The ProtoDUNE Photon Detection System: technology validation and performance

Claudia Brizzolari (on behalf of the DUNE collaboration)

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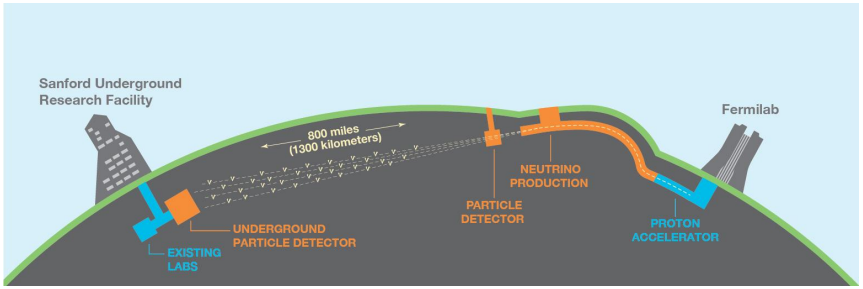
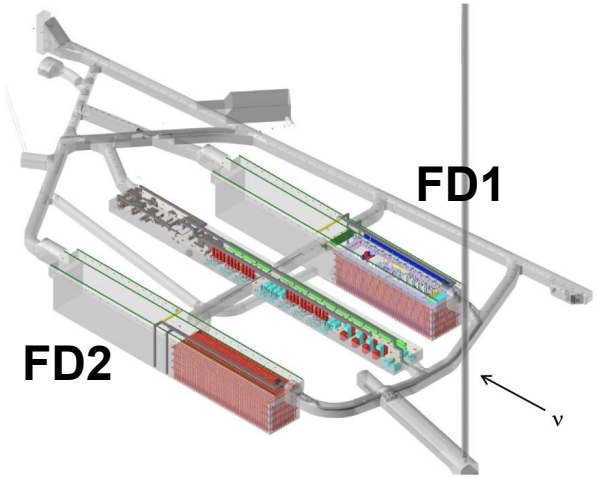
The DUNE experiment





Technology:

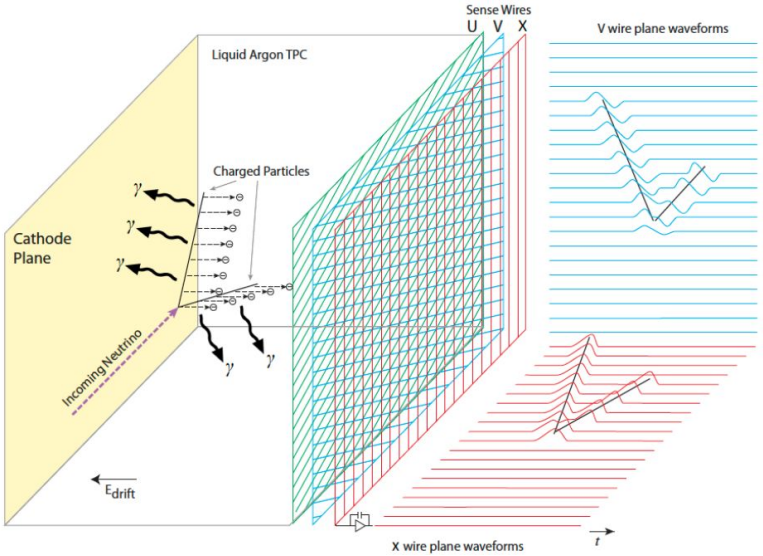
- Wide band ν (and anti-ν) beam w/ long baseline
  1.2 MW proton beam, upgradable to 2.4 MW
- Near detector complex for beam characterization
  Movable (NDLAr, TMS) + on-axis (SAND) detectors
- Huge far detector w/ superior PID capability
  3 x 17 kton total mass LArTPCs, 1.5 km underground, + 1 Module of Opportunity

Physics Programme:

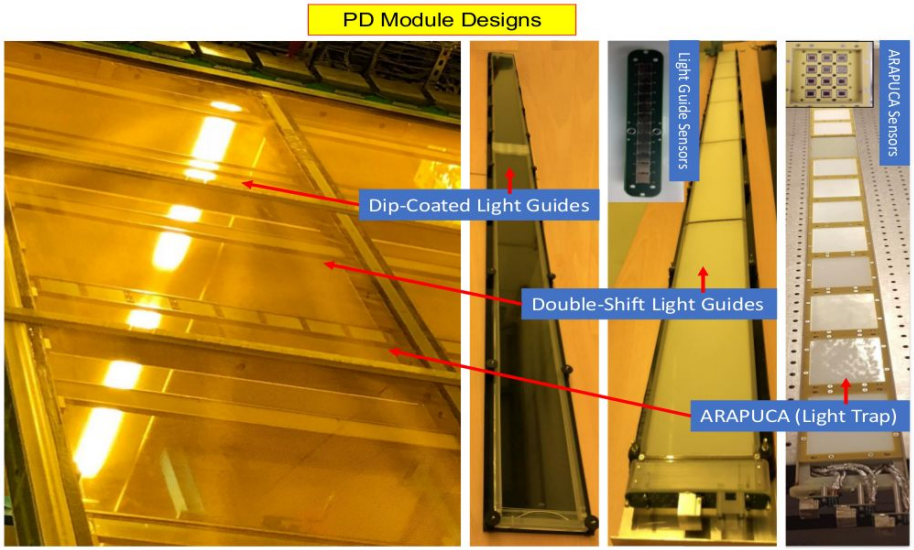
- ν mass ordering, CP-violating phase δ_{CP}
- Measurement of PMNS parameters octant of θ_{23}, Δm^2_{13}, precision measurement of δ_{CP}
- Physics with natural ν sources
  1st obs. of HEP, galactic SN bursts, meas. of θ_{12}
- BSM physics
  neutrino anomalies @ LBNF, proton decay, dark matter

Far Detector technology

Charge detection



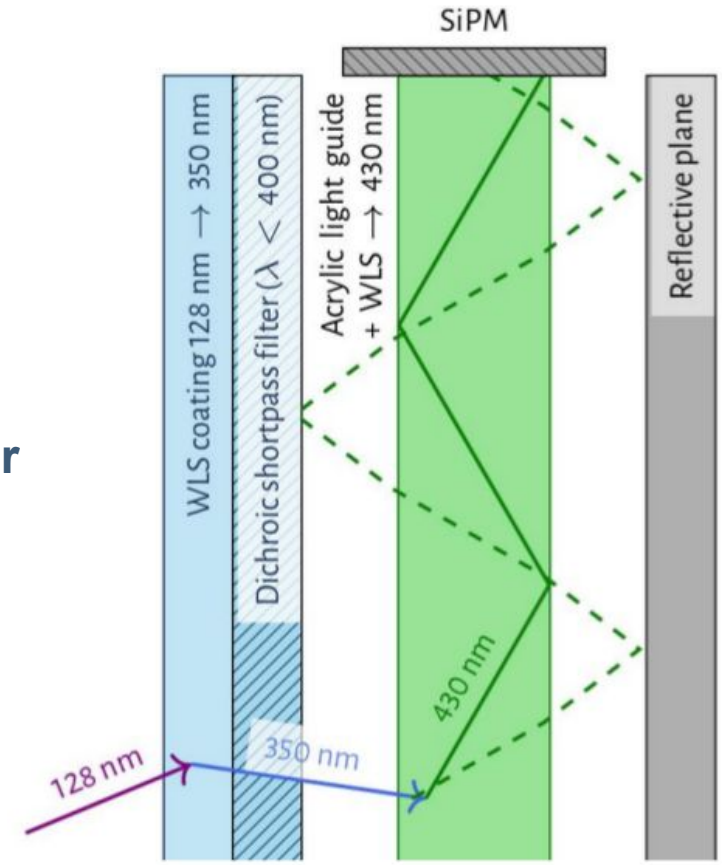
Photon detection



- A charged particle in **LAr** produces two signals proportional to the energy deposit
  - Drifted electrons, allowing for precise imaging
  - VUV scintillation photons (λ = 128 nm), providing precise event timing (and reconstruction on the drift axis)
- Two independent readout systems: anodic charge readout and **photon detection system**

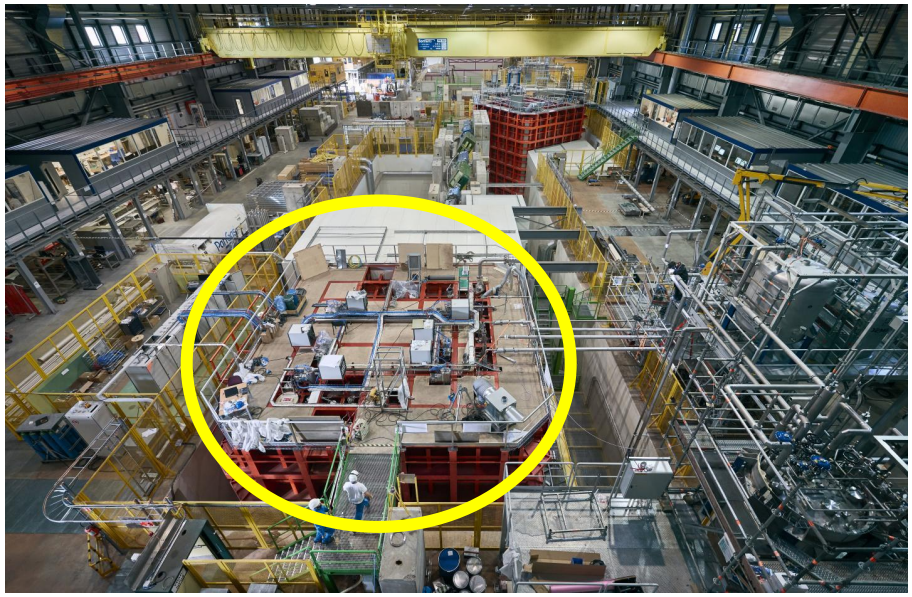
Photon detection system: X-ARAPUCA (XA)

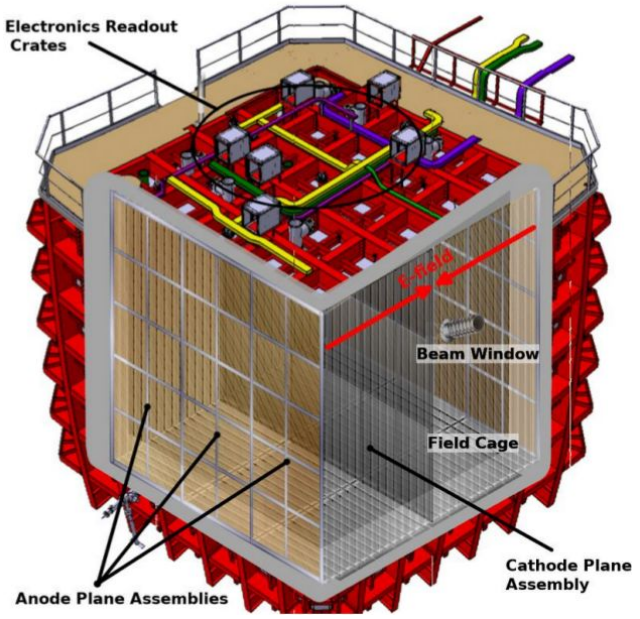
- LAr VUV scintillation light abundant (25k photons/MeV @ 500 V/cm) → combined with TPC signal **improves calorimetry**, especially at low E
- fast component τ = 7 ns → **provides trigger for non-beam events**
- **improves vertex reconstruction (from ~1 cm to ~ 1 mm)**



Light detection: reflective box equipped with an entrance window, two photon downshifting stages, one dichroic filter and one light guide coupled to SiPMs.

ProtoDUNE-Horizontal Drift Run I at CERN



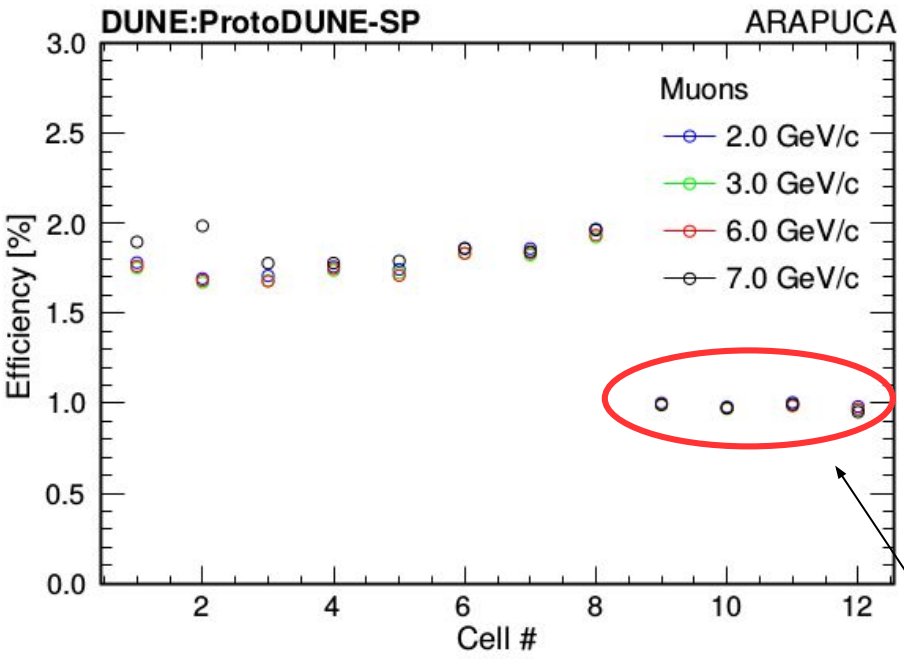


- Ran from 2018 to 2020, collecting data from cosmic rays and beam @ the CERN neutrino Platform
- 10 bar-shaped photon detectors (207.4 x 8.2 cm^2 optical area each) embedded in the anode planes

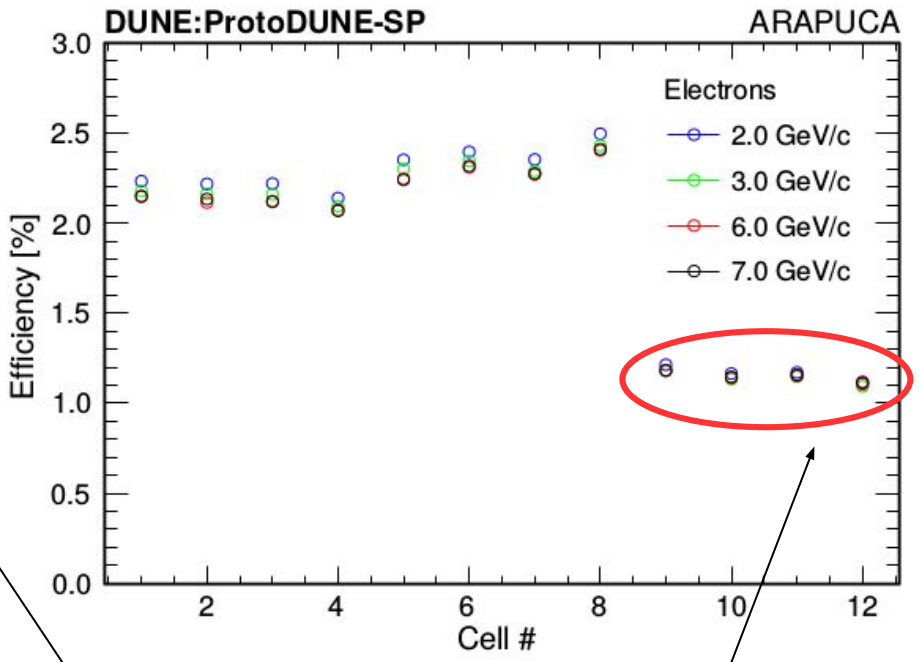
ARAPUCA: efficiencies in ProtoDUNE Run I

Efficiency of the cell from the detected-to-incident ratio.

Muon beam



Electron beam

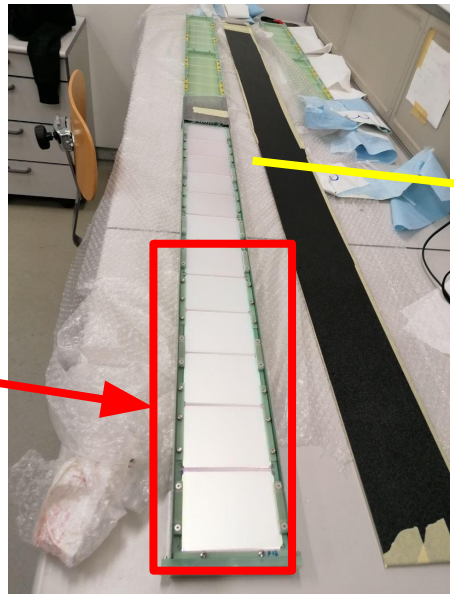


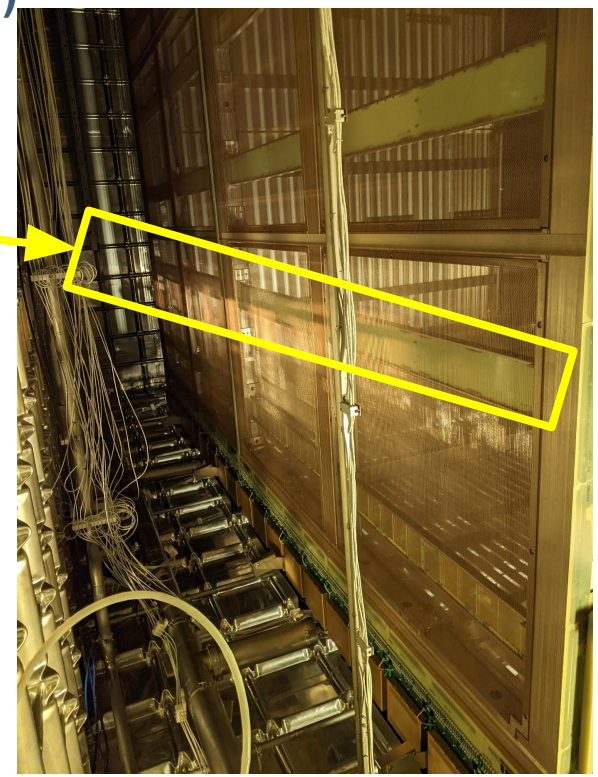
Results published in *B. Abi et al, First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform, 2020, JINST, vol. 15, issue 12, P12004*

Cells with double size but equal number of photosensors

ProtoDUNE-HD Run II at CERN

- 4 FD1-XA for Module, 10 modules for APA, 4 APA
- Installation completed in September 2022, cooldown delayed to Spring 2024 due to LAr shortage
- New X-ARAPUCA design: 48 ganged SiPMs correspond to 1 FD1-XA (channel readout, active window 46.2 x 10 cm^2)





ProtoDUNE-HD Run II at CERN

FD1-XA in ProtoDUNE equipped with one of 4 different configurations:

- **Two different WLS guides:**
  - **Glass To Power (G2P), PMMA based**
  - **Eljen (EJ-286), PVT based**
- **Two different SiPMs:**
  - **HAMAMATSU HPK DUNE-75um-High Quenching Resistance**
  - **FBK Triple Trench**

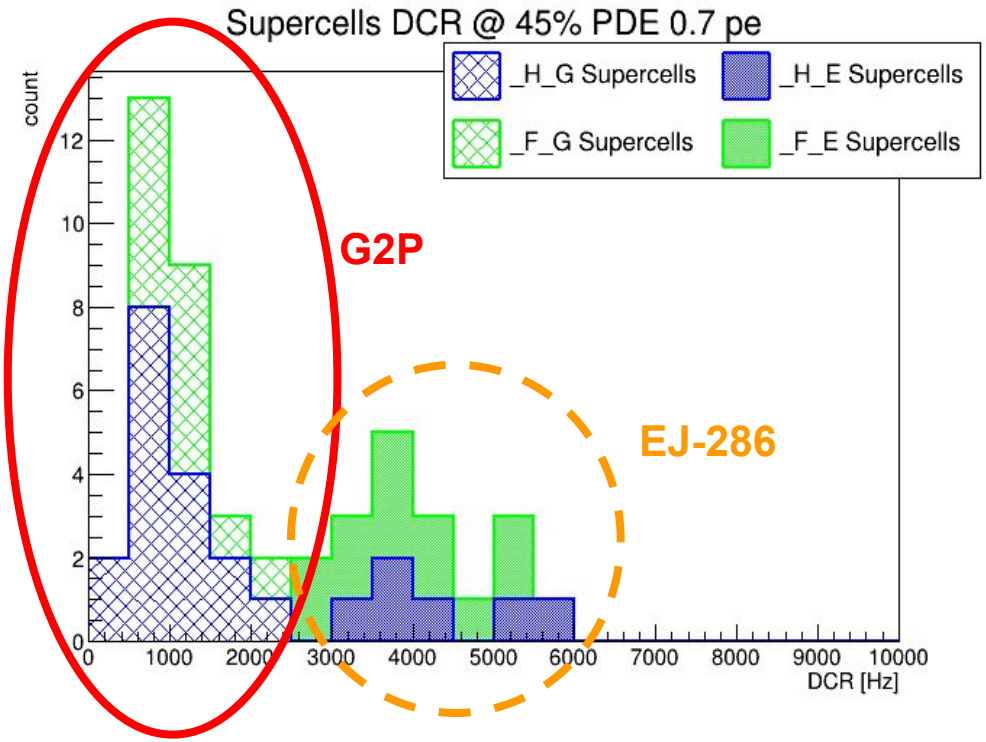
All configurations w/ OPTO-Campinas (Brazil) dichroic filters, substrate B270, size 7.7 x 10 cm^2.

Achieved ganging of 48 SiPM with S/N>4 for both types.

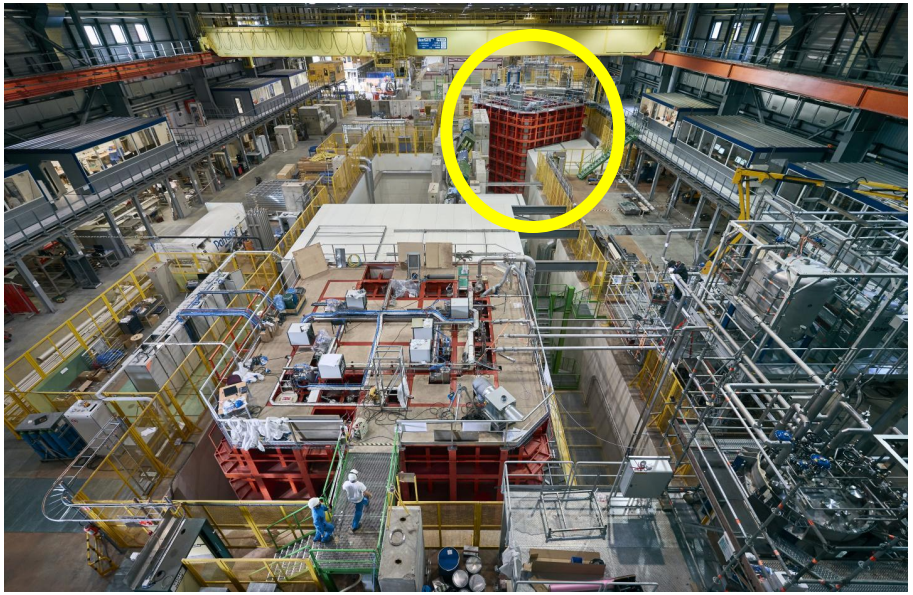
FD1-XA PDE and DCR performances

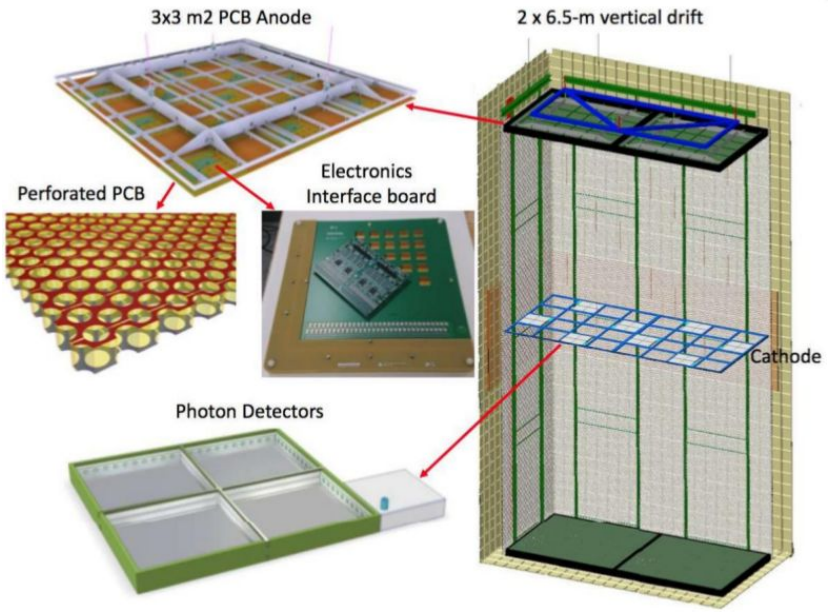
- FD1-XA PDE tested in Milano-Bicocca and CIEMAT
- For all configurations **PDE ~2%**
- **G2P bar outperformed the EJ one** both w.r.t. the PDE and the DCR (PVT is a scintillator, PMMA is not)

Subset of FD1-XA for ProtoDUNE tested @ MiB in shallow lab, DCR measurement



ProtoDUNE-Vertical Drift

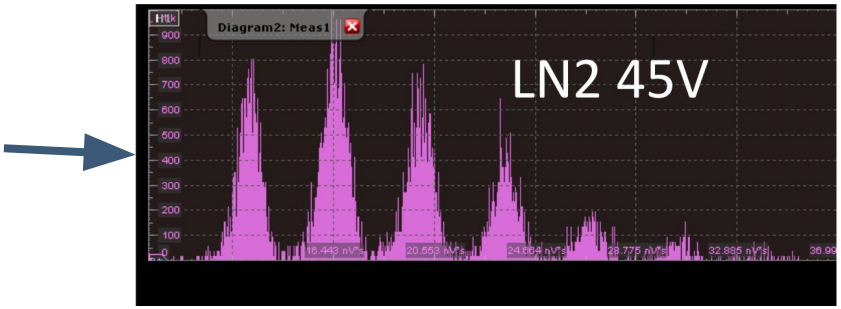




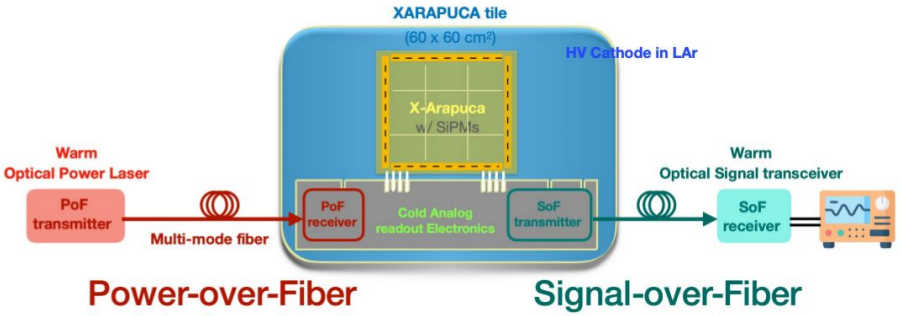
- **Second ProtoDUNE @ CERN and FD2 exploit the Vertical Drift technology**
- **PDS in the cathode (300 kV!) + outside the field cage ("Membrane"), light uniformity improved w/ Xe doping**

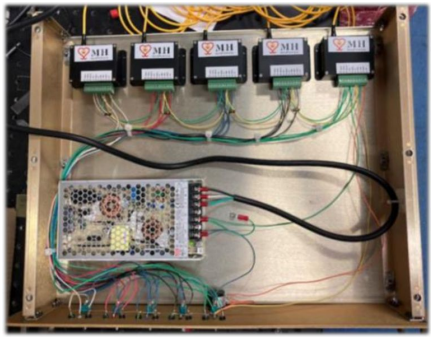
ProtoDUNE-VD PDS

- Ganging of 80 SiPM with S/N~8 @ MiB for Membrane module, preliminary measurement with HD amplifier

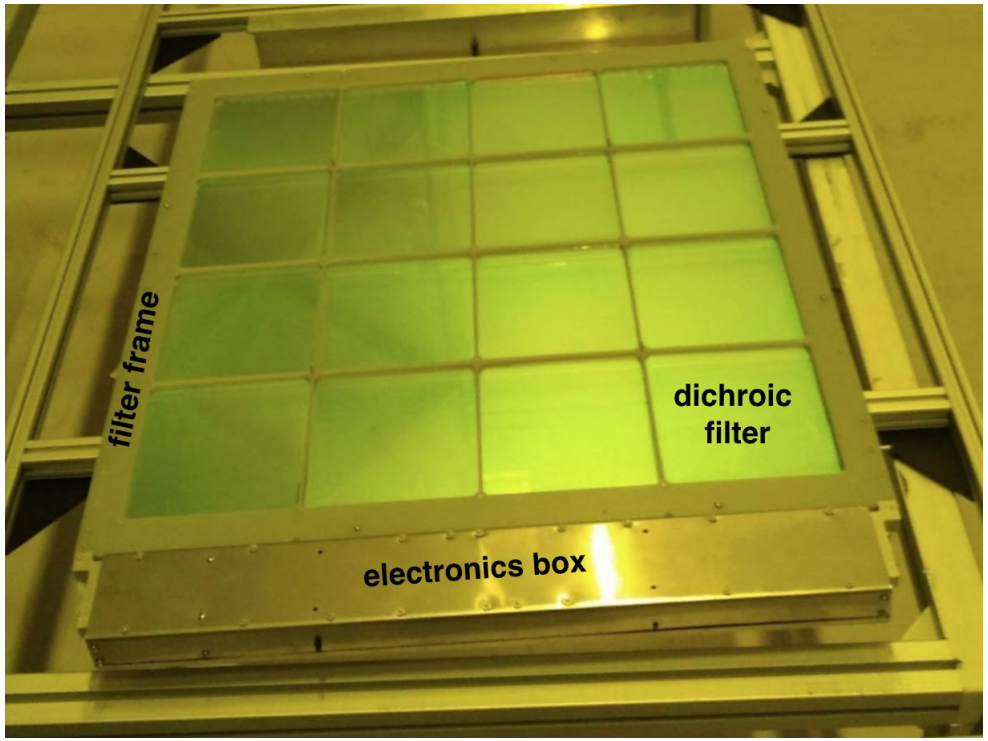


- To power and read SiPMs in a 300 kV electric field: Power over Fiber (PoF)
  - based on GaAs laser and commercial system, power through optical fibers converted to DC at cold
  - Signal Over Fiber: analog signal transmission using IR laser light
- ProtoDUNE-VD now installed at CERN w/ novel PoF X- ARAPUCA
  - PDE of VD PDS membrane modules recently validated w/ a dedicated measurement (~2% preliminary), to be performed on PoF modules





Vertical Drift FD2-XA

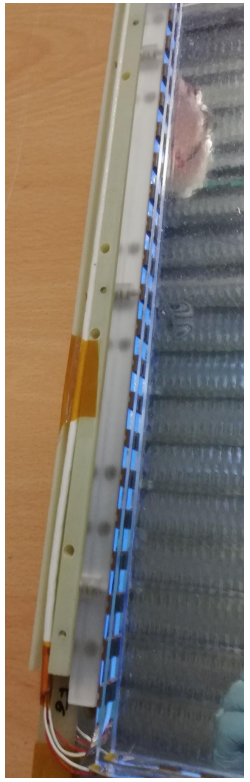


Same technology but different SiPM coverage and dimensions, WLS plate dimensions 60.7 x 60.7 x 0.4 cm^3:

- maximize photon detection
  - SiPM-WLS coupling
  - optimize Optical Path and plate thickness vs attenuation length i.e. dye concentration
  - new dichroic filters
- maximize active area
  - larger dichroic filters

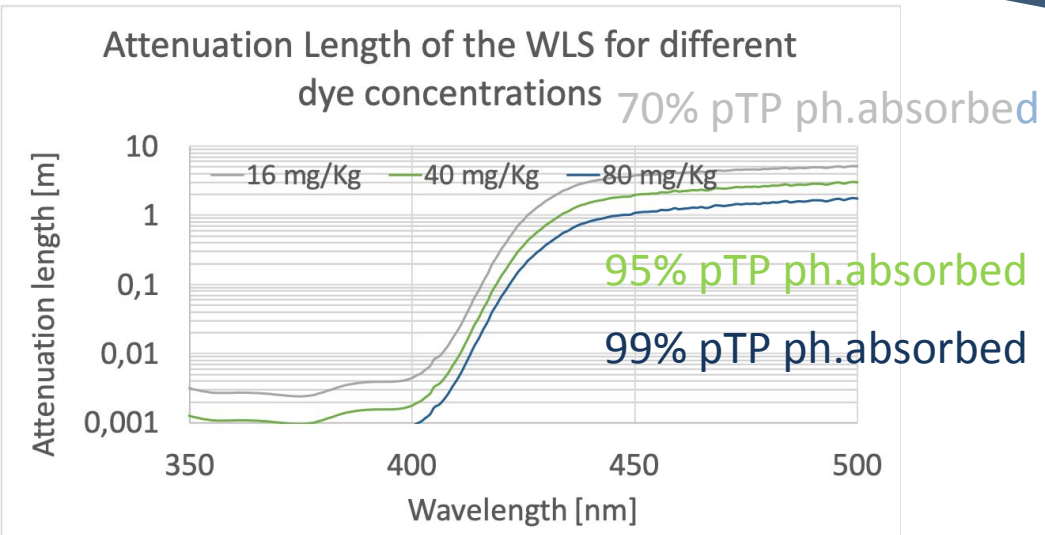
SiPM to WLS coupling

- To minimize gap between SiPM and WLS in LAr → SiPMs on flex circuits + spring loaded mount to compensate WLS shrinking (~1% i.e. 6 mm)
- Also tested SiPM fitting in dimple cuts (flat or cylindrical) machined at the edges of WLS

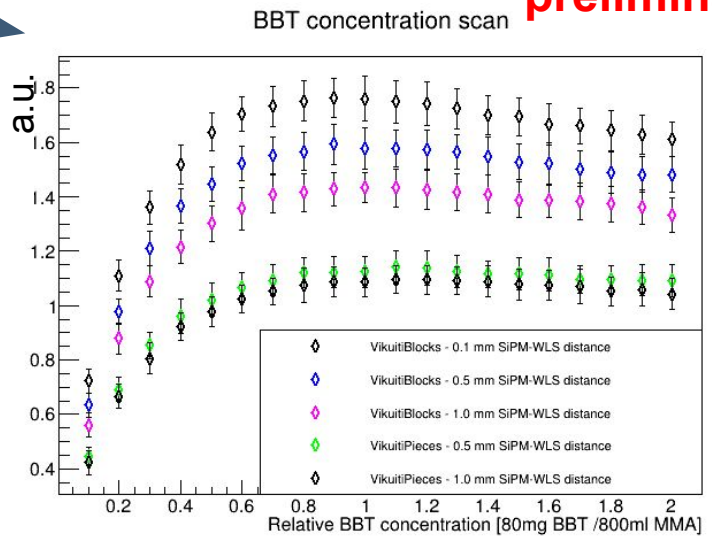


WLS: attenuation length (λ_{att})

- For PMMA based WLS in LAr, the critical angle for light trapping at the surfaces is 56° = θ_c . For $\theta > \theta_c$ light is trapped and guided by TIR to SiPMs
- Due to multiple reflections the optical path inside large size WLS may reach a couple of meters → dye concentration tailored to FD2 size and optical path → optimization driven by simulations

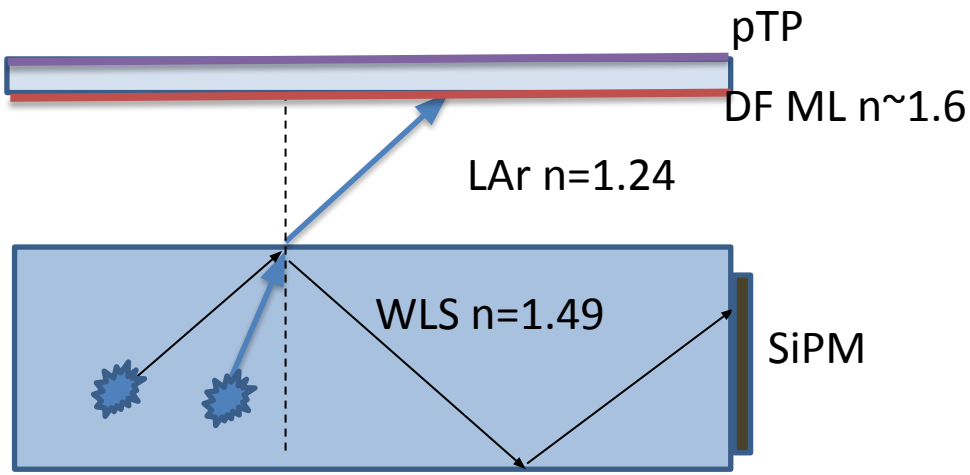


preliminary



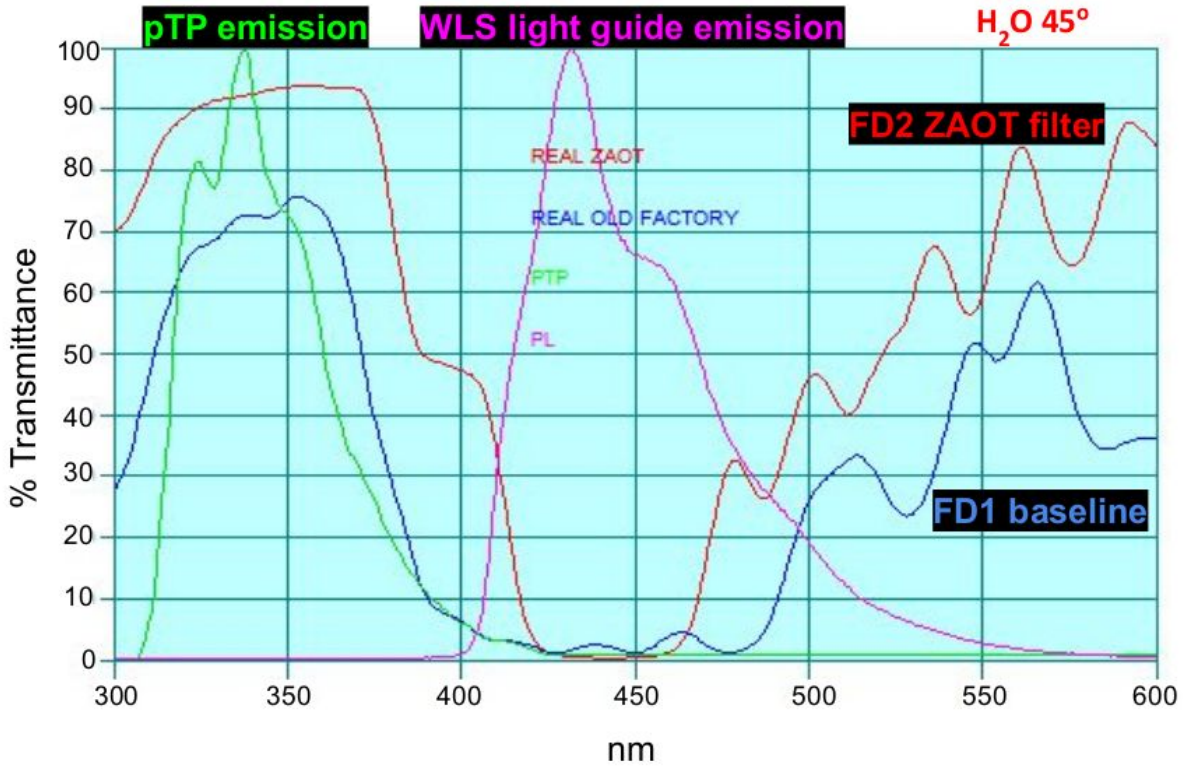
Dichroic filters

- Dichroics Filter (DF) are made of thin film multilayer coatings on a glass/fused silica substrate. They act as Fabry-Perot interferometer to selectively transmit/reflect light.
- For Large volume LAr detectors → Large area DF (minimize optical window dead areas) → challenge: pTP coating uniformity
- The glass window is coated with a primary WLS (pTP) to downshift the 128 nm light to ~350 nm



Dichroic filters

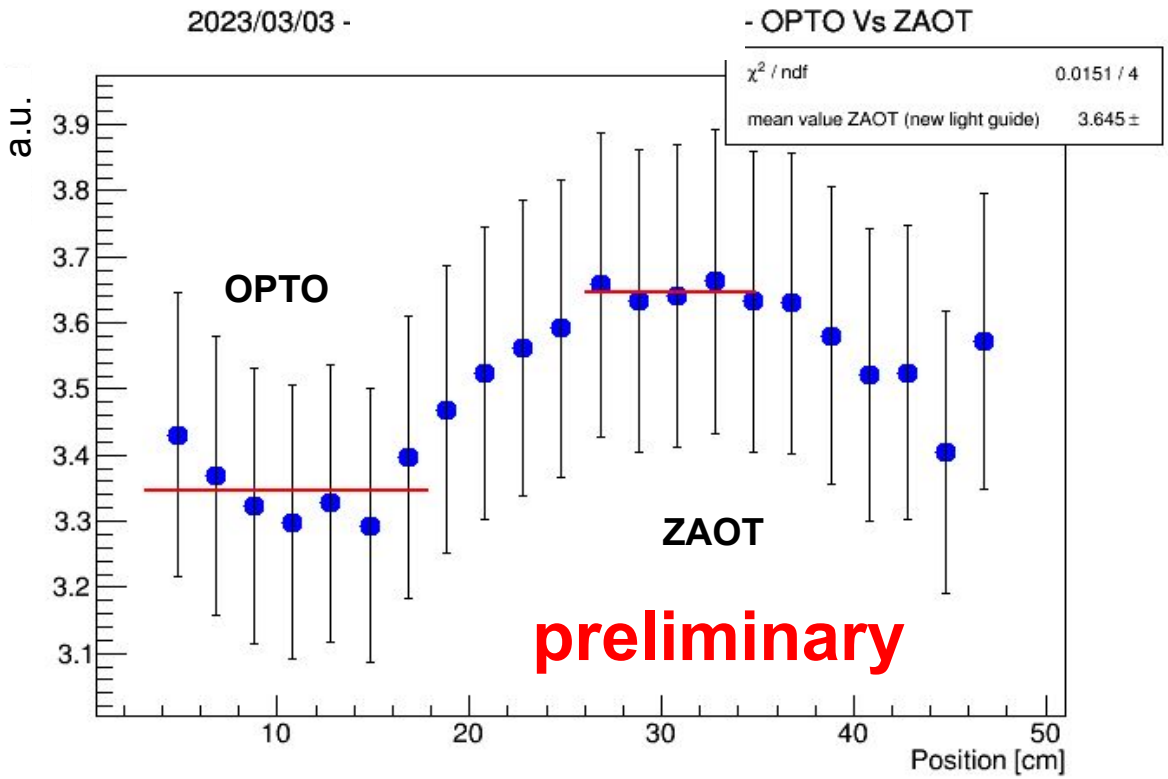
- Filters have been optimized to operate in LAr (@45°)
- Higher transmittance in the pTP emission range
- Higher reflectivity in the light guide WLS chromophore emission range
- But narrower reflectivity window

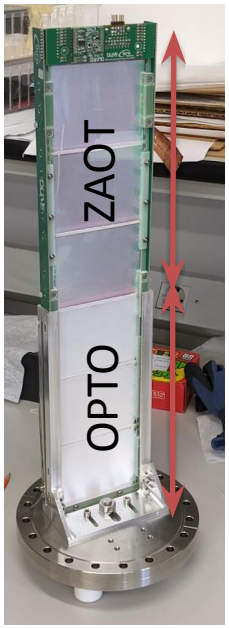


- ZAOT (MiB industrial partner - Italy) substrate Borofloat 33 Optical Glass
- PhotonExport (Spain) Substrate Fused Silica

Assessment of DF performance in LAr

- Measurements of the PDE in LAr of one FD1-XA equipped with three OPTO, three ZAOT
- Effect foreseen by GEANT based Simulations

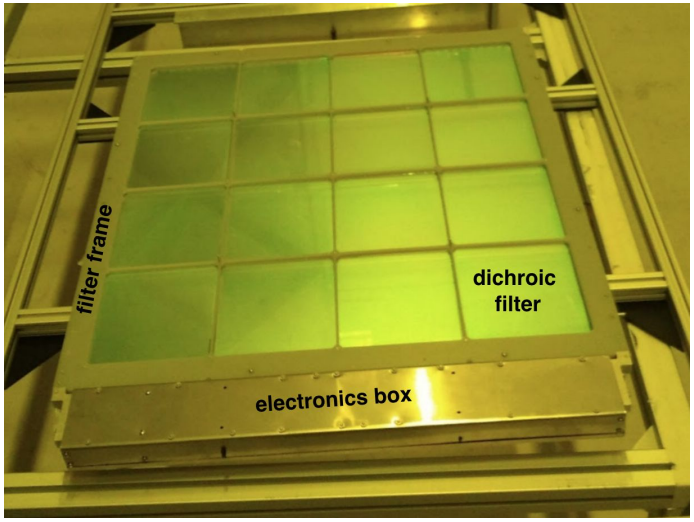


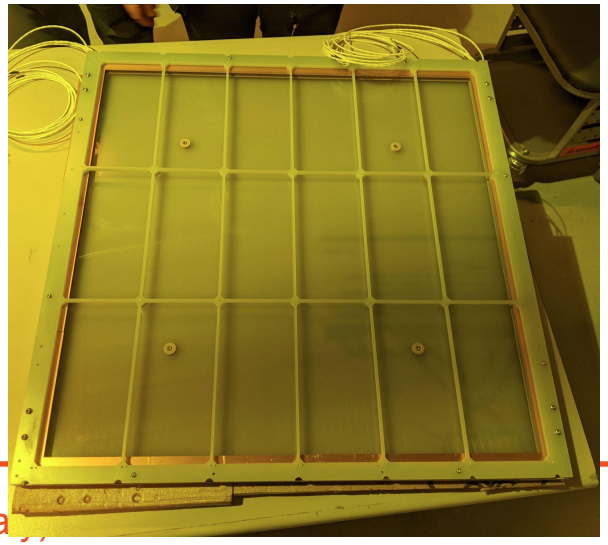


FD2-XA configurations

- PDE measurements of the large area X-Arapuca are being performed at different sites:
  - INFN Naples
  - CIEMAT (Madrid)

	WLS dimples	DF size (mm^2)	DF	SiPM	PoF	SoF	shared elec. box
M1		100x200	ZAOT	HPK			x
M2		100x200	ZAOT	HPK			x
M3	x	100x200	ZAOT	HPK			x
M4	x	100x200	ZAOT	HPK			x
M5	x	150x150	PE	FBK		x	
M6	x	150x150	PE	HPK			
M7	x	150x150	PE	HPK			
M8	x	150x150	PE	FBK			
C1		100x200	ZAOT	HPK	x	x	
C2		100x200	ZAOT	HPK	x	x	
C3		150x150	PE	FBK	x	x	
C4	x	150x150	PE	HPK	x	x	
C5	x	150x150	ZAOT	HPK	x	x	
C6	x	150x150	ZAOT	HPK	x	x	
C7	x	150x150	ZAOT	FBK	x	x	
C8	x	150x150	ZAOT	HPK	x	x	



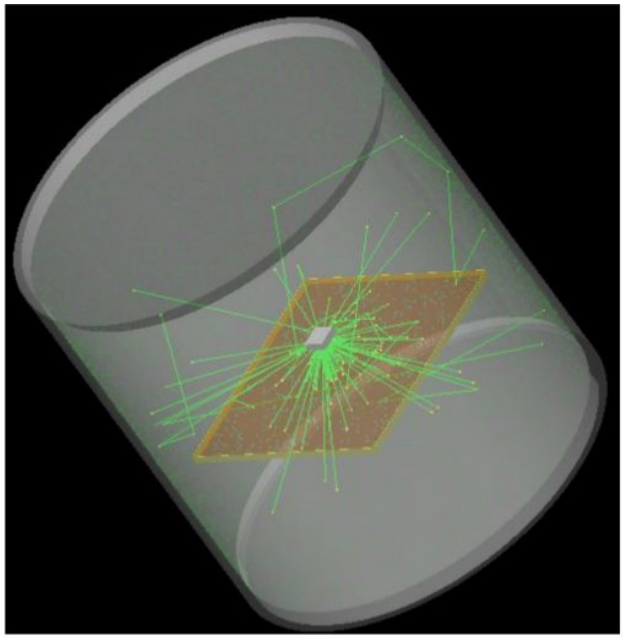


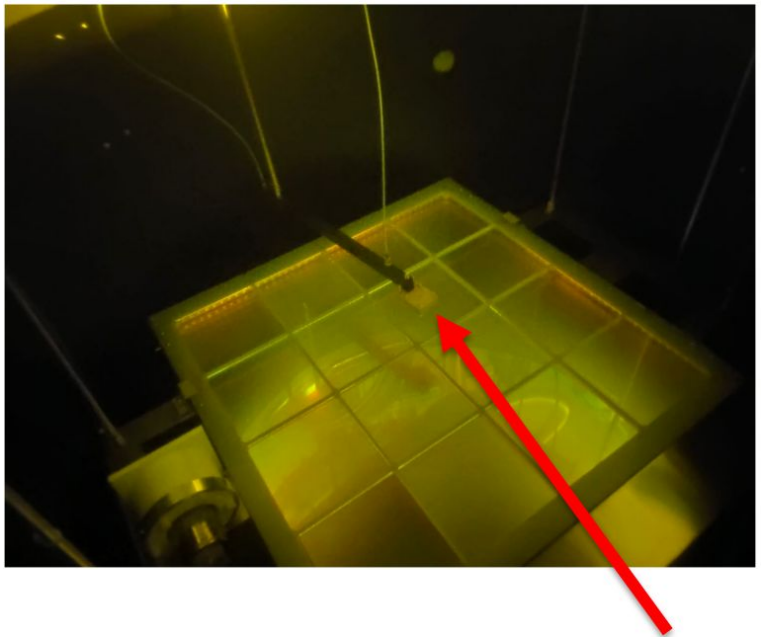
FD2-XA tests @ Naples

Tests for Membrane modules (PDE ~2% preliminary)

Configuration:

- **150 x 150 mm^2 ZAOT dichroic filters**
- **FBK SiPMs**
- **G2P WLS w/ dimples**





α source (^{241}Am)

See F. Di Capua's talk at TIPP 2023, "Photon Detection System in the far detector module of the DUNE experiment"

Conclusions

- Installation of ProtoDUNE-HD completed in September 2022, cooldown delayed to Spring 2024 due to LAr shortage
- Tests for the PDE of the baseline configuration of FD1-XA performed in two sites: MiB and CIEMAT, results within specs, ~2%

- Installation of ProtoDUNE-VD in progress
- Test for the PDE of FD2-XA in progress in two different sites: Naples and CIEMAT, preliminary result ~2%

- Ongoing efforts to further improve the PDE for both FD1-XA and FD2-XA