Development of instrumentation for tagged and monitored neutrino beams

Valerio Mascagna on behalf of the **ENUBET Collaboration**

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (G.A. n. 681647)

Outline

- The ENUBET project
- Status of the **positron tagger**
- Overview of the R&D and test beam results
- Conclusions and outlooks

The ENUBET Collaboration

Enhanced **N**e**U**trino **BE**ams from kaon **T**agging

60 physicist, 12 institutions

ERC-CoG-2015, G.A. 681647 (2016-2021)

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Padova University, INFN

http://enubet.pd.infn.it/

A monitored neutrino beam

> The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino creation ($\pi \to \mu\nu$, $K \to \mu\nu$,

B. Pontecorvo, Lett. Nuovo Cimento, 25 (1979) 257

The goal of ENUBET is to demonstrate the technical feasibility and physics performance of a neutrino beam where lepton production at large angles is **monitored** at **single particle level**.

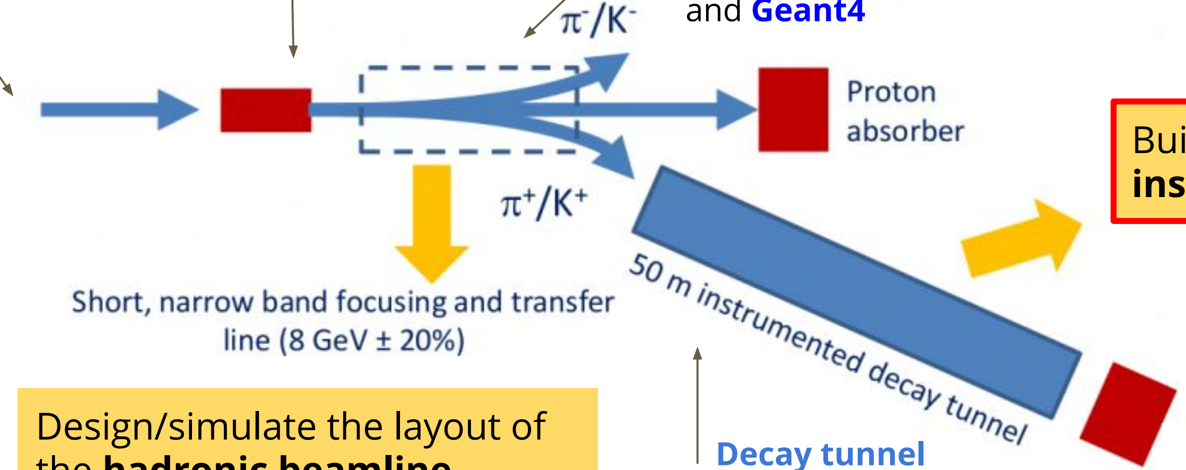
Based on **conventional technologies**, aiming for a **1% precision** on the ν_e flux

The ENUBET beamline

Proton driver
CERN (400 GeV)
FNAL (120 GeV)
J-PARC (30 GeV)

Target
(Be, graphite. **FLUKA**)

Transfer Line
Horn vs **Static** focusing under study (tested at the **CERN SPS**)
TL kept short, optimized with **TRANSPORT** to a 10% momentum bit centered at 8.5 GeV/c
Particle transport and interaction: full simulation with **G4beamline** and **Geant4**



Build/test a **demonstrator** of the **instrumented decay tunnel**

~500 T neutrino detector 100m from the target.
E.g. :
ICARUS@FNAL, ProtoDUNE@CERN or Water Cher @J-PARC

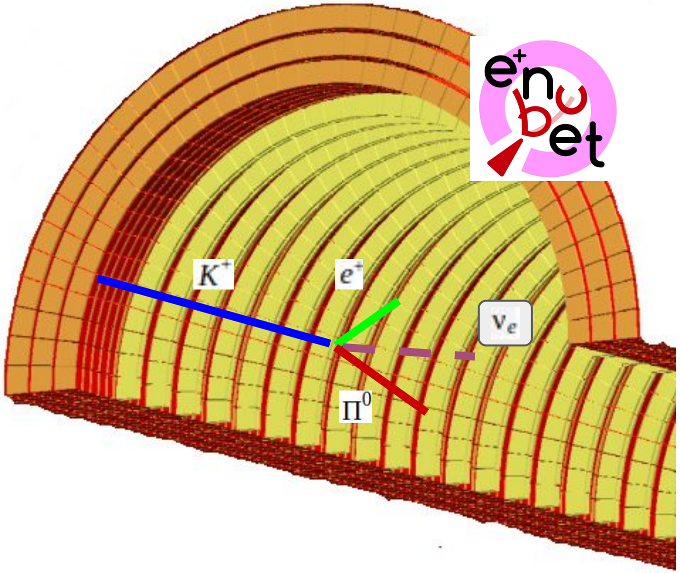
Design/simulate the layout of the **hadronic beamline**

Decay tunnel
R = 1 m, L = 50 m

Hadron dump

The positron tagger

protons → (K^+, π^+) → K decays → e^+ ν_e → neutrino detector



K+ decay modes

>99.98%

$\mu^+\nu_\mu$	(63.55 ±0.11) %
$\pi^0 e^+ \nu_e$	(5.07 ±0.04) %
$\pi^0 \mu^+ \nu_\mu$	(3.353±0.034) %
$\pi^+ \pi^0$	(20.66 ±0.08) %
$\pi^+ \pi^0 \pi^0$	(1.761±0.022) %
$\pi^+ \pi^+ \pi^-$	(5.59 ±0.04) %

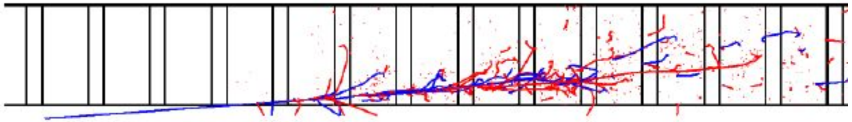
$K_{e3} \rightarrow \langle\theta_{e+}\rangle$ = 88 mrad

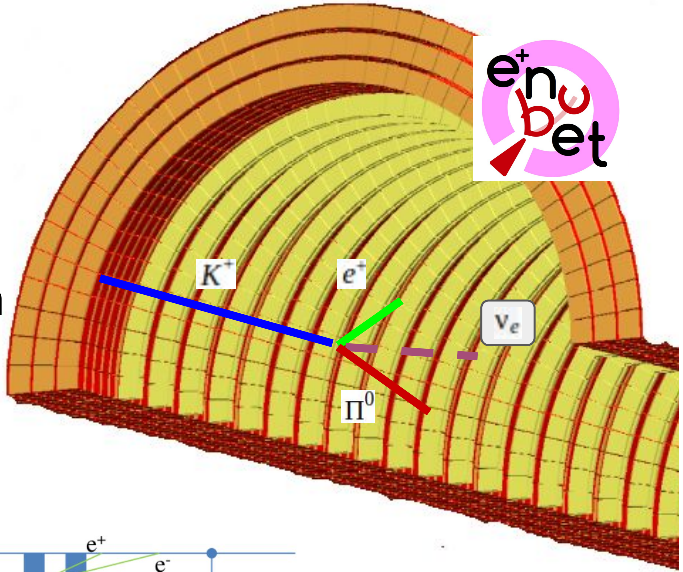
Background: μ^+, $\pi^\pm$, π^0

The positron tagger

Sampling **calorimeter** → Longitudinal segmentation

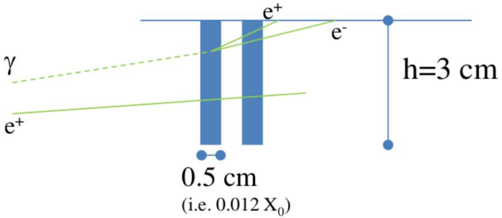
$e^+/\mu^+/\pi^\pm$ separation





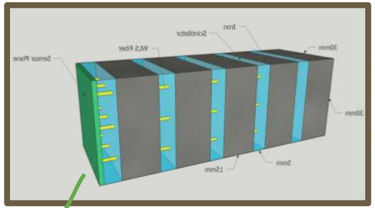
Integrated **photon veto** → scintillator

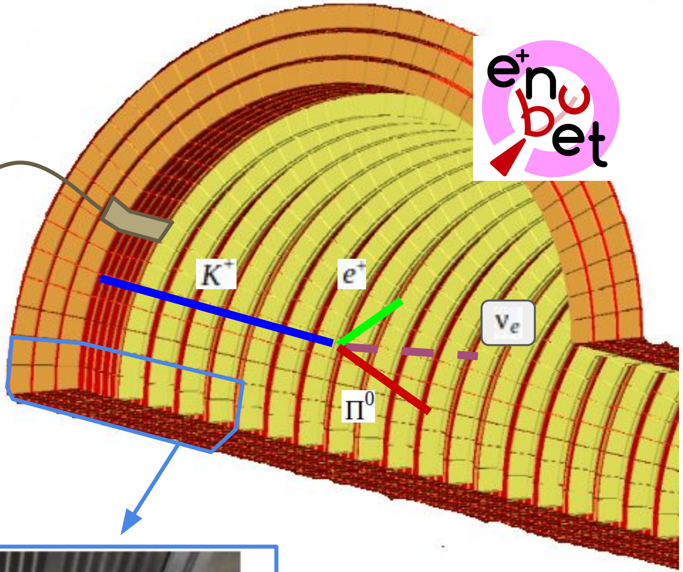
π^0 rejection

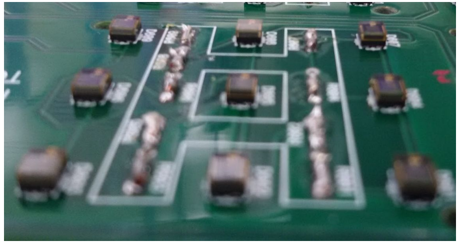


The positron tagger UCM

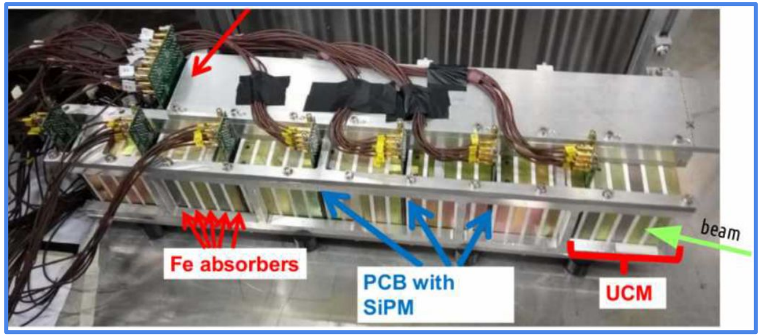
Ultra **C**ompact **M**odule
10 cm → 10 X_0
Plastic scintillator + iron absorber
Shashlik readout scheme with WLS fibers and **integrated** SiPMs







SiPM - HD RGB by FBK
1x1 mm^2 , 12-15-20 μm cell size



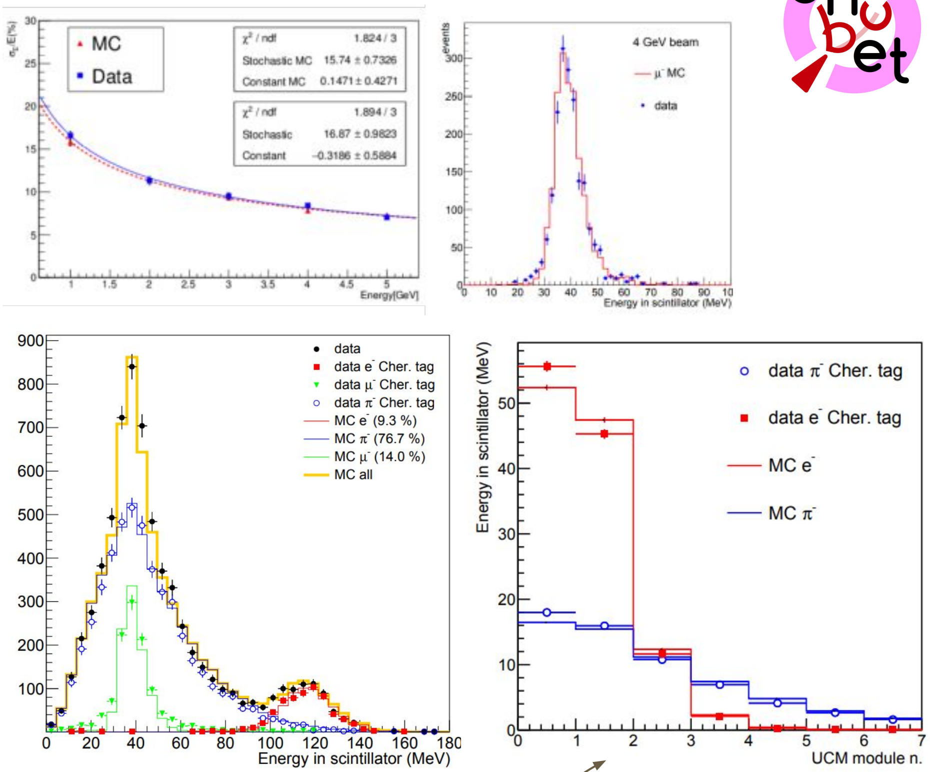
CERN PS, Nov 2016

7x4x2 UCMs

Test beam results

Calorimeter prototype performances
Test-beam data @ **CERN-PS T9 line** 2016-2017

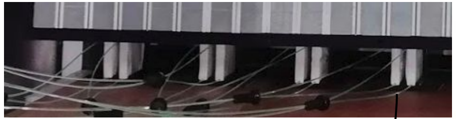
- Tested response to **MIP**, **e** and **π⁻**
- Energy resolution 17%/sqrt(E) (GeV)
- Linearity deviations <3% in 1-5 GeV range
- From **0 to 200 mrad** → No significant differences
- Work to be done on the fiber-SiPM coupling (major source of non uniformities
- Equalizing UCM response with MIPs (MC/data in a good agreement)
- Longitudinal profiles of **partially contained π** reproduced with MC @ 10% precision

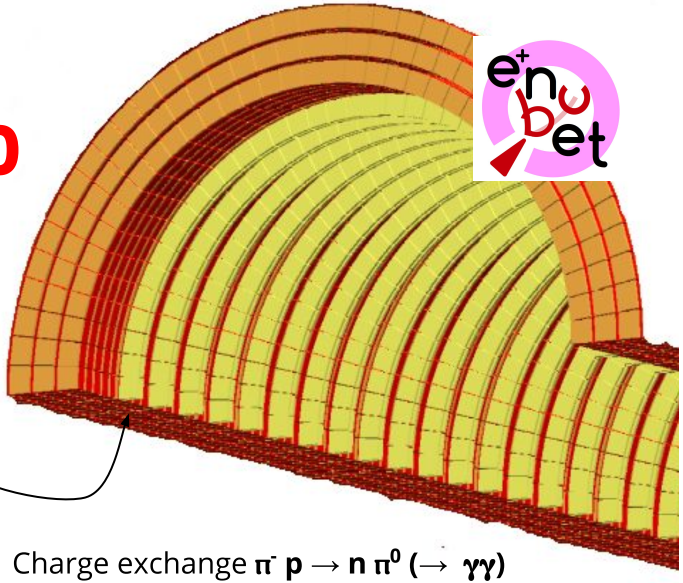


Ballerini et al., JINST 13 (2018) P01028

The positron tagger - Photon veto

γ/e^+ **discrimination** (+ timing)

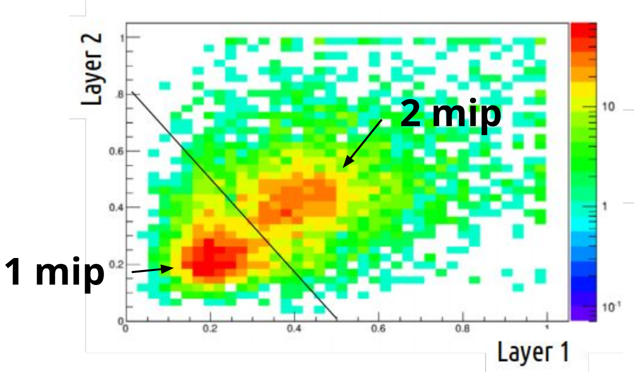


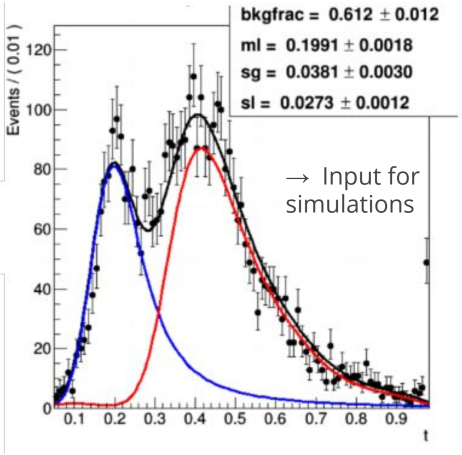


Tests @ CERN-PS T9 line 2016 - 2018

Scintillator (3x3x0.5 cm3) + WLS fiber (30cm) + SiPM

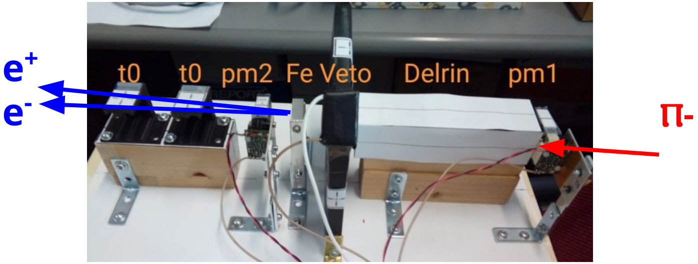
- Light collection efficiency → **> 95%**
- Time resolution → $\boldsymbol{\sigma_t}$ **~ 400 ps**
- **1 mip / 2 mip** separation





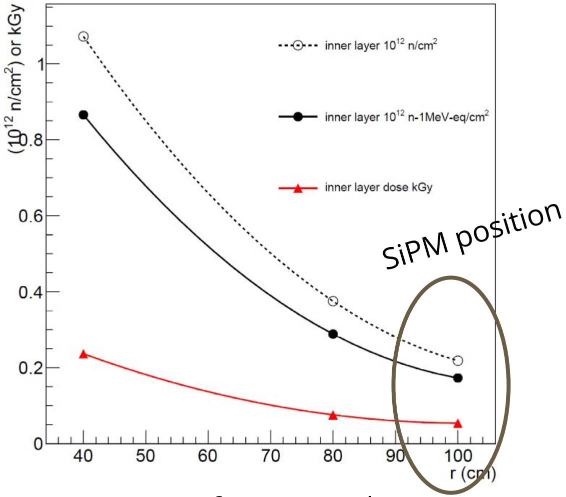
Charge exchange $\pi^- p \rightarrow n\, \pi^0$ (→ $\gamma\gamma$)

Trigger: pm1 + veto + pm2



SiPM irradiation

Expected 5-years neutron doses from K decays (**FLUKA**)



Distance from tunnel axis

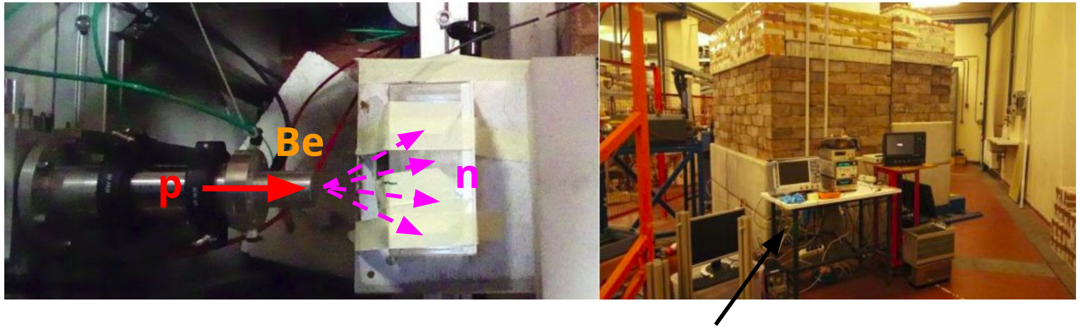
Irradiation campaign @INFN-LNL - **July 2017**

Van de Graaf CN accelerator

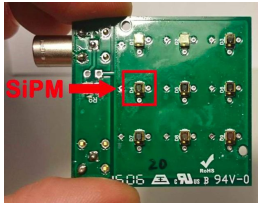
7MV and 5 mA proton current on a **Be target**

p (5 MeV)+^{9}**Be** → **n** + X

→ **1-3 MeV neutrons** with fluences up to **10^{12}/cm^2** in ~hours

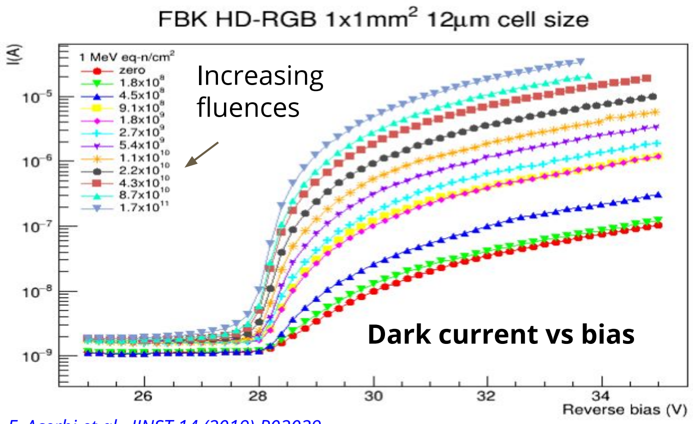


Frontend readout and instrumentation outside the bunker

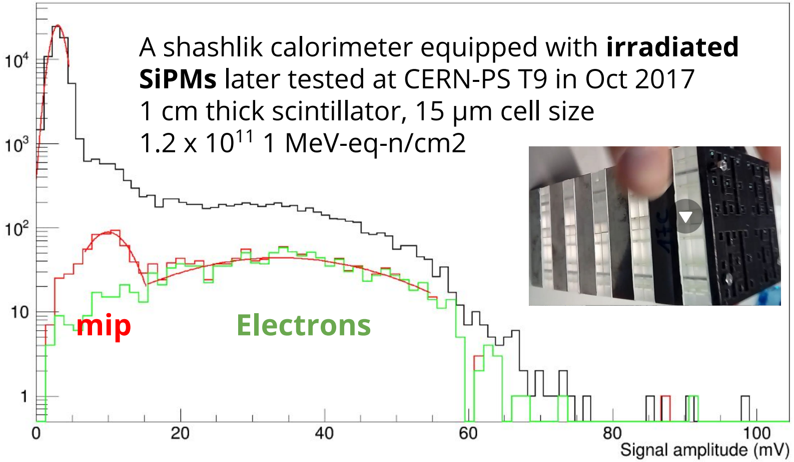


Tested 12,15,20 µm (cell size) SiPMs up to ~ **2 x 10^{11} 1-MeV-eq n/cm^2**

SiPM irradiation results



F. Acerbi et al., JINST 14 (2019) P02029



- By choosing SiPM cell size and scintillator thickness (~light yield) properly mip signals remain **well separated** from the noise even after typical expected irradiation levels

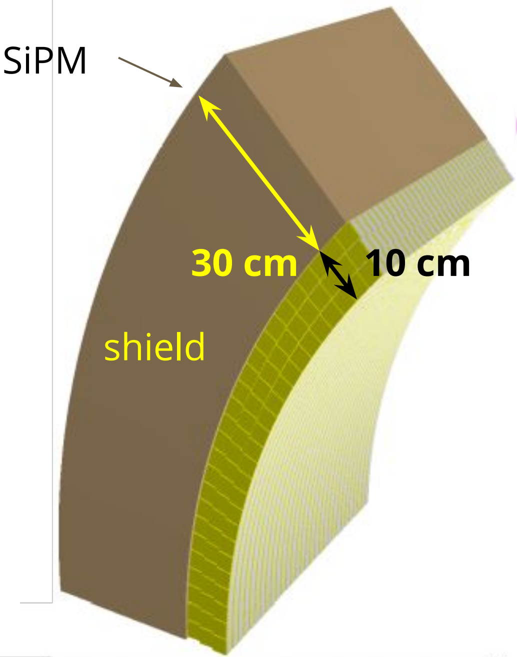
- Mips can be used for **channel-to-channel intercalibration** even after maximum irradiation.

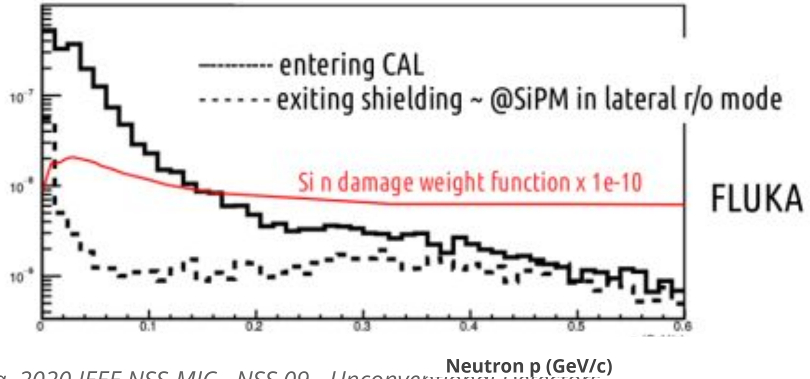
Alternative design: lateral readout

Moving **SiPM + frontend** 30 cm away from the calorimeter bulk

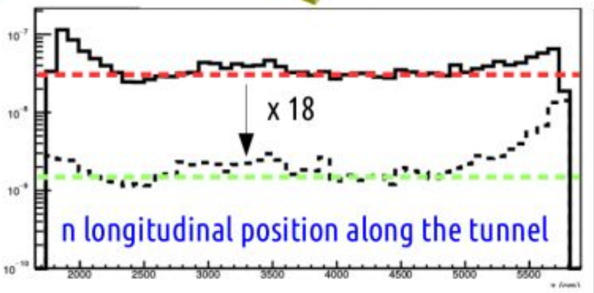
- Borated polyethylene shielding
- FLUKA full simulation, 400 GeV protons.

→ Very good suppression especially below 100 MeV.
Factor **~18 reduction** averaging over spectrum.





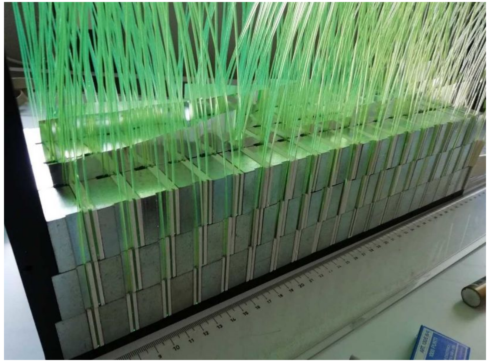
Preliminary



Lateral readout prototype

Light collected from **scintillator sides** and bundled to a **single SiPM** reading 10 fibers (1 UCM).
SiPM are not immersed anymore in the hadronic shower → less compact but:

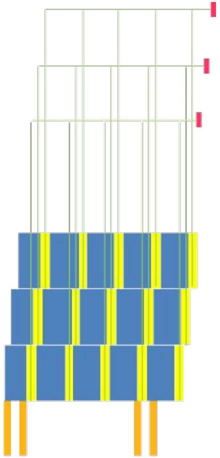
- much reduced neutron damage (larger safety margins)
- better accessibility, easier replacement.
- better reproducibility of the WLS-SiPM optical coupling.

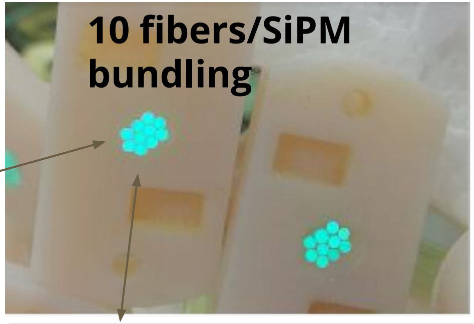


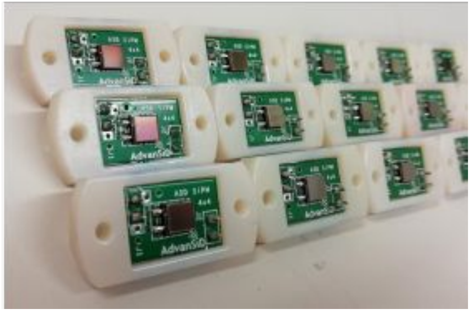
Sampling calorimeter with lateral WLS light collection

May 2018, CERN-PS

Large area (**4x4 mm²**) SiPM
AdvanSiD ASD-RGB4S-P

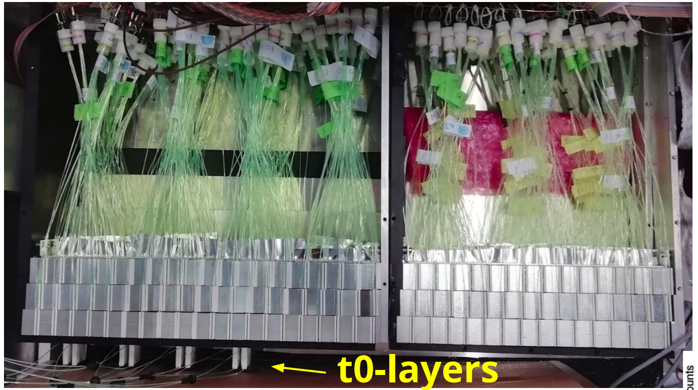


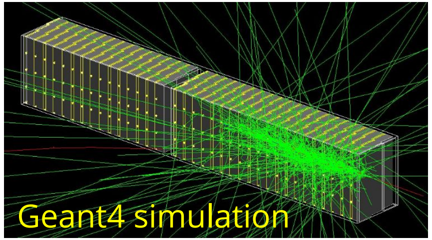


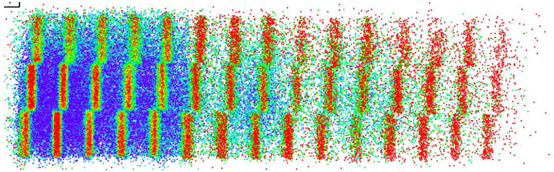


Test beam results and prototype R&D

September **2018 CERN-PS**: a module with hadronic cal. for **pion containment** and **integrated t0-layer**



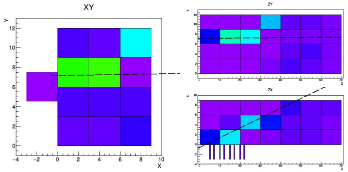




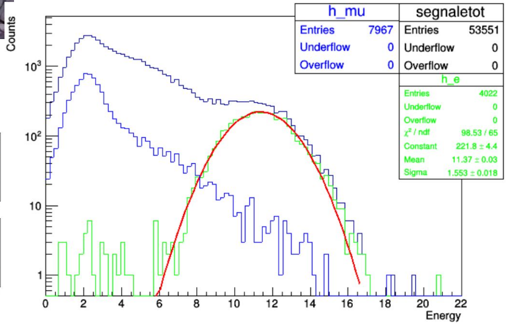
Efficiency maps

JINST 15 (2020) 08, P08001

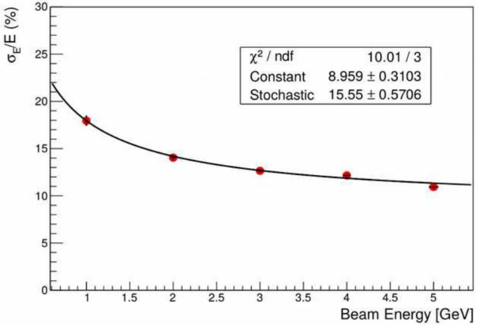
Particle ID



Particle ID



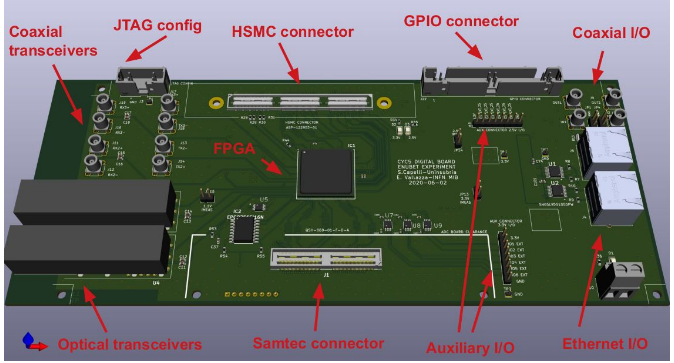
Energy resolution



Readout electronics

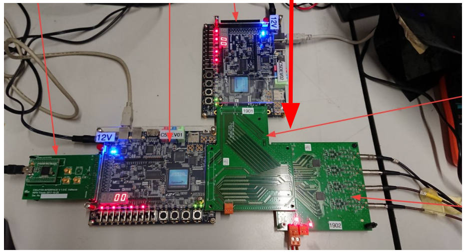
Development of custom waveform digitizers
8 ch, 14-bit ADC, 500 MS/s
10 ms spill (horn) → **40 MB/spill/UCM**

Prototyping



4 ch ADC board already tested and validated
4 amplifiers with gain = 4 (ADA4930 OpAmp)
2 x ADS4249 ADCs (14bit, 250 MS/s)

+ **1 digital interface board**



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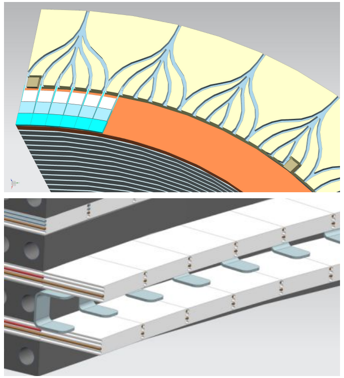
Mid-term plan:

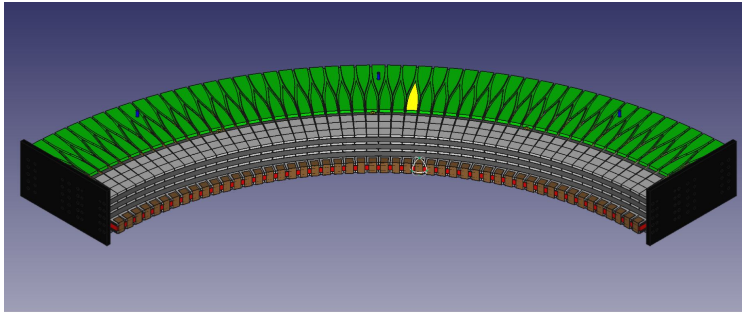
- Final 8-channel waveform digitizer board
- VME interface

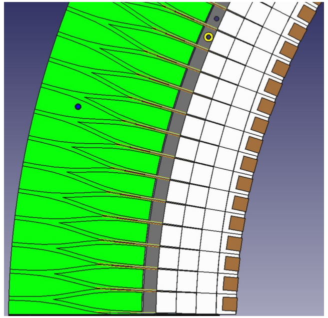
2021 - demonstrator construction

- **Length ~ 3 m, fraction of φ** → 4000-5000 channels
- allows containment of shallow angle particles in **realistic conditions**
- Due by 2021
- Will be tested at the CERN renovated East Area after Long-Shutdown 2
- Demonstrate physics, scalability and cost effectiveness



Fiber routing optimization to avoid tile staggering





Conclusions and outlooks

ENUBET is demonstrating that a **high precision monitoring** of the flux at source **O(1%)** is feasible.

The **positron tagger** prototyping phase has been concluded:

- test beams campaigns completed before CERN Long Shutdown 2. Particle ID and energy resolution fulfill the requirements
- neutron damage of the sensors assessed
- Lateral readout option → ensures a long lifetime and accessibility of the photosensors
- In-house readout electronics (full waveform digitizer, VME interfaces)

Next steps:

- Full assessment of systematics on the neutrino fluxes (simulation)
- Build the demonstrator prototype of the tagger (2021)
- Conceptual Design Report at the end of the project (2021): physics and costing
- >2021: (likely) propose a full scale experiment implementation supported by a larger international collaboration.