# Lepton reconstruction in the ENUBET tagger and detectors for the high precision cross section program

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*on behalf of the* ***ENUBET Collaboration***

Istituto Nazionale di Fisica Nucleare

**62 physicist – 13 institutions**


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

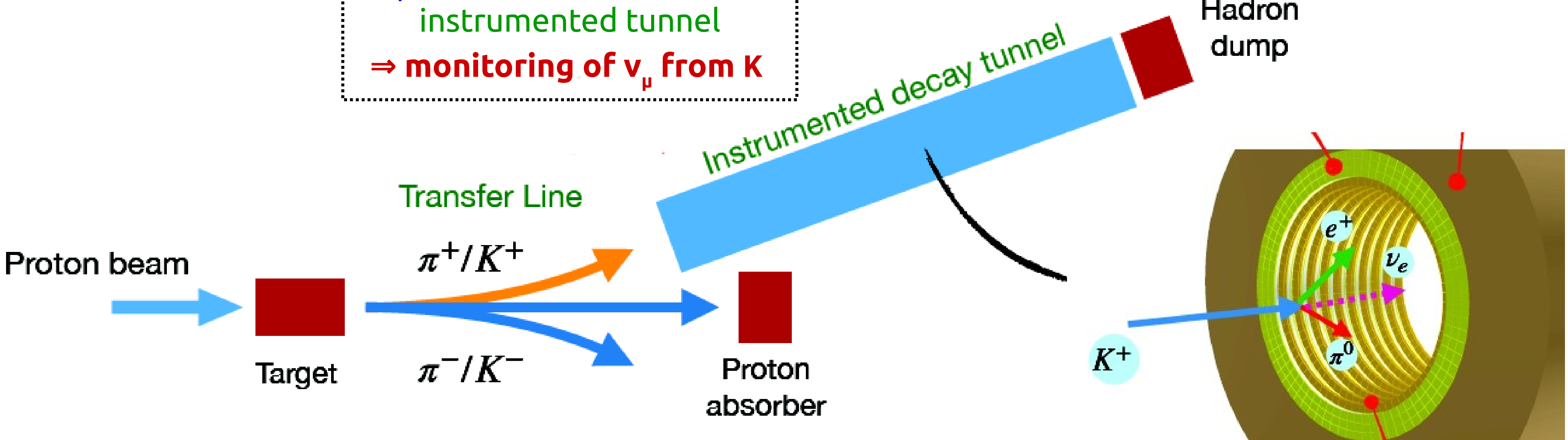
# ENUBET: the first monitored neutrino beam

**Monitored ν beams**

Measure rate of leptons ⇔ monitor ν flux

**muons** measured by a range meter in the hadron dump
**⇒ monitoring of $\nu_\mu$ from π**

**$K_{\mu\nu}$ muons** measured in the instrumented tunnel
**⇒ monitoring of $\nu_\mu$ from K**




**$K_{e3}$ positrons** measured in the instrumented tunnel
**⇒ monitoring of $\nu_e$**

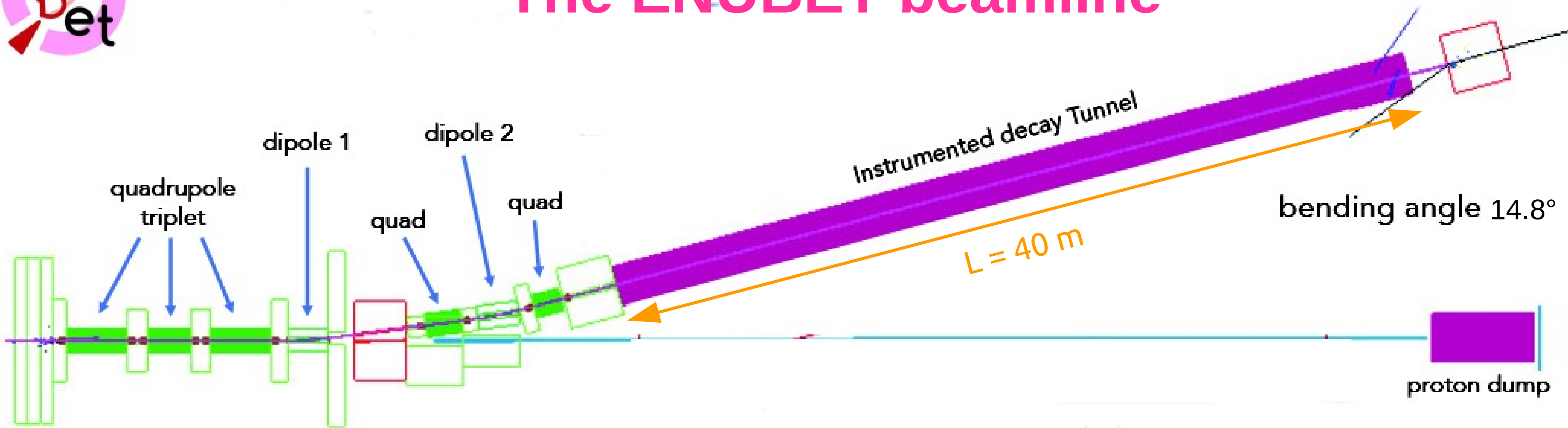
**Main systematics contribution on the flux bypassed:**

- Hadron production, beamline geometry and focusing, POT

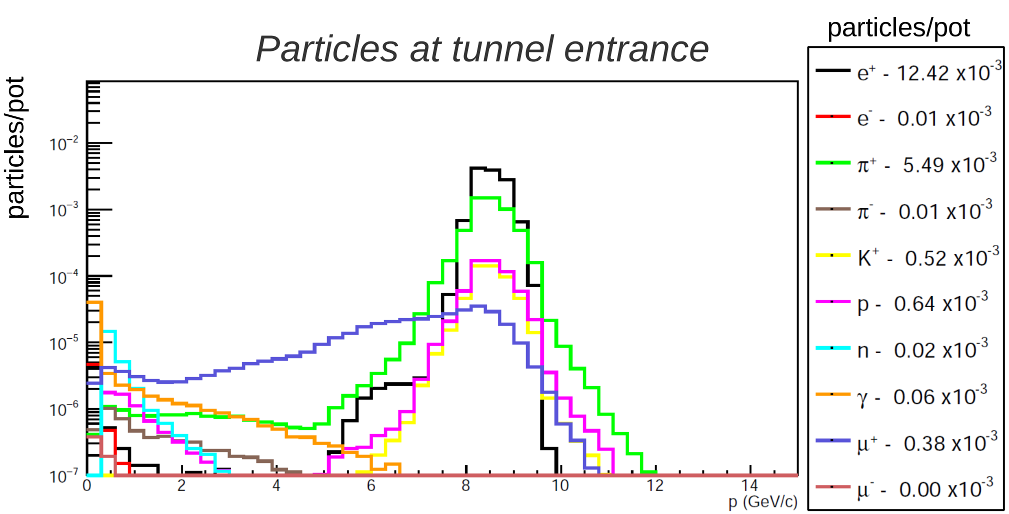
For a full review of the ENUBET project check G. Brunetti talk in WG3 on 7/09

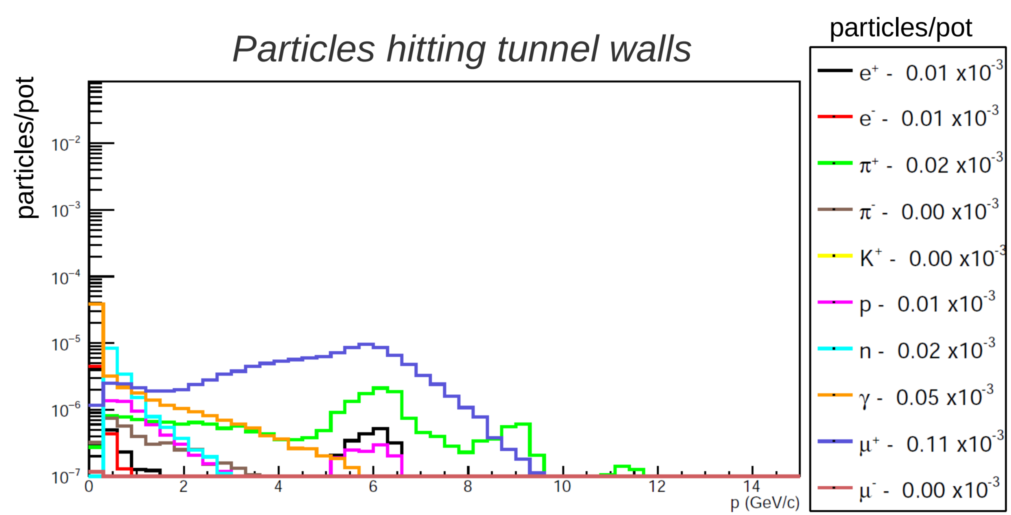
Latest update:
SPSC Annual Report 2021

# The ENUBET beamline




- Static focusing option → coupled to slow proton extraction (assuming 4.5x10$^{13}$ – 400 GeV pot in 2 s)
- Optimized to transport mesons with p=8.5 GeV ± 10% (narrow-band beam)




- Trade-off between a larger meson yield (larger ν flux) and a sustainable background on the tunnel walls

Further details on beamline optimization in today M. Pari talk

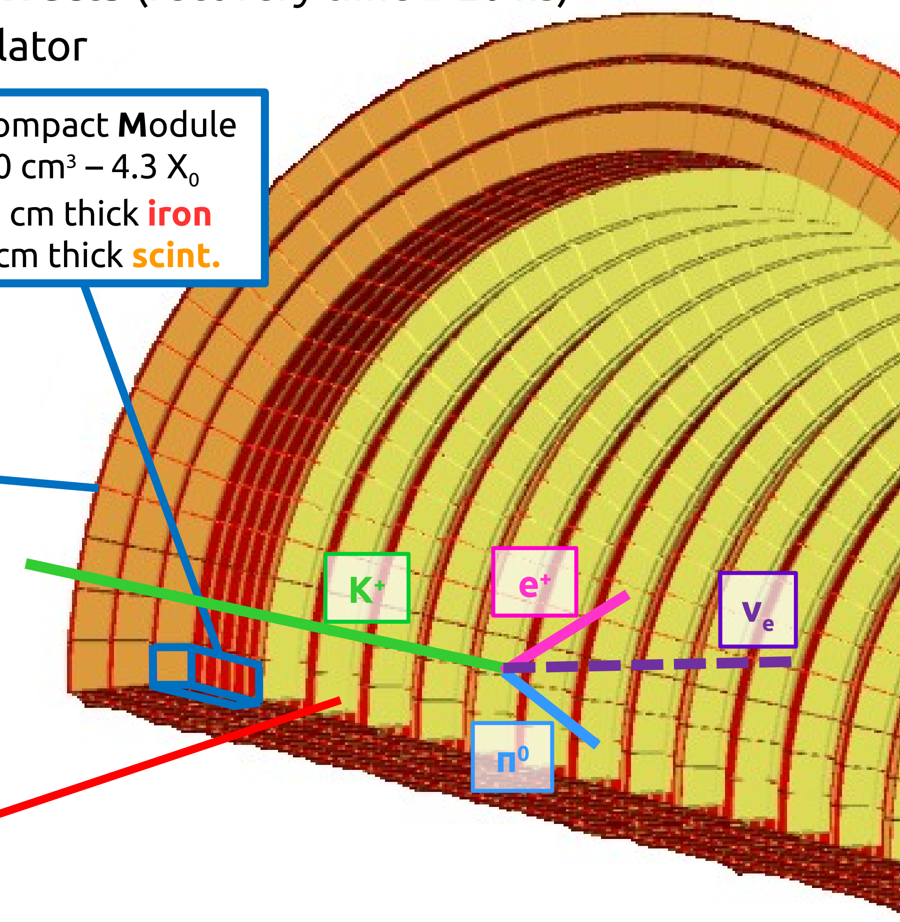
# The instrumented decay tunnel

Further details on detector R&D in today F. Iacob talk

**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

**Lateral Compact Module**
$3\times3\times10$ cm$^3$ – 4.3 $X_0$
Five 1.5 cm thick **iron**
Five 0.7 cm thick **scint.**




## Calorimeter

Longitudinal segmentation
Plastic scintillator + Iron absorbers
Lateral light readout with WLS+SiPM

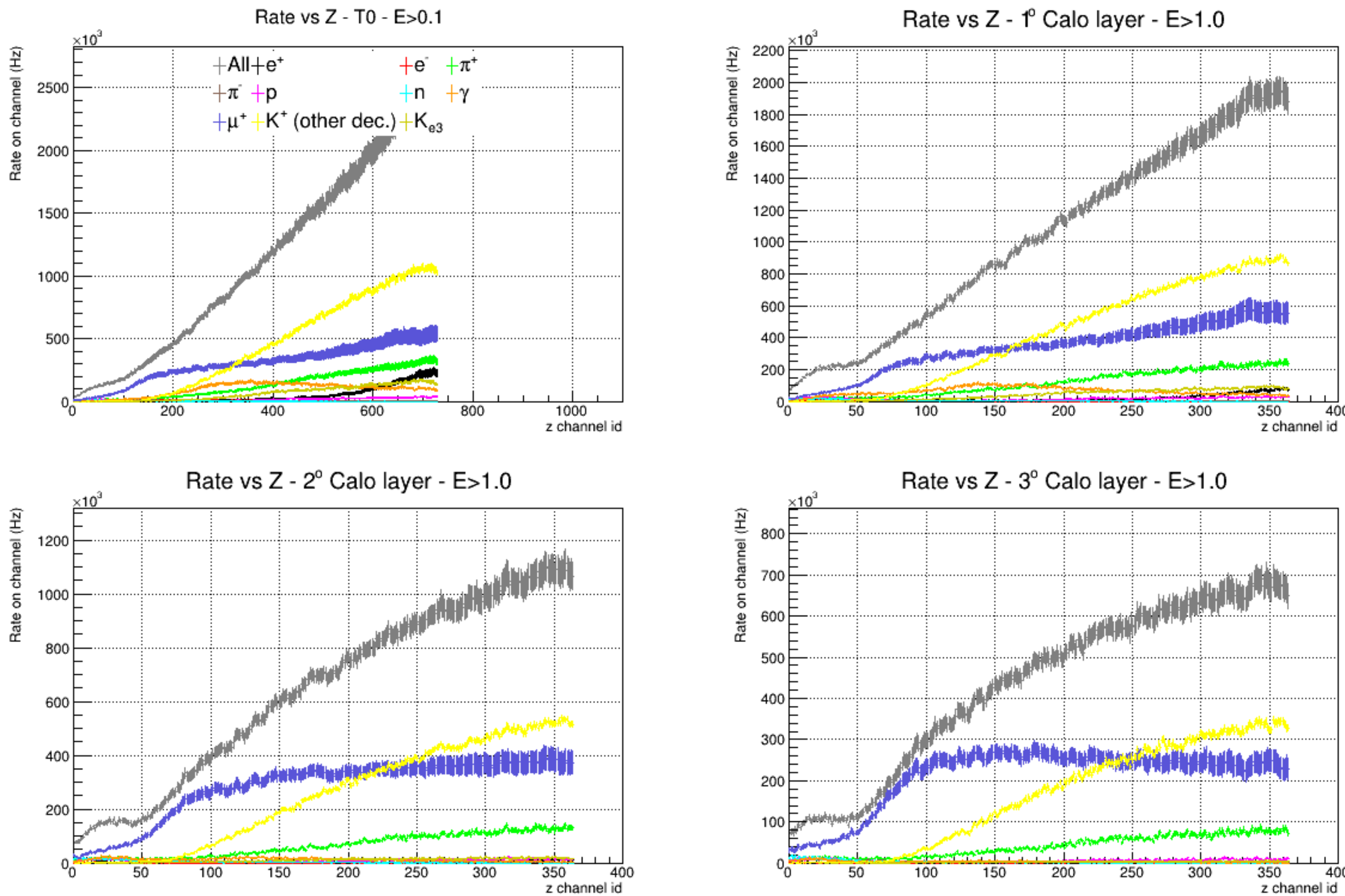
**→ $e^+/\pi^\pm/\mu$ separation**

## Integrated photon veto (t0-layer)

Plastic scintillators
Rings of $3\times3$ cm$^2$ pads readout by SiPM

**→ $\pi^0/\gamma$ rejection**

# Hit rate on tunnel instrumentation

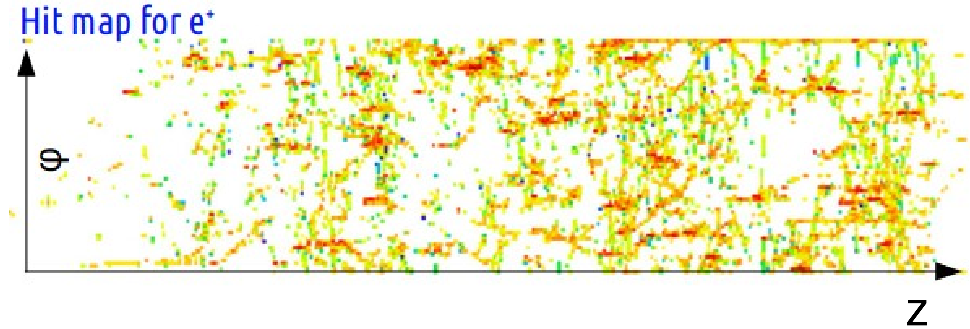



- Maximum rate of O(MHz)
- Dominated by residual uncollimated **pions**, halo **muons** and **kaon decays**
- Halo **muons** are the main background for Kμν
- **Positrons** from the beam represent a not negligible background for **ke3** monitoring

# $K_{e3}$ positron identification

**Full GEANT4 simulation of the detector**

- hit-level detector response
- validated by prototype tests @ CERN



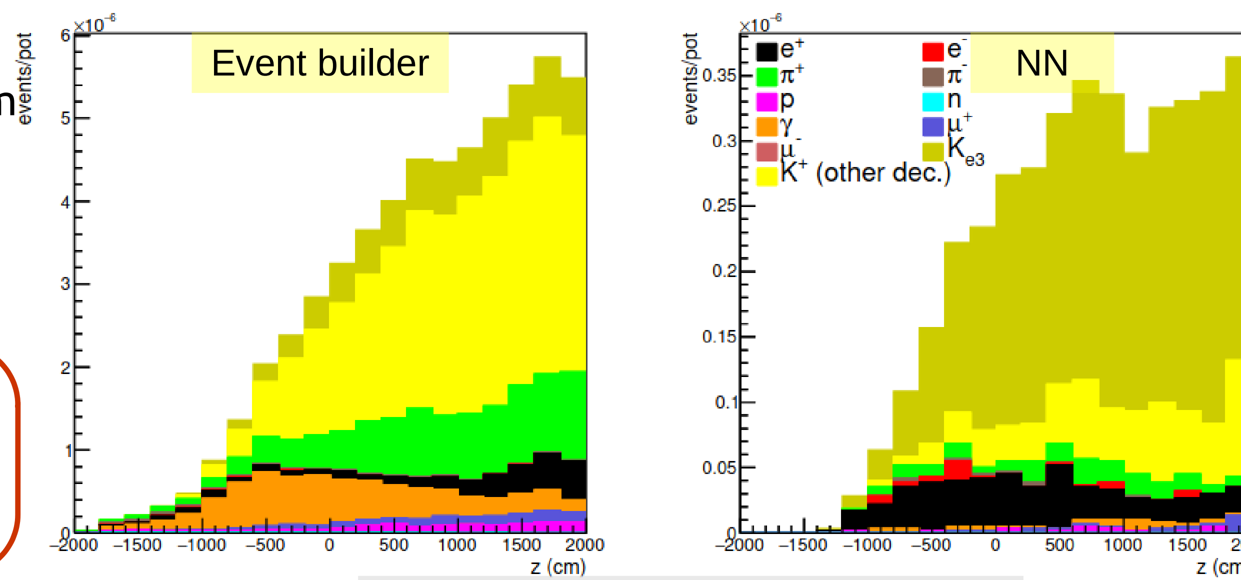

**Analysis chain:**

1) Event builder:

- start from event "seed" (LCM with E>28 MeV in first layer) to preselect e.m. showers
- cluster energy deposits compatible in space ($-5<\varphi_{seed}<5$ ; $-3<z_{seed}<10$) and time ($-1<\Delta t<1$ ns)
- associate T0 hits on the 8 upstream tiles wrt to seed in the same φ sector (Δt within 1 ns)

2) e / π / γ / μ separation:

- Multivariate analysis (MLPNN from TMVA) exploiting 19 variables (energy pattern in calorimeter, event topology, photon-veto)




Longitudinal position along tunnel

**Performance**

**S/N = 2**

**Efficiency: 22% (~ half geom.)**

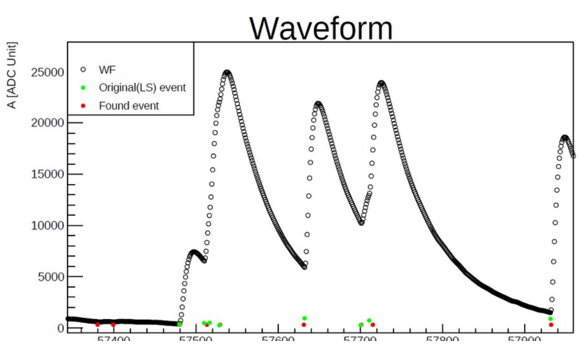
$K_{e3}$ BR ~5% and K make ~5–10% of beam composition

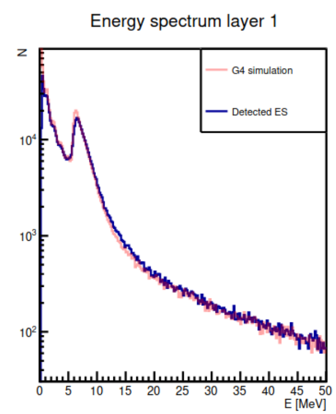
Variable used in the fitting procedure to constrain the $\nu_e$ flux → Today A. Branca talk

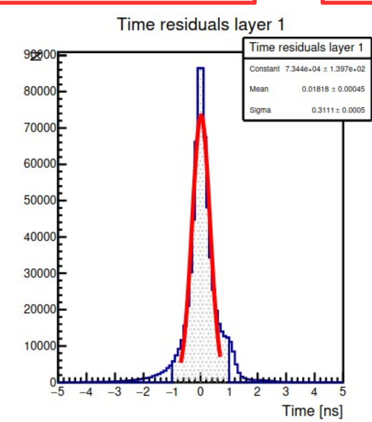
# Waveform simulation and reconstruction

Software framework implemented to simulate tagger response at single channel level
→ fully realistic treatment of pile-up effects

| | | | |
|---|---|---|---|
| Conversion of energy deposits in p.e. Conversion factor (15p.e./MeV) from test beam data | SiPM response simulated using the GosSiP software Waveform digitization | Pulse detection algorithm → Peak amplitude and time determination | Standard analysis chain |

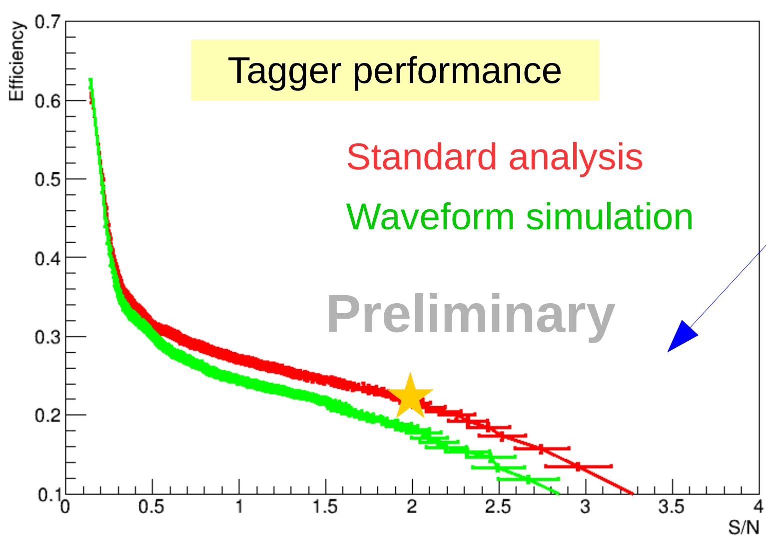



Eff.: 95÷98%

$\sigma_t$: 0.3÷0.4 ns




Efficiency vs S/N for different cuts on the NN classifier

- Improvement to close the gap expected when processing the NN training sample with the same chain
- Full control on the pile-up effects and on the reconstruction chain up to the signal processing level

# $K_{\mu\nu}$ muon identification

Large angle muon tracks reconstructed in the tagger with dedicated event builder and multivariate analysis

Main background from **halo muons** is identified and can be used as control sample

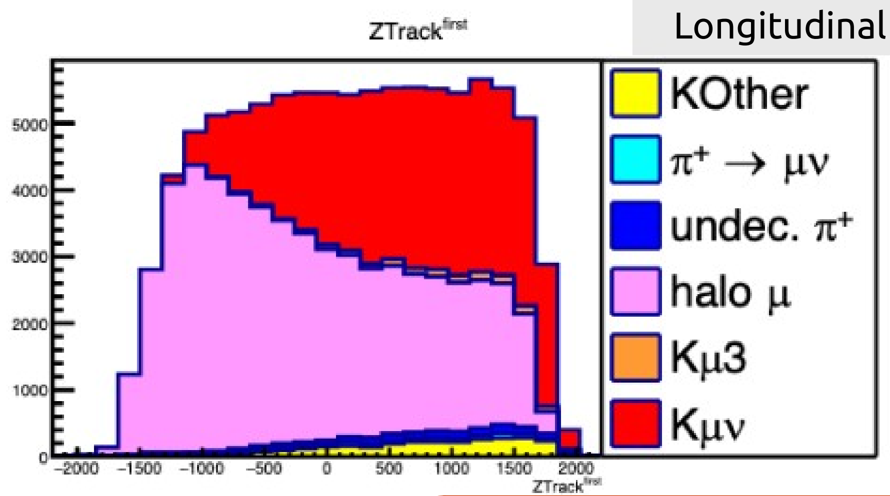
**Analysis chain:**

1) Event builder:

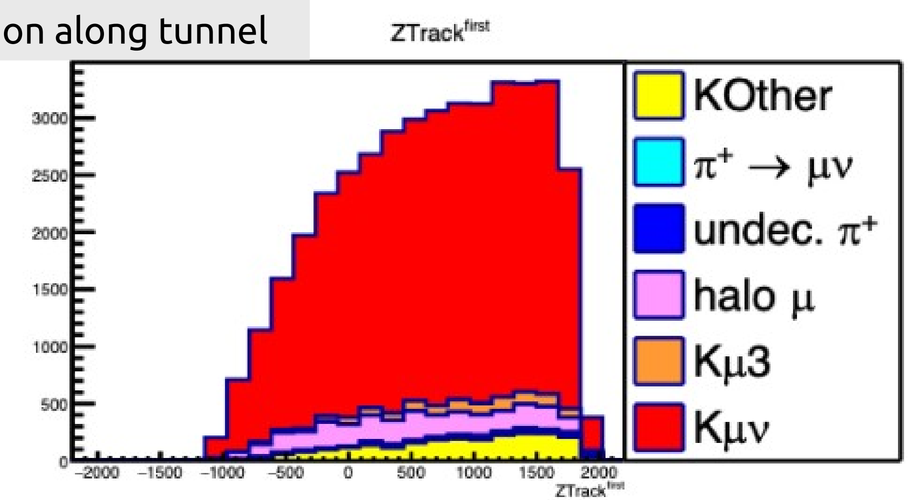
- start from event "seed" (LCM with 5<E<15 MeV in first layer) to preselect mip-like particles
- look for a pattern of aligned energy deposits around the seed

2) μ-like background separation:

- multivariate analysis (MLPNN from TMVA) with 13 variables exploiting track topology (to suppress halo muons) and energy pattern




Longitudinal position along tunnel




**Performance**

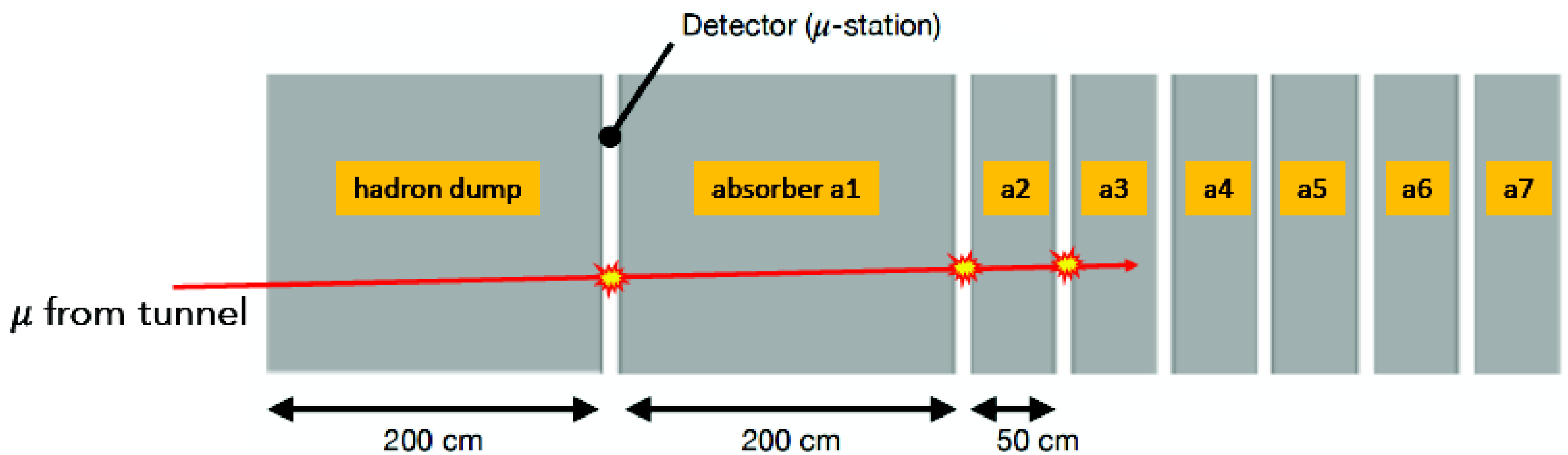
**S/N = 6**

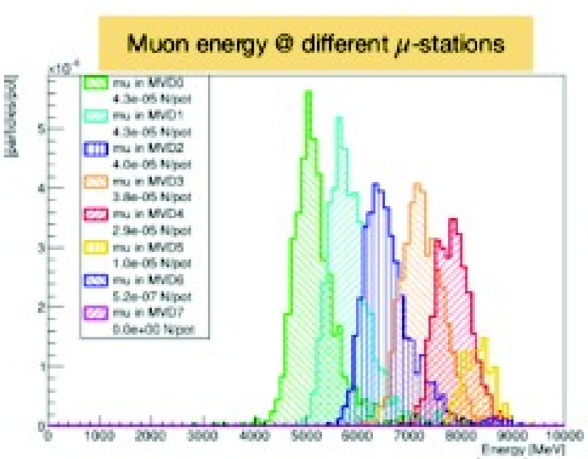
**Efficiency: 34% ($K_{\mu2}$) & 21% ($K_{\mu3}$) [~ half geom.]**

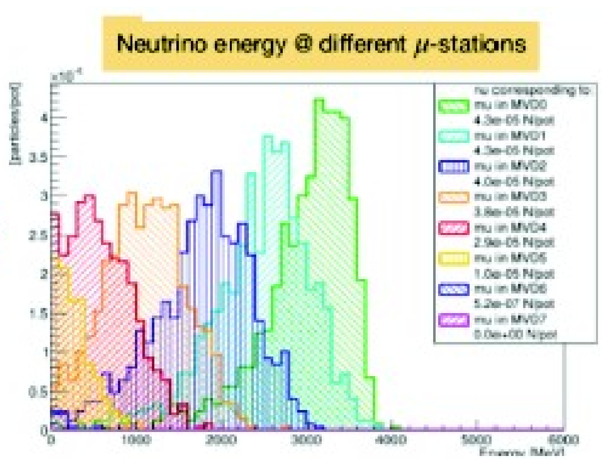
# $\pi_{\mu 2}$ muon identification

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

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

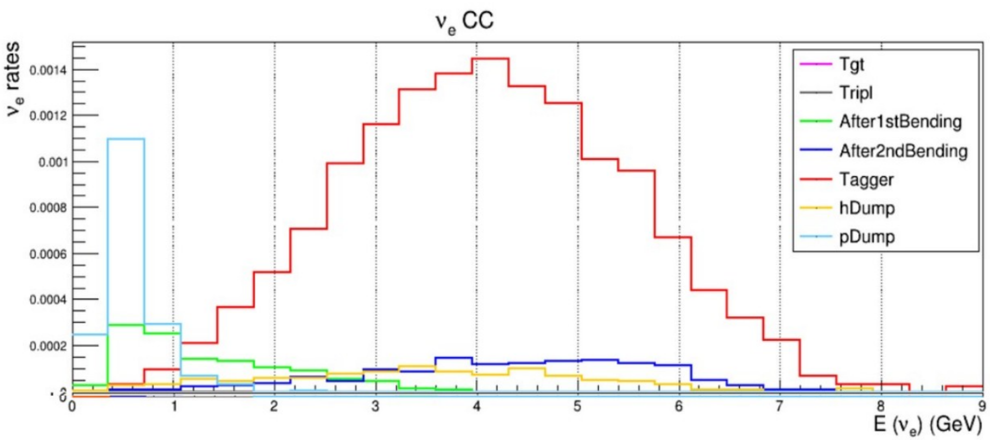
Max μ rate: 2 MHz/cm²
Max n fluence: $10^{12}$ 1-Mev-neq/cm²

# Neutrino spectra

Assuming:
- $4.5 \times 10^{19}$ pot/year
- 500 ton Lar ν-detector ($6 \times 6$ m$^2$) @ 50 m from h-dump

$10^4$ $\nu_e^{CC}$ interactions in ~2y of data taking

<E> ≈ 4 GeV




- Taggable component:

80% monitored by measuring positrons in the decay tunnel

- Non-taggable component 1:

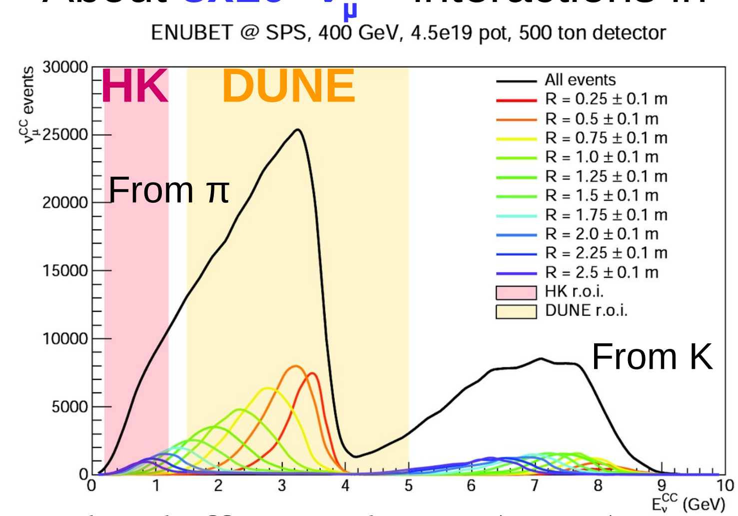
5-10% low-E n from p-dump

Can be removed with energy cut

- Non-taggable component 2:

10% from decays in the transfer line

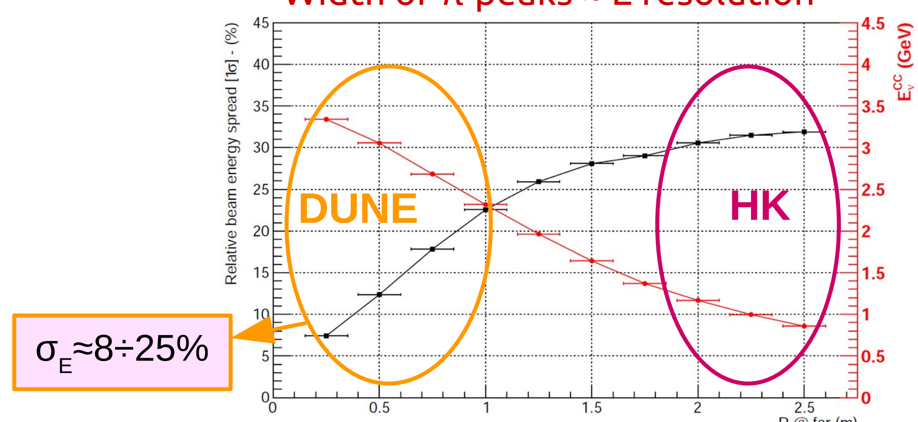
About $8 \times 10^5$ $\nu_\mu^{CC}$ interactions in ~2y




Narrow-band off axis technique (NBOA):
- Narrow p width (O(10%))
- Finite dimesion of near ν-detector

→ Strong correlation between $E_\nu$ and radial vertex pos (R)

Width of π peaks ≈ E resolution



# Cross section measurements

ENUBET is an ideal facility for high precision ν-N cross section measurements at the GeV scale

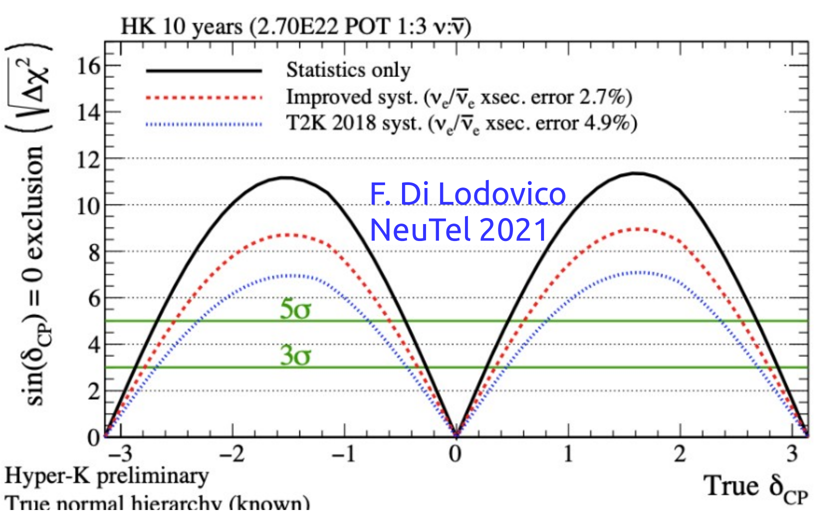
$$N \sim \int \phi(E)\,\sigma(E)\,\epsilon(E)\,dE$$

- Absolute normalization and flavour content know at ~1%
- Abundant source of $\nu_e$ (the appearing species in LBL experiments)

- ν energy known a priori at 10-20% on an event by event basis
- Remove biases from nuclear effects and FSI that are affecting the energy reconstruction through final state particle kinematics

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

*A. Branca, G. Brunetti, A. Longhin, M. Martini, FP, F. Terranova*
Symmetry 2021, 13, 1625




**A complex with a variety of detector concepts is highly desirable**

- Water-Cherenkov (HK) and LAr TPC (DUNE)
- Fine-grained detectors with superiorir PID performance and low thresholds allowing for a complete characterization of the hadronic system
- Detectors with Hydrogen and Deuterium (lowest Z isoscalar nucleus) targets would be pivotal for a cross-section model building not affected by nuclear effects and for nucleon structure studies with a bare weak probe

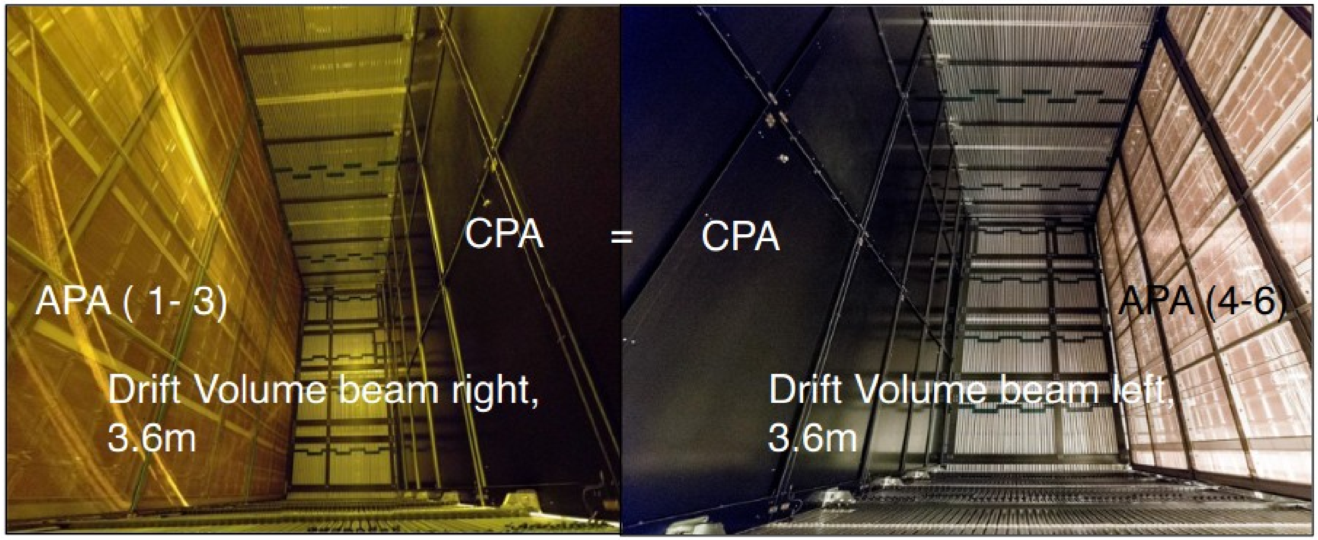
# LAr TPC - ProtoDUNEs

Wenjie Wu talk in WP6 on 9/09

**ProtoDUNE-SP** and DP @ CERN represent an excellent option for **$\sigma \times \varepsilon$** measurement:

- Very same technology as the DUNE far detectors
- Almost full containement of the neutrino interaction (unlike the ND-LAr of DUNE)
- ProtoDUNE-SP response to charged particles already fully characterized in EHN1 exposure

## Drift volume



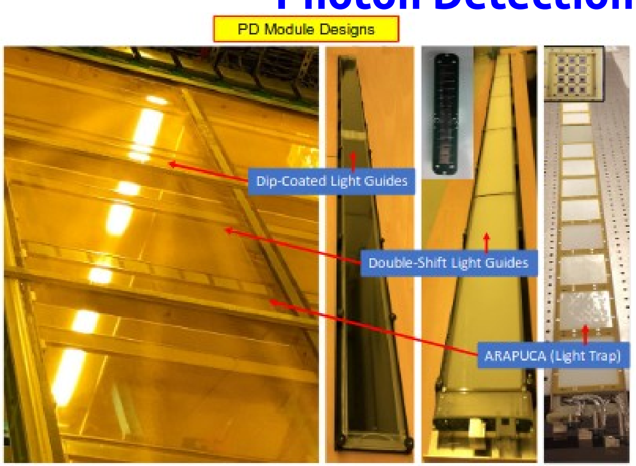

- 7.2x6 $m^2$ transverse dimensions
- 7 m length in the beam direction
- ~400 ton mass

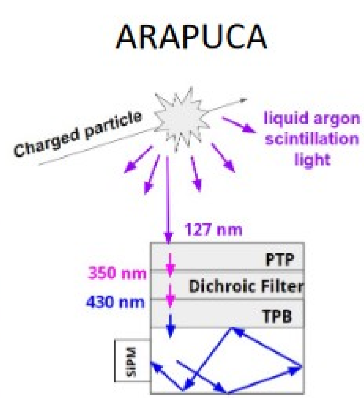
Sensing planes composed by 3 Anode Plane Assemblies on each side

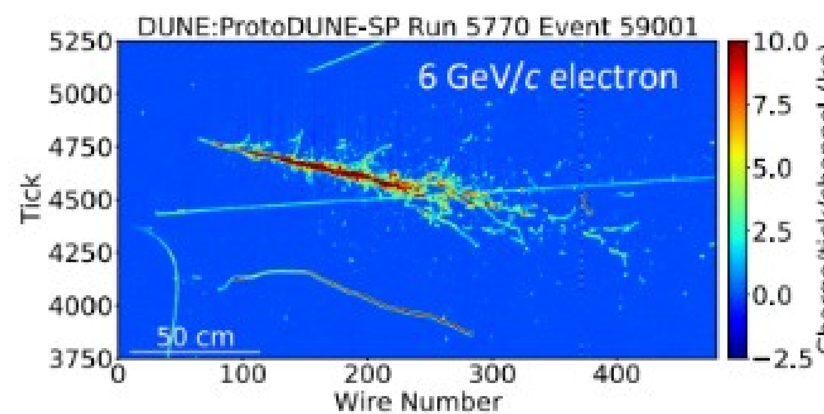
3 Cathode Plane Assemblies in the middle

*B. Abi et al*
2020 JINST 15 P12004

## Photon Detection system



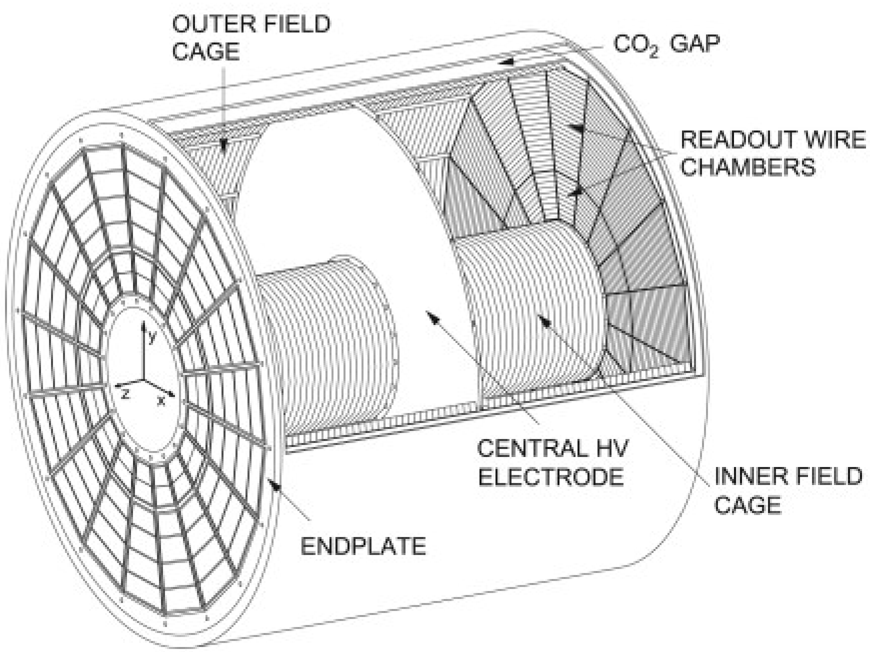



# HPTPC with Argon

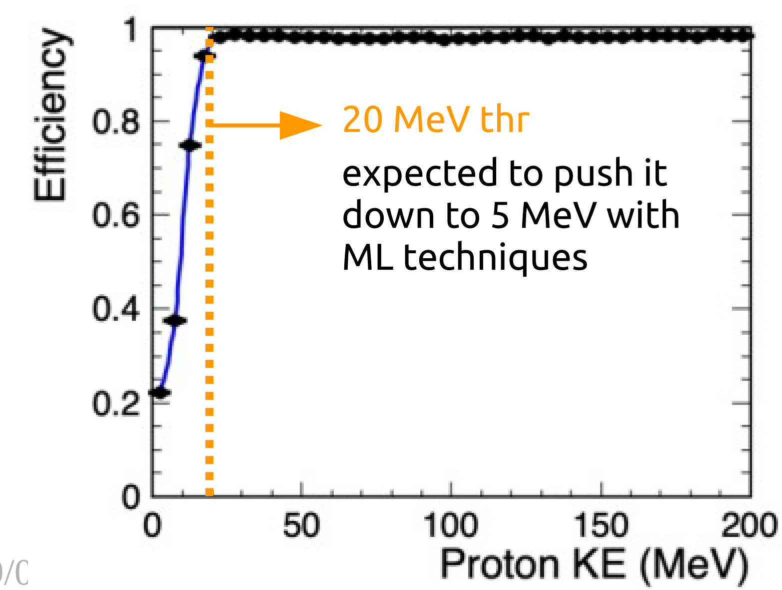
The simultaneous use of a liquid and a **gas phase TPC** could be an ideal solution to decouple the neutrino cross section **(σ)** in Argon from the detector efficiency **(ε)**

An example is provided by the TPC of the **DUNE ND-GAr**, whose design is inherited from ALICE one




- Argon-CH4 mixture at 10 bar
- R=2.5 m
- L=5 m
- ~1.8 ton active mass

*DUNE-ND-CDR*
arXiv:2103.13910




**Main advantages:**

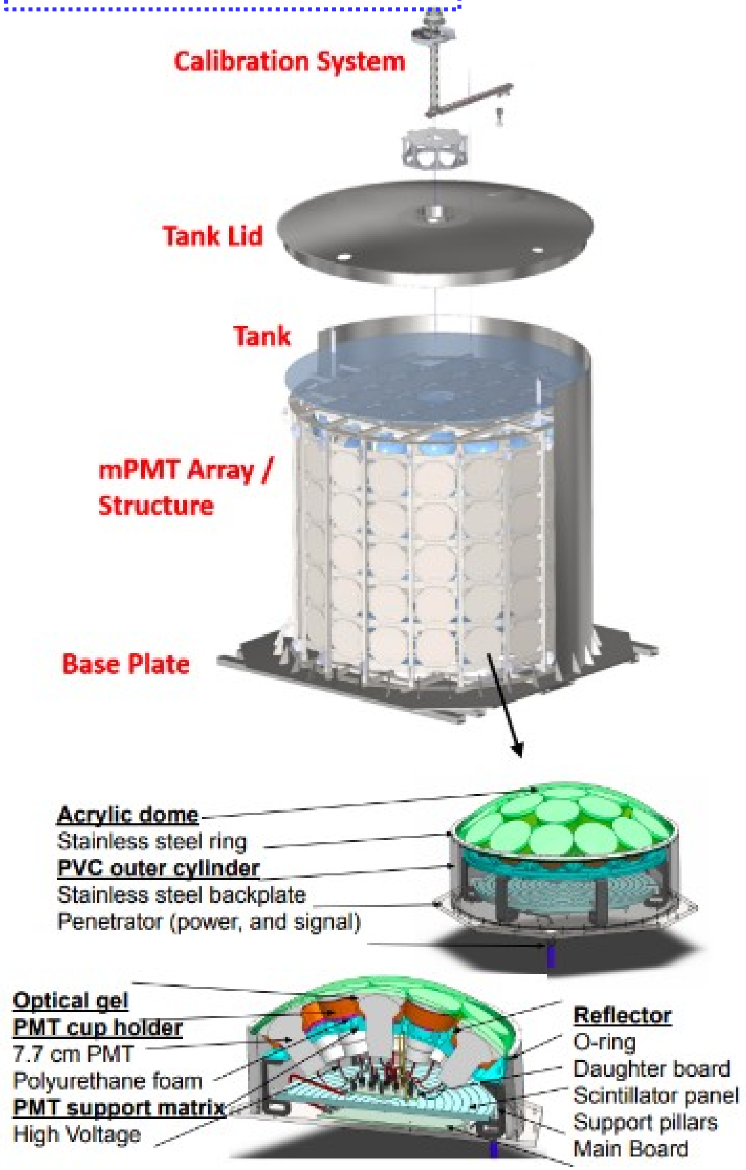
- Excellent momentum resolution (B field)
- Improved particle-id (especially p/π separation)
- Significantly lower energy threshold → full characterization of the hadronic system (low-E p and π)

# Water Cherenkov Test Experiment

L. Anthony talk in WG6 on 8/09

The exposure of a small **WC detector** is planned in 2022-2023 @ CERN to pursue R&D studies for future detectors including the **Hyper-K** far one

*M. Hartz*
CERN SPSC 13/04/2021




*WCTE proposal*
CERN-SPSC-2020-005, SPSC-P-365

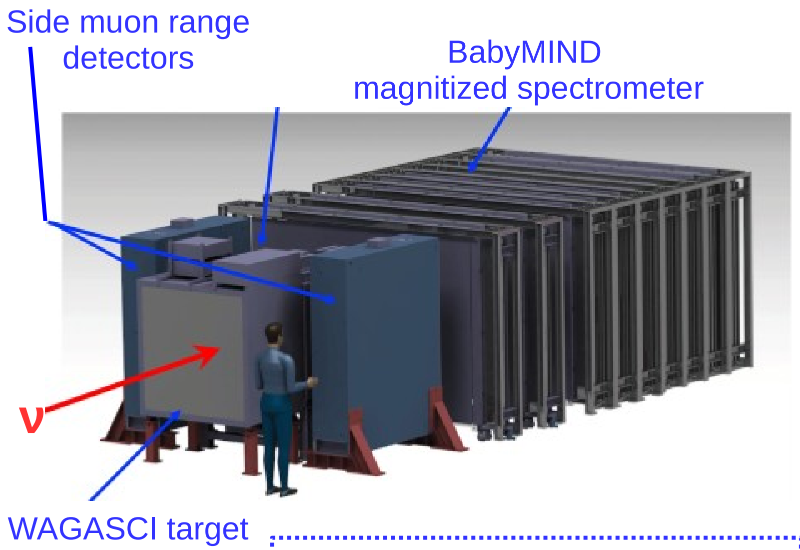
- H=4 m
- R=4.1 m
- ~50 ton fiducial mass
- 19 PMT (8 cm Ø) arranged in 128 multi-PMT optical modules

It could represent an interesting opportunity for the cross section measurement in water:

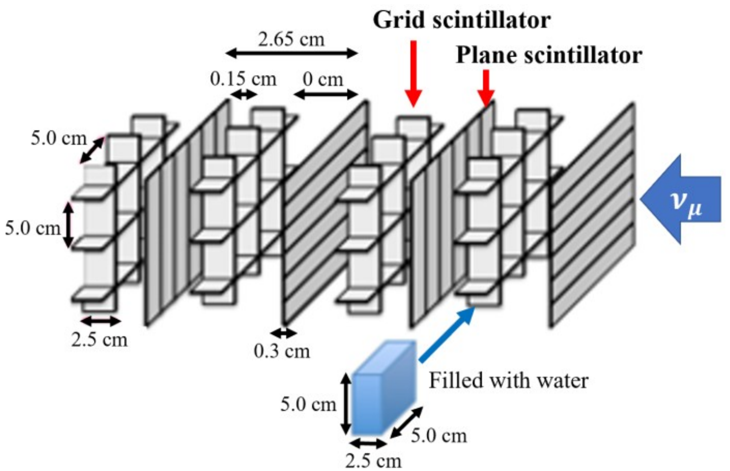
- Full prior characterization of the response to charged particles
- Despite the smaller PMT size (driven by the smaller Cherenkov rings size) the detector technology and the event reconstruction are very similar to those of HK
- Should be complemented by a spectrometer for p measurement
- Given the small mass, not possible to have enough νe-int. with a moderate intensity beam like ENUBET, but still possible to measure double differential cross section with $\nu_\mu$ ($O(10^4)$ events)

# High precision measurements in water

**Fine-grained detectors** with **$H_2$0 targets** can be used to disentagle the neutrino cross section from the detector efficiency



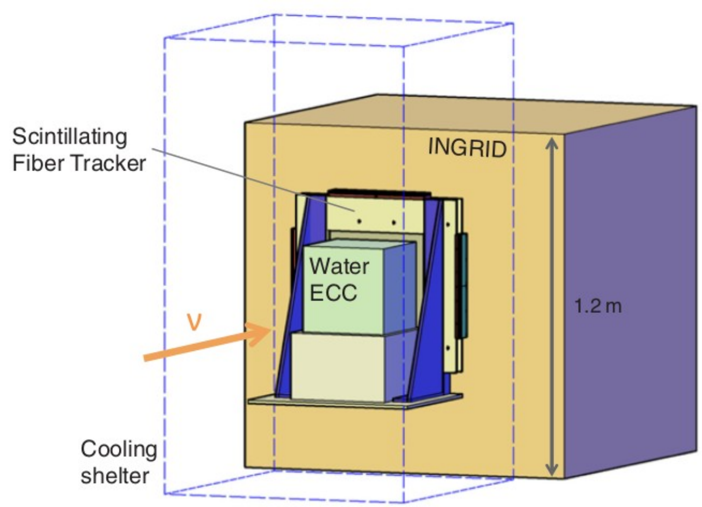

E. Noah talk @ EPS-HEP2019



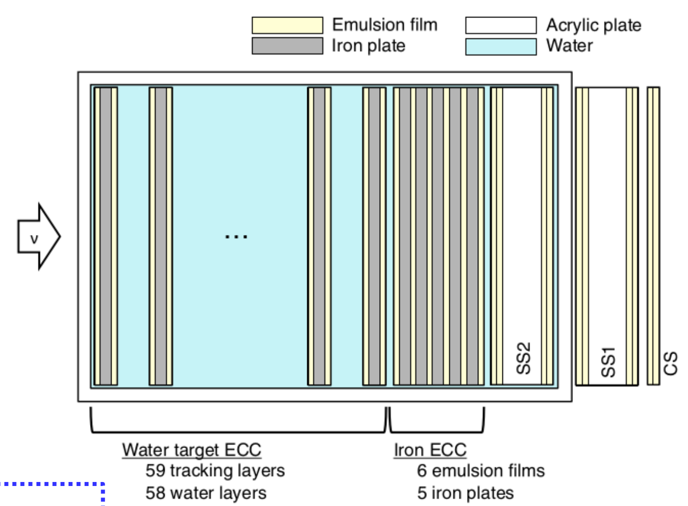

*G. Pintaudi*
PoS 2019, 2019, 142

## WAGASCI

- 0.6 ton water target
- Encompassed by a 3D grid-like structure of plastic scintillator strips enclosing cells of O(cm) size
- Side modules (steel plates+scint. Slabs) and BabyMIND spectrometer for muon p-measurement




*A. Hiramoto et al.*
Phys. Rev. D 102, 072006 (2020)



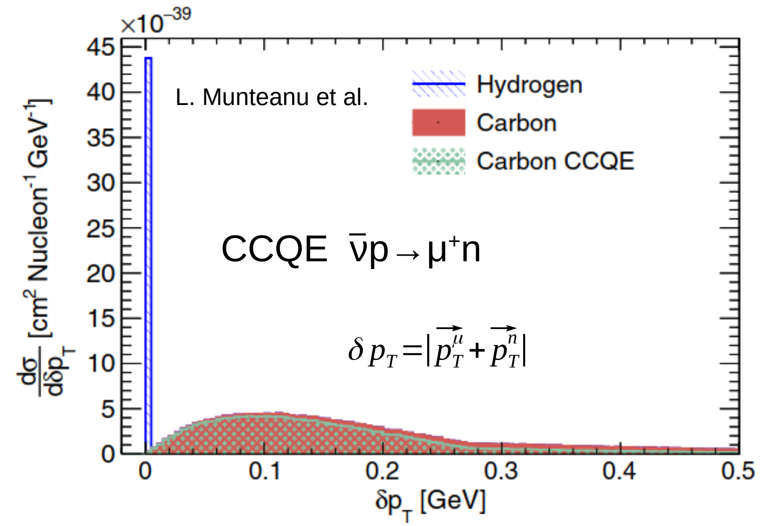

## NINJA

- Nuclear emulsion films and iron plates intervealed in a sandwich-like structure with 2 mm water layer
- Scintillating fiber tracker downstream to timestamp and match tracks in emulsion
- One INGRID module for muon range measurement
- P-threshold:
  200 MeV/c for p
  50 MeV/c for π

# ν-H interactions

- The measurement of neutrino interactions with Hydrogen would provide a clean and solid base to build reliable models not affected by nuclear effects scalable to higher Z materials
- It would also be major asset for electroweak nuclear physics and the study of nuclear media

Indirect approaches exploiting the transverse momentum imbalance due to nuclear effects have been recently proposed to disentangle hydrogen interactions from those with other nuclei in composite materials (like e.g. hydrocarbon targets)




H. Duyang, B. Guo, S. Mishra, R. Petti, Phys. Lett. B 2019, 795, 424
L. Munteanu at al., Phys. Rev. D 101, 092003 (2020)
P. Hamacher-Baumann, X. Lu, J. Martin-Albo, Phys. Rev. D 102, 033005 (2020)

A fully unbiased measurement would be provided by using a **liquid-H target**


- Constraints posed by modern safety requirements for underground experimental halls make this option challenging
- Recently in the SNOWMASS framework it has been proposed a revival of the time-honoured magnetized bubble-chamber technique with modern digital camera technology and machine-assisted reconstruction techniques to improve precision and data analysis speed.

*L. Alvarez-Ruso et al.*, LoI-Neutrino Scattering Measurements on Hydrogen and Deuterium

Thanks for the attention