

# Photon-Detection System of DUNE Far Detector

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on behalf of DUNE Collaboration



# DUNE: Long-Baseline Neutrino Experiment

## Far Detector

### LAr-TPC (17 kton)

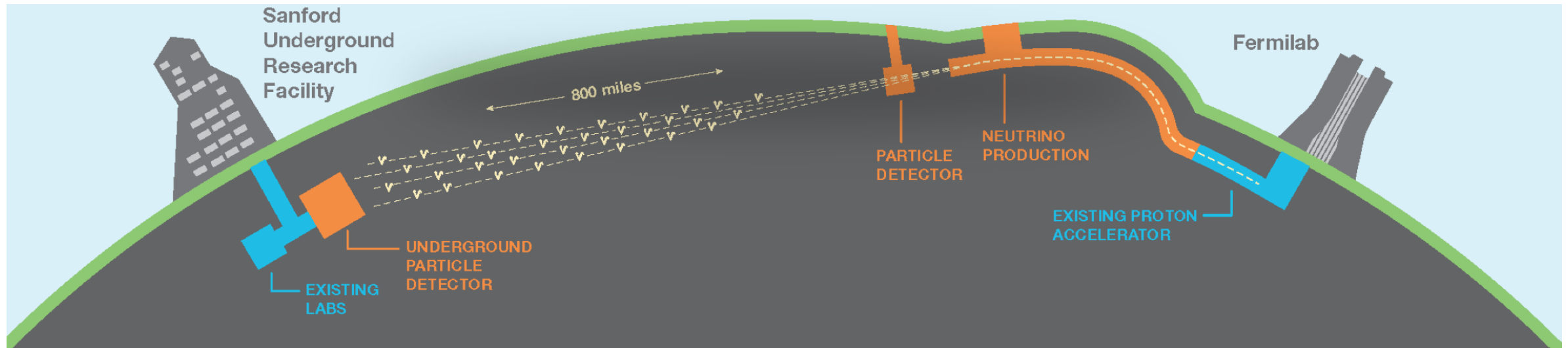
- 1300 km from Fermilab
- Measurement of oscillated neutrinos

## Near Detector

- Monitoring unoscillated neutrino energy spectra & composition
- Crucial for systematic errors control
- $\nu$ Ar cross-section measurements

## Muon neutrino beam

- LBNF Neutrino Beam
- 1.2 MW beam power
- Upgradeable to 2.4 MW



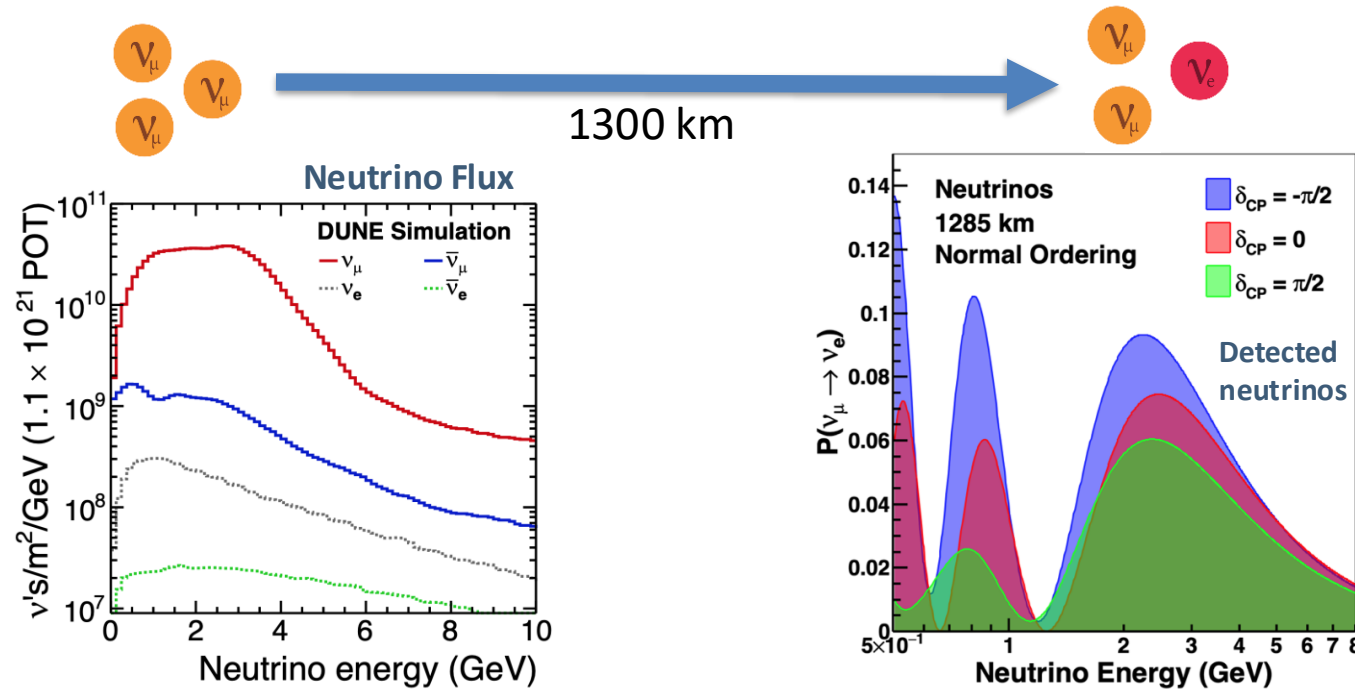
# DUNE Physics

Measurement of  $\nu_e$  appearance and  $\nu_\mu$  disappearance with a wide range energy  $\nu_\mu$  beam at 1300 km would allow

- Definitive measurement of neutrino Mass Ordering
- Discovery potential for CP violation for wide range of  $\delta_{CP}$
- Precise measurement of neutrino mixing parameters

## No Beam Physics

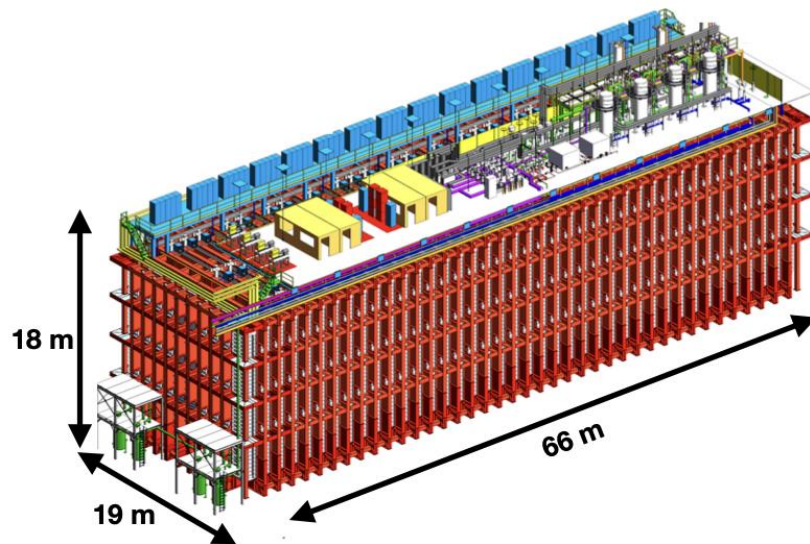
- Supernova Neutrino Burst
- Solar neutrino
- Proton Decay
- BSM physics



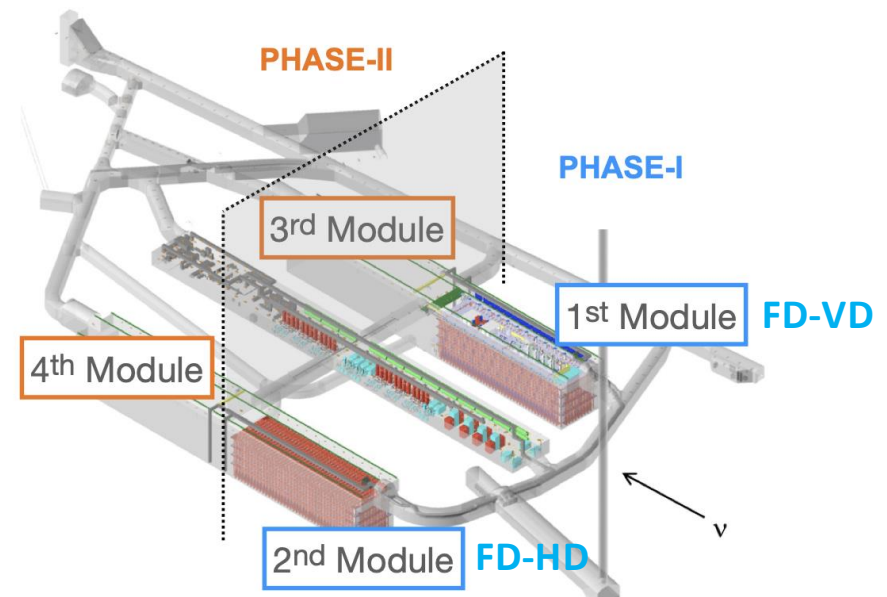
*Eur.Phys.J.C* 80 (2020) 10, 978

# DUNE Far Detector

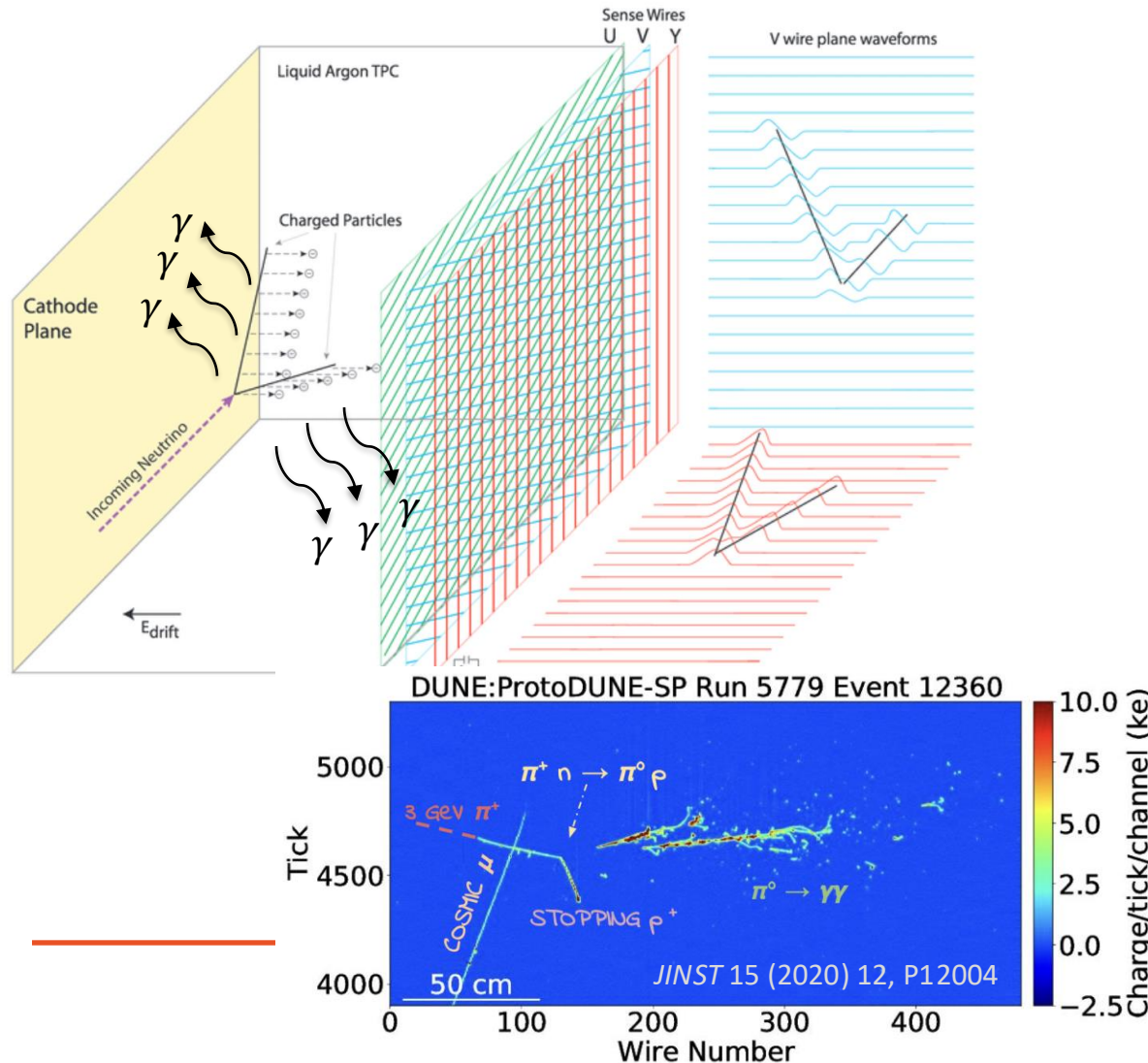
- Detector located 1.5 km underground at SURF
- 4 detector modules filled with 17kton of liquid Ar (-184 deg C)
- Detector deployment in stages:
  - DUNE PHASE-I (Modules 1<sup>st</sup> & 2<sup>nd</sup> )
  - DUNE PHASE-II (Modules 3<sup>rd</sup> & 4<sup>th</sup>)



Two-phase approach  
Improvements in technology  
implemented in Phase-II



# DUNE Far Detector: LAr TPC



## Neutrino detection in LAr TPC

Two signals proportional to the energy deposit

**Ionization electrons**  
~27000 e-/MeV

**Scintillation photons**  
~24000 ph/MeV

For 500 V/cm drift field

Drifted and collected in  
anode planes

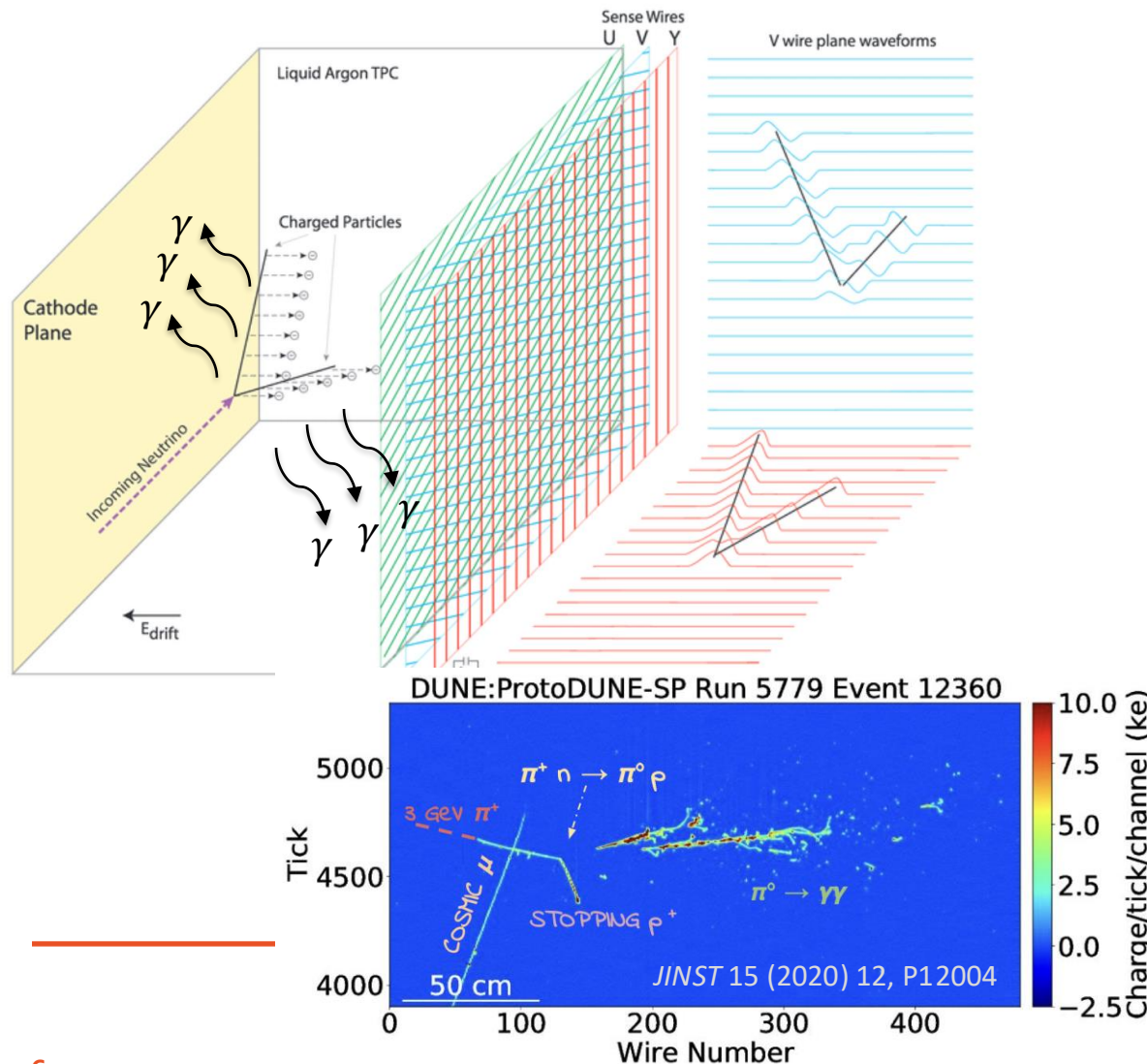
Collected by  
photon-detectors

Precision tracking  
calorimetry

T0 and complementary  
calorimetry



# DUNE Far Detector: LAr TPC



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T0 and complementary calorimetry



# Photon-Detection System

The Photon-Detection System (PDS) is crucial to fulfil DUNE physics goals

## Nucleon decay

Reducing the background is a must for nucleon decay triggering

→ Fiducialization with t<sub>0</sub>: PDS will be able to determine t<sub>0</sub> with a resolution of  $\sim 1\mu\text{s}$

## Supernova Neutrinos

→ Improving Time and Energy resolution with t<sub>0</sub> (and complementary calorimetry)

→ Redundancy trigger

→ Improving signal reconstruction thanks to PDS-cluster matching

## Solar neutrinos

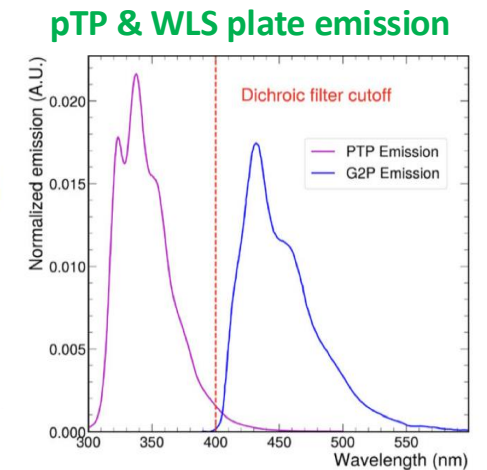
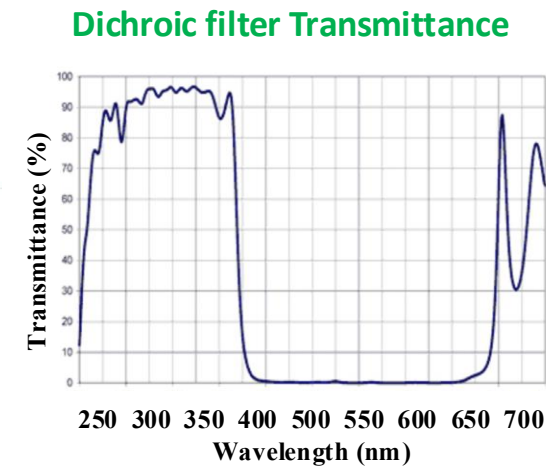
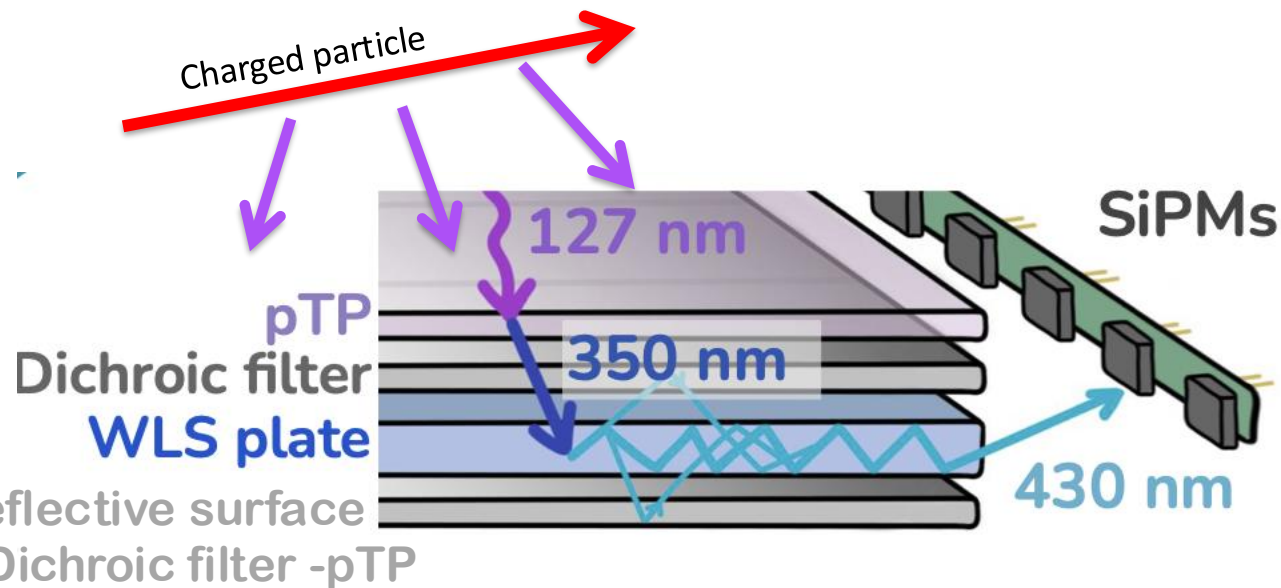
→ Improving signal reconstruction thanks to PDS-cluster matching

Different proposals for 3<sup>rd</sup> and 4<sup>th</sup> Phase-II modules are focused in the improvement of the PDS to extend the scope of DUNE non-beam physics

# Photon-Detection System: X-ARAPUCA

## Large-area compact devices

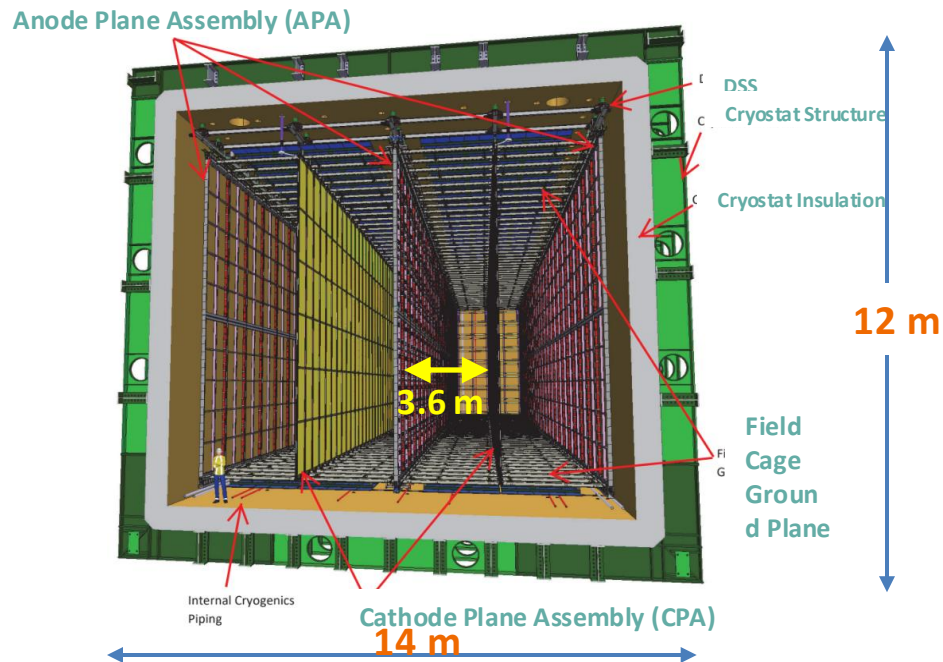
1. The pTP converts VUV light to a wavelength below the dichroic filter (DF) cutoff ( $\sim 400\text{nm}$ )
2. The **dichroic filter** transmits 350 nm photons
3. The **wavelength shifter plate** shifts the light above DF cutoff (430 nm) and guides the photons to the **SiPMs** coupled to the plate



# DUNE Far Detector

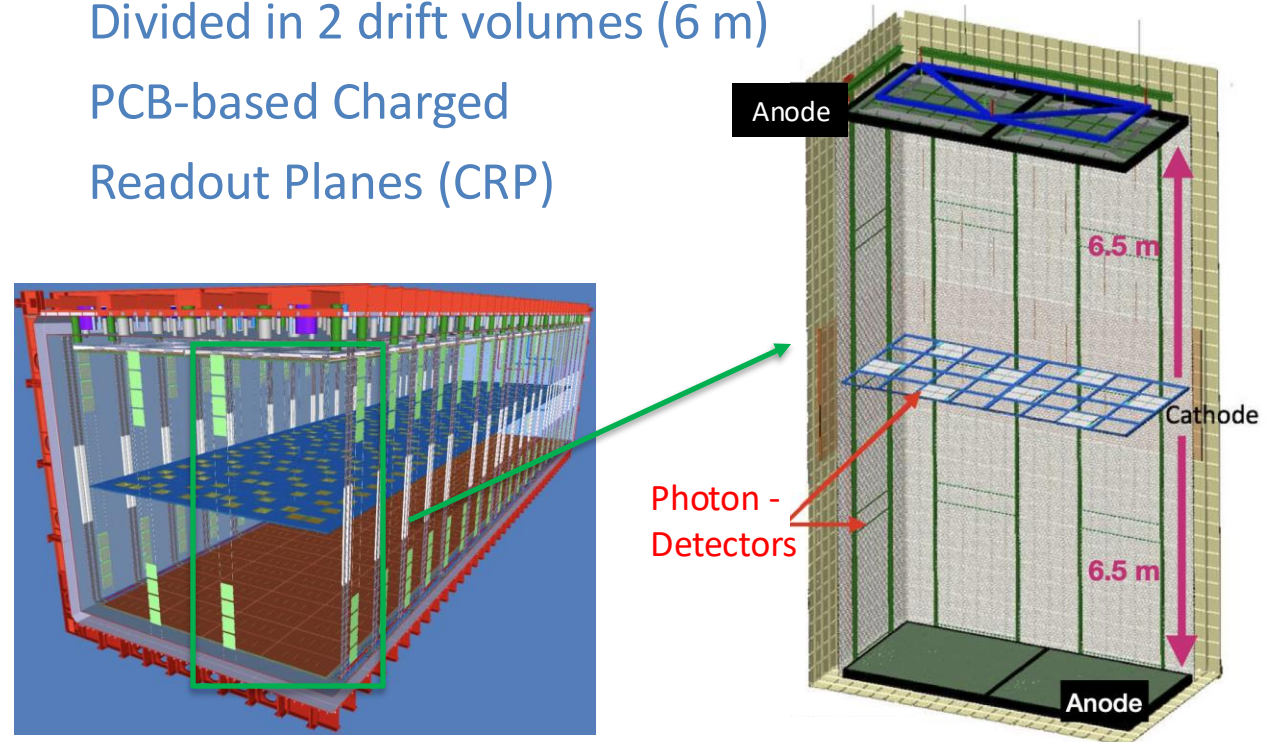
## Horizontal-Drift **FD-HD**

Divided in 4 drift volumes (3.6 m)  
 Charge readout based on wires (APA)



## Vertical-Drift **FD-VD**

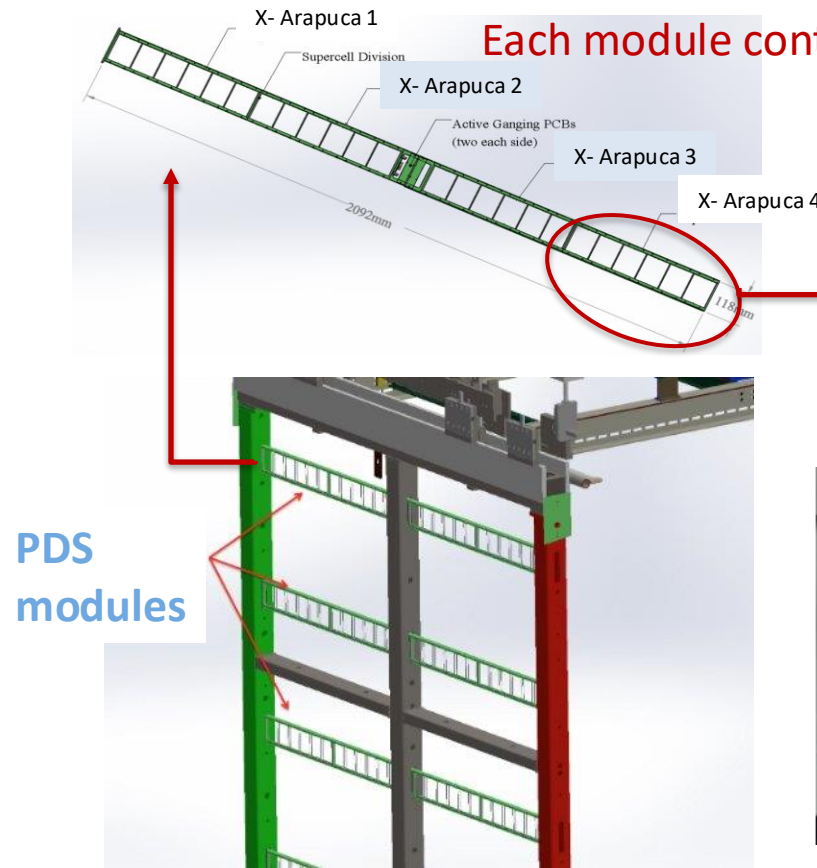
Divided in 2 drift volumes (6 m)  
 PCB-based Charged Readout Planes (CRP)



# Photon-detection system: FD-HD

10 X-ARAPUCA modules placed in the inactive space of every Anode Planes Assembly (APA) (150)

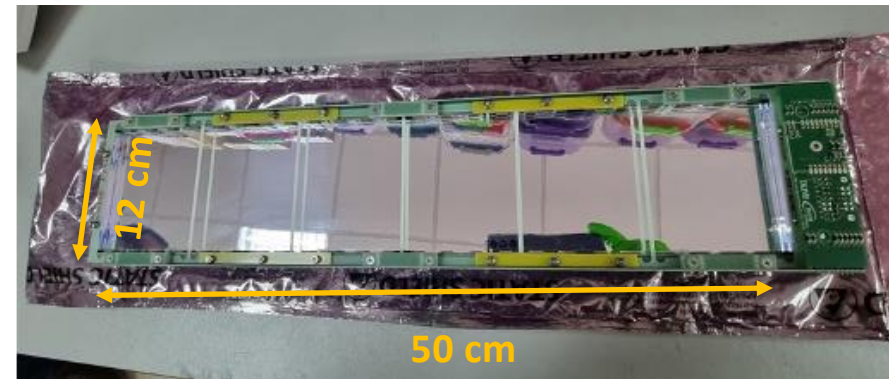
ProtoDUNE-HD



Each module contains 4 X-ARAPUCA

- 6 dichroic filters
- 1 WLS plate
- 48 6x6 mm<sup>2</sup> SiPMs. (Hamamatsu and FBK)
- One readout channel only

X-ARAPUCA HD



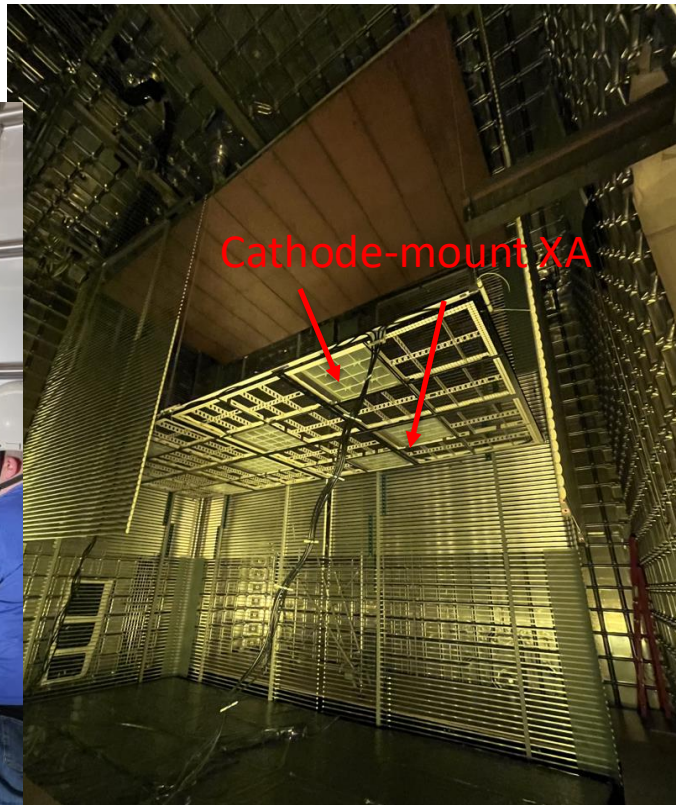
PDS modules

# Photon-detection system: FD-VD

Double-sided X-ARAPUCA embedded in the cathode – 300kV (power and signal over fibre technology)  
[JINST 19 \(2024\) 10, P10009](#)

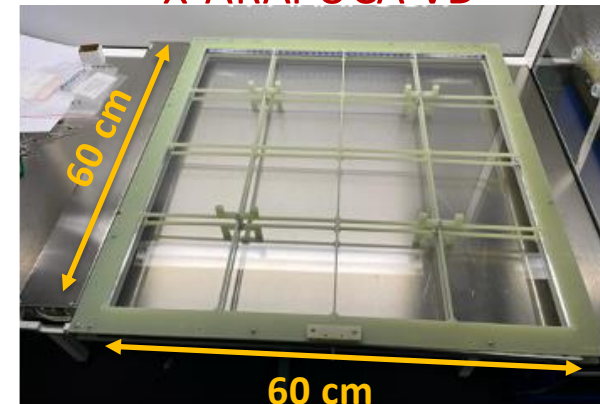
Single-sided X-ARAPUCA in the membrane walls (copper cable) – semi-transparent field-cage

Wall-mount XA

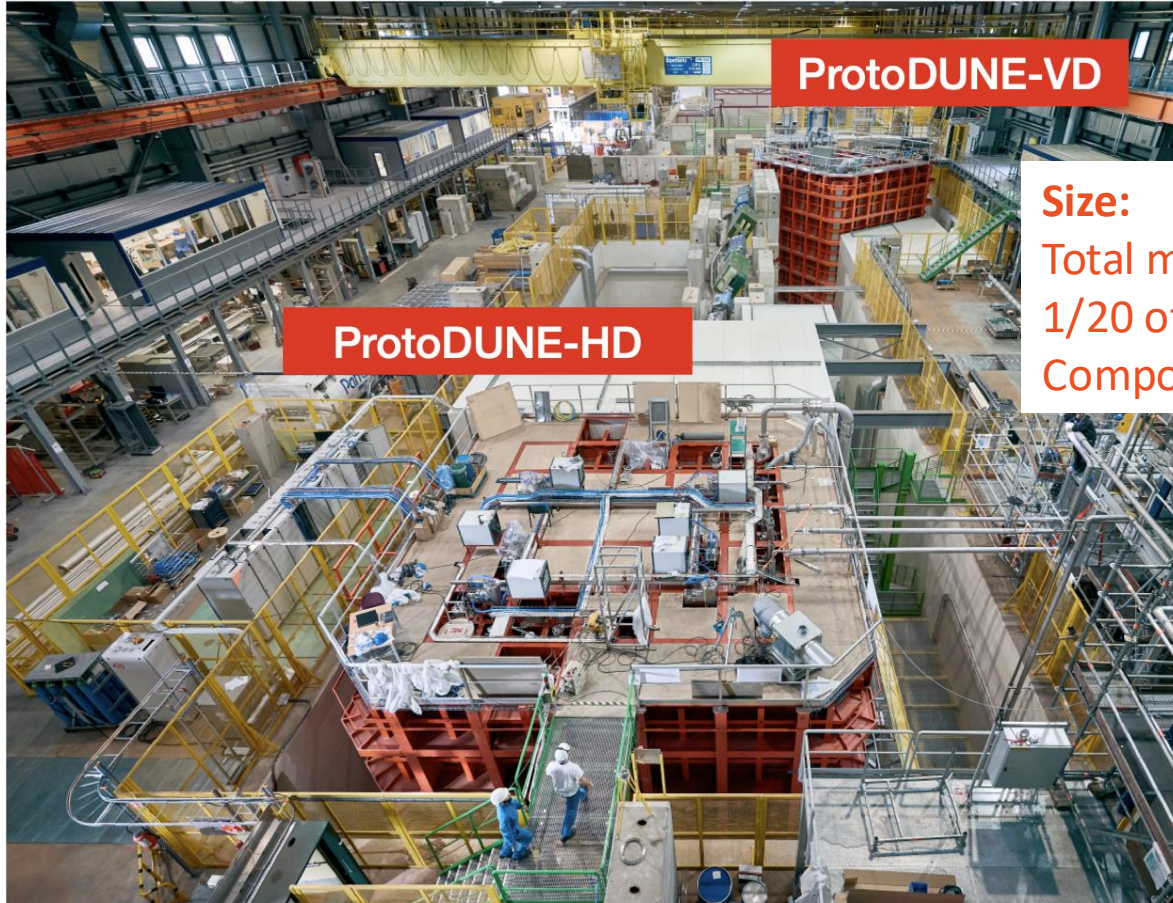


- 16 dichroic filters
- 1 WLS plate
- 160 6x6 mm<sup>2</sup> SiPMs. (Hamamatsu and FBK)
- Grouped in two readout channels

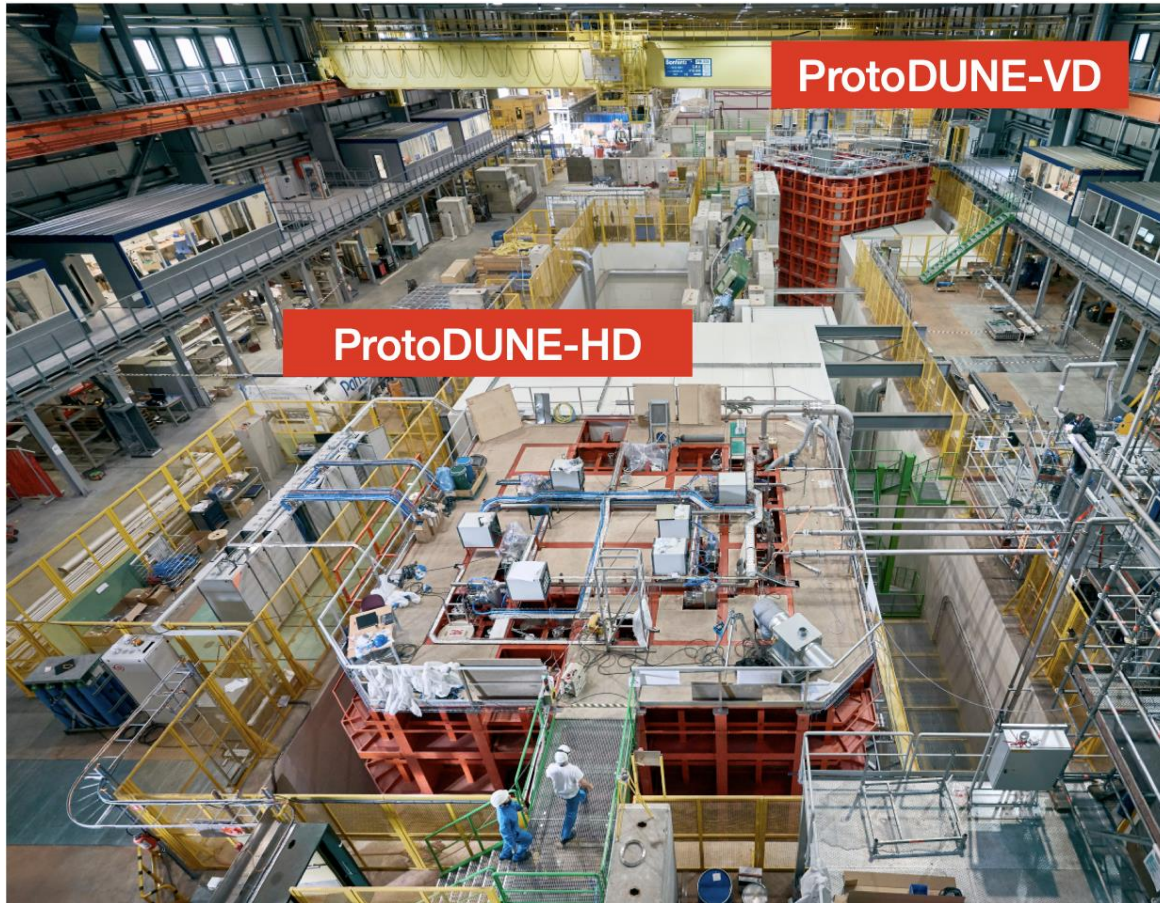
X-ARAPUCA VD



# ProtoDUNE program at CERN



# ProtoDUNE program at CERN



## ➤ Successful run of ProtoDUNE-HD 2018 – 2020

- First results of ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at CERN Neutrino Platform

[JINST 15 \(2020\) 12, P12004](#)

- Design, construction and operation of the ProtoDUNE-SP Liquid argon TPC [JINST 17 \(2022\) 01, P01005](#)

- Other publications: [JINST 19 \(2024\) 08, P08005](#),  
[Phys.Rev.D 107 \(2023\) 9, 092012](#), [Eur.Phys.J.C 83 \(2023\) 7, 618](#),  
[Eur.Phys.J.C 82 \(2022\) 10, 903](#)

## ➤ New runs:

**ProtoDUNE-HD (NP04)** (beam data in summer 2024)

Test upgraded components in their final design and more beam data

- Test of 40 X-Arapuca modules 

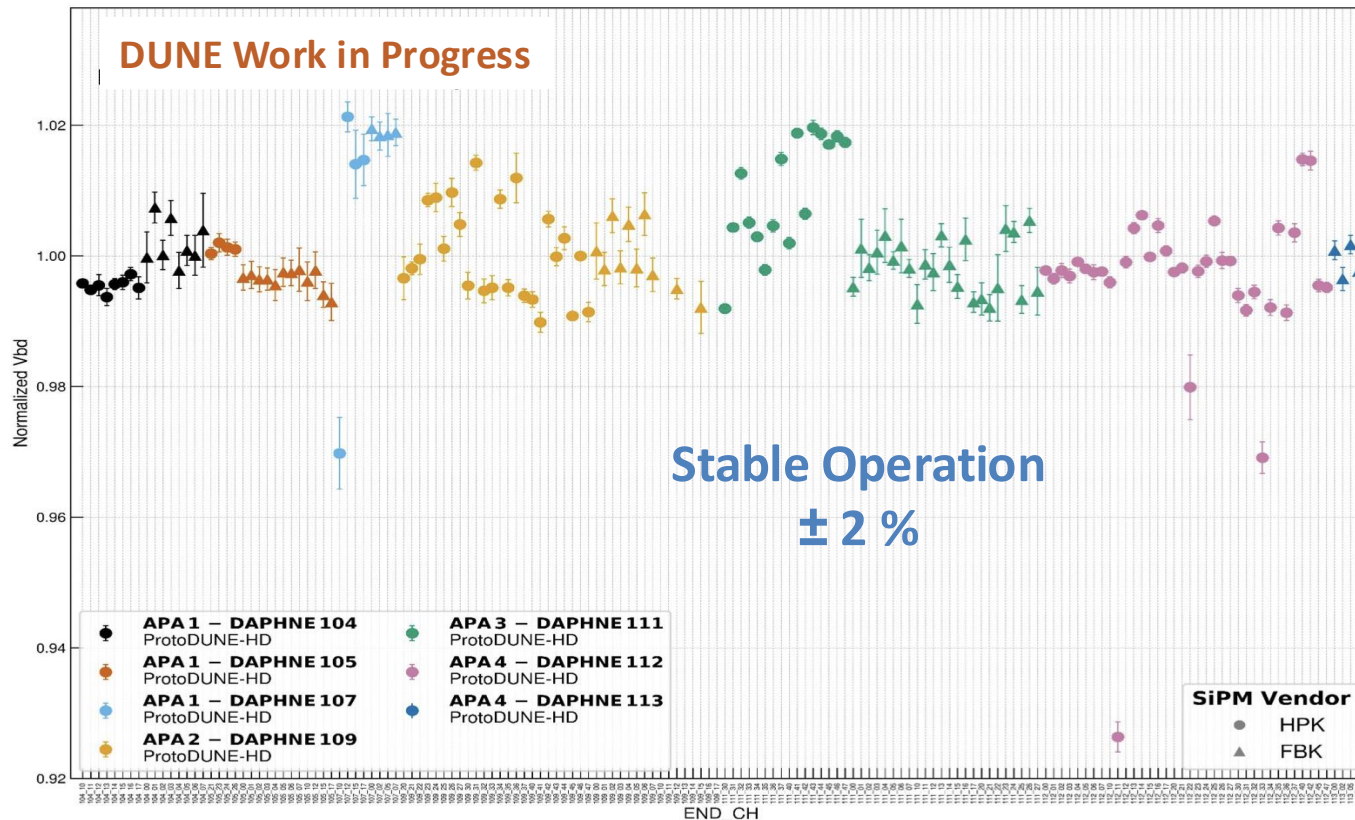
**ProtoDUNE-VD (NP02)** (beam data summer 2025)

Test the VD concept for the first time at large scale

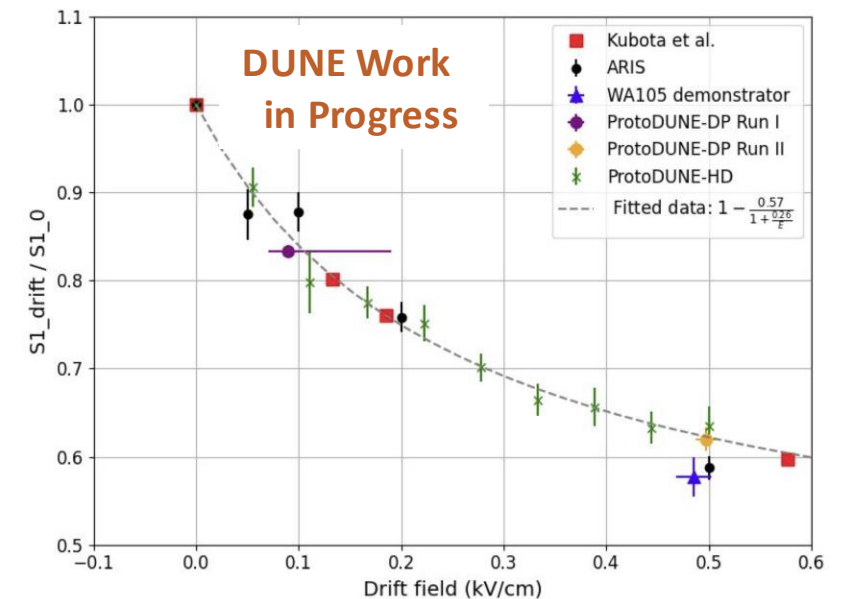
- Test of 16 X-Arapuca modules

# Photon-detection system performance in ProtoDUNE-HD

Data analysis is on-going



Scintillation Light-yield vs Drift field



# X-ARAPUCA Characterization: Efficiency measurement

- The **measurement of the absolute efficiency** allows the full characterization of the X-ARAPUCAS (XA)

→ Validation and Optimisation of their design

The value of the efficiency is needed to do:

- Efficient non-beam events triggering
- Calorimetry

- The **FD-HD X-ARAPUCAs** (configurations tested in ProtoDUNE-HD) were measured at CIEMAT and Milano-Bicocca U. Labs (2022-2023)

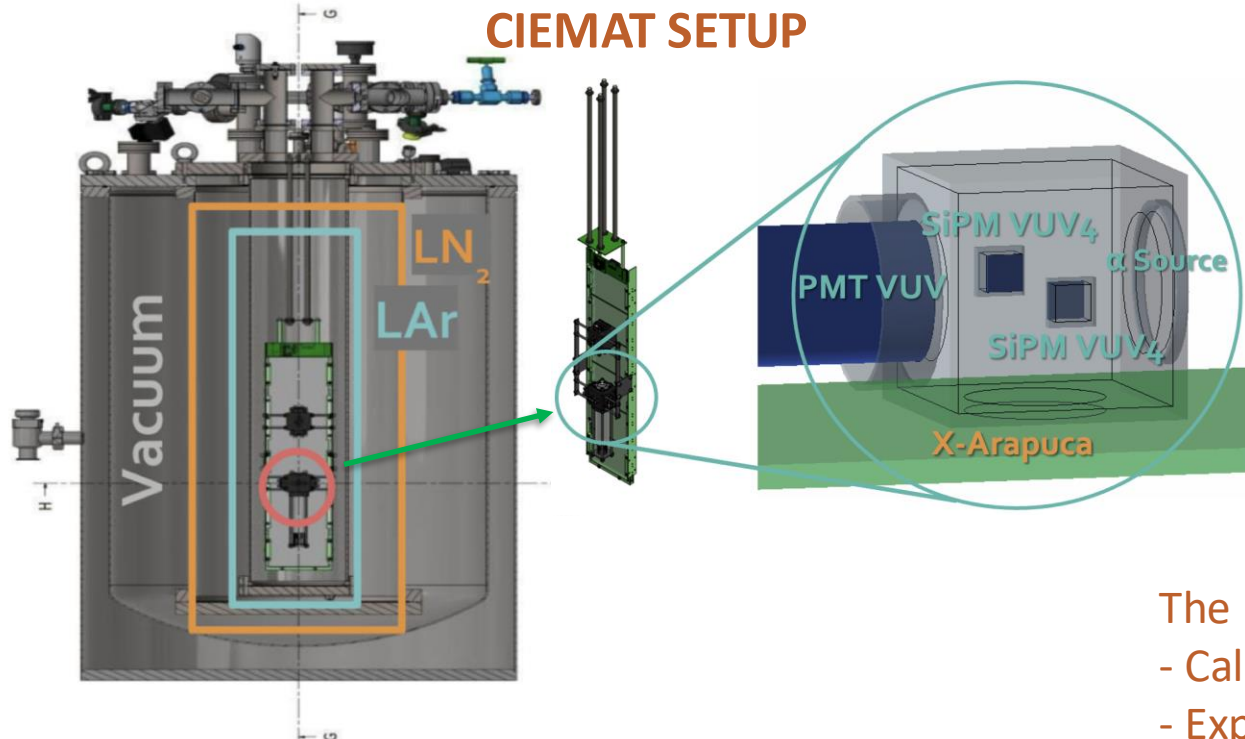
- > Selection of the WLS plate
- > Helpful for the optimization of FD-VD XA

- Optimized designs of FD-HD XAs are currently being measured at the same labs.

- Several configurations of **FD-VD X-ARAPUCAs** have been characterized at CIEMAT and Naples U., leading to an improved design (2024-2025).

- All the tests were carried out submerging the XA in LAr. Low-activity electrodeposited  $^{241}\text{Am}$  alpha source is used to produced scintillation light

# X-ARAPUCA – FD-HD



The alpha particle deposits its energy inside a small black box with a hole ( $\varnothing = 23\text{mm}$ ) facing the XA (the rest of the SC is covered with a black sheet)

$$\text{Efficiency} = \frac{N \text{ of collected photons}}{N \text{ of photons hitting XA}}$$

- 300 L cryogenic vessel with two concentric volumes:
  - 100 L with LN<sub>2</sub>
  - 18 L GAr (99.9999%) and X-ARAPUCA
- GAr liquefied with LN<sub>2</sub> at 2.7 bar.

The number of photons hitting the XA are determined from:

- Calibrated VUV4 SiPMs
- Expected light-yield for 5.5 MeV  $\alpha$  (<sup>241</sup>Am)

Monte Carlo simulations are performed to determine the solid angle of each sensor

# X-ARAPUCA – FD-HD

## RESULTS

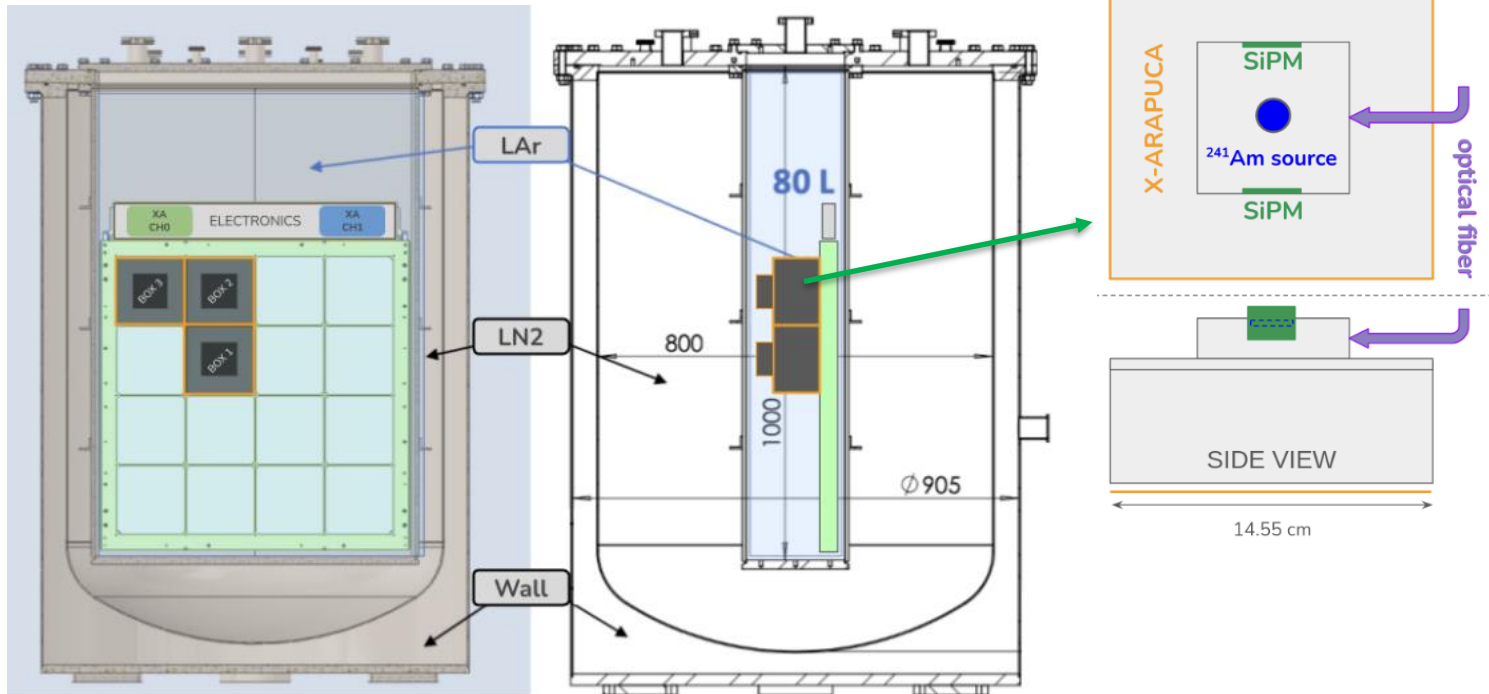
The **Absolute Efficiency** has been obtained by two independent measurements  $\sim 1.5 - 2.5 \%$   
The error ( $\gtrsim 10\%$ ) is systematics dominated

Tested configurations	X-Arapuca absolute efficiency (%)	
	CIEMAT	MiB
SiPMs / plate		
FBK –TT / Ej-286PS-1	$1.34 \pm 0.24$	$1.80 \pm 0.15$
HPK 75HQR / Ej-286PS-1	$1.59 \pm 0.29$	-
FBK –TT / G2P	-	$2.22 \pm 0.19$
HPK 75HQR / G2P	$2.13 \pm 0.38$	$2.40 \pm 0.20$

L. Pérez-Molina et al. [Eur. Phys. J. C 84](#) arXiv:2405.12014

# X-ARAPUCA – FD-VD

## CIEMAT SETUP

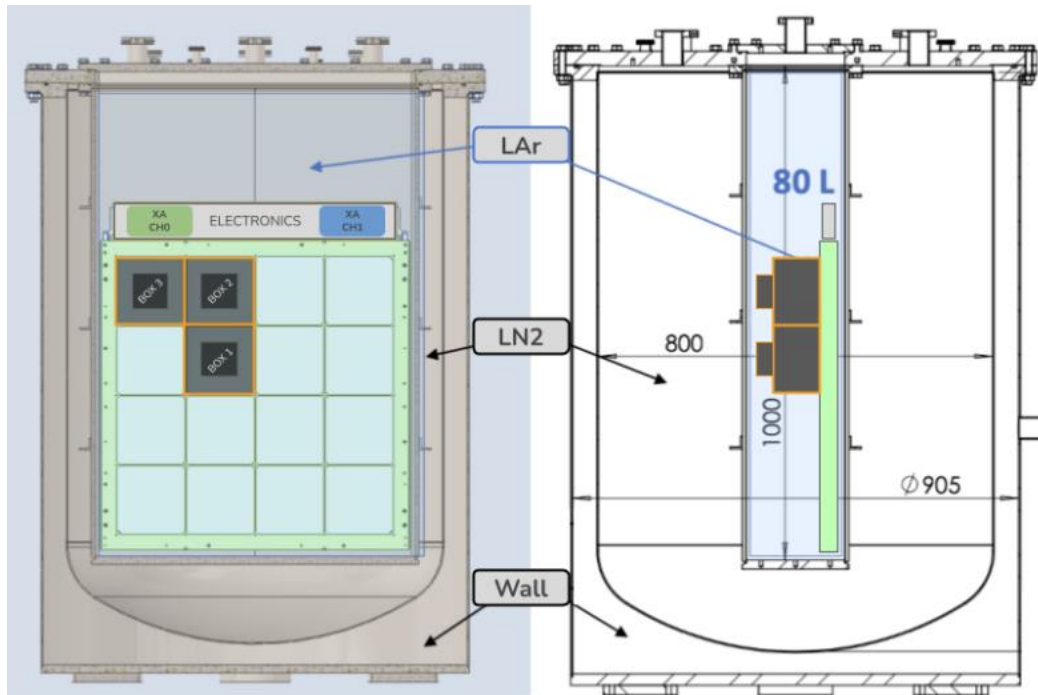


The  $\alpha$ -particle deposits its energy inside a black box (~15cm) that covers one filter (the rest of the XA is covered with a black sheet) and holds two calibrated SiPMs.

- Cryogenic vessel with two concentric volumes:
  - 300 L with LN2
  - 80 L GAr (99.9999%) and X-ARAPUCA
- GAr liquefied with LN2 at 2.7 bar.

# X-ARAPUCA – FD-VD

## CIEMAT SETUP



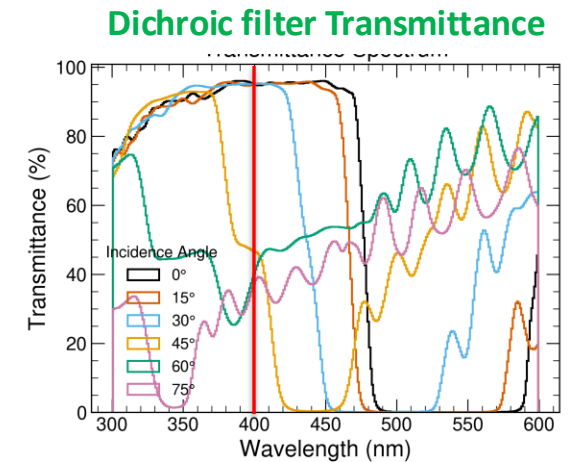
- Cryogenic vessel with two concentric volumes:
  - 300 L with LN2
  - 80 L GAr (99.9999%) and X-ARAPUCA
- GAr liquefied with LN2 at 2.7 bar.

Main goal is the design optimization

After simulations and devoted measurements on the transmittance of the **real DF**, the following **configurations** have been tested:

- Single-sided XA
- Single-sided XA **no-DF**
- Double-sided XA
- Double-sided XA **no-DF**

The cutoff position & transmittance depends on the incident angle



Dichroic filter cutoff at 45°

# X-ARAPUCA – FD-VD

## RESULTS

Tested configurations	X-Arapuca absolute efficiency (%)	
	CIEMAT	U. Naples
In all cases: HPK 75HQR and G2P plate		
Single-sided	$3.7 \pm 0.3$	$3.1 \pm 0.5$
Double-sided	$4.0 \pm 0.4$	-
Single-sided no-DF	$4.5 \pm 0.4$	-
Double-sided no-DF	$4.5 \pm 0.4$	-

**The Absolute efficiency has been obtained by two independent measurements  $\sim 3.5\%$**   
 (More efficient than XA-HD due to better SiPM-plate coupling and larger number of SiPMs)

- An improvement ( $\sim 20\%$ ) is observed when the Dichroic Filter is replaced by a pTP coated Glass, as predicted
- No difference observed between single and double sided

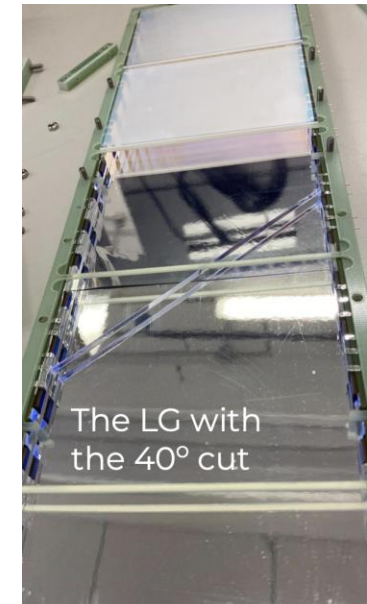
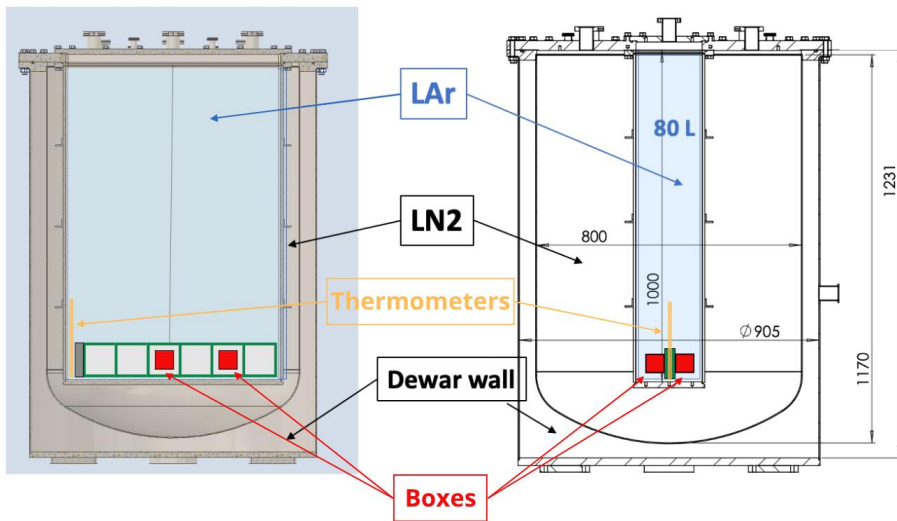
# X-ARAPUCA – FD-HD

## Further optimization

Optimized designs are being characterized at CIEMAT:

- pTP coated glass instead of DF
- WLS plate 40° cut

(MiB measurement showed an important improvement avoiding uneffective photon tracks inside the plate)



# Summary

- DUNE experiment relies on LArTPC technology to make precise measurements of neutrino mixing parameters
- The detection of the scintillation VUV light is crucial to fulfil DUNE physics goals
- The DUNE Photon-Detection System will be the X-ARAPUCA: a large area, compact design device based on SiPMs
- The X-ARAPUCA design has been improving and adapted to the different TPC layouts.
- X-ARAPUCAs with different configurations in terms of SiPM model, WLS plate manufacturer and Dichroic filters have been fully characterized in several institution labs.
- The ProtoDUNEs (HD & VD) at CERN provide an opportunity to test the X-Arapucas under real operation conditions.