Contribution to the waveform analysis of the ENUBET calorimeter

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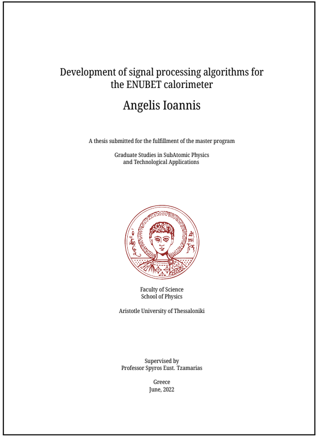
Outline

- ENUBET Project and the ENUBET Decay tunnel
- Analysis of the simulated waveforms
- Individual pulse analysis and timing corrections
- Results
- Conclusions and next steps

The methods and algorithms presented are based on ideas that were developed during the master thesis:


Development of signal processing algorithms for the ENUBET calorimeter

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A thesis submitted for the fulfillment of the master program

Graduate Studies in SubAtomic Physics
and Technological Applications

Faculty of Science
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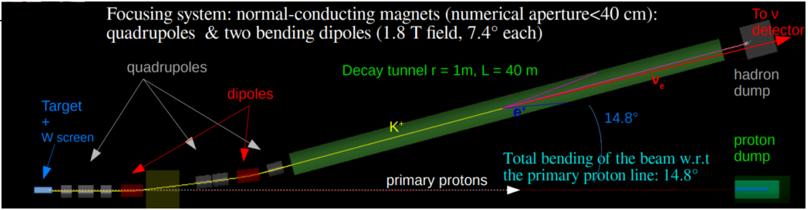
The ENUBET Project

ENUBET: **E**nhanced **N**e**U**trino **BE**ams from kaon **T**agging

- Approved CERN Neutrino Platform experiment (NP06) since 2019.
- Narrow band beam ($p = 8.5 GeV/c \pm 10\%$)
- Monitoring decays by instrumenting the decay tunnel
- ν_e and ν_μ flux prediction from e^+/μ^+ rates
- "By-pass" uncertainties of hadro-production, protons on target, beam line efficiency uncertainties

ENUBET: 62 physicists, 13 institutions



The ENUBET Project

Concept of monitored neutrino beams:

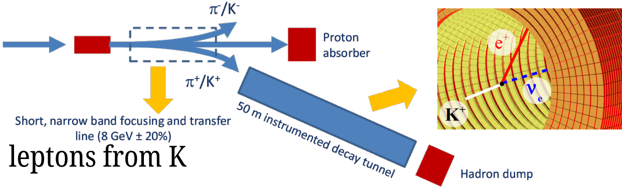
- Narrow band off axis method
- Monitoring the decays in the tunnel (tag high-angle leptons)
- “By-pass” uncertainties of hadro-production, protons on target, beam line efficiency uncertainties

Goals:

- Reducing the uncertainty of ν_e, ν_μ fluxes in neutrino beams

Currents Goals:

- Desing and simulate the layout of the hadronic beamline
- Build and test a demonstrator of the instrumented tunnel



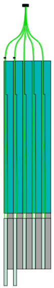
Tagger: leptons from K

$$K^+ \rightarrow e^+ \nu_e \pi^0$$
$$K^+ \rightarrow \mu^+ \nu_\mu$$
$$K^+ \rightarrow \mu^+ \nu_\mu \pi^0$$

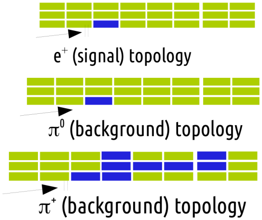
Hadron dump instr: muons from pions: $\pi^+ \rightarrow \mu^+ \nu_\mu$

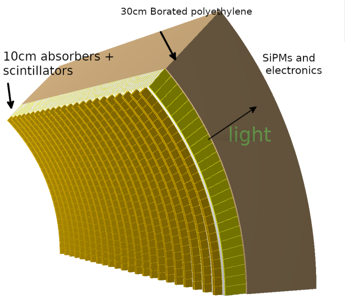
The ENUBET decay tunnel

- The decay tunnel is segmented in the longitudinal, radial and azimuthal coordinates
- The building block is the Lateral Compact Module (LCM)
- Single LCM: five $3 \times 3 \times 1.5\ cm^3$ steel tiles interleaved with five $3 \times 3 \times 0.7\ cm^3$ plastic scintillator tiles
- Integrated photon veto (t0-layer).
- 3 LCM arrays for the calorimeter
- Light from scintillators is measured with SiPMs



Different topologies of energy deposition in the 3 calorimeter layers





1) Calorimeter
   - LCMs
   - Light readout with SiPM
   - $e^+, \pi^\pm, \mu$ separation
2) Integrated γ-veto
   - Plastic scintillators
   - π^0 rejection

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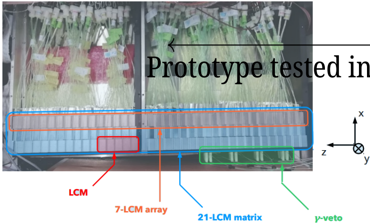
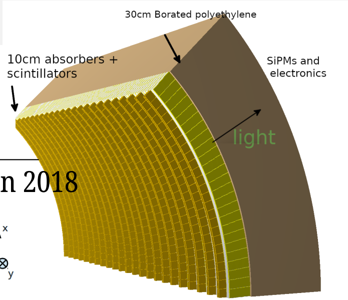
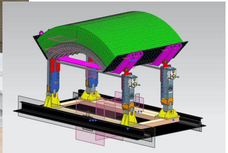


Prototype tested in 2018



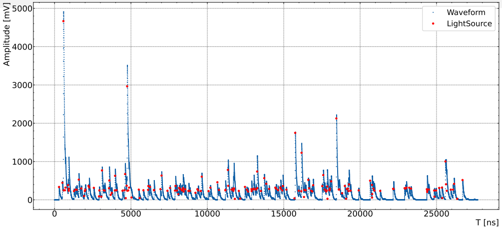


Demonstrator

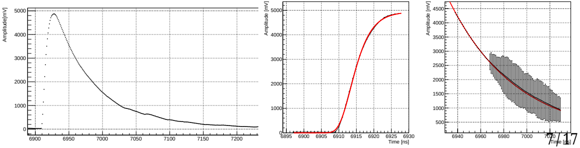
Pre-Demonstrator Prototype (ENUBINO)

Waveform Analysis

- GEANT4 simulation generates the photon hits up to the SiPMs
- SiPM response and waveforms are simulated through GosSiP (Generic framework for the simulation of Silicon Photomultipliers).
- Electronic noise simulated by adding a term from a $Gauss(0, 2)$ distribution to every digitization.
- Study of pile-up effects on the waveforms
- Waveforms are analyzed, arrival time and peak amplitude is found
- Association with lightsources (time of arrival of first photon, number of photons)
- Peak amplitude and lightsource amplitude are converted to MeV units (conversion factor coming from the prototype runs ~ 15 p.e./MeV)

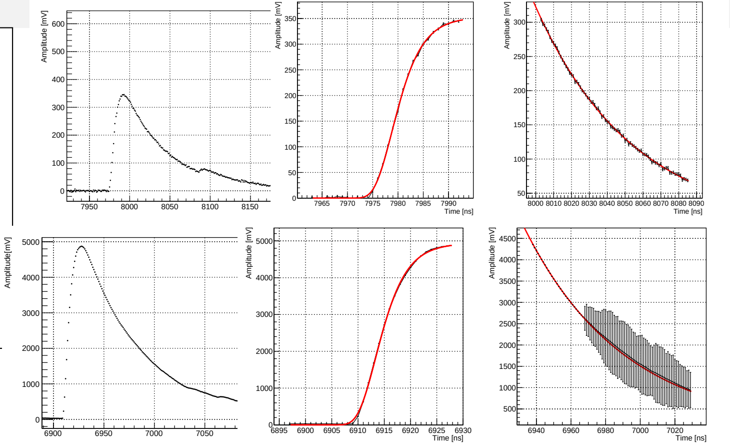


- Contribution with alternative waveform analysis algorithms
- Dealing with pile-up effects first to disentagle each pulse
- Treat every single pulse individually



Waveform Analysis

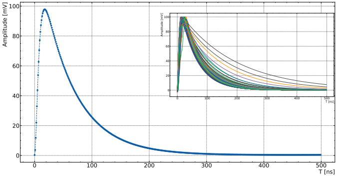
- Fit the leading and falling edge of isolated peaks
- Isolated peaks: Next peak start $\sim 400ns$ from the peak maximum
- Leading edge fit with Gompertz function $f(t) = ae^{-e^{b-ct}}$
- Falling edge fit with $e^{p_0+p_1 t}$
- Fit on the first part, set the statistical error for the next points as the distance from the first fitted exponential



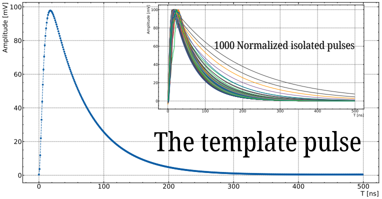
Isolated peaks can be used to create an average pulse

Normalized and synchronized peaks

Can be used as a template



Finding peaks with Fourier Deconvolution



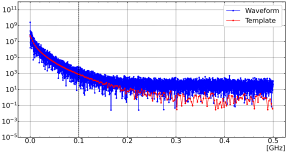
- Using a template pulse $g(t)$
- Assuming that a single peak has the functional form with a scale factor α and a shift factor τ: $\boxed{h(t;\alpha,\tau) = \alpha g(t-\tau)}$
- Assuming that a waveform is a sum of N single pulses:

$$\boxed{f(t) = \sum_{i=1}^{N} \alpha_i g(t-\tau_i)}$$

- We expect the deconvolution output $r(t)$ to be a sum of delta functions.
- Represented graphically as series of spikes.
- Spike position τ_i defines the arrival time.
- Spike amplitude α_i defines the peak amplitude.

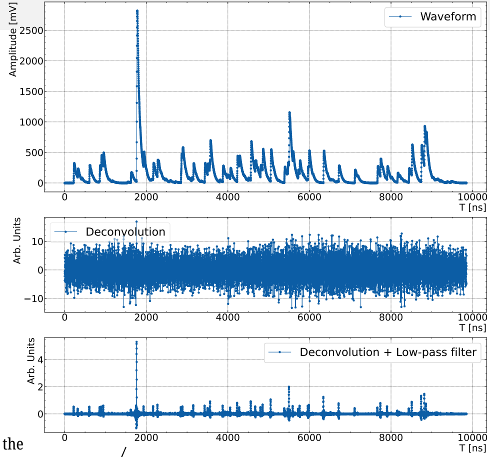
$$\boxed{r(t) = \sum_{i=1}^{N} \alpha_i \delta(t-\tau_i)}$$

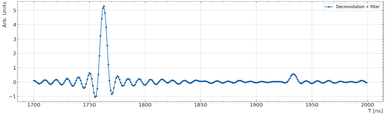
- Noise reduction with a low-pass filter during the transformation of the signal
- Selection of the frequency cut from the power-spectrum of the template pulse



- Due to the noise and the filtering process, the spikes are widened
- Now we have only an approximation of the peak position and amplitude

$$Peak\ Amplitude \propto \sum_{t_{start}}^{end} y_t \delta_t$$



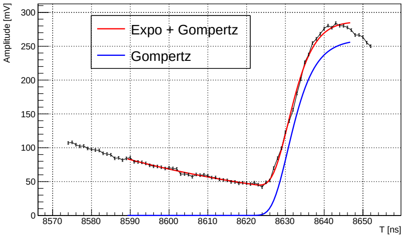


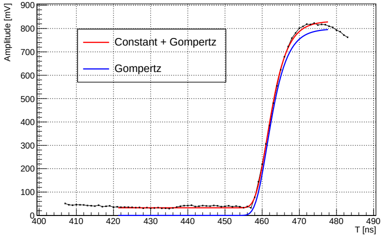
Pulse Analysis

- Candidate peaks based on the deconvolution method
- Analysing each peak
- Fit the leading edge with a Gompertz function for each peak found, along with any contribution of previous peaks.

$$f(t) = ae^{-e^{b-ct}}$$

- Calculate peak amplitude and arrival time at @2% of peak amplitude.





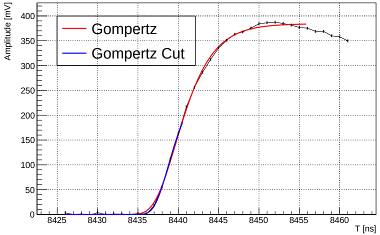
Pulse Analysis

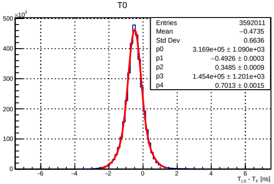
To match better the initial part of the leading egde, a second fit up to the half maximum is used

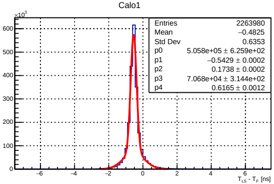
The contribution part is used as previously

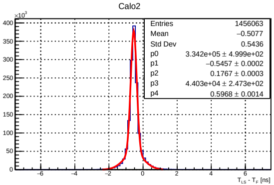
The c parameter will be used to describe the slope

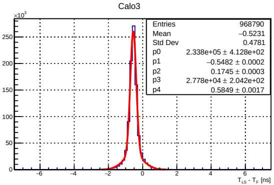
$$f(t) = ae^{-e^{b-ct}}$$











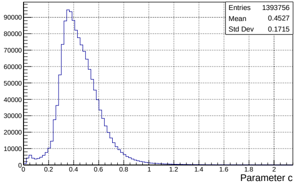
Fit with 2 Gaussians, with the same mean

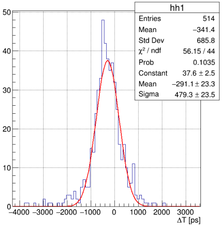
Layer	Resolution (ps)
T0	547.04 ± 0.3
Calo1	382.30 ± 0.2
Calo2	362.34 ± 0.3
Calo3	345.28 ± 0.3

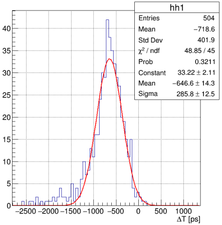
- The associated peaks we are interested are in a $1ns$ window from the lightsource
- The mean value from the time resolution distributions is $\sim -0.5ns$
- Need of a correction method

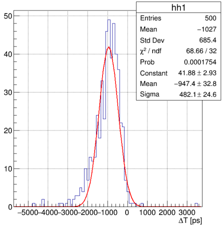
Time Correction

- → Parameterization of the signal arrival time with the slope of the leading edge described by the parameter c
- → Measurement of μ and σ from the Gaussian fits for bins of the c parameter

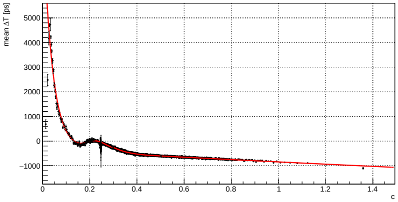


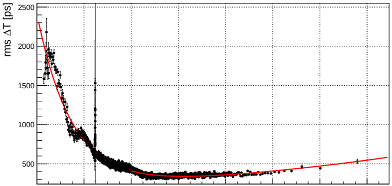






μ and σ from the Gaussian fits have a dependence on the c parameter

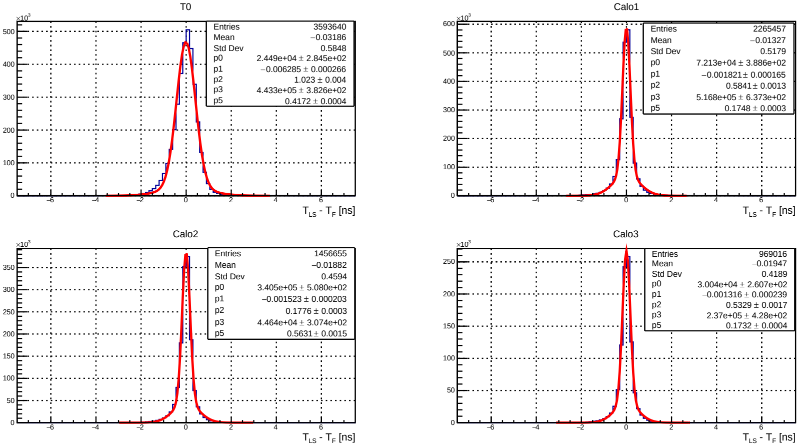




Time resolution after time Correction

σ from 2 Gaussians fit

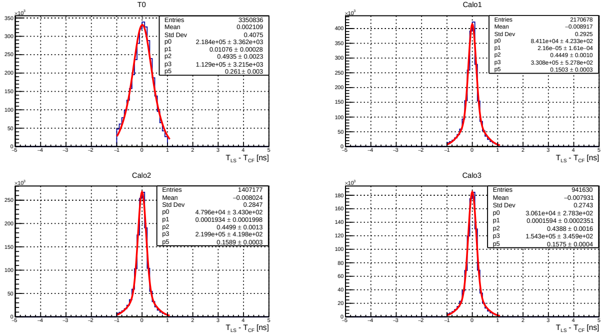
Layer	Time Resolution
T0	527.4 ± 4.0 *ps*
Calo1	359.6 ± 1.3 *ps*
Calo2	339.7 ± 1.5 *ps*
Calo3	318.2 ± 1.7 *ps*

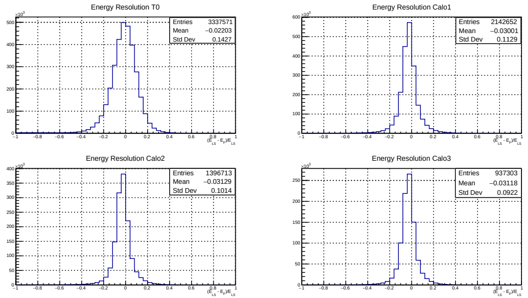


Results

- Interested on associated peaks in $\pm 1ns$ from the lightsource time
- Time correction to gather ΔT around zero

Layer	Resolution ($\pm 1ns$)
T0	$453.74 \pm 1.82ps$
Calo1	$312.87 \pm 0.29ps$
Calo2	$304.77 \pm 0.29ps$
Calo3	$290.71 \pm 0.39ps$





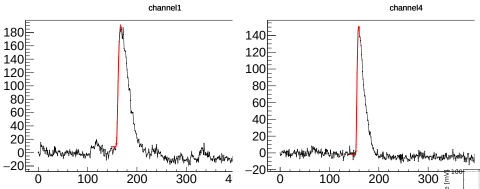
Efficiency table

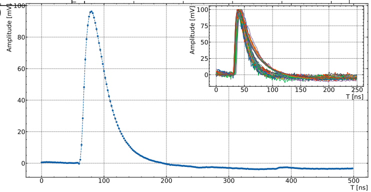
Layer	Associated (%)	Associated $\pm 1ns$ (%)
T0	96.38	89.87
Calo1	94.55	90.59
Calo2	96.40	93.12
Calo3	97.47	94.72

Conclusions and Next Steps

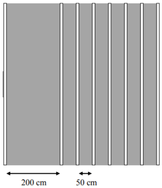
- Techniques for disentaglement of pulses from pile-up effects and timing methods were presented
- Currently, these methods are being used to study the testbeam data from ENUBINO
- The Fourier deconvolution method is studied on a convolution of testbeam data for a selection of hit rates
- Next step is the study for the hadron dump geometry and the consideration of PICOSEC Micromegas detectors for the instrumentation of the dump

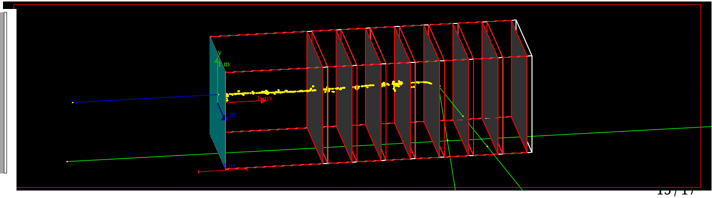
Preliminary analysis with ENUBINO pulses





Initial layout of hadrom dump (Work in progress)





Thank you

References

→ ENUBET webpage

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

→ JINST 15(2020)08, P08001

→ SPSC Annual report 2020

→ SPSC Annual report 2021

→ SPSC Annual report 2022

→ ENUBET submission for Snowmass 2021 DPF Community Planning Exercise