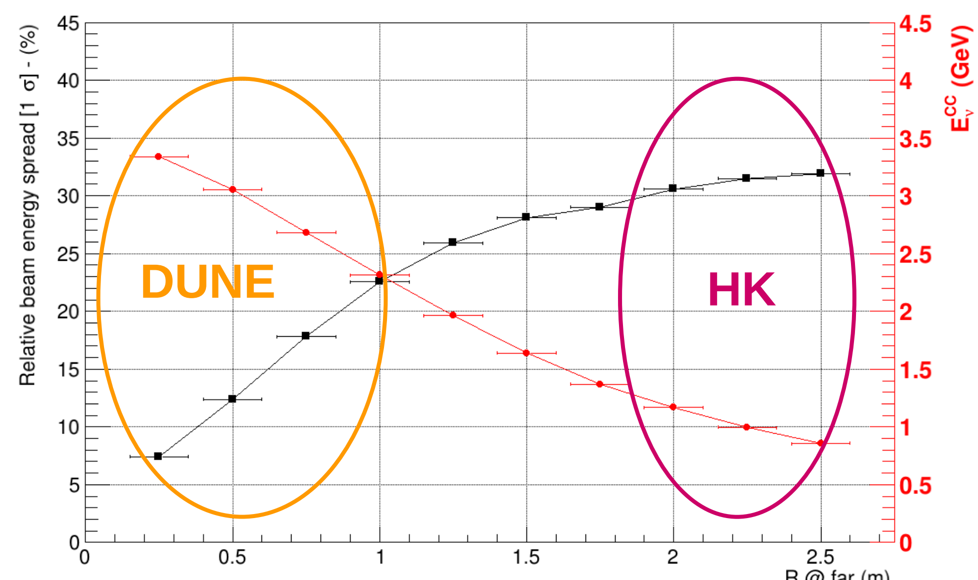
*F. Acerbi et al., CERN-SPSC-2018-034

- 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 8×10^5 ν_μ^{CC} interactions in ~2 years



Width of π peaks ≈ E resolution

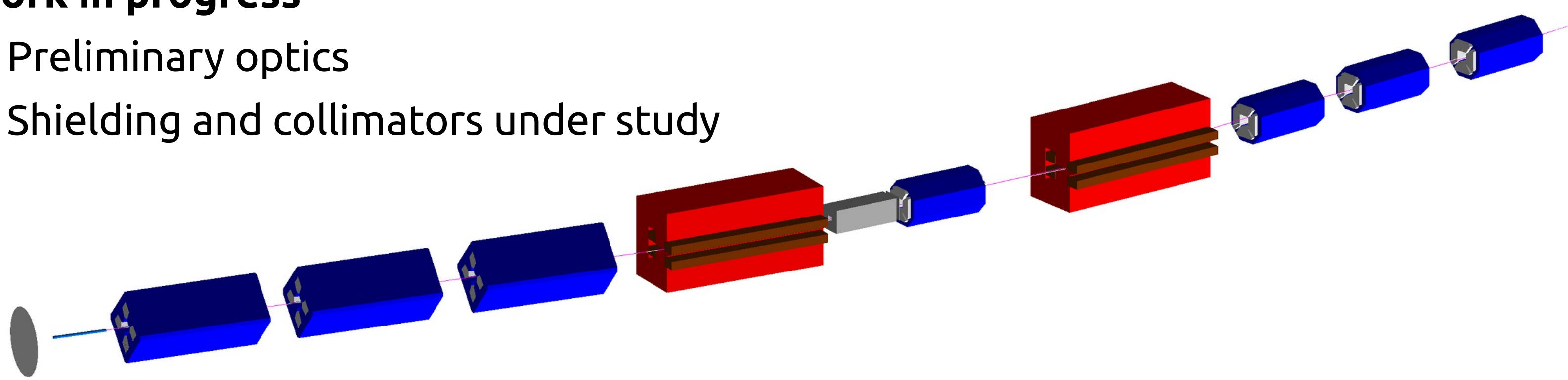


ENUBET beam optimized for DUNE

ENUBET multi-momentum transferline

- A parallel study ongoing for the hadron beamline to focus **8.5**, **6** or **4** GeV/c secondaries by changing the magnetic fields only

Work in progress
- Preliminary optics
- Shielding and collimators under study



- Add flexibility and allow a set of different neutrino spectra **from Hyper-K to Dune** regions of interest

Towards a cross section facility in EU

- The ENUBET facility has reached an high level of maturity and offers an exquisite control of ve and vμ fluxes coupled to an a-priori determination of E with O(10-20%) precision

- Recently included in the PBC initiative to get support for a realistic implementation
A full CdR will be prepared at the end of the ERC project (2022)

- **EUROPE** can play a key role for the success of the oscillation programs in USA and JAPAN through a hub for detailed cross section experiments at CERN

Detectors

- Upgrade and re-use of the ProtoDUNEs

- Use of detectors with the same target as the LBL (water and LAr) for **σ x ε**

- HP-TPC (Argon) or high granularity detectors complemented with low Z targets to decouple **σ and ε**