Silicon Photomultipliers for calorimetric applications

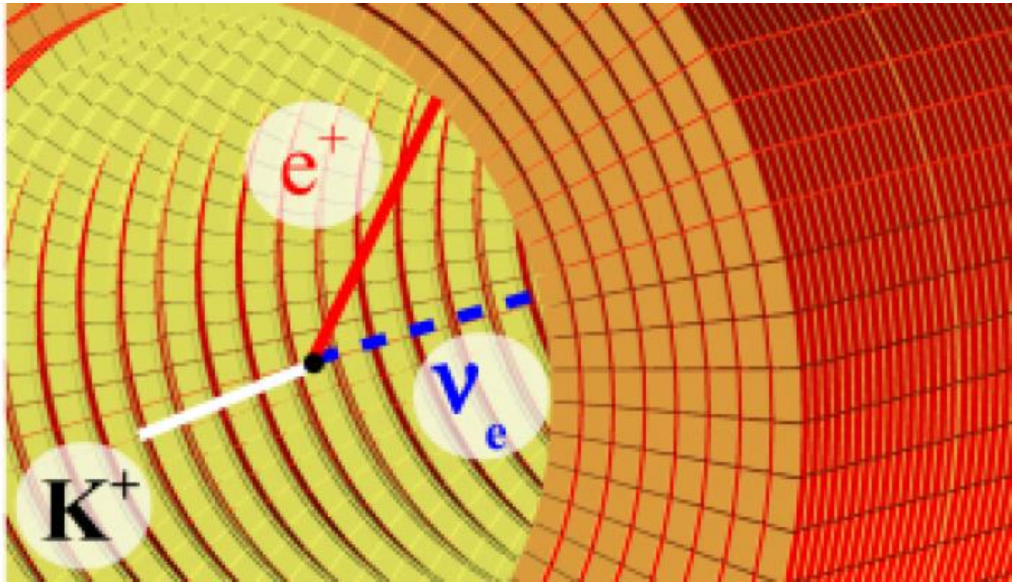
A.Falcone
University of Milano-Bicocca & INFN

Phose2023
Workshop on "Photodetectors and sensors for particle identification and new physics searches "

CERN – 22 November 2023

Overview

Two approach for SiPM calorimetry in neutrino physics:

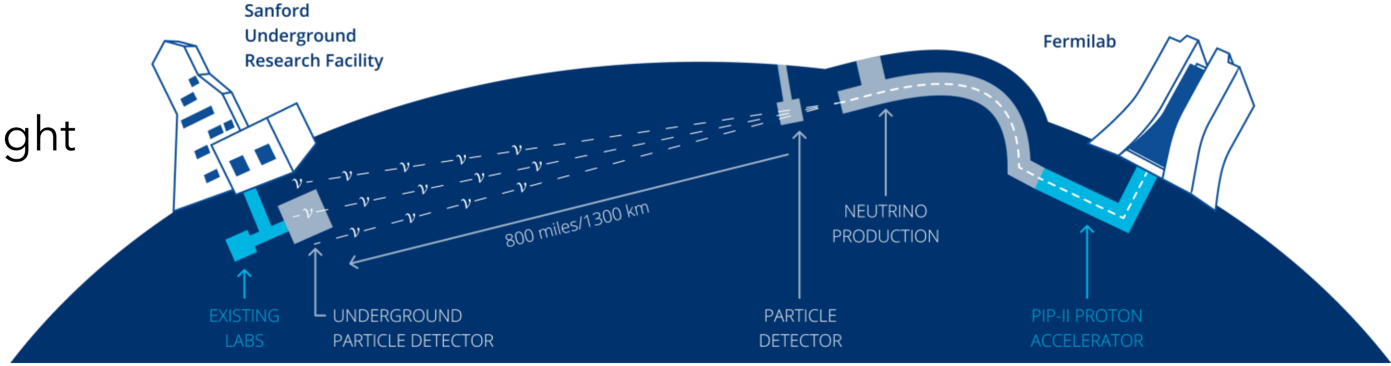


ENUBET

- Calorimeter with all read-out performed by SiPMs

DUNE

- Energy resolution improvement with the use of light

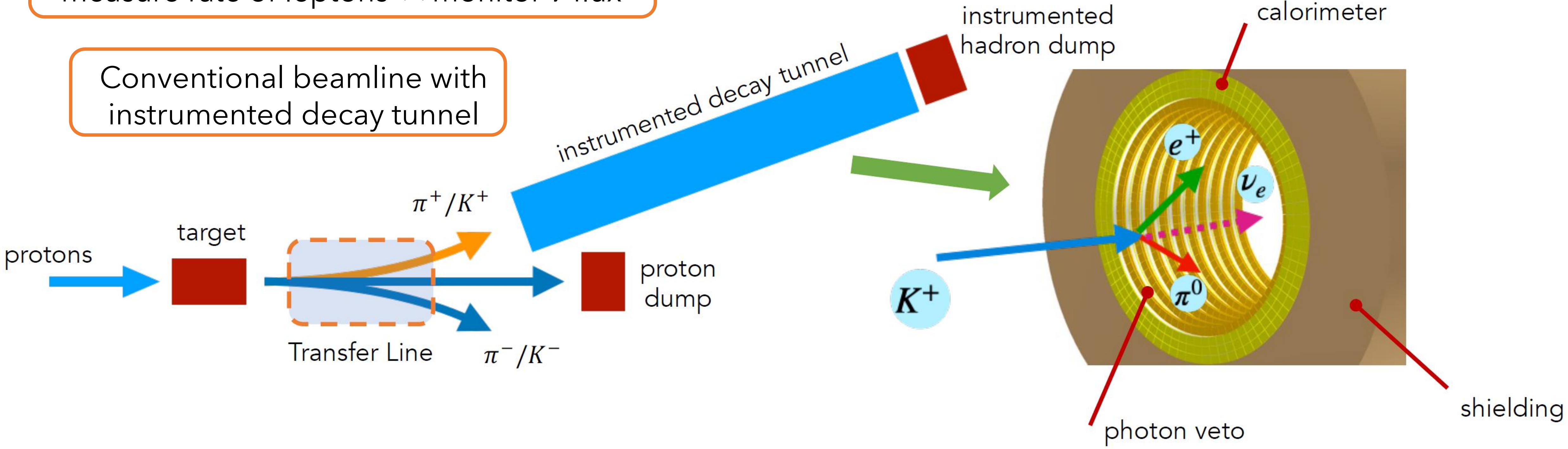


ENuBET: the first monitor neutrino beam

Monitored ν flux from narrow-band beam
measure rate of leptons ⟺monitor ν flux

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

Conventional beamline with instrumented decay tunnel



➢ Project focused on:

- measure positrons (instrumented decay tunnel) from K_{e3} ⟹ determination of ν_e flux.

- extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ ⟹ determination of ν_μ flux.

Decay tunnel instrumentation

Shielding

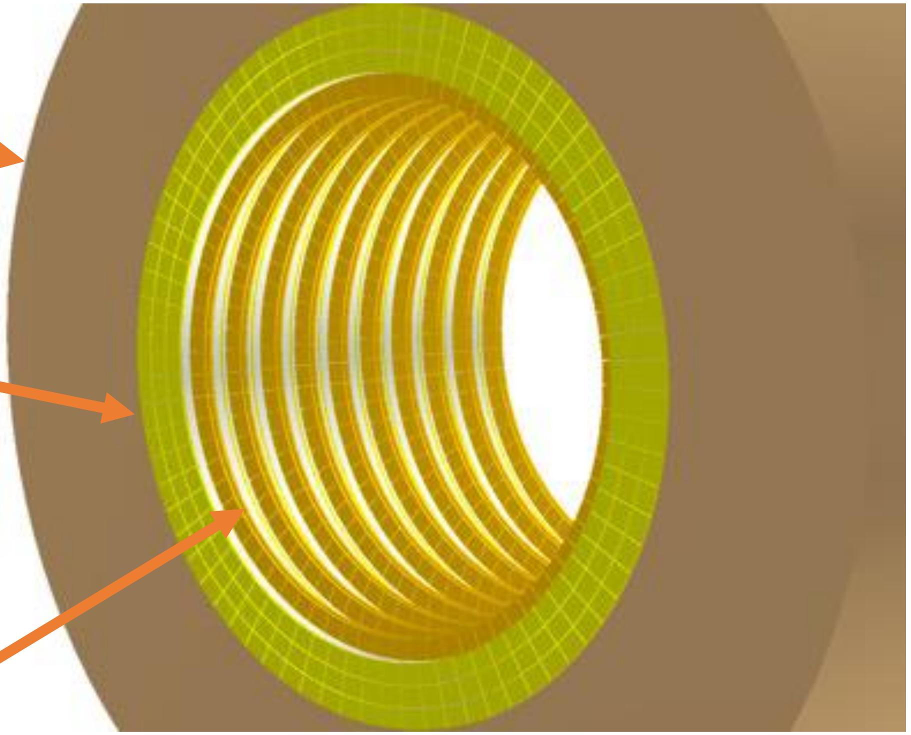
- 30 cm of borated polyethylene;
- SiPMs installed on top -> factor 18 reduction in neutron fluence.

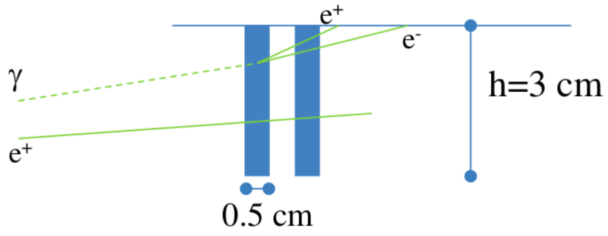
Calorimeter with $e/\pi/\mu$ separation capabilities:

- sampling calorimeter: sandwich of plastic scintillators and iron absorbers;
- three radial layers of LCM / longitudinal segmentation;
- WLS-fibers/SiPMs for light collection/readout.

Photon-Veto allows π^0 rejection and timing:

- plastic scintillator tiles arranged in doublets forming inner rings;
- time resolution of ~400 ps.

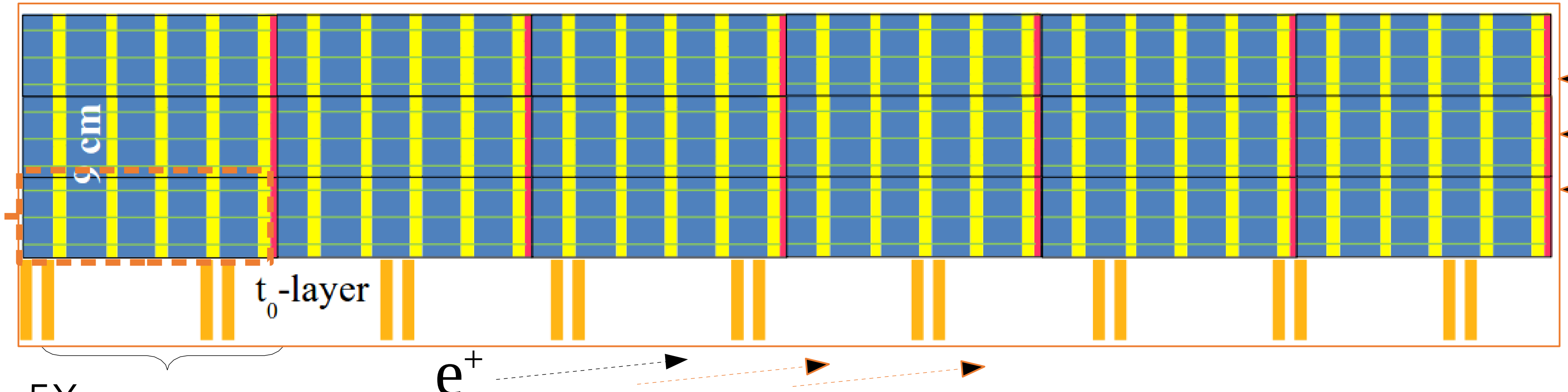




LCM: Lateral Compact Module
5 x Lead+Scint - 3x3x10 cm^3 - 4.3 X_0

e^+ (signal) topology | π^0 (background) topology | π^+ (background) topology | μ^+ (signal/bkg) topology

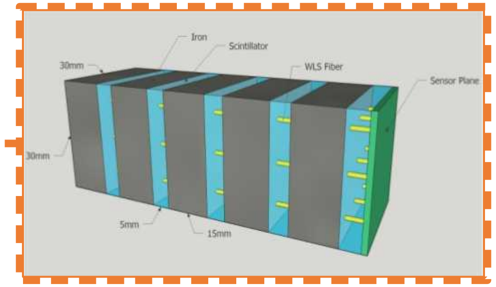
The shashlik prototype



10 cm = $5X_0$

UCM: ultra compact module.

SiPM and electronics embedded in the shashlik calorimeter



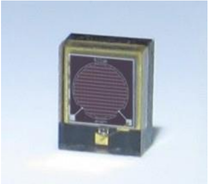
5 x (ABSORBER + SCINTI) ⟶ ~4 X_0

Fe-15mm + EJ200

TiO2 painting

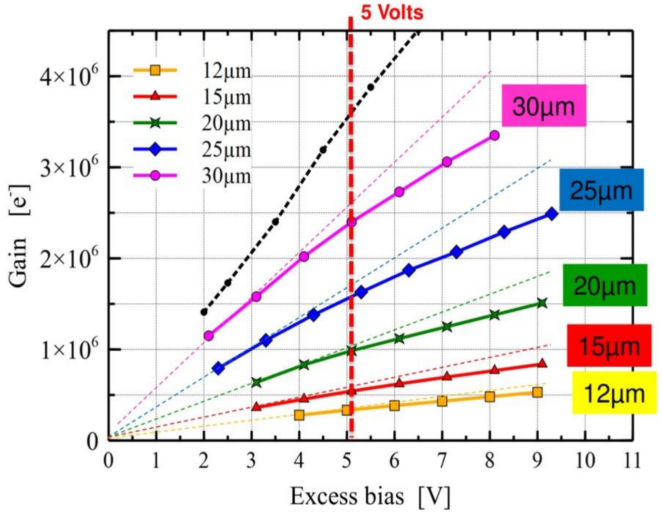
WLS: Kuraray Y11 double clad, 1mm diameter

SiPMs: FBK HD-RGB, 1mm^2



Required:
Fast ~10ns ⟵ avoid pileup
Rad.hard (10^{12} n/cm^2)

CS	FF	Cell Density
12 × 12 μm²	52 %	~7000 cells/mm²
15 × 15 μm²	62 %	~4444 cells/mm²
20 × 20 μm²	66 %	2500 cells/mm²
25 × 25 μm²	72 %	1600 cells/mm²
30 × 30 μm²	77 %	~1111 cells/mm²



The shashlik prototype

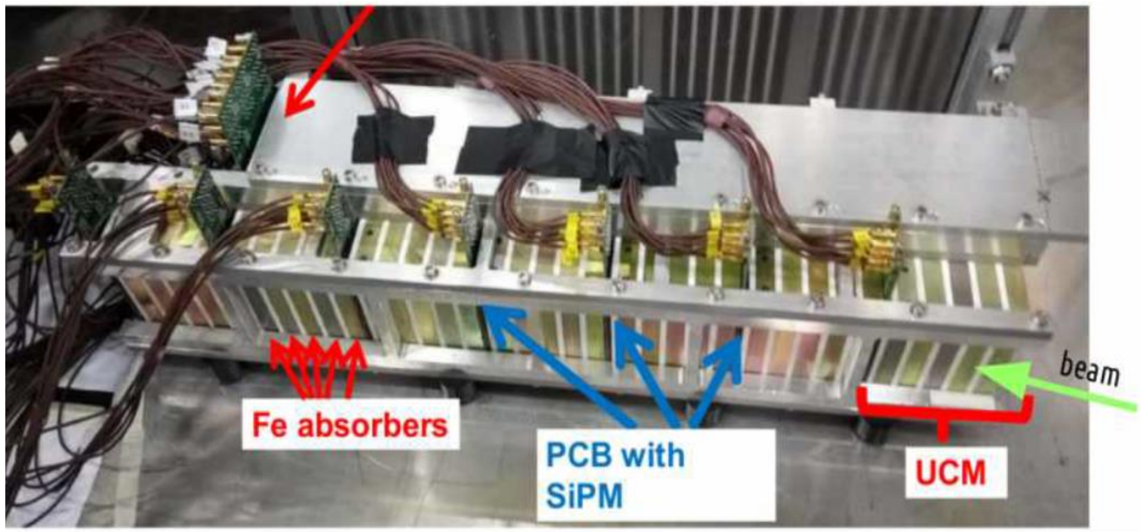
Tested response to MIP, e and π⁻

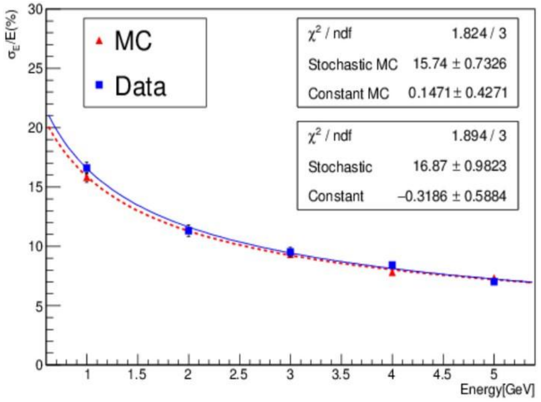
- e.m. energy resolution: 17%/√E (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences

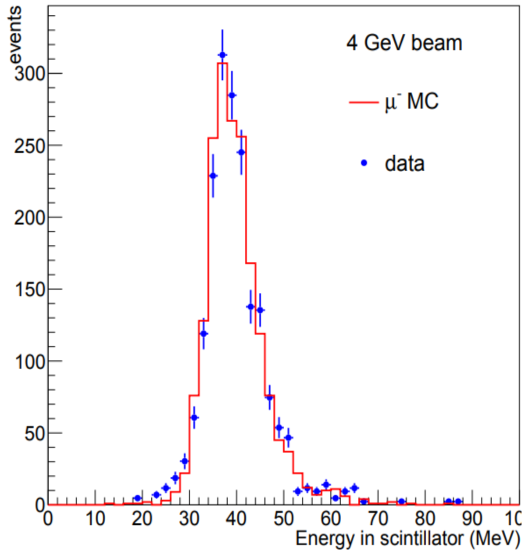
MC/data already in good agreement

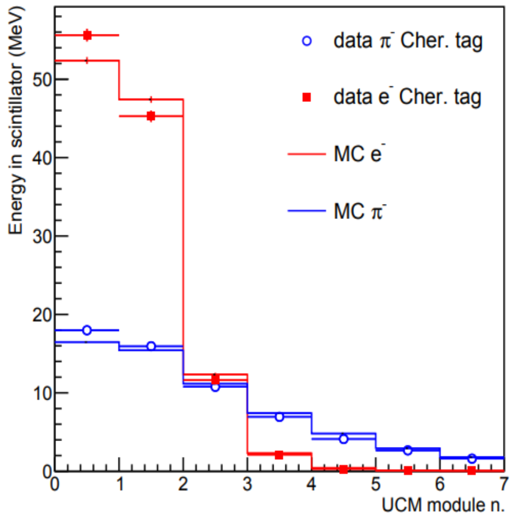
- Longitudinal profiles of partially contained π reproduced by MC @ 10% precision

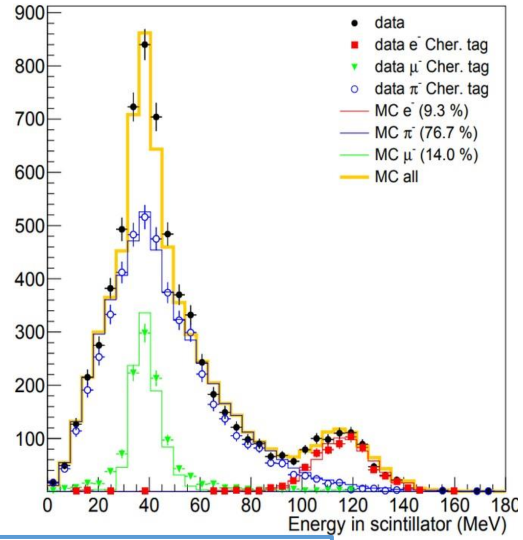
CERN PS, Nov 2016 7x4x2 UCMs







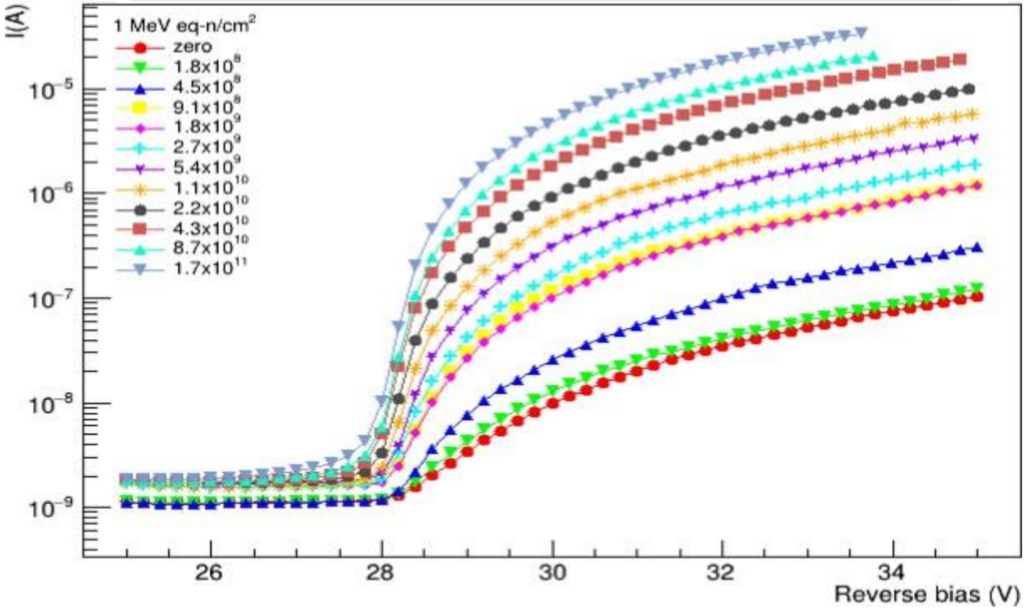




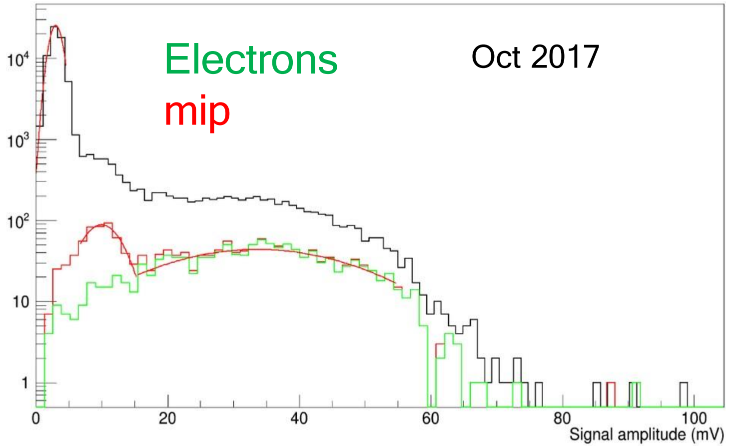
Ballerini et al., JINST 13 (2018) P01028

SiPM irradiation at LNL

Dark current vs bias at increasing n fluences
FBK HD-RGB 1x1 mm^2



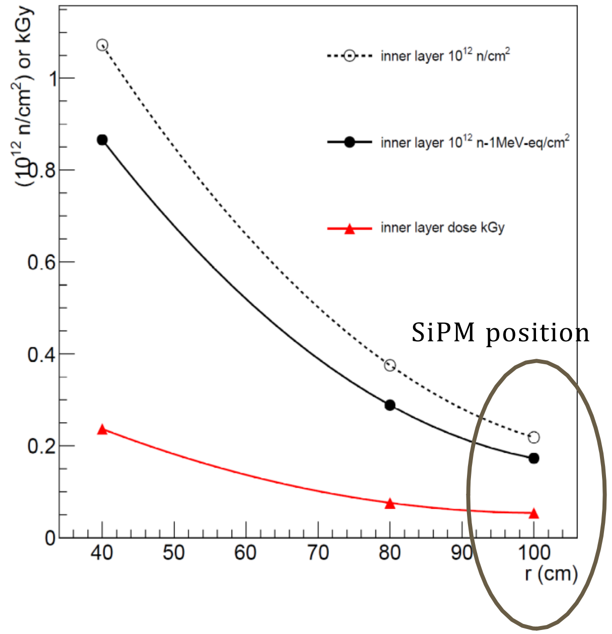
A shashlik calorimeter equipped with irradiated SiPMs later tested at CERN-PS

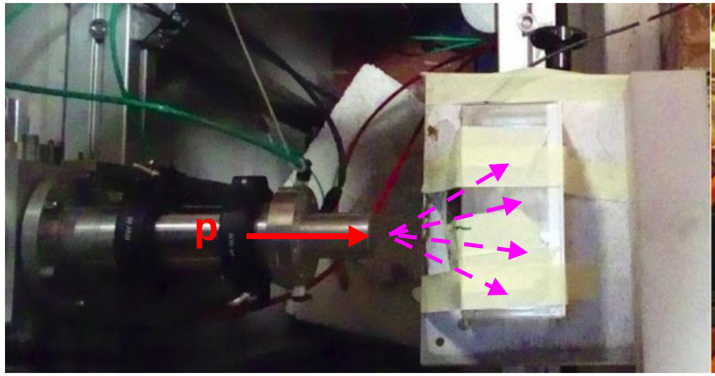


1.2×10^{11} n-1MeV-eq/cm^2

Acerbi et al., JINST 14 (2019) P02029

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

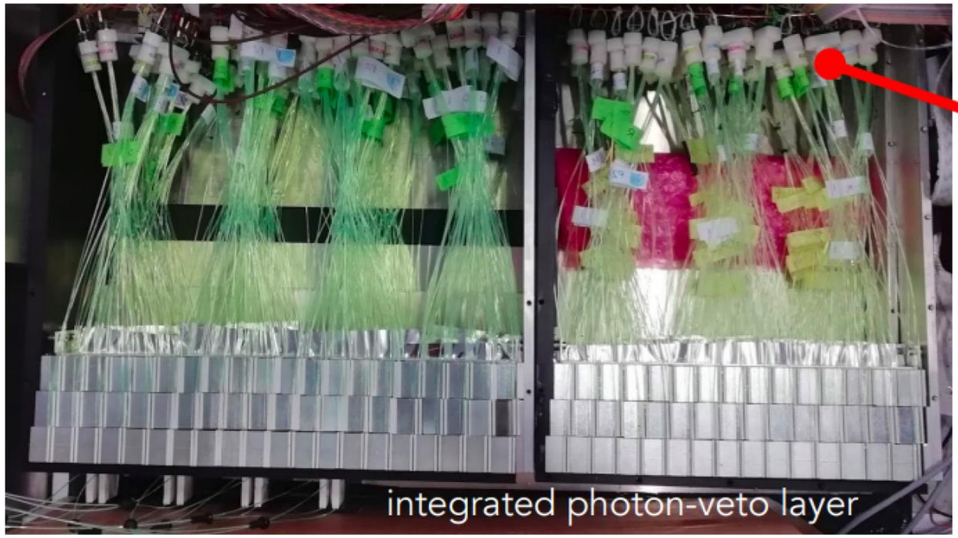




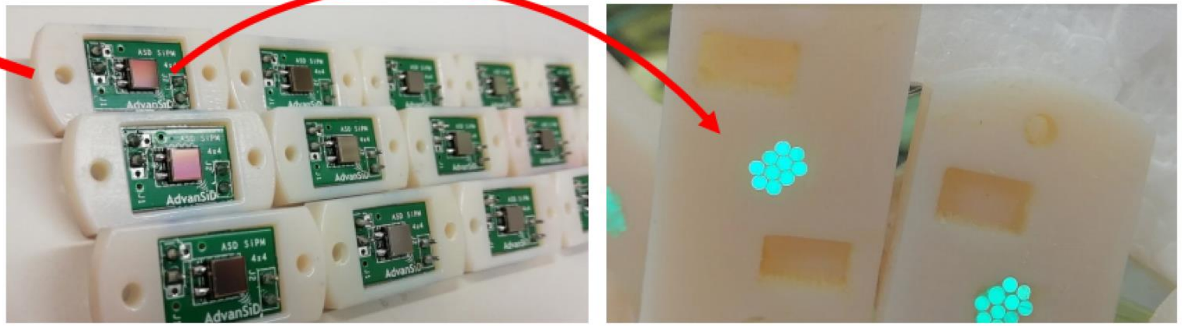
- By choosing SiPM cell size and scintillator thickness (i.e. light yield) properly mip signals remain well separated from the noise even after typical expected irradiation levels.
- Mip can be used from channel-to-channel intercalibration even after maximum irradiation.

The lateral readout prototype

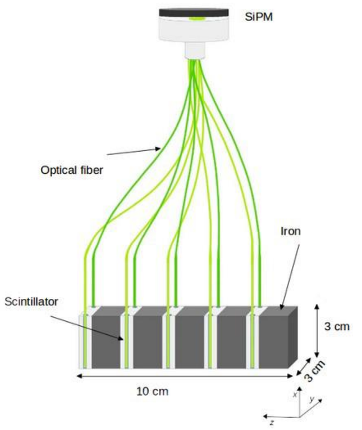
Tested during 2018 test beams runs @ CERN-PS: Prototype of sampling calorimeter built out of LCM with lateral WLS-fibers for light collection (Hamamatsu S14160 50 μm cell)



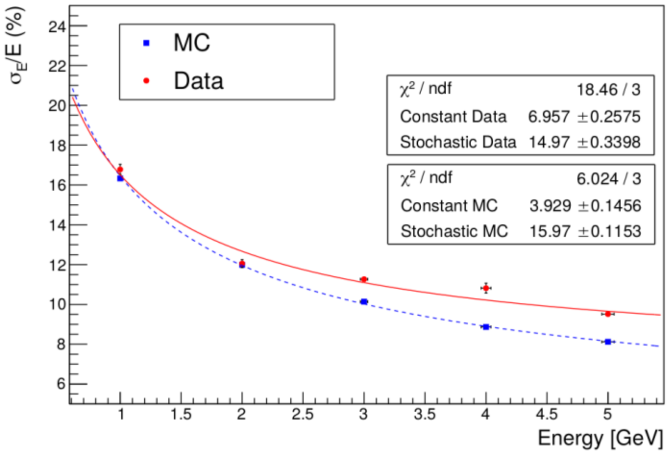
Large SiPM area (4x4 mm2) for 10 WLS readout (1 LCM)



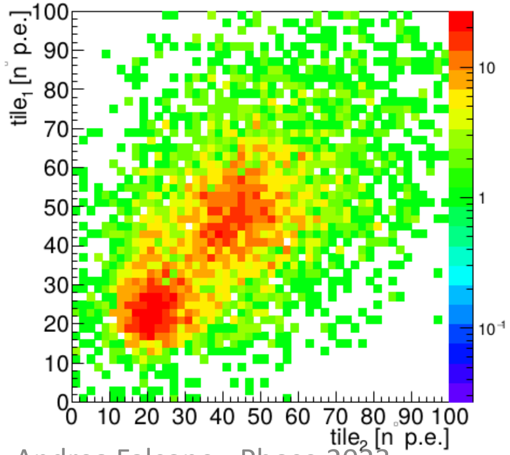
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging



Electron energy resolution



1/2 mip separation



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

Status of calorimeter:

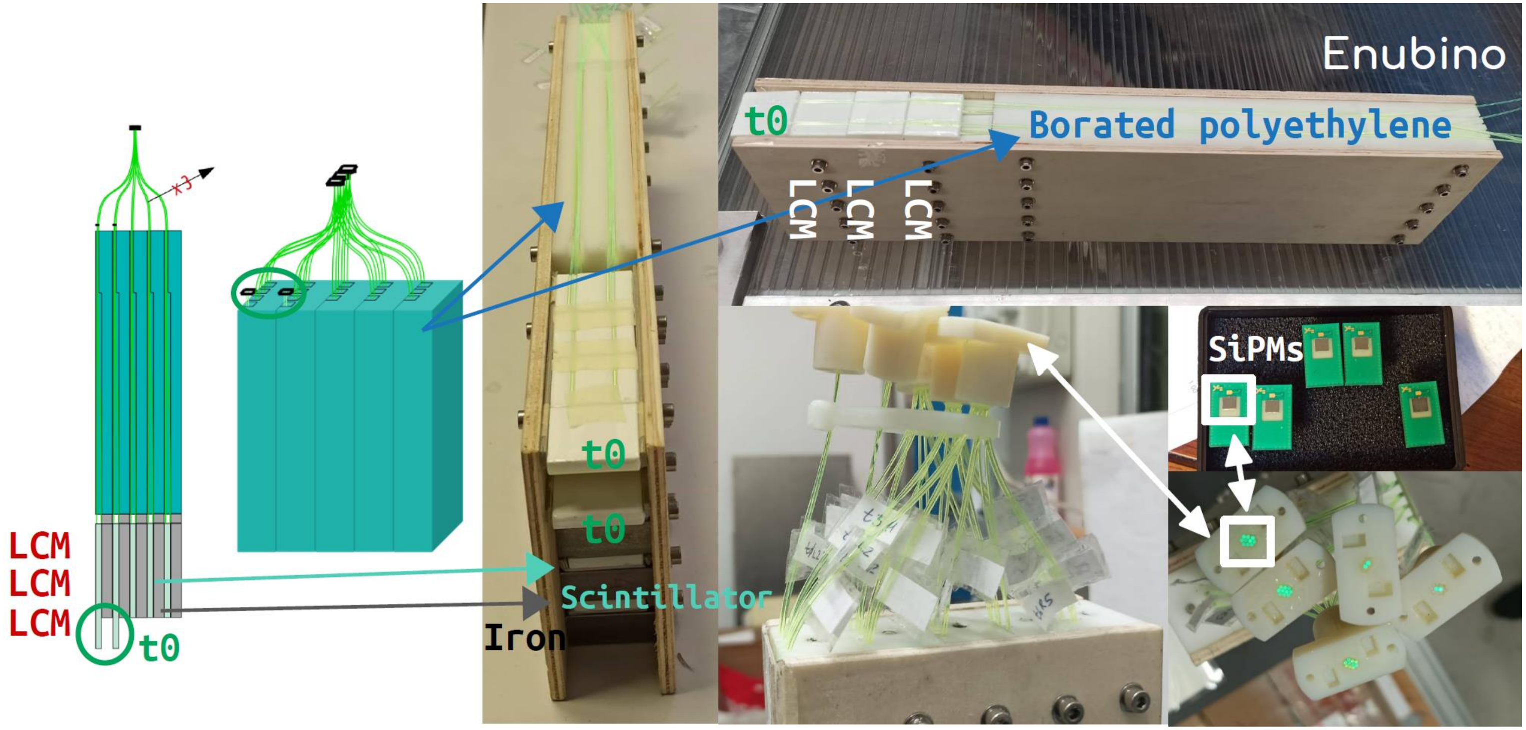
- longitudinally segmented calorimeter prototype successfully tested;
- e.m. energy resolution: 15%/√E (GeV)
- photon veto successfully tested.

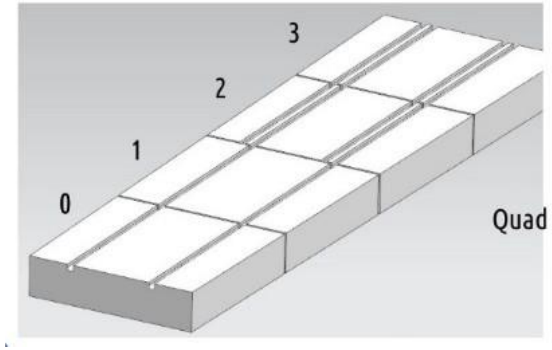
Enubino

2021 test beam @ CERN-PS:

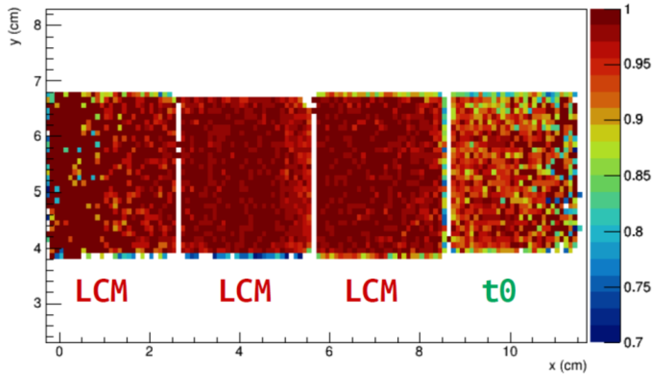
- Sampling calorimeter: plastic scintillator + iron absorber + BPE.
- Fibers collect the scintillation light frontally
- Uniform light collection.
- Fiber routing through BPE to SIPMs.

New frontal readout scheme & fibers bundling, again with 1 LCM bundled to a 4x4 mm^2 SiPM.

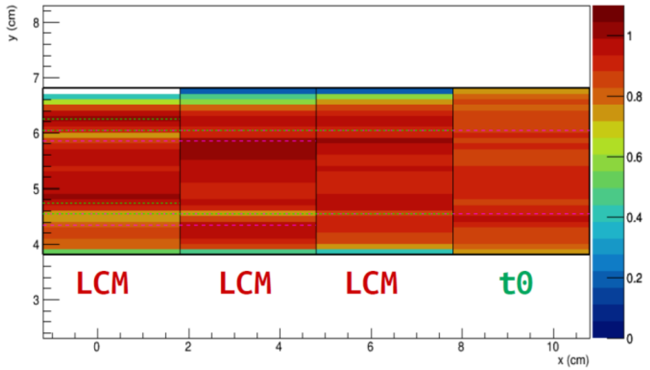




Efficiency map



Uniformity



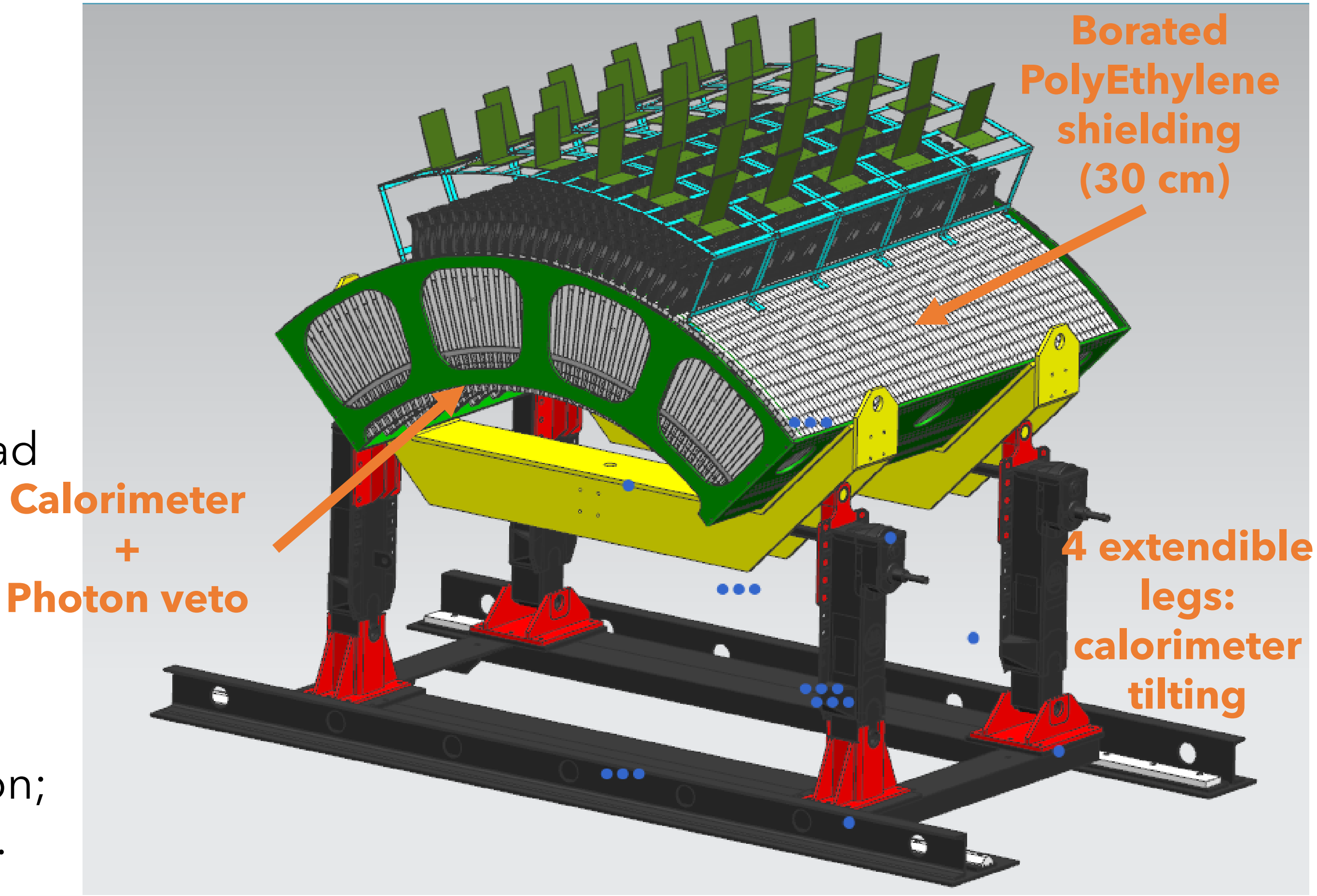
The tagger demonstrator

- Detector prototype to demonstrate performance / scalability / cost-effectiveness:
  - 1.65 m longitudinal & 90° in azimuth;
  - 75 layers of: iron (1.5 mm thick) + scintillator (7 mm thick) => 12x3 LCMs.

- Central 45° part instrumented: rest is kept for mechanical considerations;

- Modular design: can be extended to a full 2π object by joining 4 similar detectors (minimal dead regions);

- New light readout scheme with frontal grooves instead of lateral grooves:
  - driven by large scale scintillator manufacturing: safer production and more uniform light collection;
  - performed GEANT4 optical simulation validation.

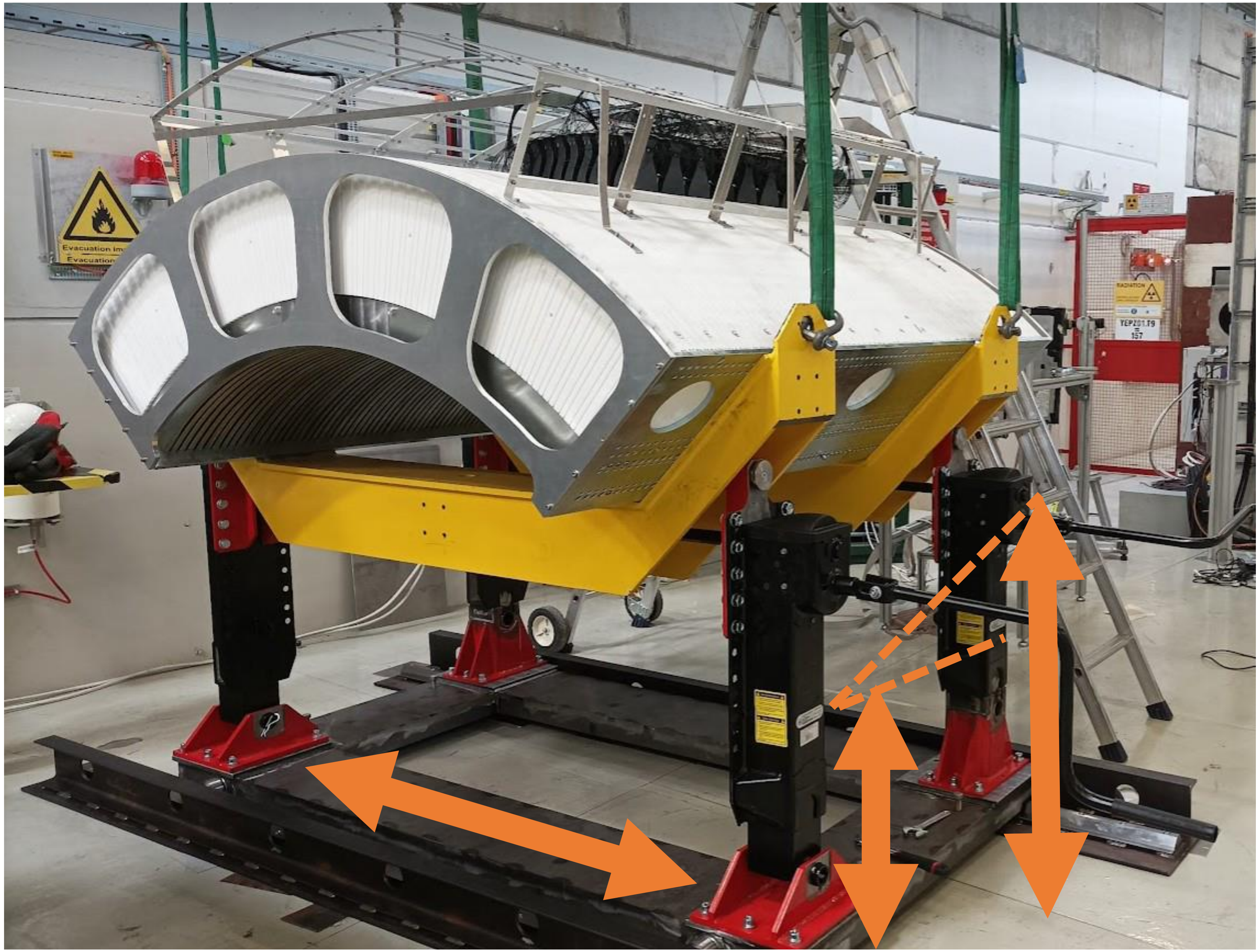


The tagger demonstrator at CERN in 2022

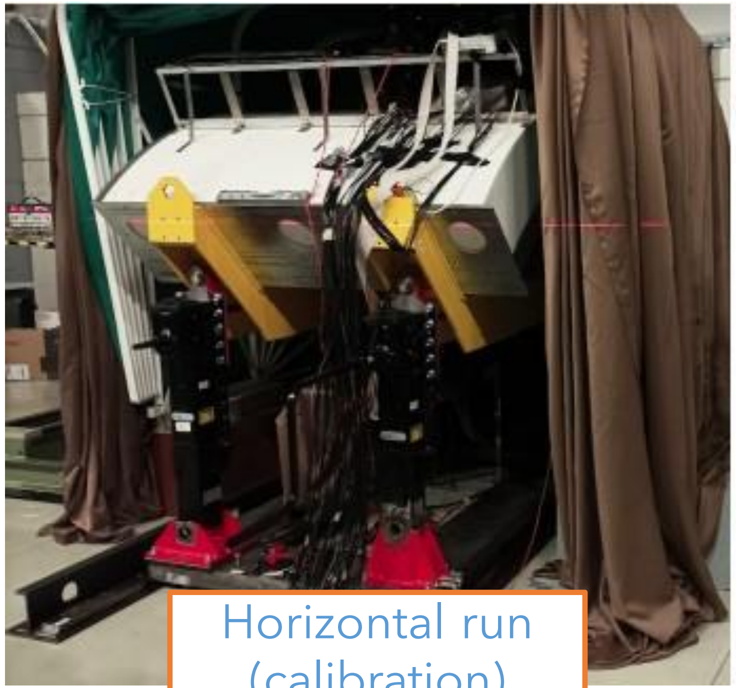
- Scintillator tiles: 1360
- WLS: ~ 1.5 km

- Channels (SiPM): 400
  - Hamamatsu S14160 50 μm cell
  - 240 4050HS SiPM 4x4 mm^2 (calo)
  - 160 3050HS SiPM 3x3 mm^2 (t0)

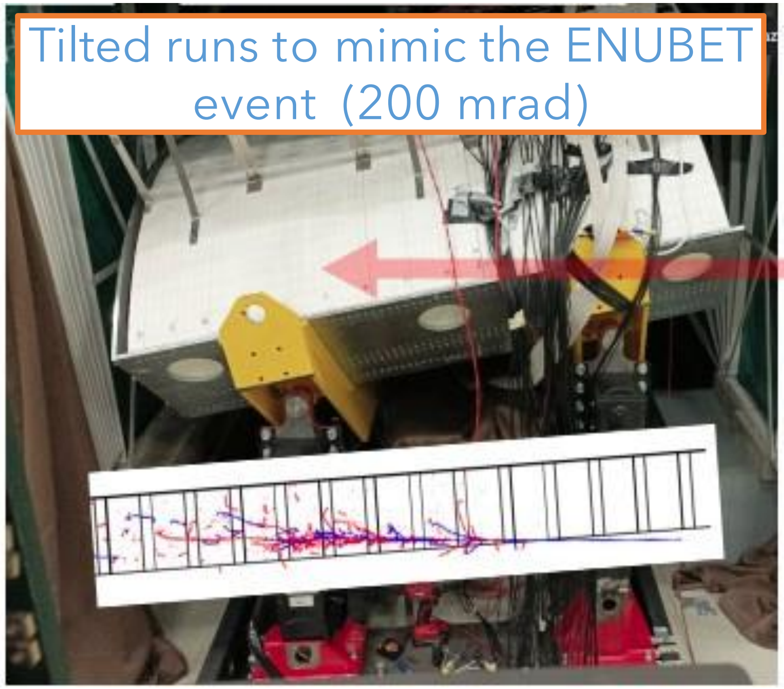
- Fiber concentrators, FE boards: 80
- Interface boards (hirose conn.): 8
- Readout 64 ch boards (CAEN A5202): 8
- Commercial digitizers: 45 ch
- Hor. movement ~1m
- Tilt >200 mrad



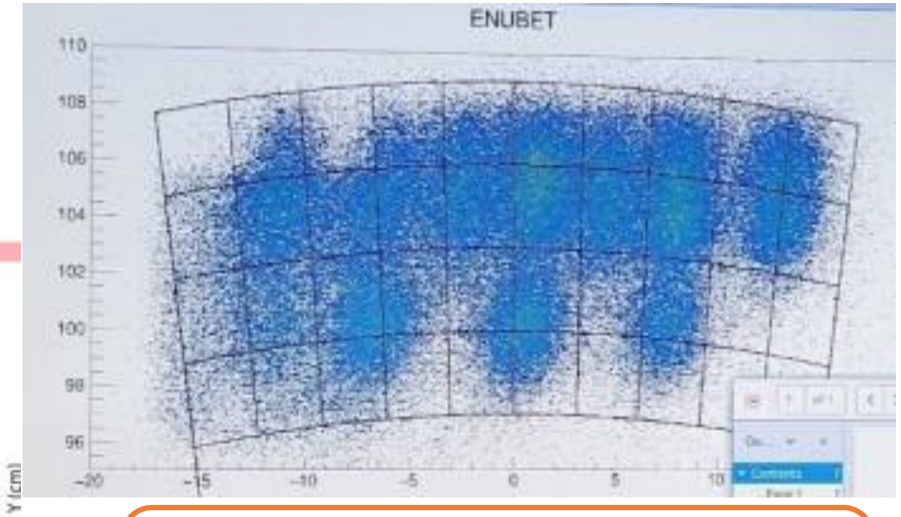
The tagger demonstrator at CERN in 2022



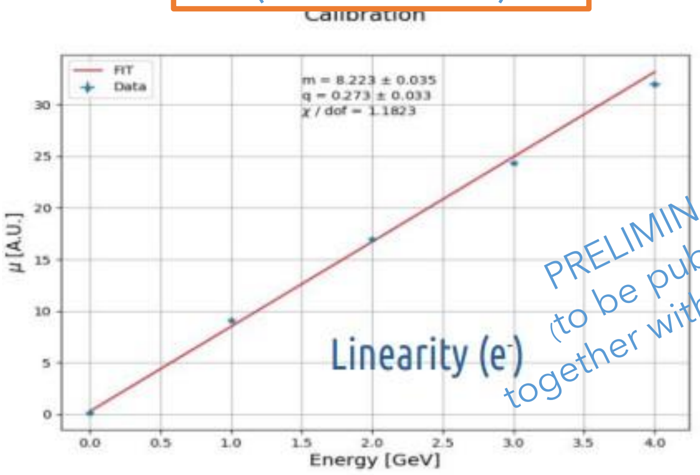
Horizontal run (calibration)

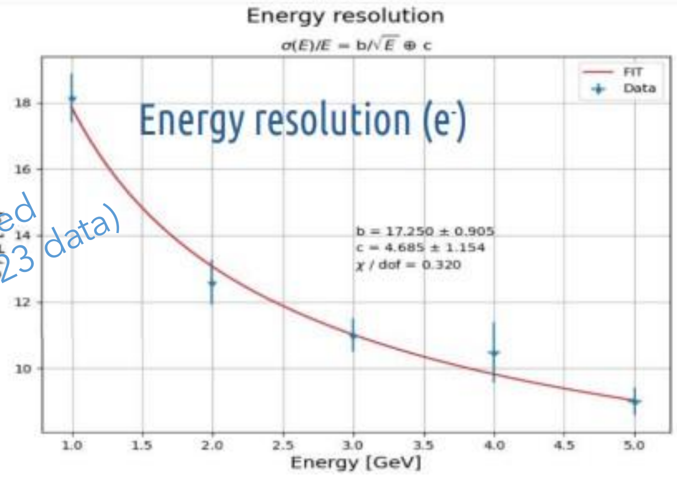


Tilted runs to mimic the ENUBET event (200 mrad)



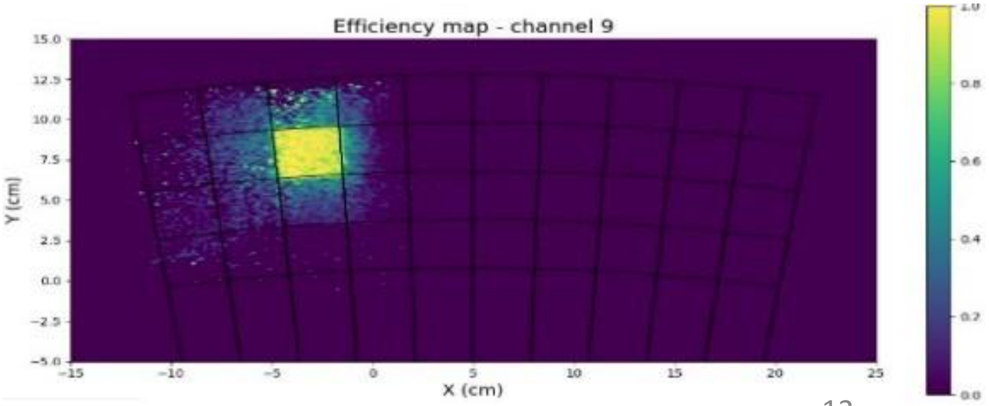
Beam spot at the detector face after several runs illuminating different region of the detector





PRELIMINARY
(to be published together with 2023 data)

Efficiency map of 1 LCM (calorimeter channel)



The tagger demonstrator at CERN in 2023

2022:

- 8 upstream z layers with 10 Φ sectors (400 ch)

2023:

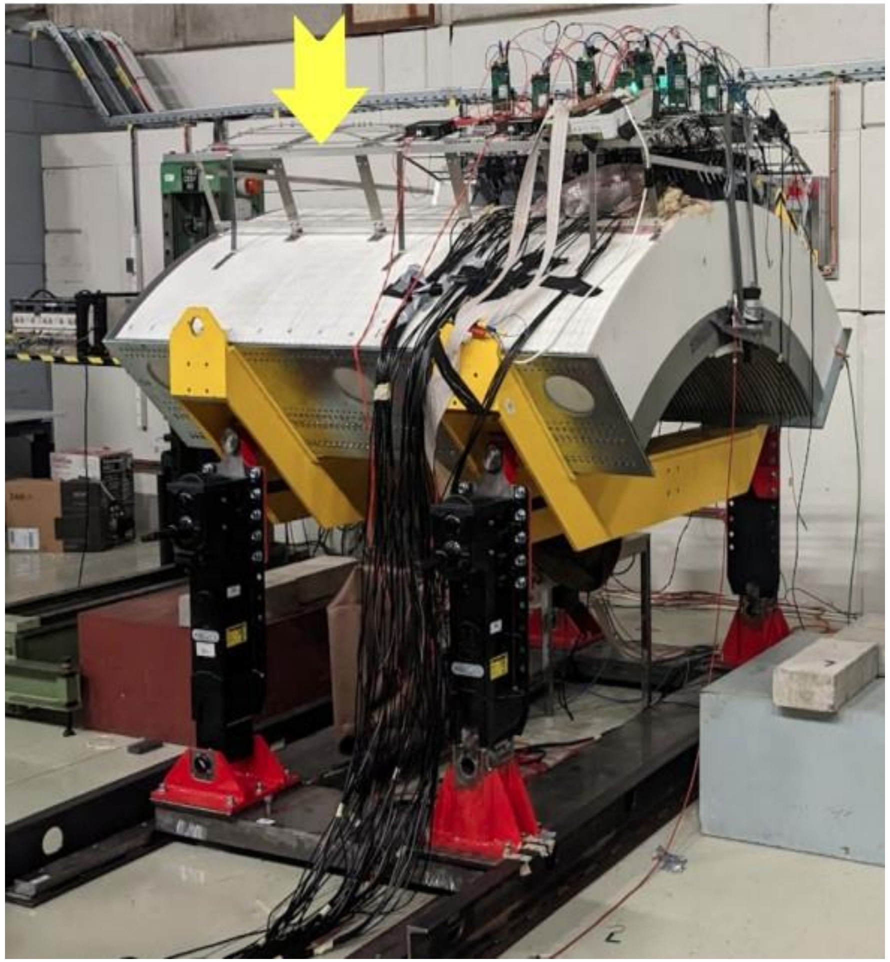
- add 7 downstream z layers with 25 Φ sectors;
- from 400 to 400+875 = 1275 channels;
- Larger acceptance → run in "decay region" mode i.e. with the detector off-beam to detect K decay products.

2022 demonstrator numbers

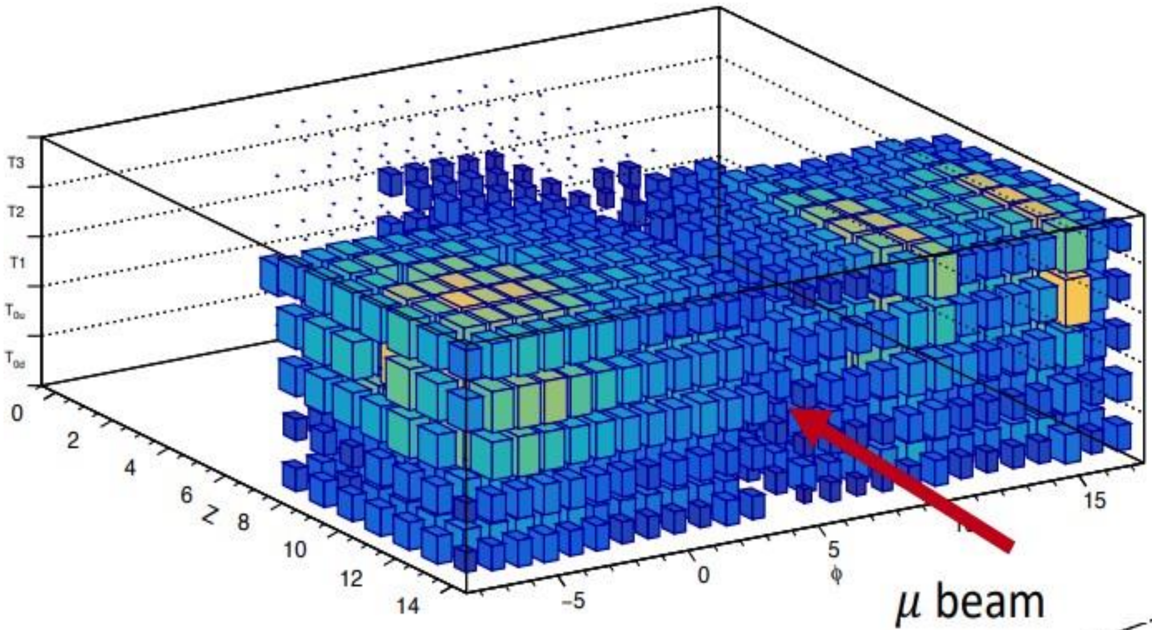
Parameter	Quantity or range
Scintillator tiles (7 shapes)	1360
WLS	1.5 km
Channels (SiPM) Hamamatsu (50 μm cell)	400 240, 4×4 mm^2 - calo, 160 3×3 mm^2, t_0
Fiber concentrators (FE boards)	80
Interface boards	8
read-out boards (A5202)	8
CAEN digitizers	45 ch
horizonthal movement	$\sim$ 1 m
vertical tilt	up to $\sim$ 200 mrad

… x 3 !

2023

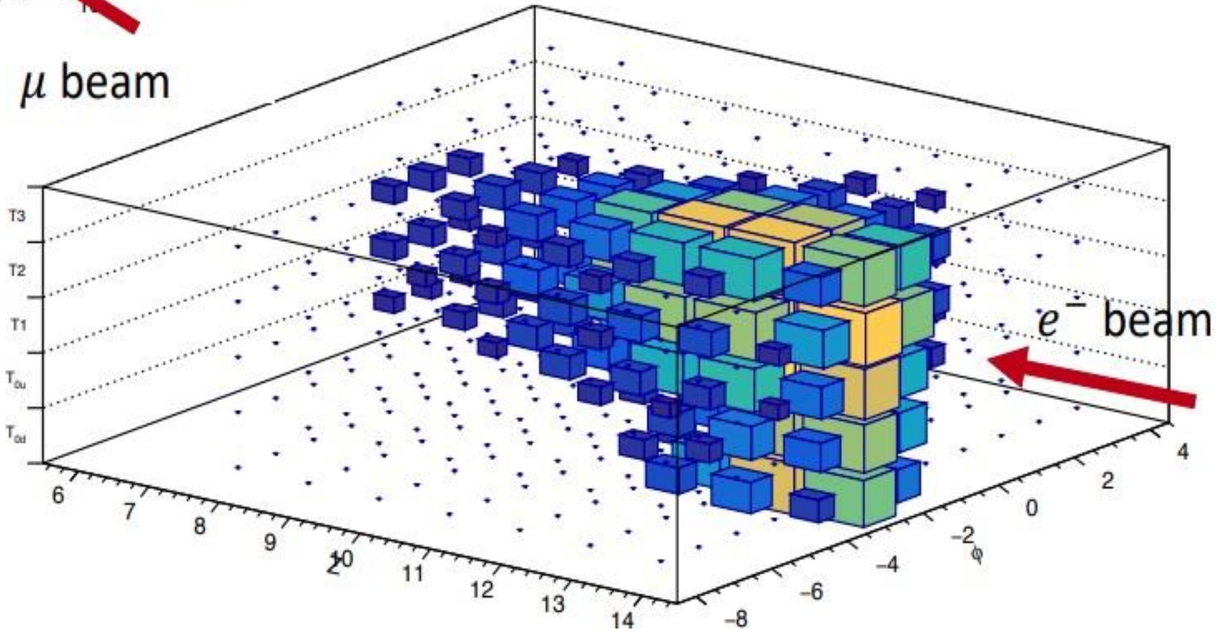


The tagger demonstrator at CERN in 2023



Calibration runs with 10 GeV muons

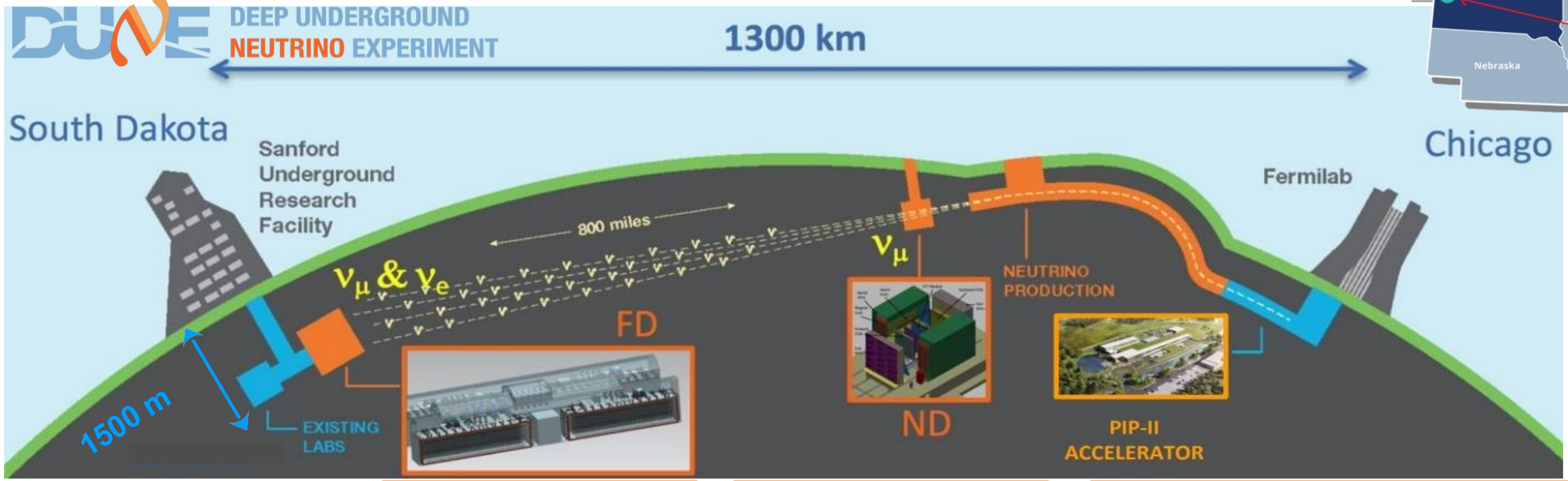
- All channels have been covered by a large amount of statistics with MIPs → will allow good equalization of channels



Example of shower profile from 5 GeV e run

- Energy scan with electron beams at different energies for linearity and resultion studies

The DUNE experiment



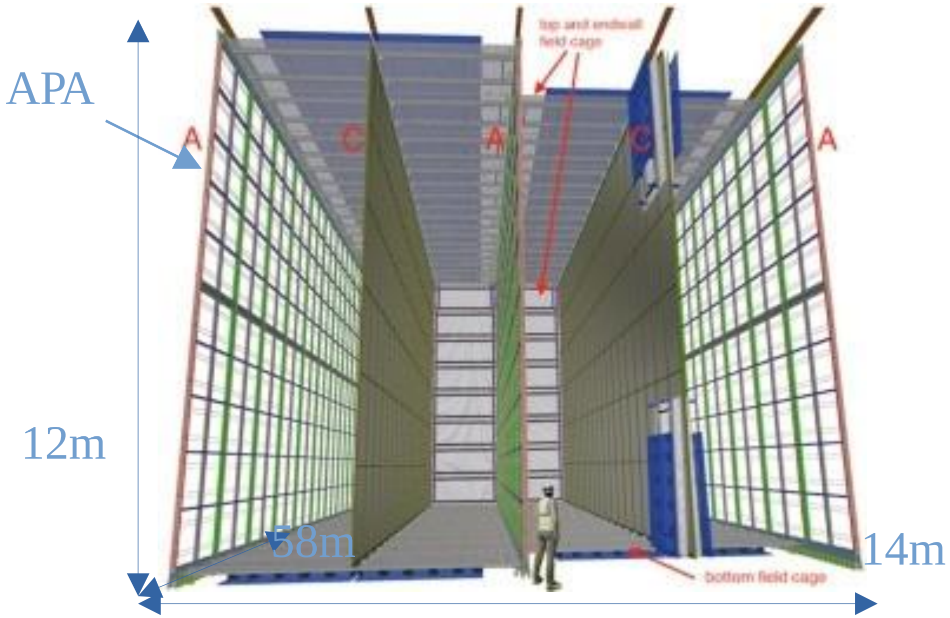
A large mass, high precision, Deep-underground accelerator Neutrino Experiment for a wide physics program:

Huge Far Detectors: 4x17kton total mass LAr TPC ← Near detector complex for beam characterization ← 1.2MW proton beam, upgradable to 2.4MW → Powerful LBL wide band beam

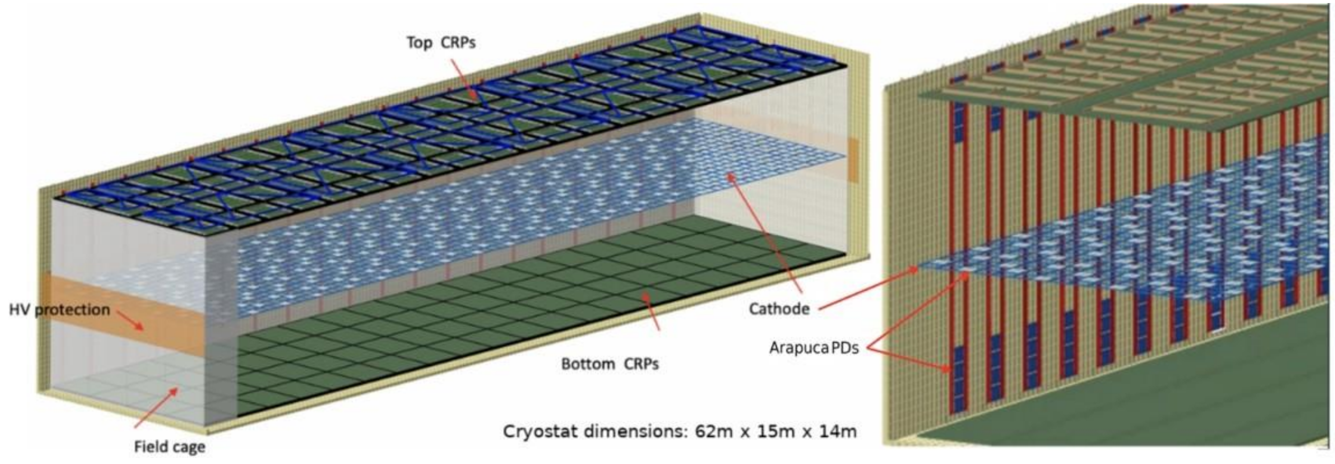
- Discovery of CP-Violating phase δ_{CP}, ν mass ordering .
- Measurement of PMNS parameters: θ_{23} octant, Δm^2_{13}, precision measurement of δ_{CP} .
- Astrophysical ν sources: SN burst, solar neutrinos.
- BSM physics: anomalies @ LBNF, dark matter, proton decay.

The DUNE experiment

- Four 3.2 m Horizontal Drift regions: alternated Anode and Cathode Plane Assemblies.
- Charge readout with wires in Anode Planes Assembly (150 APA, 6x2.3m).
- E_{field} = 500 V/cm.
- PDS: 10 modules for APA = in total 1500 modules in FD-1, 4 channels per module.
- 1 Module 2092x118x23 mm^3 = 4 supercells 488x100x8 mm^3.



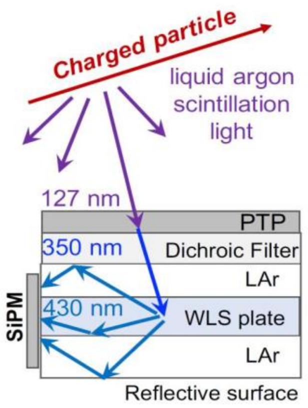
- Two 6 m Vertical Drift regions.
- Charge readout with PCB planes (160 CRPs, 3x3.4m) E_{field} = 450 V/cm , 300 kV on Cathode.
- PDS modules mounted on the cathode and on the cryostat walls:
  - Square geometry: dimension 65x65 cm^2 .
  - A single large WLS light guide plane.
  - Light readout by 160 SiPMs mounted on flexible strips.
- Xenon doped LAr and so longer Rayleigh scattering length: enhanced light collection in large volumes.



The DUNE PDS – X-Arapuca

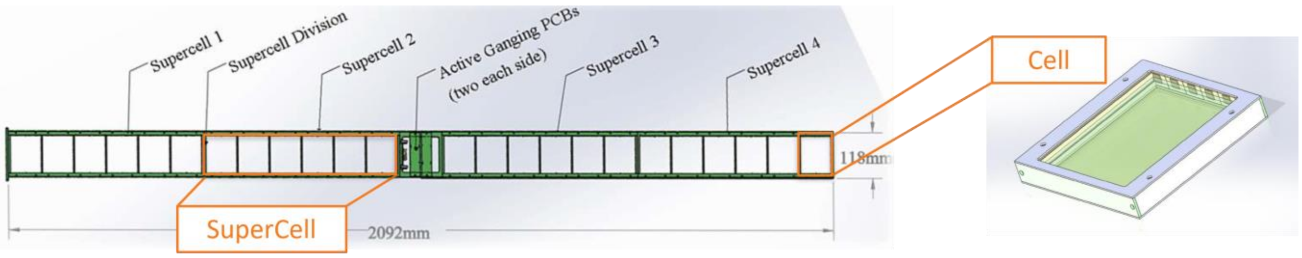
X-ARAPUCA: internal reflection and highly reflective boxes:

- efficient conversion of VUV photons;
- high fraction of captured photons;
- efficient photosensors.



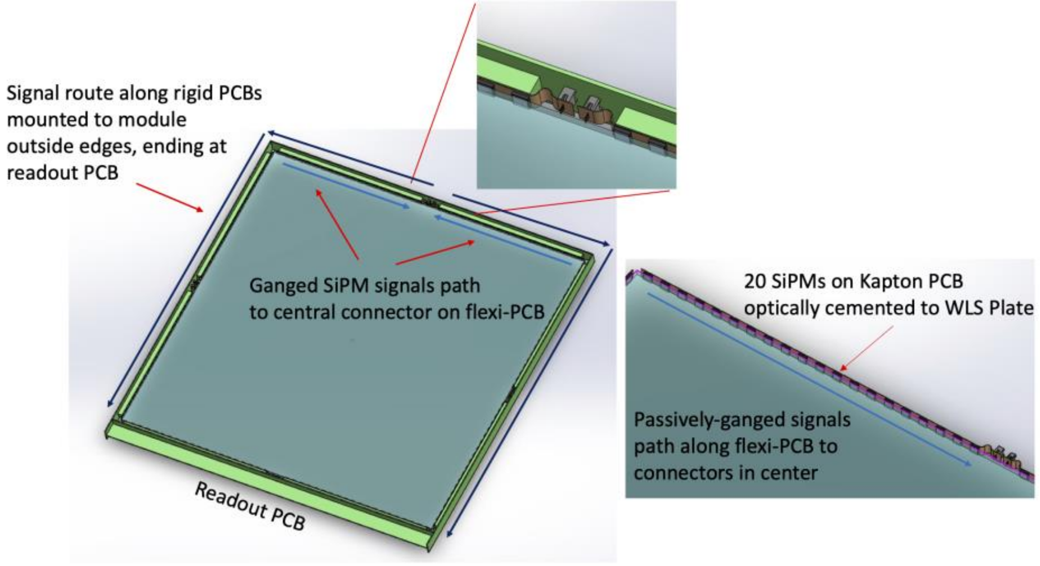
Horizontal Drift

- SuperCell: 6 cells 488 × 100 × 8 mm^3.
- Module: 4 SC 2092 × 118 × 23 mm^3 (bars configuration).
- 10 modules / APA.



Vertical Drift

- "4p" reference design.
- 320 X-ARAPUCA 60 x 60 cm^2 on cathode, and 320 + 32 on cryostat membrane (~3 m from cathode), analog readout.



The DUNE PDS – SiPM

Horizontal Drift:
- 48 SiPMs per SuperCell;
- 1 readout channel per SC (passive+active ganging);
- 288,000 SiPMs in total.

Vertical Drift:
- 160 SiPMs per Plate;
- 1 readout channel per Plate (passive+active ganging);
- 107,502 SiPMs in total.

Two photosensor vendors are being investigated, Hamamatsu Photonics (HPK) and Fondazione Bruno Kessler (FBK):
- 6 types (splits) of 6x6 mm^2 SiPMs developed specifically for DUNE: 4 from HPK (S13360 – LQR/HQR – 50/75 μm pitch) and 2 from FBK (NUV-HD-CRYO single/triple trench).

Low level specs	Value
Max nominal operating V	[50 V at cold]
Dark count rate (DCR)	<100 mHz/mm^2
Correlated noise	<35%
Time resolution	<1 μs
Thermal cycles	>20
Recovery time	τ ~ a few μs
PDE at 87 K	>35% at nominal OV
High level specs	**Value**
Dynamic range	1-2000 p.e.
S/N>4	Per supercell (48 SiPMs)
Trigger	1.5 p.e.

The DUNE PDS – SiPM

Horizontal Drift:
- 48 SiPMs per SuperCell;
- 1 readout channel per SC (passive+active ganging);
- 288,000 SiPMs in total.

Vertical Drift:
- 160 SiPMs per Plate;
- 1 readout channel per Plate (passive+active ganging);
- 107,502 SiPMs in total.

Two SIPMS selected:
- HPK S13360 HQR 75 μm pitch
- FBK NUV-HD-CRYO triple trench.

HPK HQR 75 μm

PDE	Gain (10^6)	DCR (mHz/mm^2)	Cross-talk	After pulse
40	3.73	57.54	6.62	0.86
45	4.59	64.97	8.97	1.10
50	5.44	66.32	10.96	1.30

Results in pubblications!

FBK Triple Trench

PDE	Gain (10^6)	DCR (mHz/mm^2)	Cross-talk	After pulse
40	4.73	80.79	13.76	2.85
45	6.01	86.33	15.67	3.25
50	8.21	93.35	40.50	4.05

DUNE double calorimetry : charge + light

The energy deposited in the detector goes into 2 observables: Charge and Light

- Using only the charge→standard reconstruction of deposited energy in a LArTPC, only the electrons that escape e⁻-ion recombination and successfully drift to the anode can be used: a correction must be applied to account for the charge lost:

Energy from Charge only:
$E_Q = Q * R / W_{ion}$

R= Recombination Factor = electron recombination survival probability.
Depends on the E_{field} and local ionization charge density *dQ/dx* → difficult to determine at all deposition sites, particularly for EM showers → use of an average value
W_{ion}= ionization work function

- Adding the light: charge and light are anticorrelated and their sum is directly proportional to the deposited energy:

Energy from Charge+Light:
$E_{QL} = W_{ph} (Q+L)$

W_{ph}=19.5 eV = average amount of energy deposited by a charged particle to produce an ion or exciton. Related to W_{ion} through the excitation ratio α: W_{ion}=23.6eV=(1-α)*W_{ph}

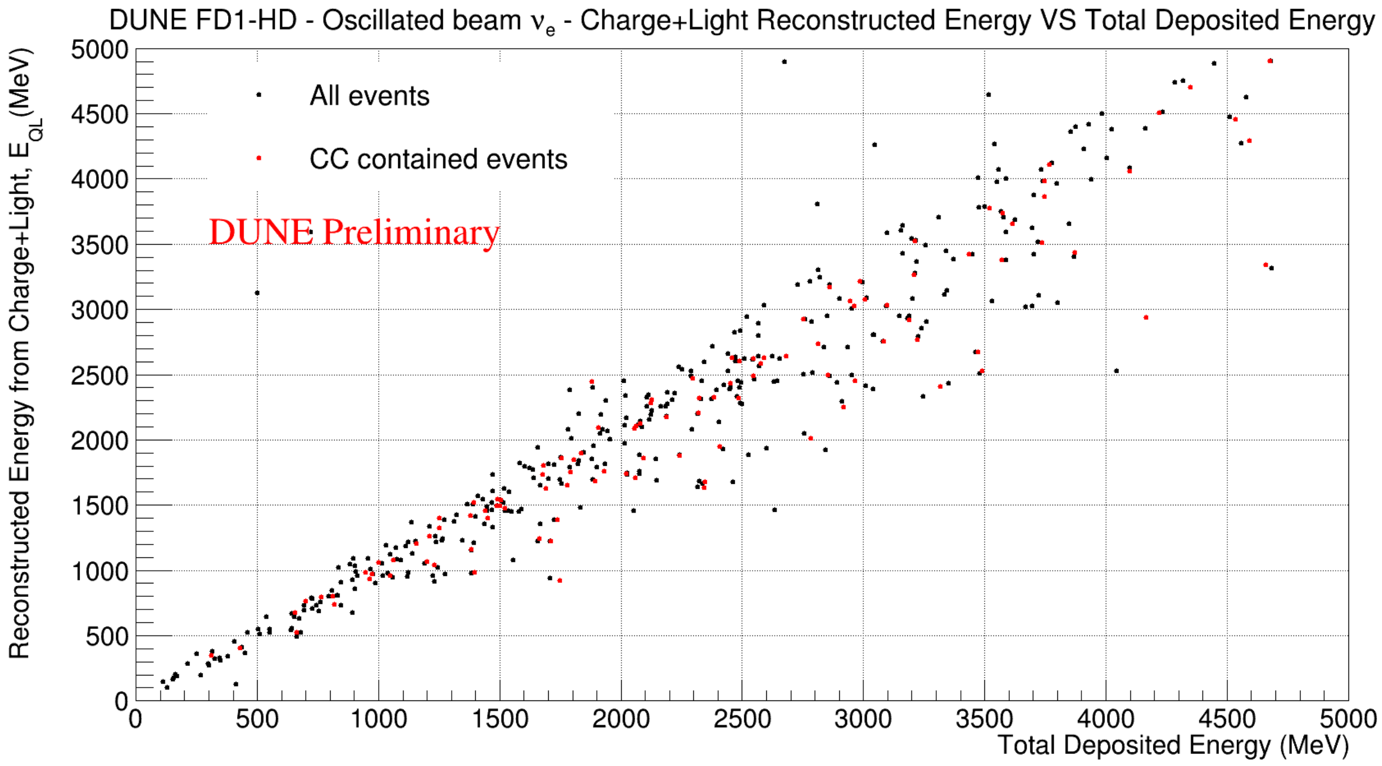
Charge: $Q = N_i R = N_e$
Light: $L = N_{ex} + N_i (1-R) = N_\gamma$
$Q+L = N_i + N_{ex} = \Delta E / W_{ph}$

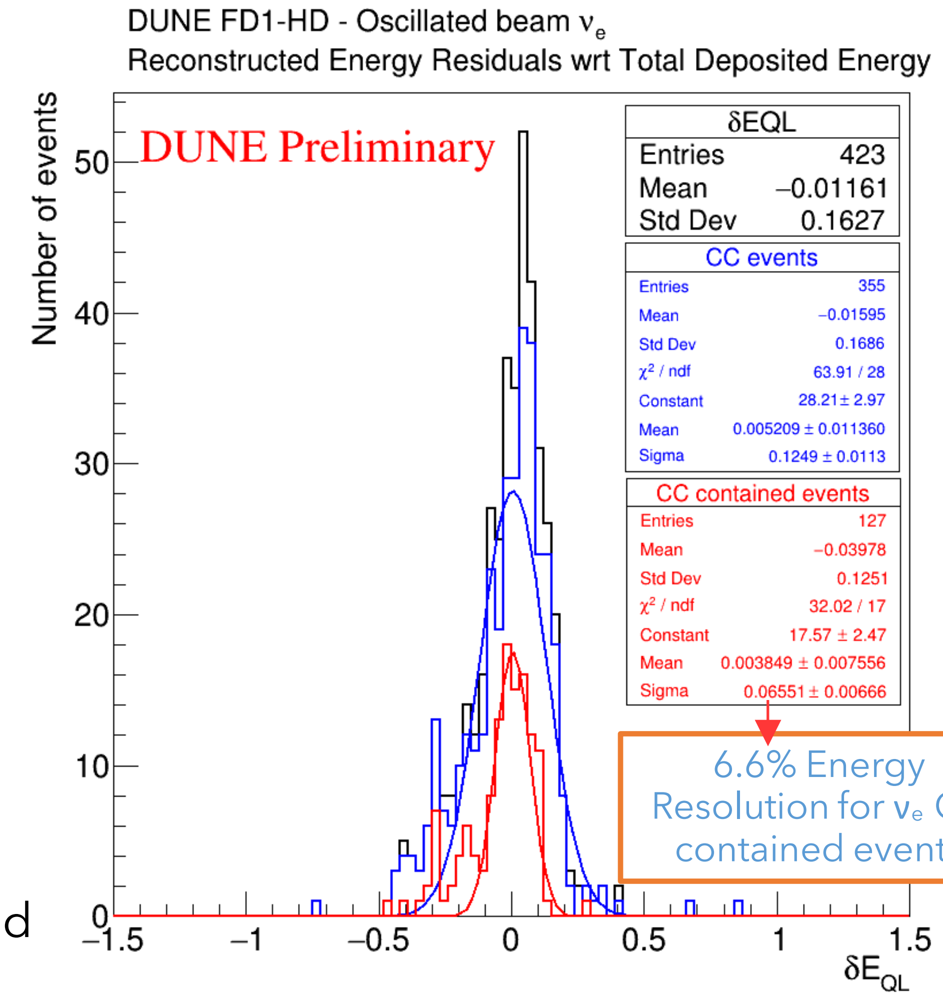
→ We can perform a calorimetric measurement by-passing the correction for recombination that is no longer necessary and improve energy resolution

DUNE double calorimetry : HD beam ν_e

G. Brunetti - Neutrino Telescope '23

Reconstructed event Energy from Charge & Light: $E_{QL} = W_{ph}(Q+L)$ → Comparison to Total Deposited Energy





6.6% Energy Resolution for ν_e CC contained events

Charge-only energy resolution in DUNE in the 0.5–4 GeV range: ~15–20%, depending on lepton flavor and reconstruction method [Eur. Phys. J. C 80, 978 (2020)]

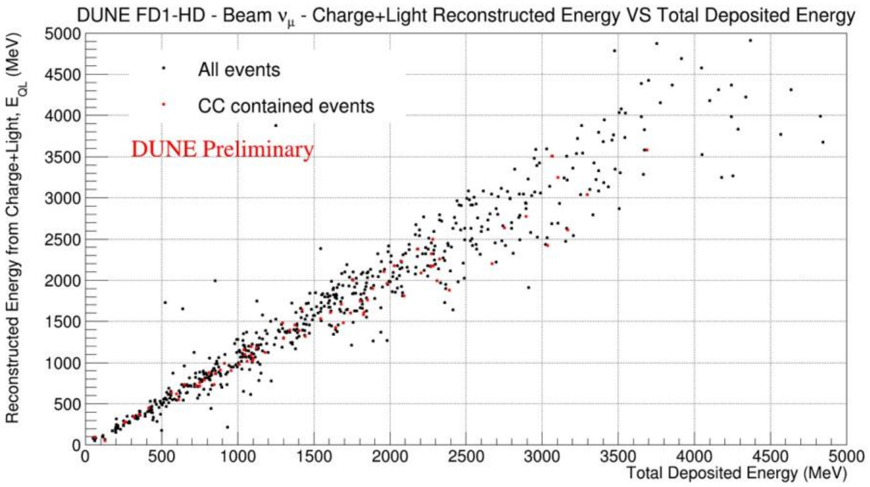
DUNE double calorimetry : HD beam ν_μ and $\bar{\nu}_\mu$

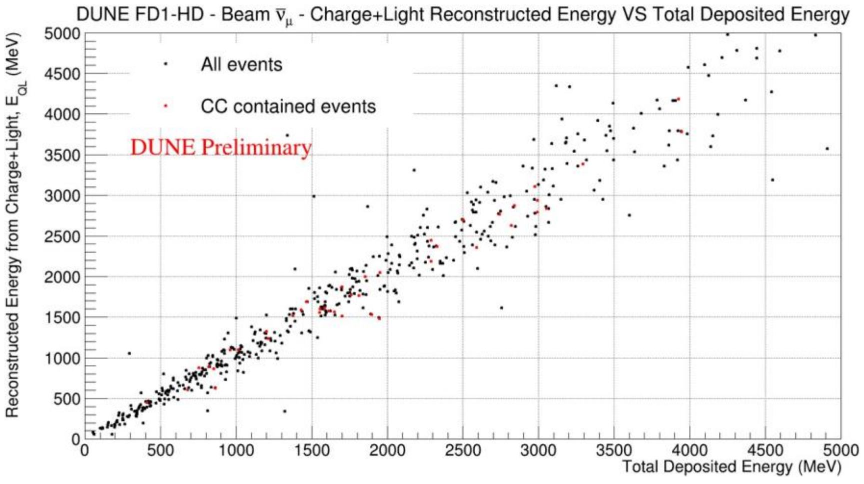
DUNE-FD1 simulated beam events:

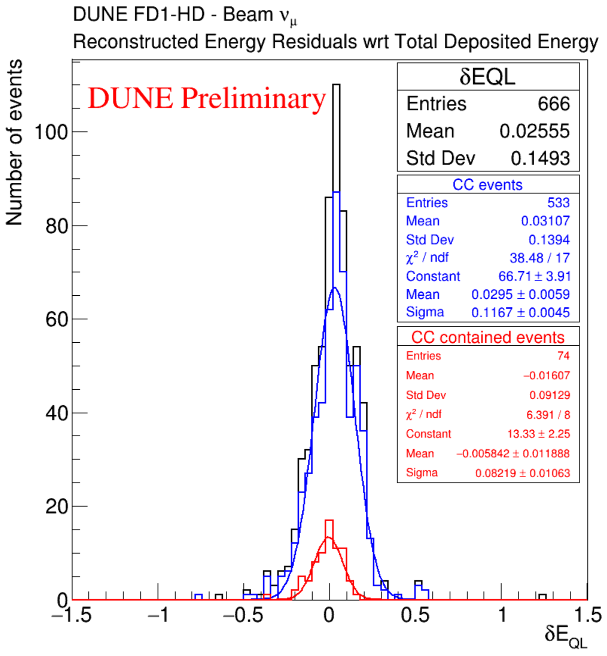
- 700 beam ν_μ & beam $\bar{\nu}_\mu$
- Energy from Charge+Light & comparison to Total Deposited Energy
- Energy Resolution:

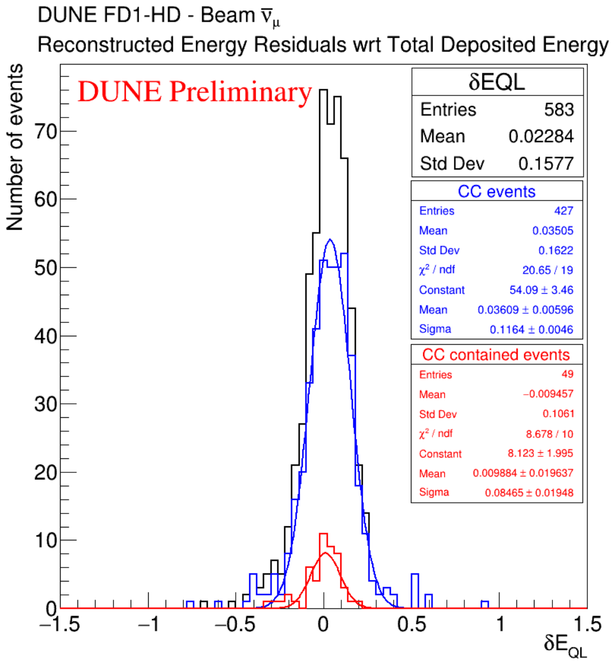
  ν_μ CC contained ~ 8.2%

  $\bar{\nu}_\mu$ CC contained ~ 8.5%









Conclusion

Two approach for SiPM calorimetry in neutrino physics:

ENUBET
- Conventional beamline with instrumented decay tunnel to monitor ν flux from narrow-band beam.
- SiPM will be used for the complete read – out.
- Different configuration have been tested, till the choice of a frontal read out calorimeter with shielding to prevent radiation damage.
- A scale prototype, built and tested, confirmed the feasibility of the project.

DUNE
- A large mass, high precision, deep-underground accelerator neutrino experiment for a wide physics program (neutrino oscillation, neutrino from astrophysical sources, BSM physics etc.).
- Two LAr TPC modules (confirmed), with SiPMs as light detection devices.
- Study for energy resolution improvement with the combined use of charge + light gives good results.

Thanks!

DUNE light simulation

1) Production: phenomenological model that modifies the Birks' charge recombination model and provides the anticorrelation between light and charge and its dependence with dE/dx and E_{field} :
$Q(dE/dx, E_{field}) + L(dE/dx, E_{field}) = N_i + N_{ex}$ N_i, N_{ex} = model input parameters, with current numerical values extracted from data

2022 JINST 17 C07009

2) Propagation: tracking individual photons in Geant4 is prohibitive → Semi-analytical model that predicts hits on a PDS module from scintillation photons produced: factorize geometry (Ω), absorption and Reyleigh scattering

Effective parametrization calibrated on heavy Geant4 simulations

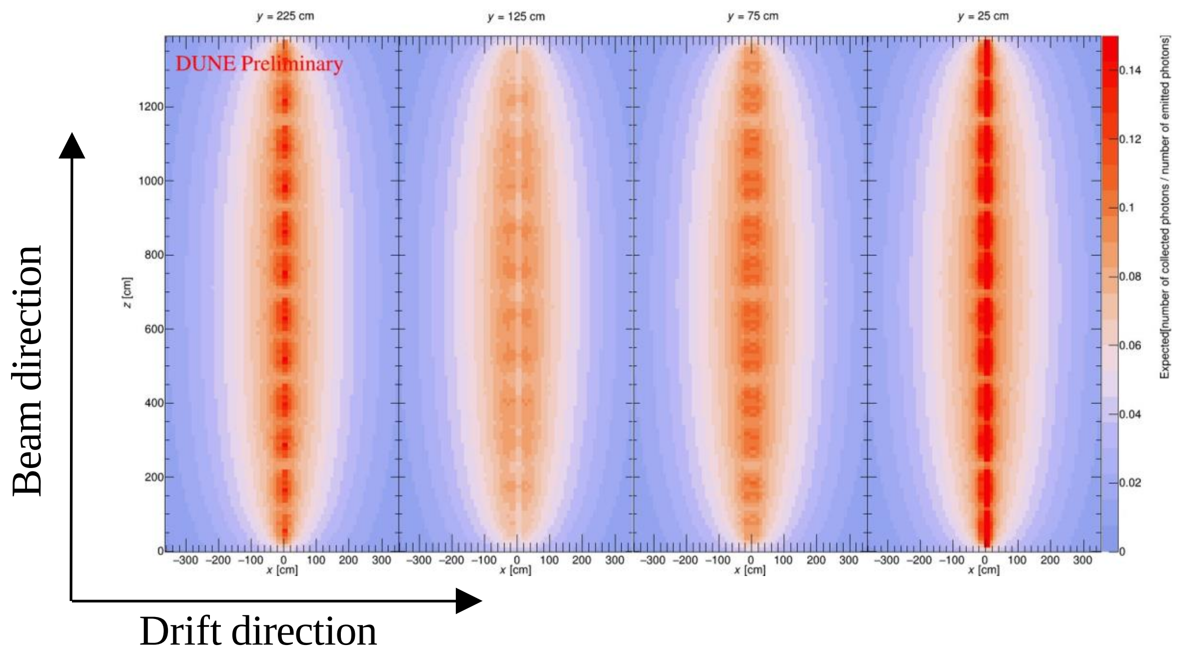
Eur. Phys. J. C 81, 349 (2021)

3) Digitization:

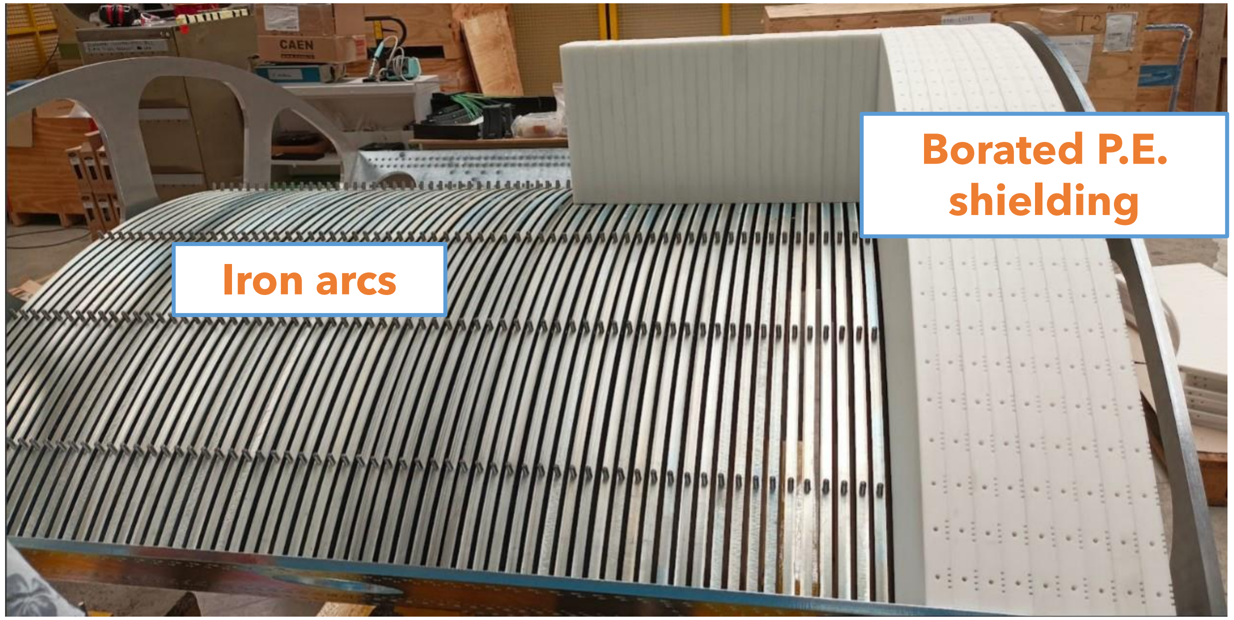
- For each p.e., a waveform is created (shape modelled on direct measurements)
- Waveforms filtered to deconvolve detector response and scintillation time profile

Visibility Map from semi-analitycal model corresponding to a fraction of FD1

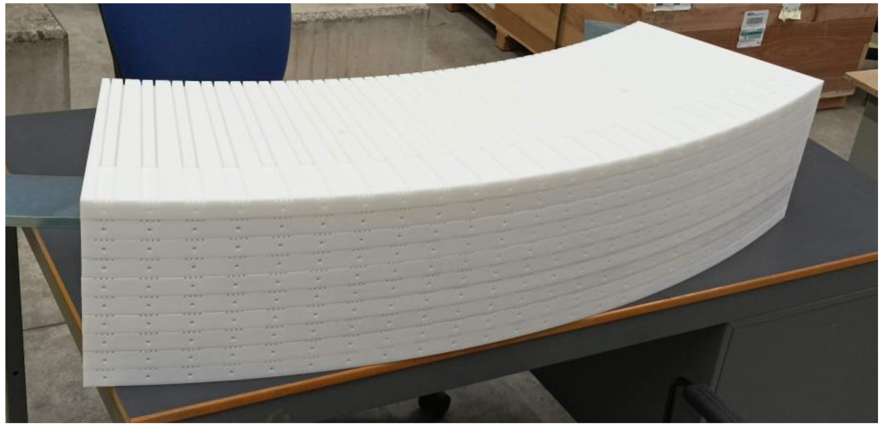
Visibility at different Y



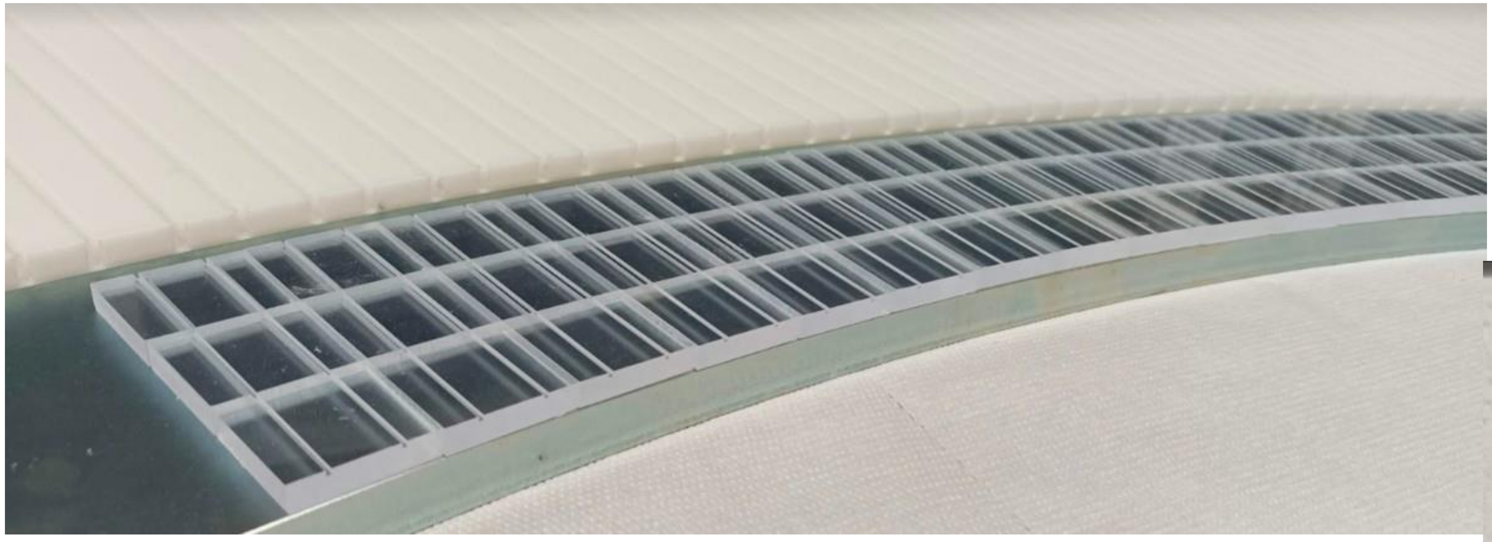
The tagger demonstrator: mechanical stracture



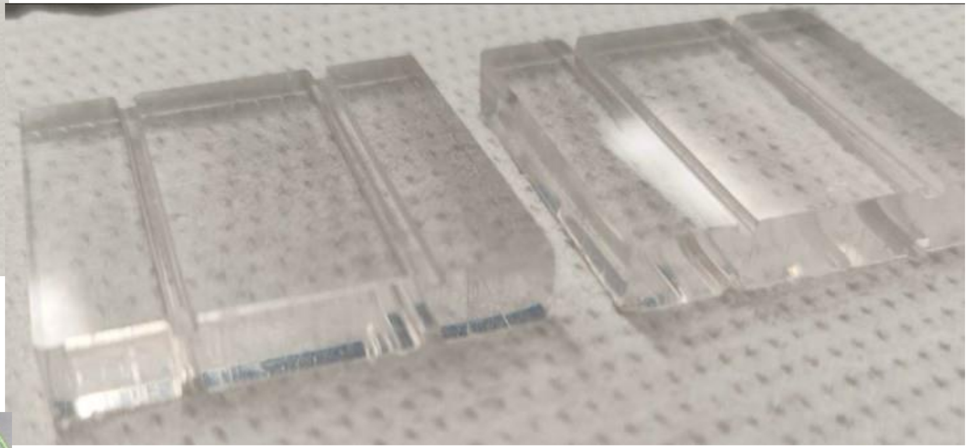
Lifting test with additional 2 tons (prototype weight ~3.2 tons)

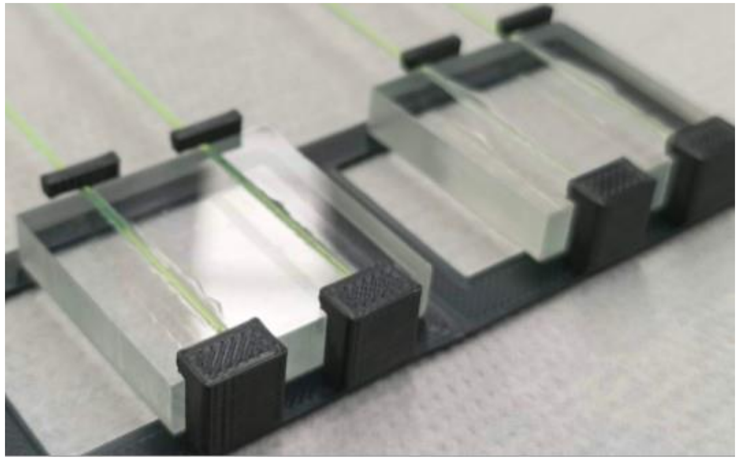


The tagger demonstrator: scintillator tiles



EJ-204 scintillator tiles ($3x3\ cm^2$) with grooves for WLS fibers

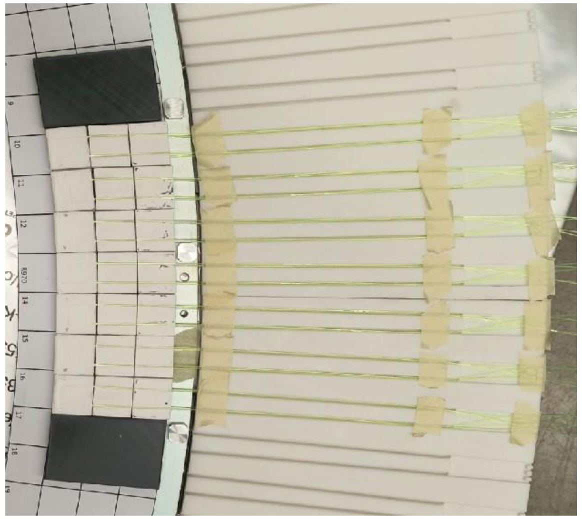




Fiber gluing
(EJ-500 optical cement)

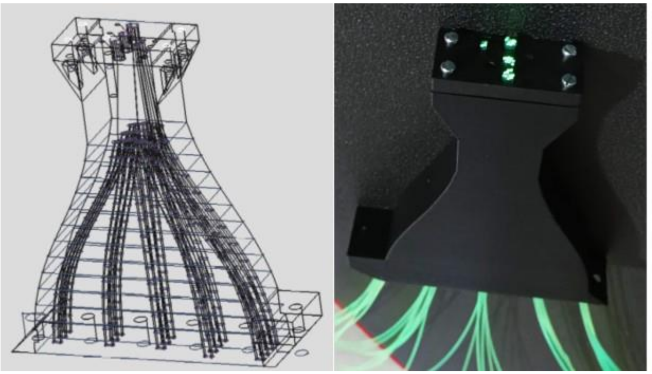
Tile painting
(EJ-510 TiO_2 reflecting painting)

Tile assembling on arcs and fiber routing



The tagger demonstrator: fiber routing

Fiber concentrators for bundling and routing to SiPMs



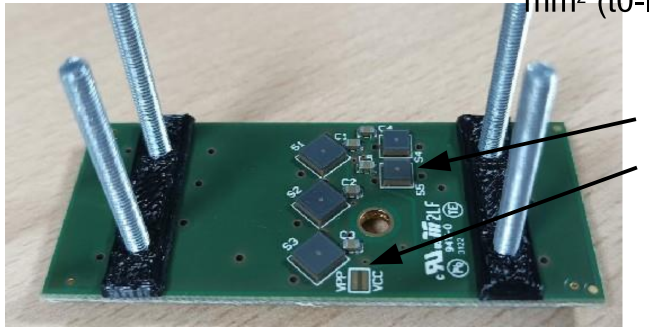
Custom design

Produced with 5 consumer level 3D printers

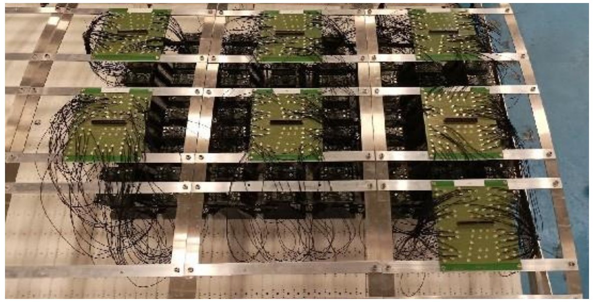
The tagger demonstrator: SiPM and front end electronics

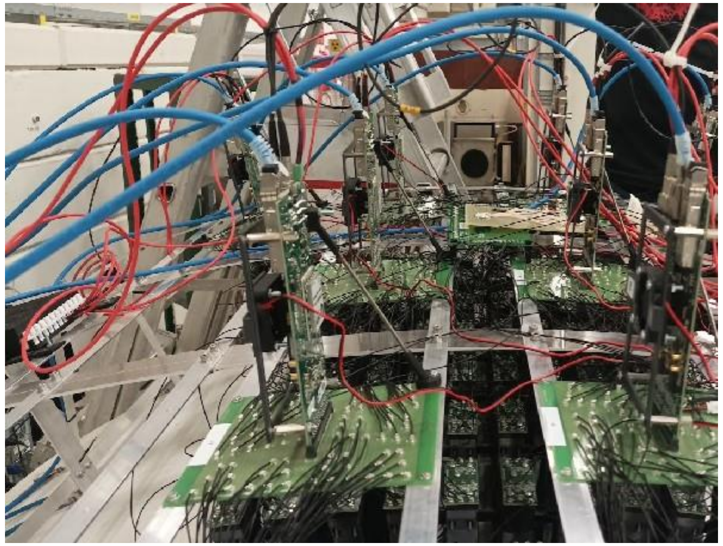
Frontend Board (FEB) equipped with:

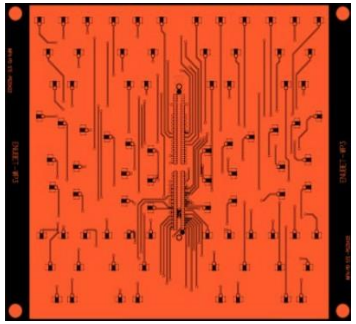
Hamamatsu S14160 series 3050HS 3x3 mm² (t0-layer) 4050HS 4x4 mm² (calo)



Typ. no.	Number of channels (ch)	Effective photosensitive area/channel (mm²)	Pixel pitch (μm)	Number of pixels/channel	Package	Window	Window refractive index	Geometrical fill factor (%)
S14160-3050HS		3.0 × 3.0		3531				
S14160-4050HS	1	4.0 × 4.0		6331				
S14160-6050HS		6.0 × 6.0		14331				
S14161-3050HS-04	16 (4 × 4)	3.0 × 3.0	50	3531	Surface mount type	Silicone	1.57	74
S14161-3050HS-08	64 (8 × 8)	3.0 × 3.0		3531				
S14161-4050HS-06	36 (6 × 6)	4.0 × 4.0		6331				
S14161-6050HS-04	16 (4 × 4)	6.0 × 6.0		14331				







Custom interface board to connect 5 FEB (60 ch) to a A5252
8 boards

CAEN A5202

64 readout channels

2 Citiroc-1A ASICs

Peak sensing

Amplitude / ToT

8 boards (2022) → 20 (2023)

ENUBET at CERN PS-T9 area

October 2022 CERN-PS-T9