3rd ANNUAL MEETING
Catania, 18-21 March 2024

CIEMAT R&D on light readout for cryogenic neutrino detectors (WP9)

CIEMAT Neutrino Group

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20th March 2024

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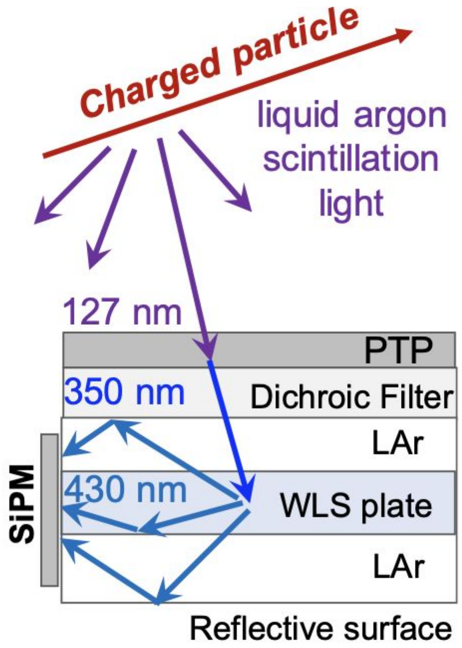
Photon Detectors in LAr: X-ARAPUCAs

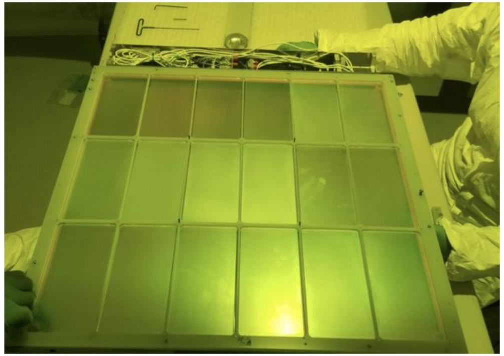


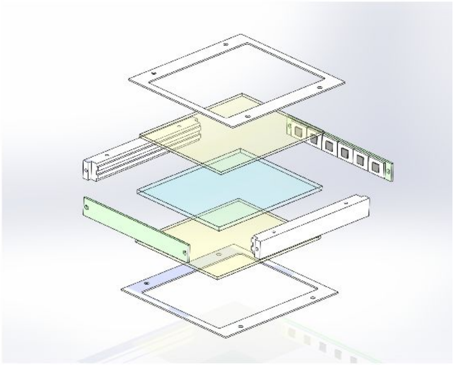
Challenges:

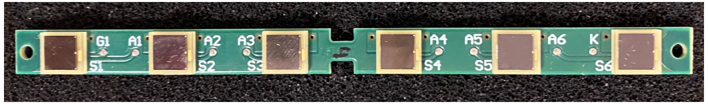
- The emitted photons' wavelength is **127 nm (VUV)** and typically photosensors are not sensitive.
- **Large detection area** is needed, but available space is limited.

X-ARAPUCA clever design:

- Traps the light and shift photons' wavelength to ~400 nm.
- More light opens additional physics opportunities like calorimetry and triggering.





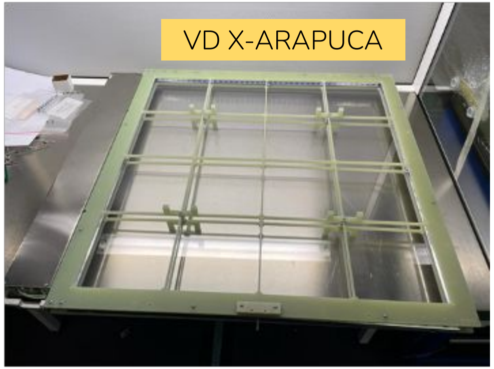


Photon Detectors in LAr: X-ARAPUCAs

- **DUNE HD X-ARAPUCAs** (10x50 cm^2): 6000 modules in DUNE FD, under commissioning in ProtoDUNE-HD.
- **DUNE VD X-ARAPUCAs** (60x60 cm^2): 672 modules in DUNE FD, to be tested in ProtoDUNE-VD in 2024.
- **SBND X-ARAPUCAs** (10x24 cm^2): 192 modules (visible and VUV sensitive), under commissioning.

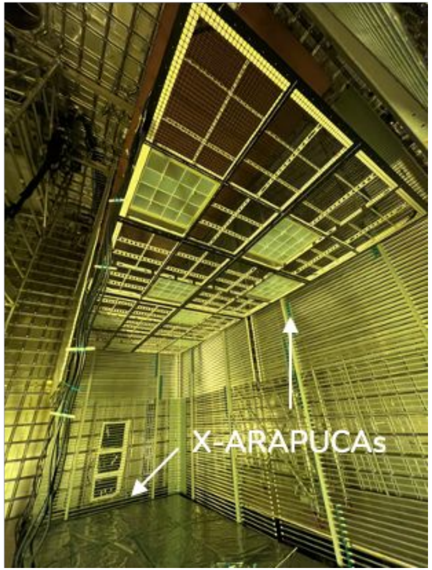
HD X-ARAPUCA

VD X-ARAPUCA

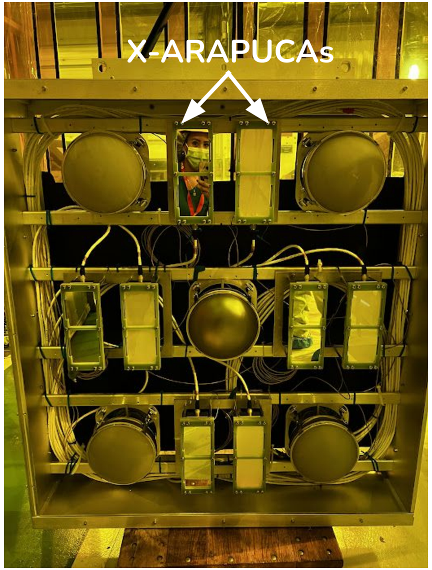


ProtoDUNE-HD

ProtoDUNE-VD



SBND



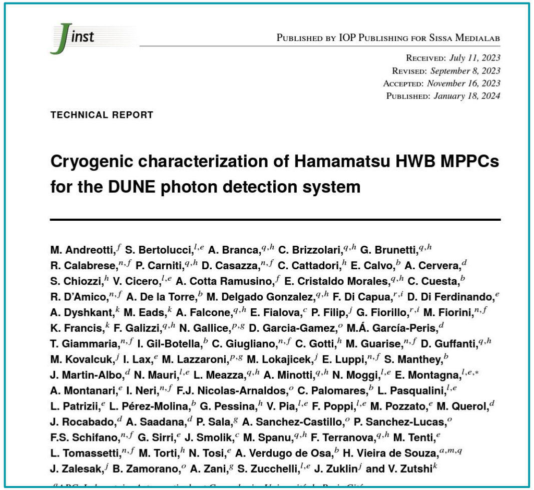
CIEMAT main activities on light readout R&D

1. SiPMs
2. DUNE HD X-ARAPUCA photon detection efficiency (PDE)
3. SBND X-ARAPUCA PDE
4. DUNE VD X-ARAPUCA PDE
5. ProtoDUNE-VD
6. DAPHNE electronics

1. R&D related to SiPMs

Publication of DUNE HPK SiPM characterization

JINST 19 (2024) T01007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TECHNICAL REPORT

Cryogenic characterization of Hamamatsu HWB MPPCs for the DUNE photon detection system

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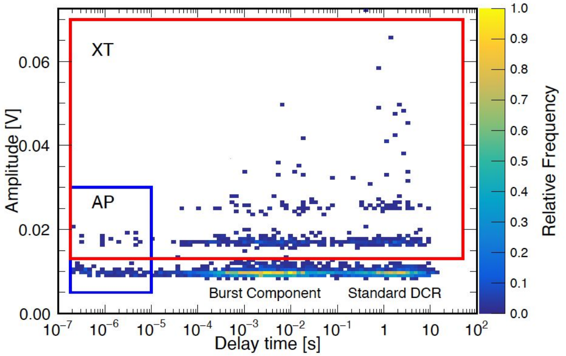
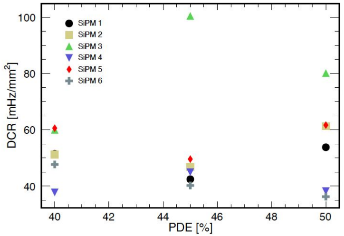
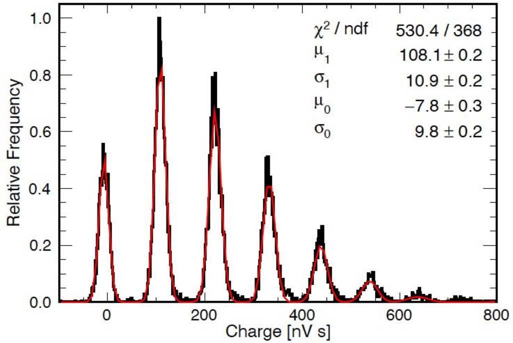
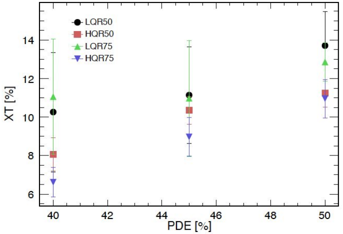
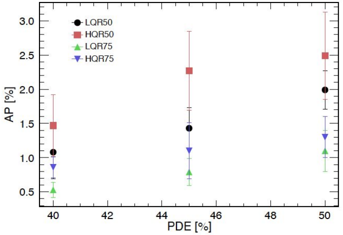






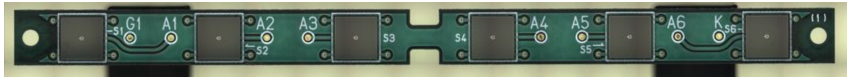


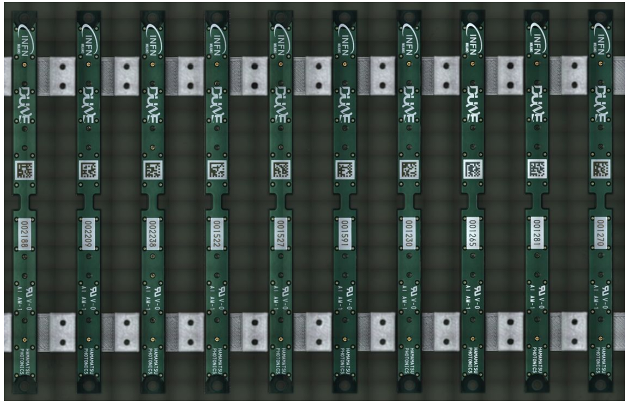


DUNE photosensor WG: CIEMAT, Czech Technical Univ, IFIC, INFN Bologna, Ferrara, Milano, Milano-Bicocca, Napoli, NIU, Campinas, Granada

Production phase: Mechanical measurements of SiPM boards

- Measurements made with a **3D vision machine.**
  Model: QUICK VISION Active 404.
  Precision: ±1.5 µm.
- **HPK:** 723 PCBs measured (4338 SiPMs & 5784 Pins).
- **FBK:** 50 PCBs measured (300 SiPMs & 400 Pins).



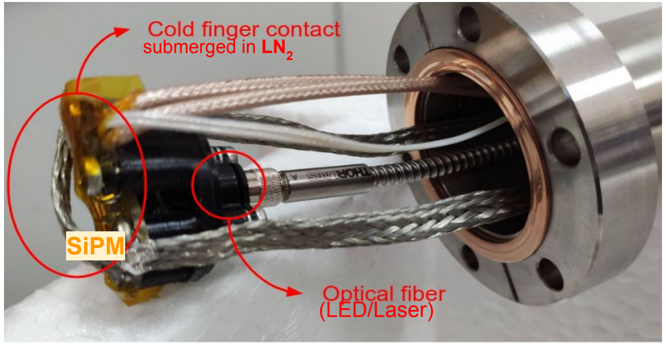


Measurement of HPK VUV4 SiPMs PDE at CT

Measure the PDE at CT relative to the one provided by HPK at RT:

$$PDE_{CT} = \frac{PE_{CT}}{PE_{RT}} PDE_{RT}$$

RESULT | CIEMAT Measurement | HPK Calibration

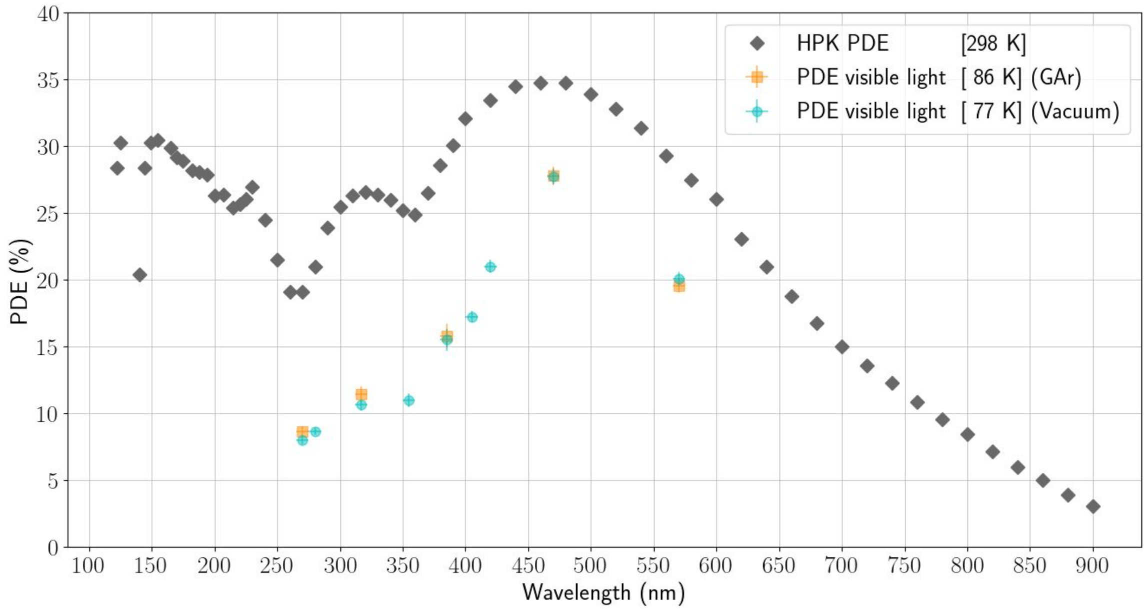


The procedure was:

1. **Gain calibration** measurements at RT for three different OV values.
2. **High-intensity light pulse** signal acquisition at RT for wavelengths between 270 – 570 nm.
3. Cooldown of the system to LN_2 temperature.
4. **Gain calibration** measurements at CT for three different OV values.
5. **High-intensity light pulse** signal acquisition at CT for wavelengths between 270 – 570 nm.

Measurement of HPK VUV4 SiPMs PDE at CT

RESULTS



- Two setups obtained compatible results showing a decrease in PDE for the Hamamatsu VUV4 SiPMs S13370 - 6075CN when operating at CT.
- The difference between PDE at different temperatures is also dependant on the wavelength: we can see less decrease in the PDE at CT for ~ [450, 480] nm.

Publication under review by NIM-A

arXiv: 2402.01584

AIDA innova

Photon Detection Efficiency

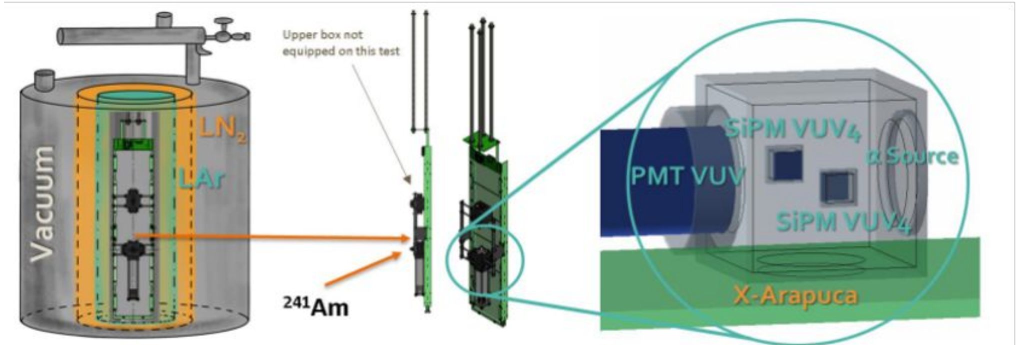
PHOTON DETECTION EFFICIENCY MEASUREMENT

- Reference parameter for:
  - X-ARAPUCA **design optimization.**
  - **Data-MC comparison** in ProtoDUNE and DUNE.
- Challenge: need to be measured with VUV light and cryogenic temperature.
- Method: comparison of detected light with a reference sensor using an alpha source in LAr:

$$\epsilon_{MAD}(XA) = \frac{\#PE_{u.a.}(XA)}{\#PE_{u.a.}(Ref.SiPM)} \cdot \frac{\Omega_{u.a.}(XA)}{\Omega_{u.a.}(Ref.SiPM)} \cdot \epsilon(Ref.SiPM) \cdot f_{corr}$$

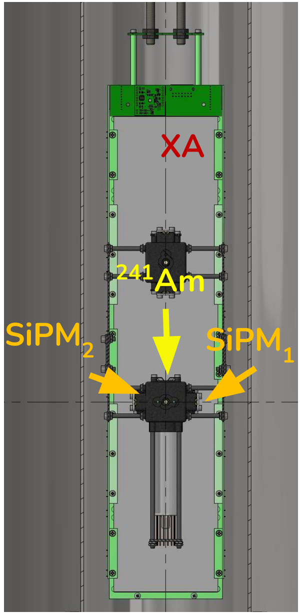
Developed different setups at CIEMAT to measure PDE of:

- FD1-HD X-ARAPUCAs
- SBND X-ARAPUCAs
- FD2-VD X-ARAPUCAs



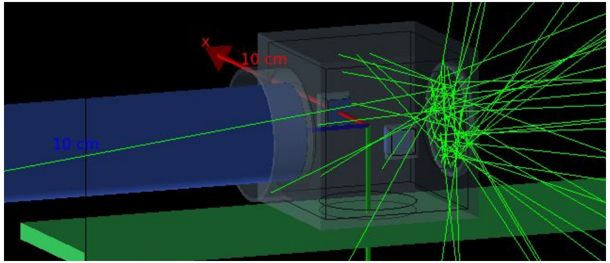
2. R&D related to DUNE HD PDE

Final results of DUNE FD1-HD X-ARAPUCA detection efficiency



Method (A): reference SiPM comparison

$$\epsilon_A(XA) = \frac{PE_{mm^2}(XA)}{PE_{mm^2}(SiPM)} \cdot f_{corr} \cdot \epsilon(SiPM)$$



Method (B): simulation based

$$\epsilon_B(XA) = 100 \cdot \frac{PE(XA)}{\gamma_{expected}} \cdot f'_{corr}$$

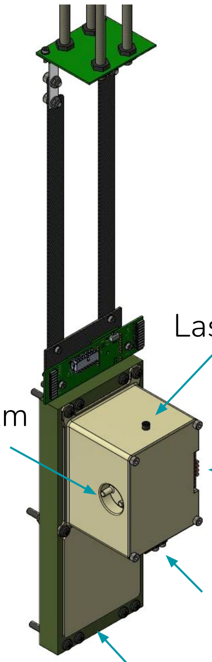
Method	PDE % FBK + EJ (OV 4.5 V)	PDE % HPK + EJ (OV 3 V)	PDE % HPK + G2P (OV 3 V)
(A)	**1.34 ± 0.24**	**1.59 ± 0.29**	**2.13 ± 0.38**
(B)	1.61 ± 0.12	1.86 ± 0.15	2.50 ± 0.21

Publication in preparation

- Results from both methods in agreement
- 3 configurations tested: G2P plates present a higher efficiency

3. R&D related to SBND PDE

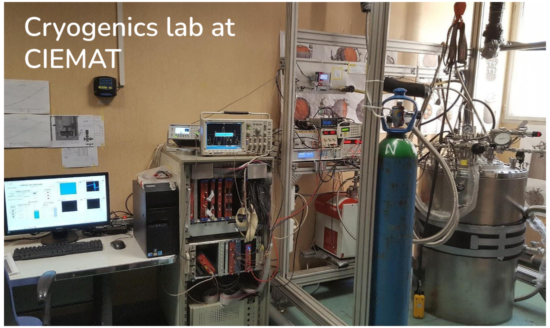
SBND X-ARAPUCA Photon Detection Efficiency

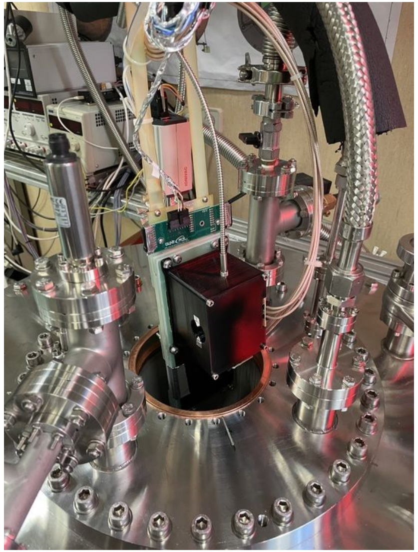


Calibration box

- VUV reference SiPM pairs in front of alpha-source and laser.
- Full X-ARAPUCA window coverage to eliminate shadowing effects.

4 SBND X-ARAPUCA configurations tested		
SiPMs	**WLS Bar**	**Filter**
SensL	Eljen 286	pTP coated 400 nm cutoff
SensL	Eljen 280	450 nm cutoff (only visible light)
HPK	Glass to power (blue)	pTP coated 400 nm cutoff
HPK	Glass to power (green)	450 nm cutoff (only visible light)

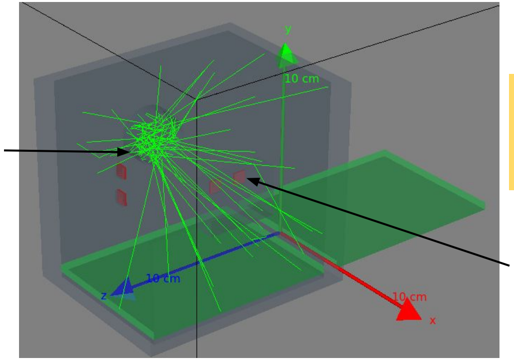




SBND X-ARAPUCA PDE simulation and raw data

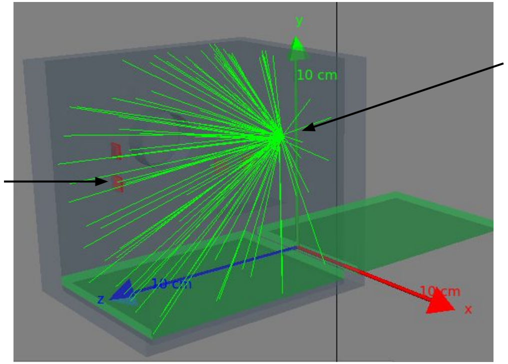
G4 simulations of the setup

^{241}Am



VUV light from α source

SiPMs x 2

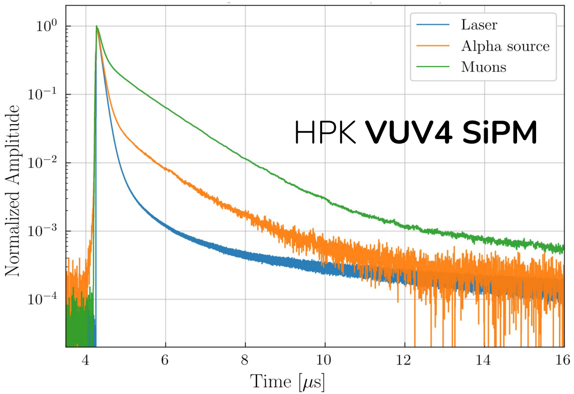


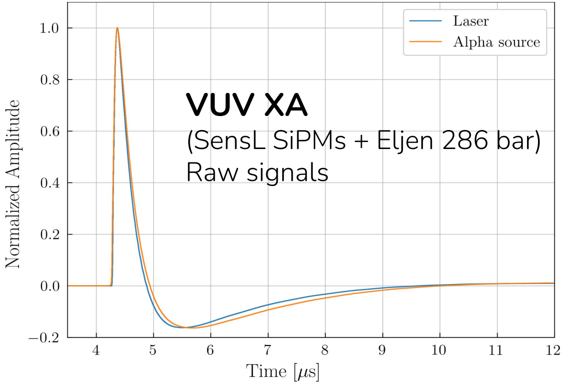
Laser (420 nm)

Visible light from laser

SiPMs x 2

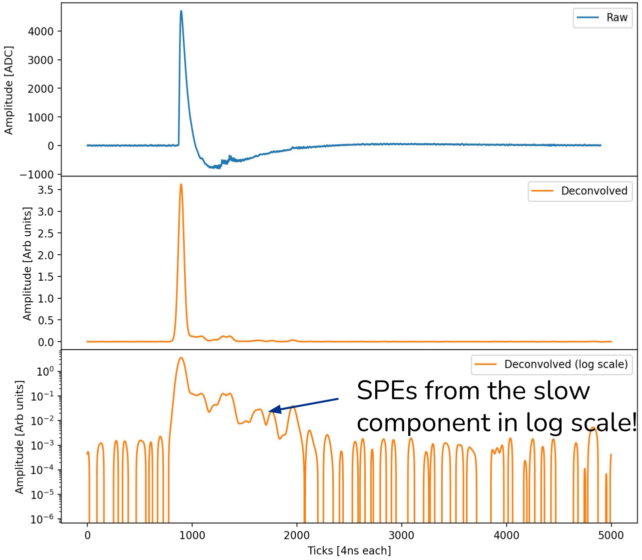
Measured averaged waveforms





SBND X-ARAPUCA deconvolution & particle ID

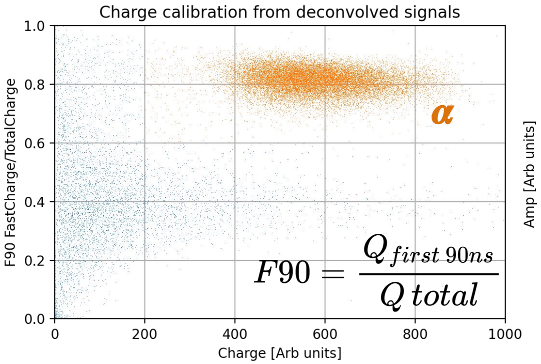
To remove overshooting and detector response, a combination of **deconvolution** and Gauss filtering of the raw signals was used.

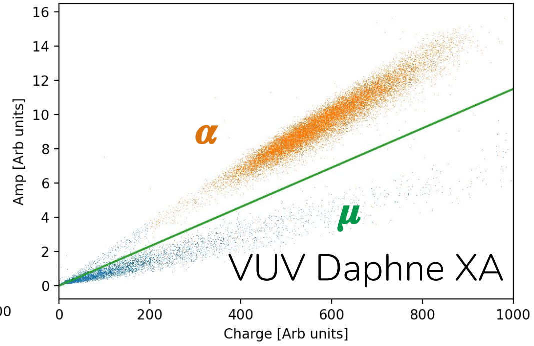


Different particles have different contributions of fast and slow components of LAr scintillation light.

This can be used to perform **particle ID**.

Same cuts:
f90>0.6, Q>200

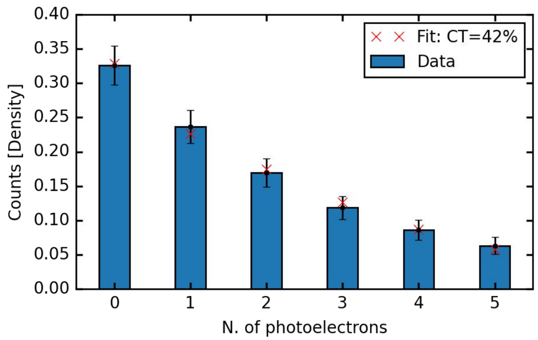




Results of VUV PDE measurement

- Calibration data was analyzed to estimate the **crosstalk probability** for both reference SiPMs and X-ARAPUCAs at different overvoltages
- From X-ARAPUCA and reference VUV SiPMs (with known PDE) charge ratio, we can determine the **PDE value for both VUV and TPB wavelengths.**

SensL pTP X-ARAPUCA, OV 6 [V]



HPK pTP X-ARAPUCA

OV [V]	PDE [%] at 127 nm
2	1.97 ± 0.22
2.5	2.16 ± 0.25
3	2.28 ± 0.25

OV [V]	PDE [%] at 420 nm
2	0.20 ± 0.01
2.5	0.23 ± 0.02
3	0.25 ± 0.01

SensL pTP X-ARAPUCA

OV [V]	PDE [%] at 127 nm
3.25	1.27 ± 0.11
4.25	1.56 ± 0.14
5.75	2.19 ± 0.20

OV [V]	PDE [%] at 420 nm
3.25	0.17 ± 0.01
4.25	0.19 ± 0.01
5.75	0.24 ± 0.01

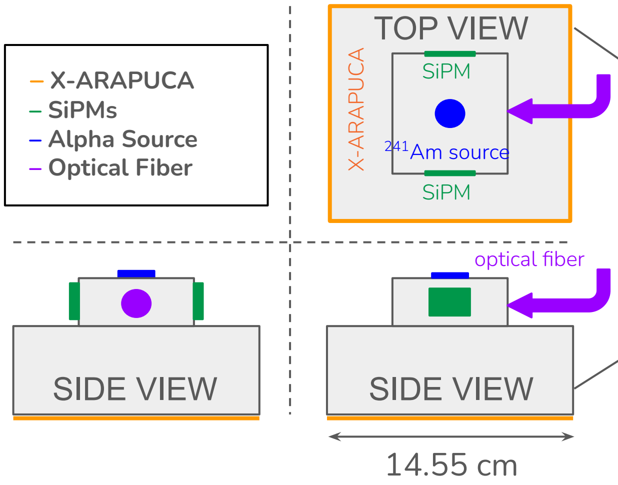
Measured at average incidence angle of 40° (dichroic filter transmittance depends on incident angle).
For VUV is not relevant as pTP re-emmits isotropically on the XA surface

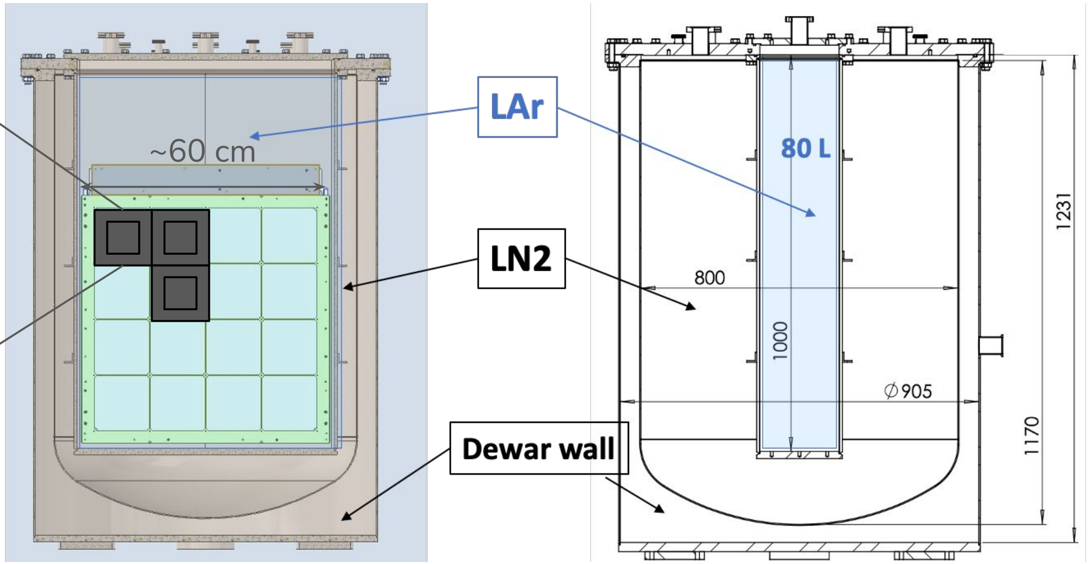
- Next data taking campaign with configurations of 450 nm cutoff (only visible light) in Spring 2024

4. R&D related to DUNE VD PDE

Setup for characterization of VD X-ARAPUCA modules at CIEMAT

PDE measured wrt. the known efficiency of reference VUV SiPMs in LAr* with light from **three ^{241}Am alpha sources** at the only **3 unidentical XA positions**.



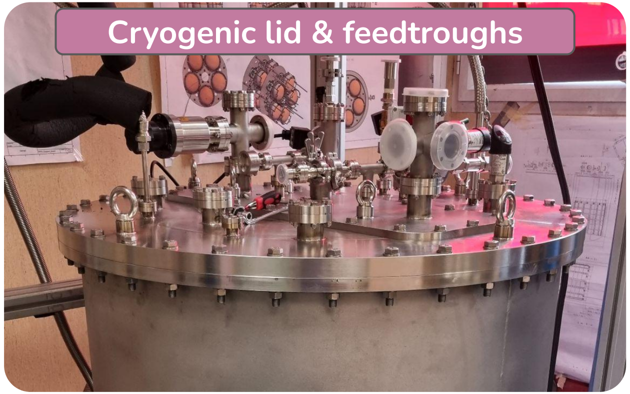


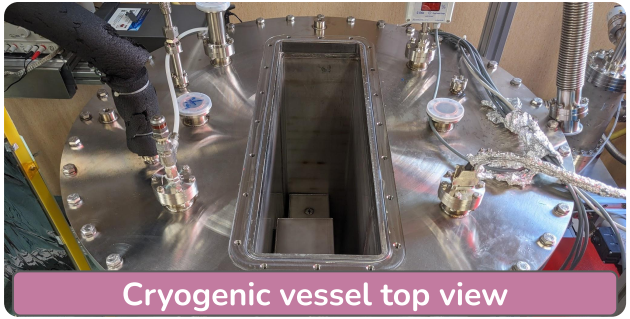
*GAr 99.9999% is liquified with LN_2 at 2.7 bar

Setup at CIEMAT: Vessel Assembly


LAr dewar

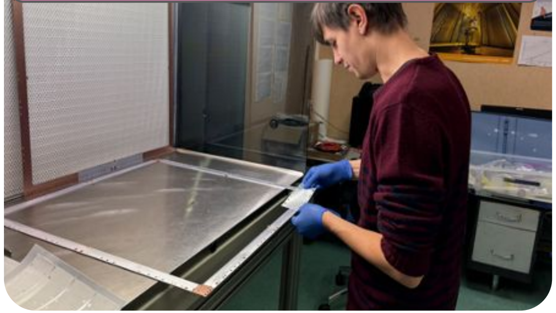

Characterization setup

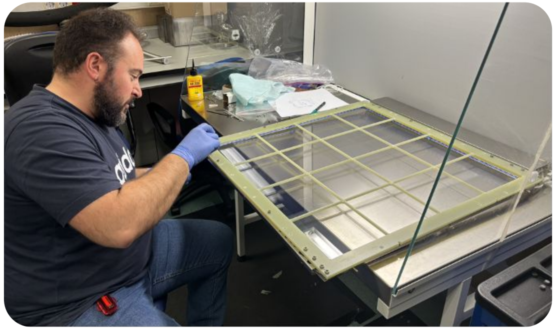

Cryogenic lid & feedtroughs


Cryogenic vessel top view

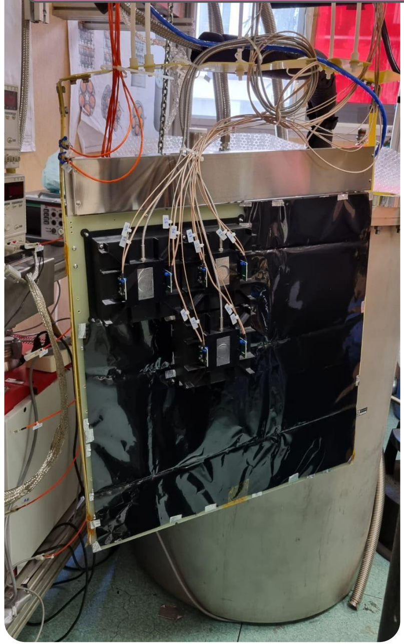
Setup at CIEMAT: X-ARAPUCA Assembly & Insertion

XA assembly





Inserting the VD-XA in the vessel

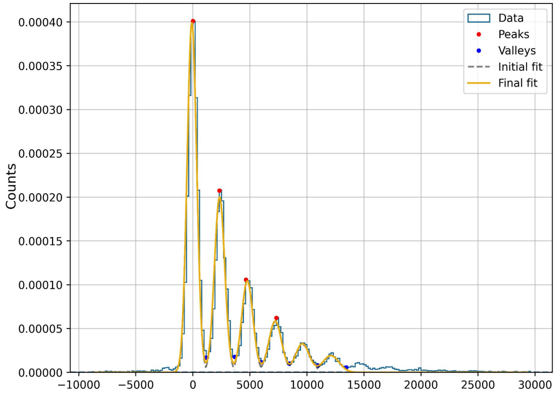


X-ARAPUCA Gain and S/N

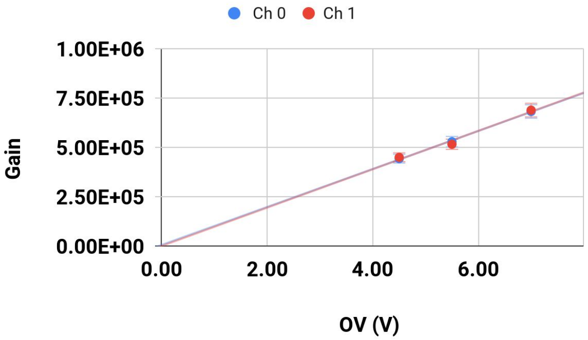
- Both XA-channels successfully calibrated.
- Same procedure followed for all 6 ref. SiPMs.

XA	Channel 0			Channel 1		
OV	Gain e⁻	DGain e⁻	S/N	Gain e⁻	DGain e⁻	S/N
7.0	6.8598E+05	1.54E+03	5.37	6.9381E+05	2.13E+03	5.86
5.5	5.2904E+05	9.28E+02	6.50	5.1812E+05	1.51E+03	7.24
4.5	4.4457E+05	1.29E+03	4.48	4.5059E+05	1.98E+03	4.54

XA - Channel 0



XA Channel Comparison

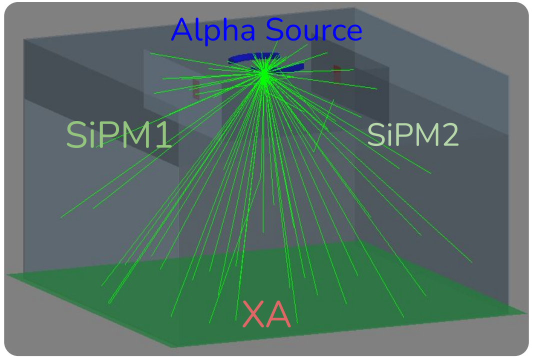


Geometric Factor

- Ratio of photons determined by **standalone GEANT4 simulation.**
- Accounts for the differences in sizes/positioning of ref. sensors.

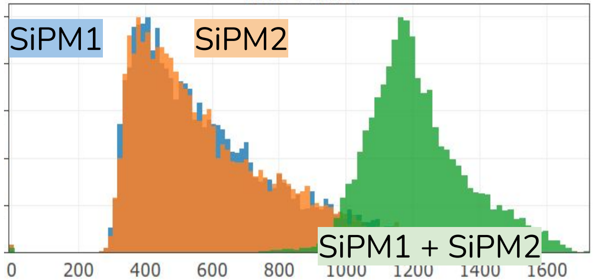
$$f_{geom} = \frac{\Omega(Ref.)}{\Omega(XA)} = (0.047 \pm 0.009)$$

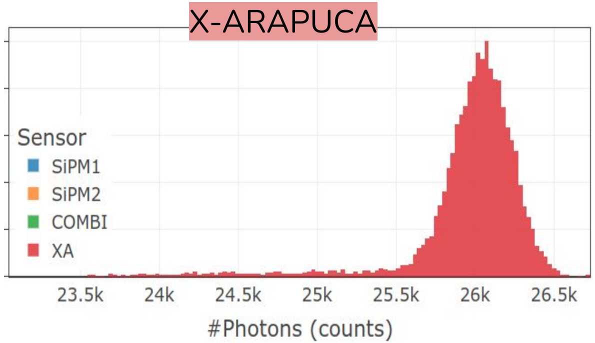
Sensor	MEAN Ph.	STD
XA (21170 mm²)	25995	312
SiPM (12 mm²)	1216	220



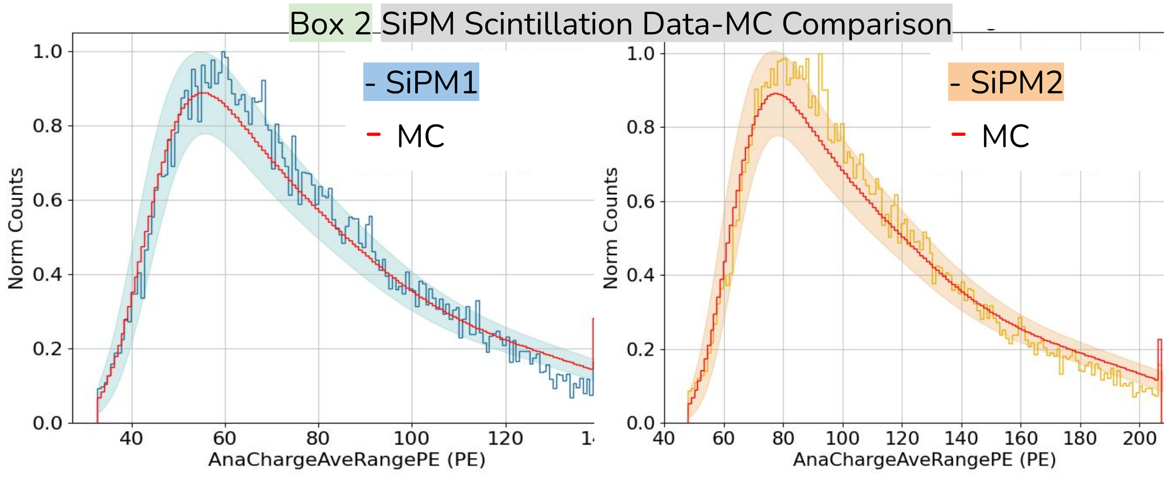
14.55 x 14.55 cm²

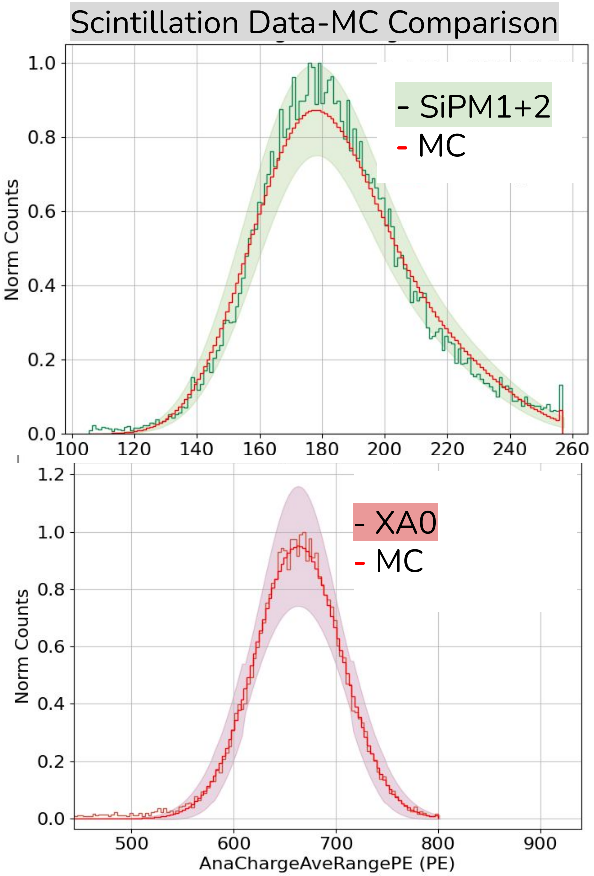
Photon distribution at sensors





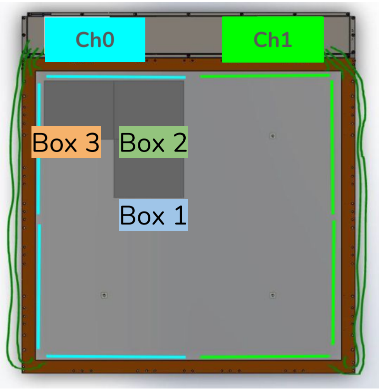
Data-MC comparison





Fitting alpha scintillation light data with simulation templates provides **good agreement** → **Simulation reproduces experiment.**

Preliminary VD X-ARAPUCA PDE results

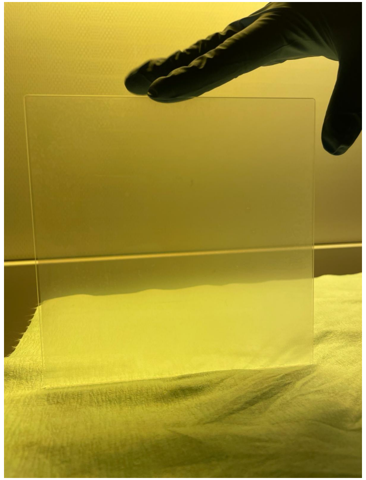


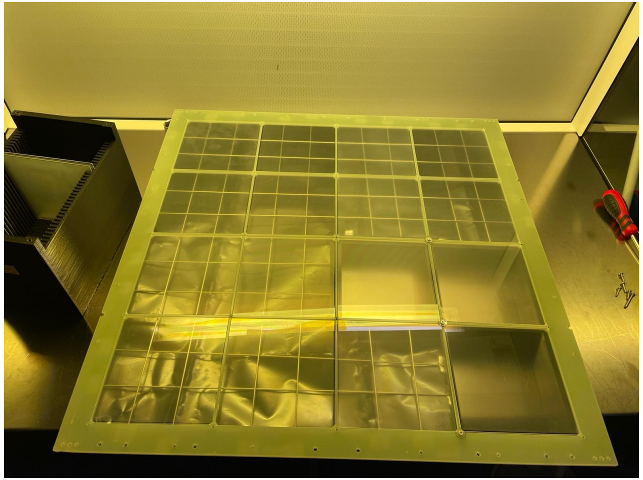
- **CIEMAT results VD-XA:**
  - Using geometric and Xtalk corrections.
  - 3 boxes representing all different positions.
  - FBK mounted SiPM boards.

	Box 1	Box 2	Box 3
OV	XA PDE	XA PDE	XA PDE
7	(3.4 - 4.2) %	(3.6 - 4.4) %	(3.7 - 4.6) %
4.5	(2.6 - 3.2) %	(2.7 - 3.4) %	(2.8 - 3.5) %
3.5	(2.4 - 2.9) %	(2.5 - 3.1) %	(2.6 - 3.2) %

Next measurement

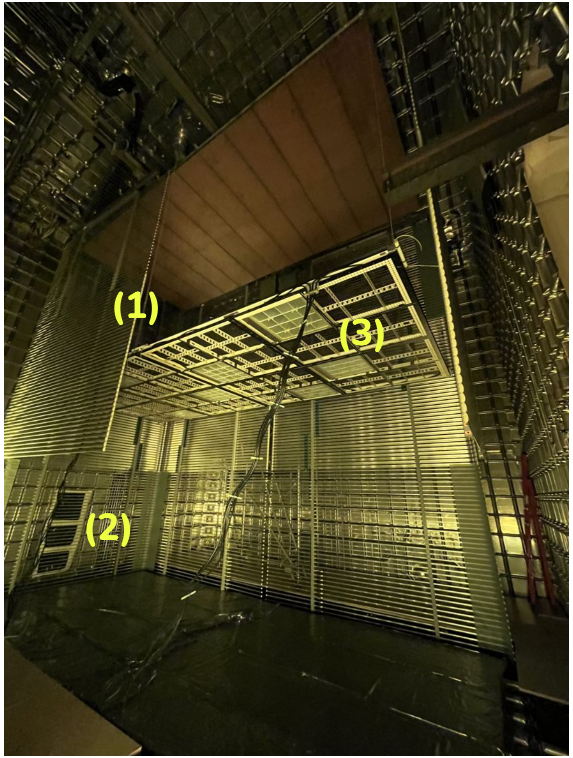
- **Filter replacement** by pTP-coated substrates.
- Measurement taken in March 2024, analysis on-going.

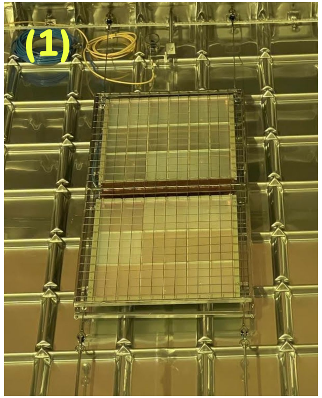




5. R&D related to ProtoDUNE-VD

Installation of Photon Detection System in ProtoDUNE-VD at CERN

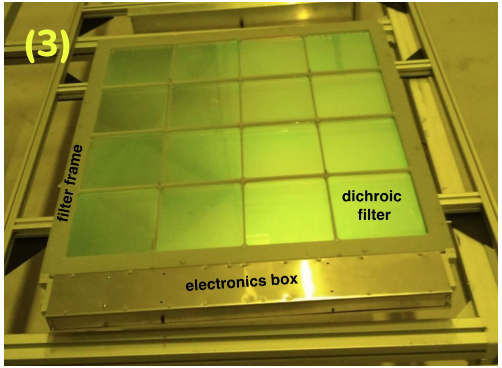




top membrane
X-ARAPUCAs

bottom membrane
X-ARAPUCAs

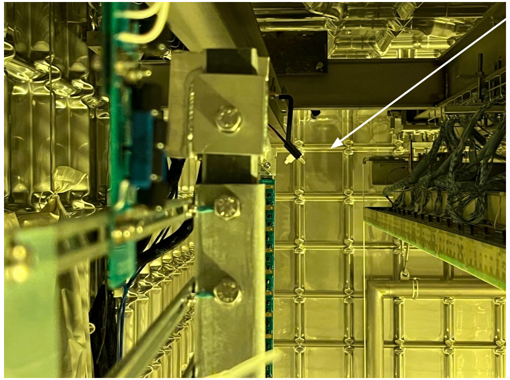
cathode X-ARAPUCA

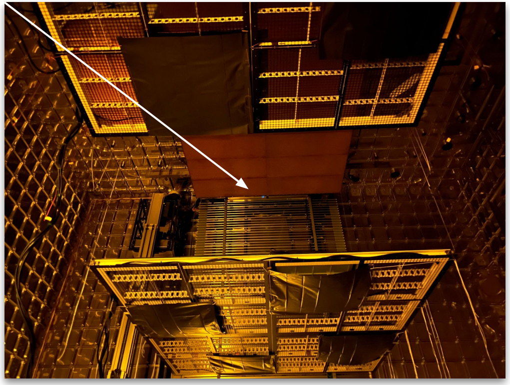


Installation of light monitoring system in ProtoDUNE-VD at CERN

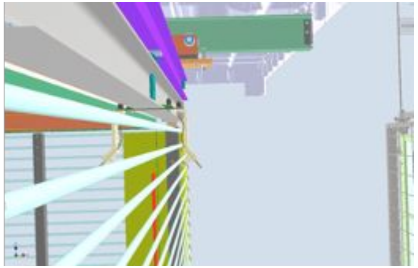
- 2 monitoring-system kits are installed at the top beams that support the field cage: 1-to-2 fiber bundle with endpoints attached at the support structure pointing one fiber towards the cathode X-ARAPUCAs and the other one towards the membrane X-ARAPUCAs.
- 2 monitoring-system kits to be installed at the bottom of the field cage.
- Fibers are **routed** towards the flange.
- Fibers are attached to the **flange**.

LED illuminated **fiber** pointing towards cathode X-ARAPUCAs





Flange

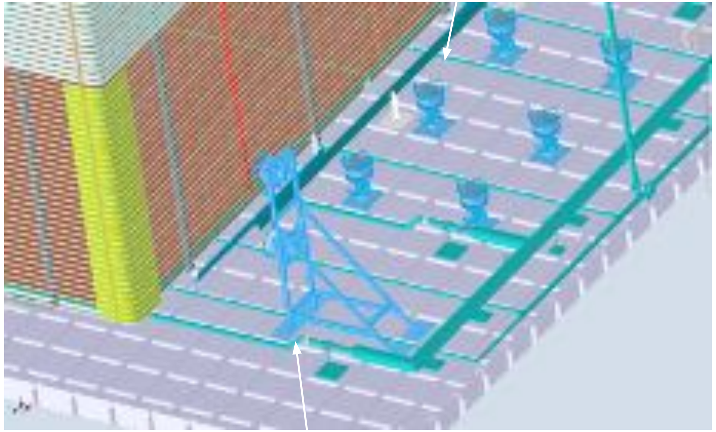


Fibers pointing towards cathode and membrane wall X-ARAPUCAs

PMTs in ProtoDUNE-VD

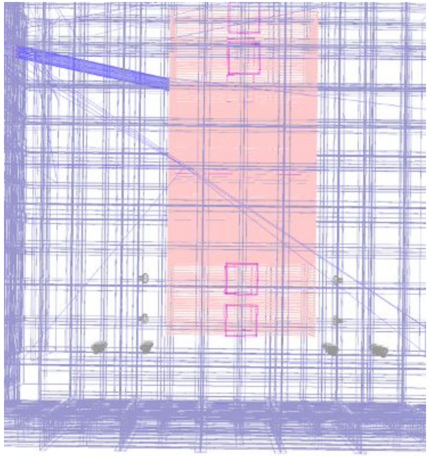
- Proposal for **installing 24 PMTs** from ProtoDUNE-DP in ProtoDUNE-VD, outside the field cage.
- **Physics goals:** photon detection efficiency measurement, study of LAr scintillation light with Xe doping and monitoring.
- Preparation for data taking with **DAPHNE** on-going.
- Installation in spring/summer 2024.

Study of light propagation in 6 m with vertical PMTs.



Measurement of photon detection efficiency with horizontal PMTs looking towards the field cage.

PMT geometry implemented in ProtoDUNE-VD simulation



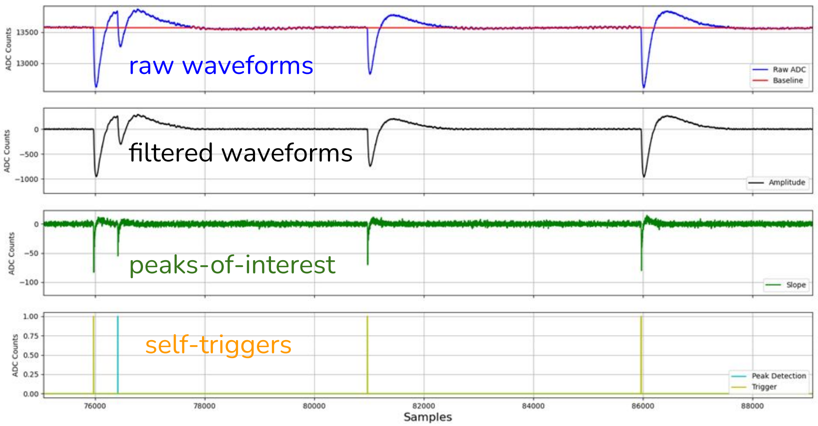
6. R&D related to DAPHNE electronics

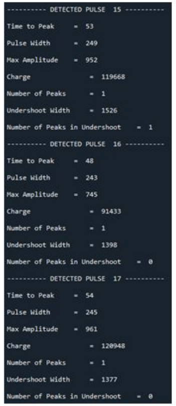
PDS trigger development for DUNE

Developed algorithm for **self-trigger** (zero suppression) and **trigger primitive** calculation for DUNE PDS readout electronics (**DAPHNE**).

- Post-synthesis timing simulation performed and implemented in the device's FPGA.

DUNE VD X-ARAPUCA waveforms





Trigger primitive values

SUMMARY

SUMMARY

1. **SiPMs:**
   - Publication of DUNE HPK SiPM characterization, JINST 19 (2024) T01007
   - Mechanical measurements of SIPM boards with a 3D vision machine (Precision: ±1.5 μm) in production phase.
   - Measurement of HPK VUV4 SiPMs PDE at CT, arXiv: 2402.01584

2. **DUNE HD X-ARAPUCA photon detection efficiency (PDE)** measured, publication in preparation.

3. **SBND X-ARAPUCA PDE** measured for VUV configurations.

4. **DUNE VD X-ARAPUCA PDE** measurement in two different configurations, analysis on-going.

5. **ProtoDUNE-VD**: installation of photon detection system and light monitoring system at CERN.

6. **DAPHNE electronics**: Developed algorithm for self-trigger (zero suppression) and trigger primitive calculation for DUNE PDS readout electronics.