Features and performances of the DUNE Far Detectors photon detection system

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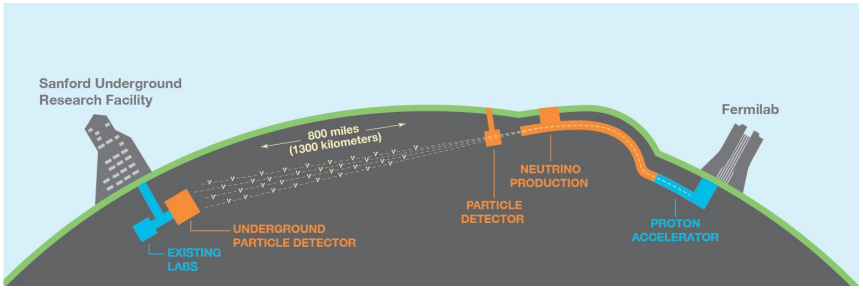
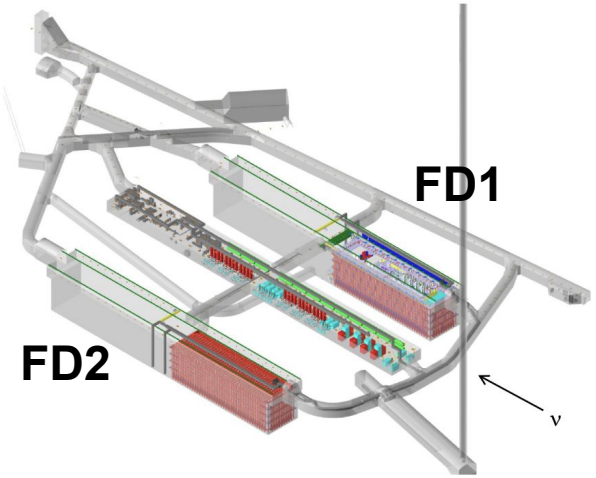
Pisa Meeting 2024
16th Pisa Meeting on Advanced Detectors

26 May 2024 to 1 June 2024
La Biodola - Isola d'Elba (Italy)

The DUNE experiment





Technology:

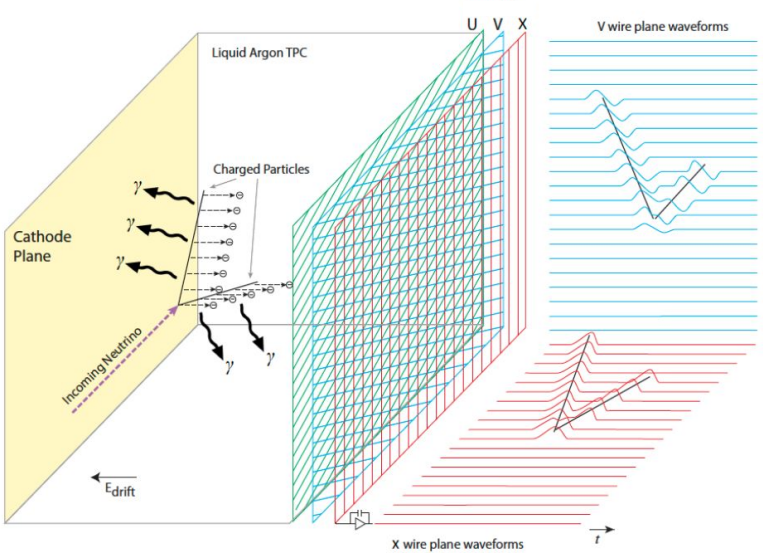
- Wide band ν (and anti-ν) beam w/ long baseline
  - *1.2 MW proton beam, upgradable to 2.4 MW*
- Near detector complex for beam characterization
  - *Movable (NDLAr, TMS) + on-axis (SAND) detectors*
- Huge far detector w/ superior PID capability
  - *3 x 17 kton total mass LArTPCs + 1 Module of Opportunity,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

Physics Programme:

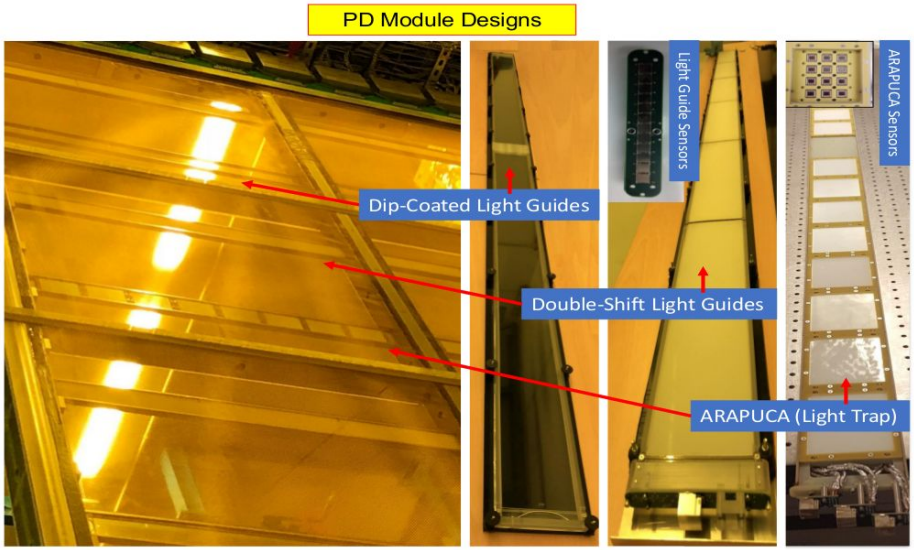
- ν mass ordering, CP-violating phase δ_{CP}
- Measurement of PMNS parameters octant of θ_{23}, Δm^2_{13}, precision measurement of δ_{CP}
- Physics with natural ν sources
  - *galactic supernova neutrino bursts*
- Beyond Standard Model physics
  - *neutrino anomalies @ LBNF, proton decay, dark matter*

Far Detector technology

Charge detection



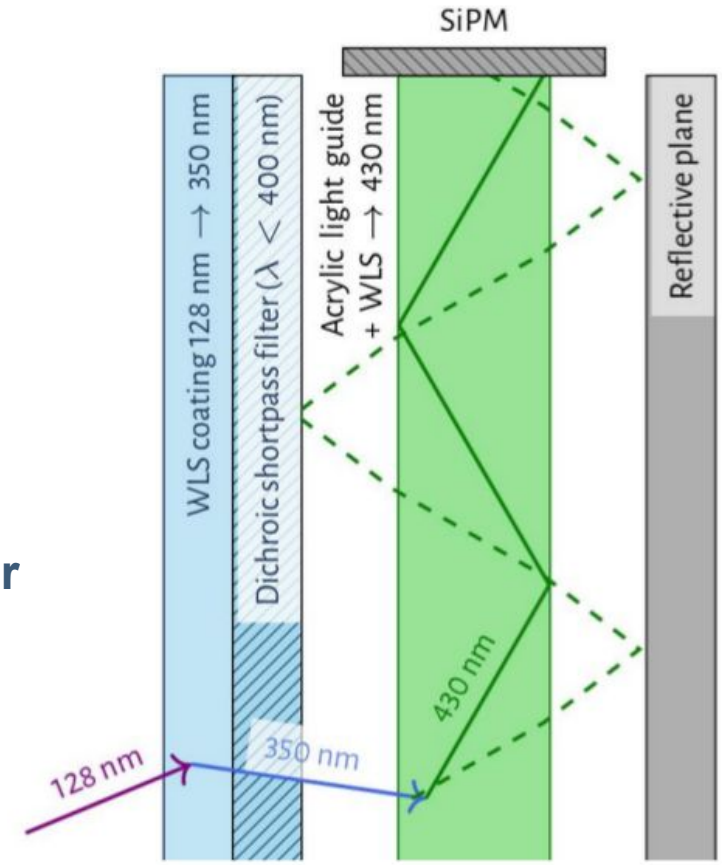
Photon detection



- 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**

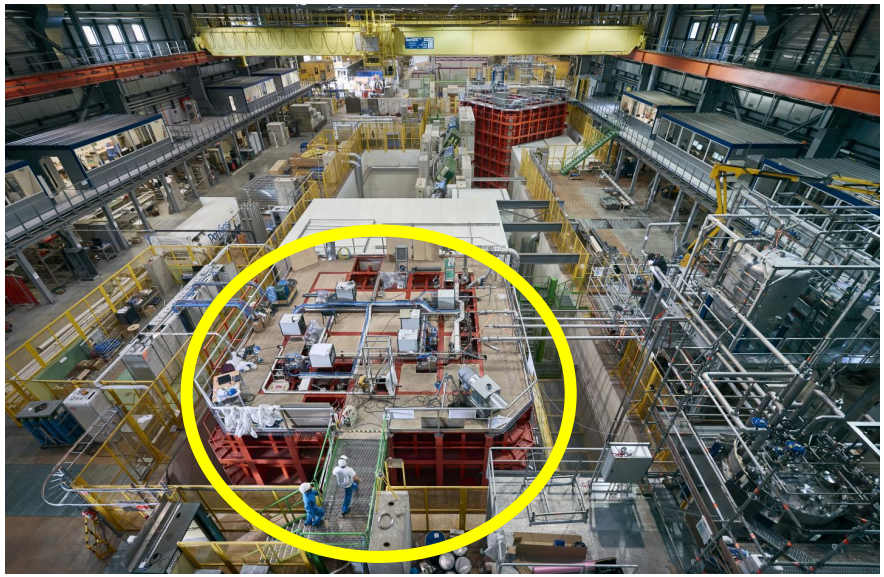
Photon detection system: X-ARAPUCA (XA)

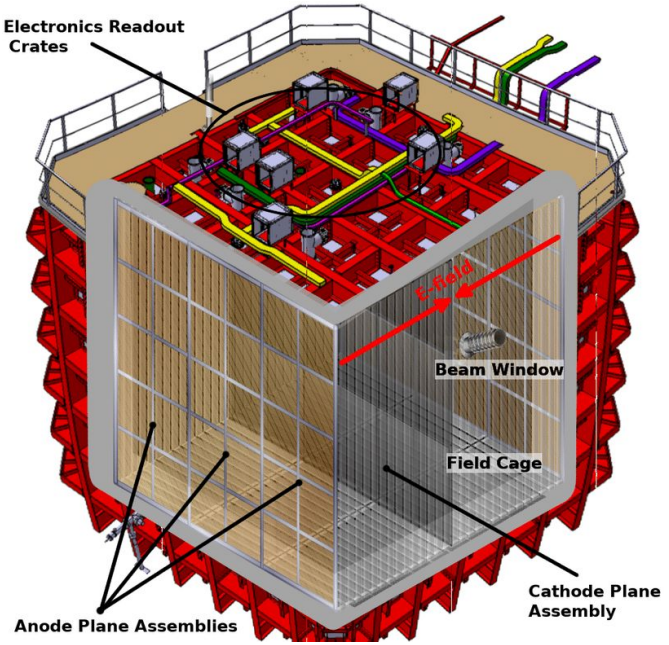
- LAr VUV scintillation light abundant (25k photons/MeV @ 500 V/cm) → combined with TPC signal **improves calorimetry**, especially at low E
- **improves vertex reconstruction (from ~1 cm to ~ 1 mm)**
- fast component τ = 7 ns → **provides trigger for non-beam events**



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 at CERN (NP04)

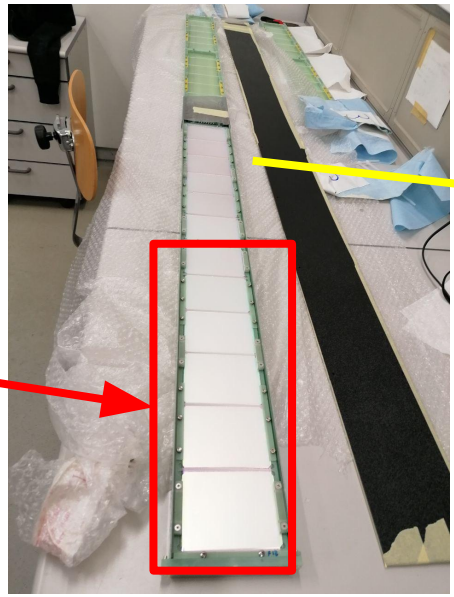


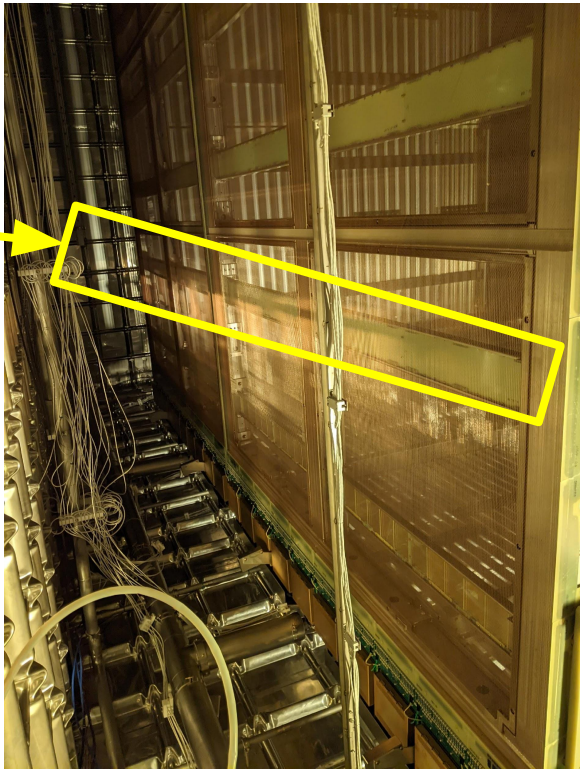


- Single-phase liquid argon time projection chamber @ CERN Neutrino Platform, North Area
- Prototype for DUNE Far Detector 1 - Horizontal Drift
- Cryostat dimensions 8.5 x 7.9 x 8.5 m^3, active volume 7.2 × 6.1 × 7.0 m^3 3.6 m drift distance

The Horizontal Drift X-Arapuca (HD-XA) device

- X-ARAPUCA design: 48 ganged SiPMs correspond to 1 HD-XA (channel readout, active window 46.2 x 10 cm^2)
- 4 HD-XA for Module, 10 modules for APA





Sides populated with SiPMs, 24 each

ProtoDUNE-HD at CERN

HD-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.

HD-XA PDE performances

- HD-XA PDE tested in Milano-Bicocca and CIEMAT
- Same SIPMs (exchanged between CIEMAT & MiB) but different WLS bars
- These four configurations are equally represented in ProtoDUNE -HD NP04 and balanced in number and position w.r.t. the beam, for a fair comparison
- cross-talk corrected

		FBK + EJ	FBK + G2P	HPK + EJ	HPK + G2P
CIEMAT	ε_{MAD}	1.34 ± 0.24	-	1.59 ± 0.29	2.13 ± 0.38
CIEMAT	ε_{MiB}	1.61 ± 0.12	-	1.86 ± 0.15	2.50 ± 0.21
MiB	ε_{MiB}	1.80 ± 0.15	2.22 ± 0.19	-	2.40 ± 0.20

ε_{MAD}: direct measurement (SiPMs VUV4 comparison)
ε_{MiB}: from known LY and Montecarlo

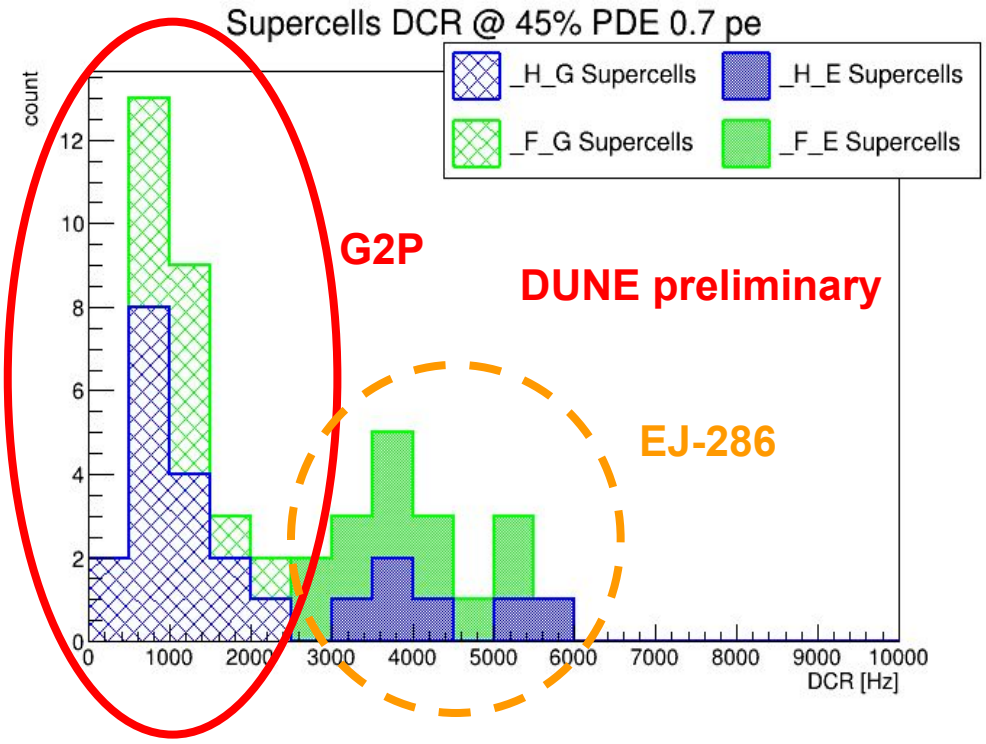
https://arxiv.org/abs/2405.12014
plan to submit to EPJC

PDE 50% for HPK and 45% for FBK (compatible gain + these PDE correspond to the operating voltages of the two SiPMs in ProtoDUNE/DUNE)

HD-XA S/N and DCR performances

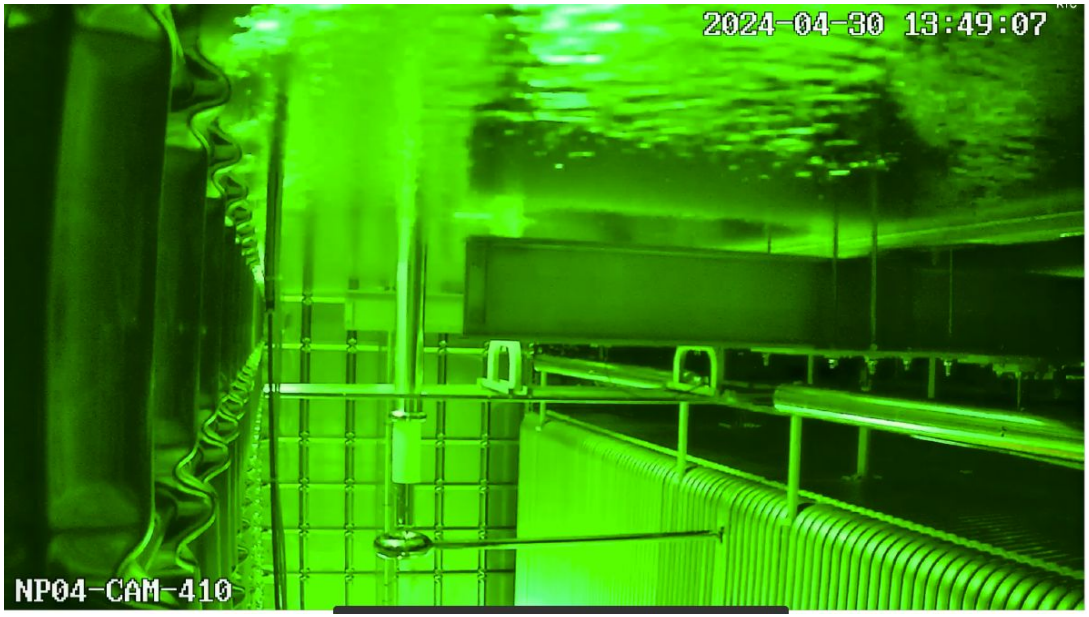
- All 160 HD-XA installed in ProtoDUNE-HD at CERN were tested in CIEMAT, MiB e CSU
- S/N and DCR measurements
- MiB subset results in line with other testing sites
- **G2P WLS bar outperformed the EJ one** both w.r.t. the PDE and the DCR (PVT is a scintillator, PMMA is not)

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



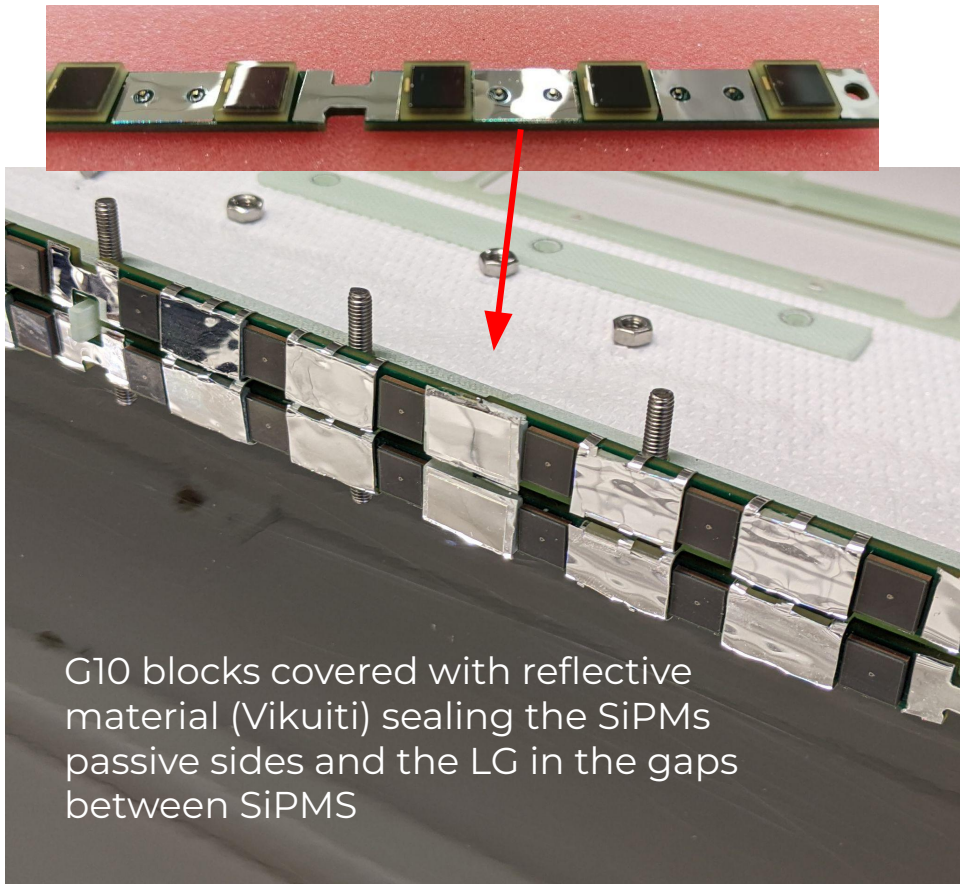
HD NP04 ProtoDUNE updates

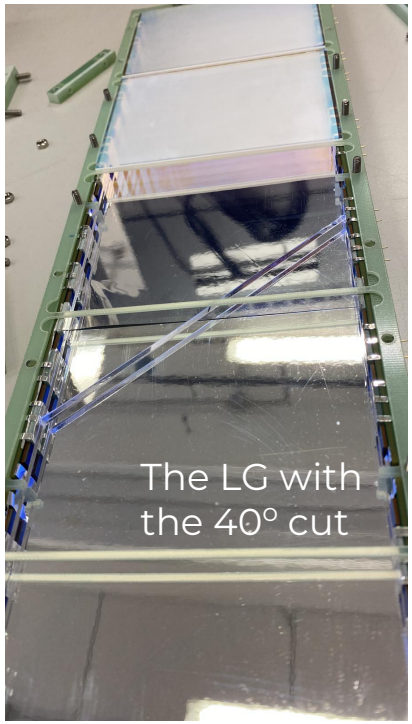
- Installation of 4 APA completed in September 2022, cooldown delayed due to LAr shortage
- LAr filling completed on April 30, 2024
- Currently working on V_{bd} assessment

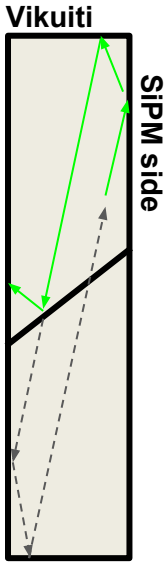


HD-XA PDE enhancement

Simulation-driven measurements in Milano-Bicocca from January to May 2023 with increased WLS light sealing and different light guide geometry (40° cut in the middle).



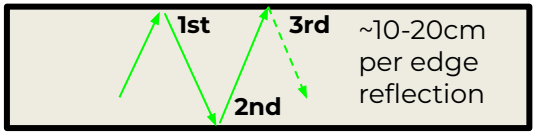




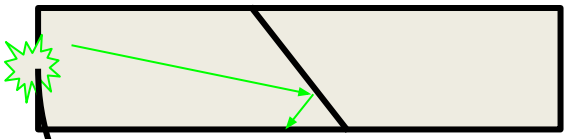
Reflective material placed directly on the short sides and on the diagonal cut of the LG

HD-XA PDE enhancement

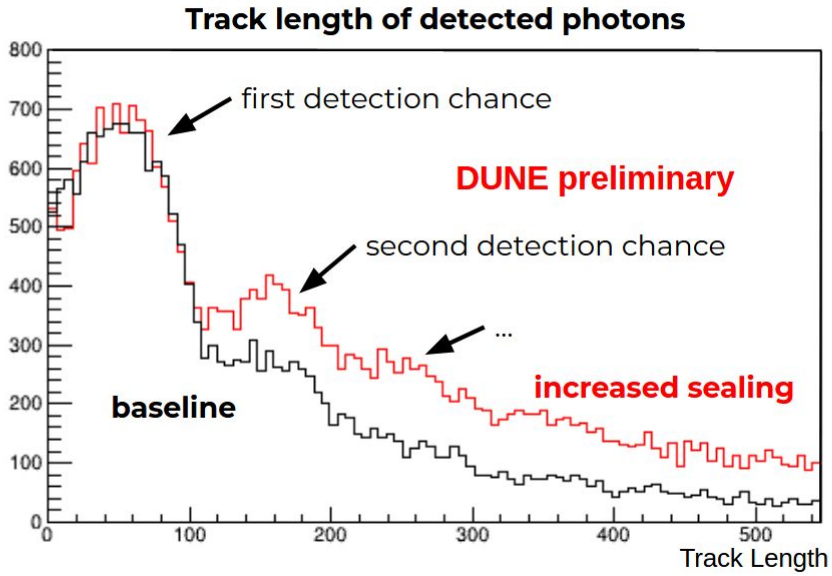
Simulation. Plot of the optical path of detected photons, “track length” between photon generation (lg WLS process 350->450nm) and detection in a SiPM peaks correspond to photons reaching an edge instrumented with SiPM and being detected.

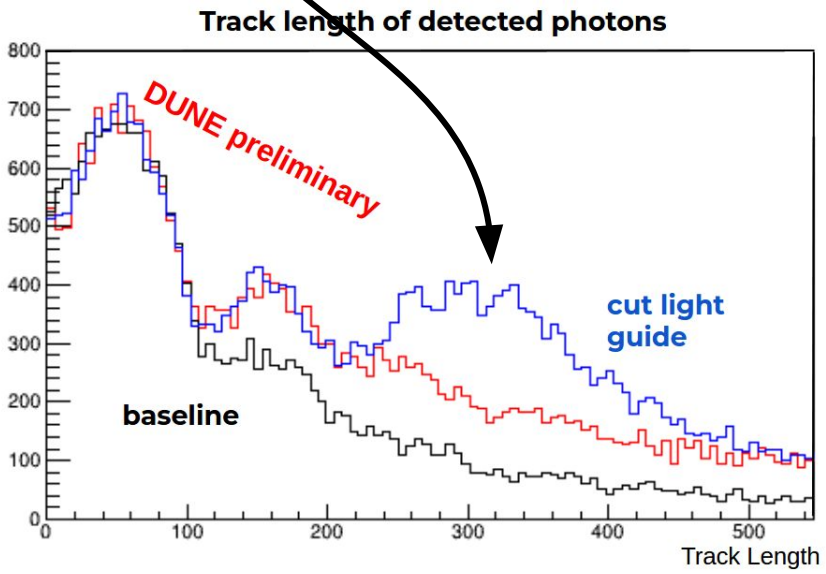


source placed at the edge of the SC in this test



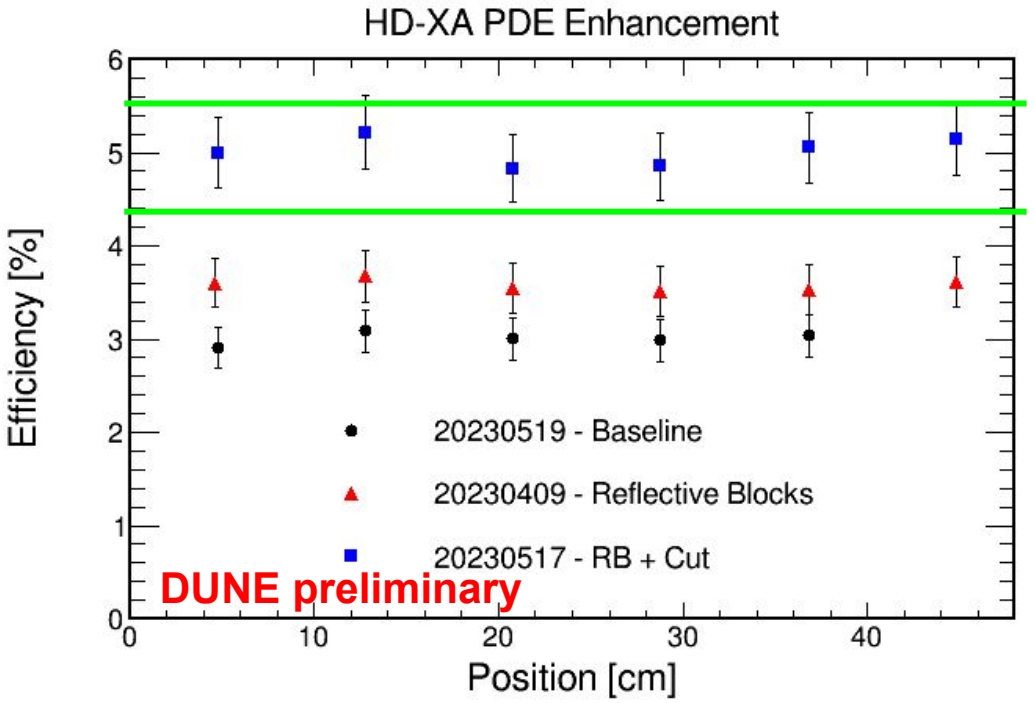
~20cm from the short side + ~5cm from the reflection
=> peak around 30cm TL





HD-XA PDE enhancement

Measurements.
HD-XA PDE improvement with reflective blocks: **~+20%** wrt baseline (depends highly on the tolerances)
HD-XA PDE improvement with reflective blocks and 40° cut: **+45-67%** wrt baseline

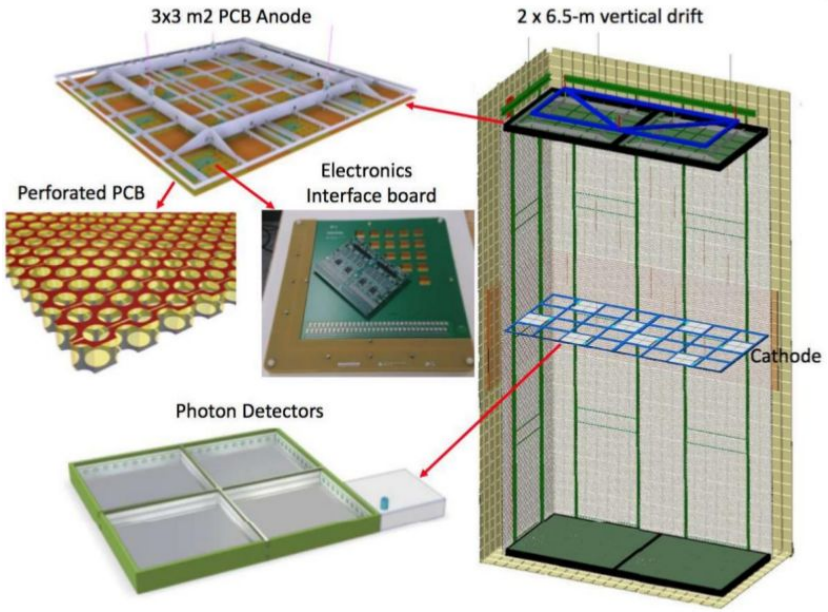


Improvement range given by variability of the assembly and mechanical tolerances.

Efficiency values not cross-talk corrected

Option under evaluation for Far Detector 1

ProtoDUNE-Vertical Drift at CERN (NP02)



- Second ProtoDUNE @ CERN and FD2 exploit the Vertical Drift technology
- Prototype for DUNE Far Detector 2 - Vertical Drift
- PDS in the cathode (300 kV!) + outside the field cage (“Membrane”), light uniformity improved w/ Xe doping

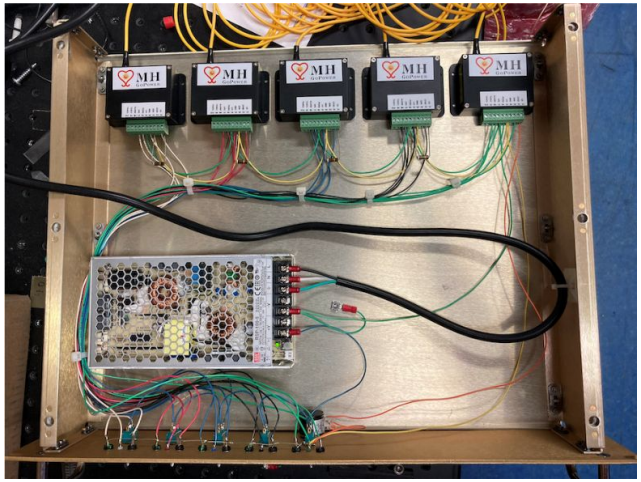
Vertical Drift electronics

- For **Membrane** modules both bias and signal are over copper

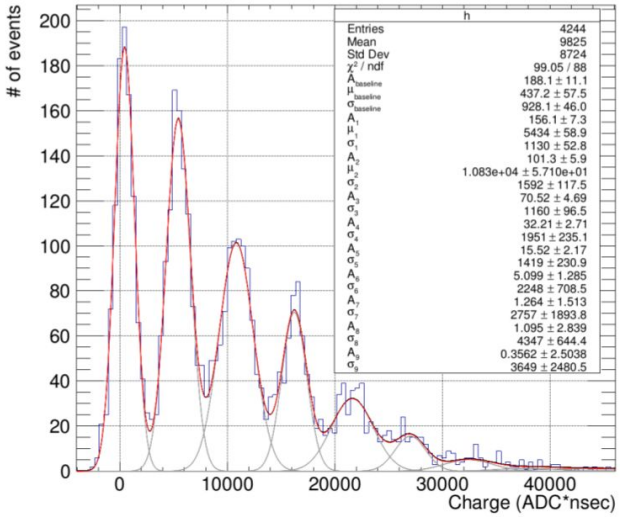
- Two main differences between HD and VD:
  - Active device for the summing/amplification stage:
    - HD customized amplifier
    - VD commercial OpAmp
  - SiPM bias transmission:
    - HD use the same twisted pair cable for SiPM power and signal
    - VD use different twisted pair cables for SiPM power and signal

Power and Signal over Fiber (PoF-SoF)

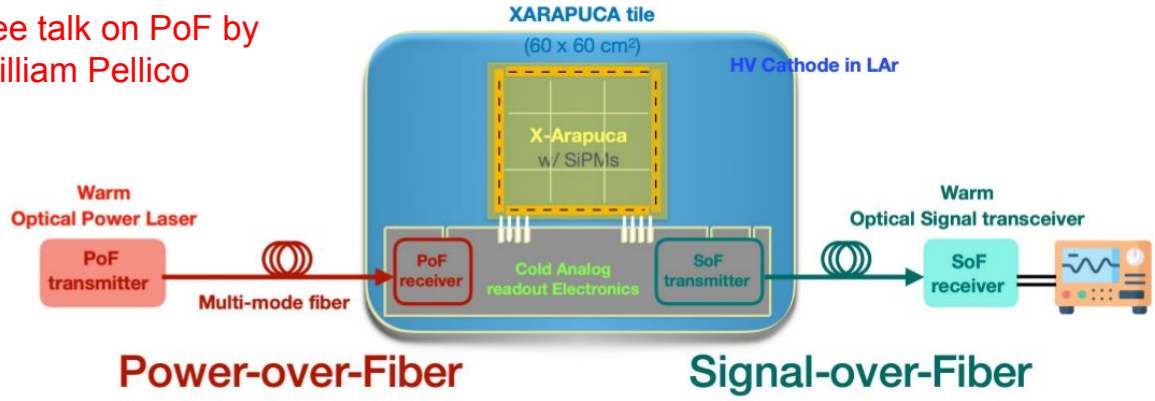
- To power and read SiPMs in a 300 kV electric field (**Cathode** modules): Power over Fiber (PoF)
  - based on commercial system with GaAs laser and OPC. Power through optical fibers converted to DC at cold.
  - Used in solar energy industry, developed (at FNAL, 2020-23) for applications HEP in LAr
- Signal Over Fiber: analog signal transmission using IR laser light
- For a full cathode module, obtained an S/R~6 (Feb 2023)



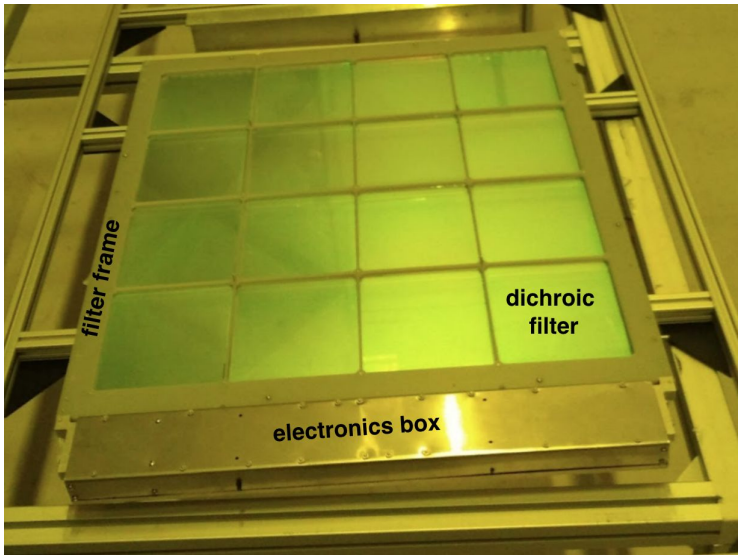
partnership betweenFNAL, Broadcom, UIUC and GoPower



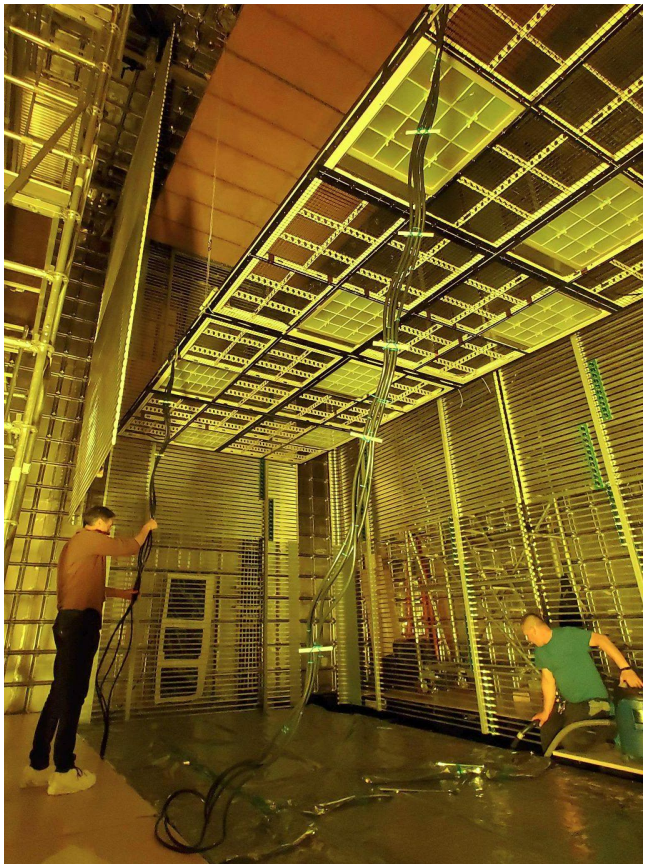
See talk on PoF by William Pellico



The Vertical Drift X-Arapuca (VD-XA) device



All 4 sides populated with SiPMs, 40 each, grouped in 2 channels



Same technology but different SiPM coverage and dimensions, WLS plate dimensions **60.7 x 60.7 x 0.4 cm^3**, SiPMs mounted on spring loaded circuits to ensure contact with WLS at LAr temperature

HD-XA vs VD-XA

- SiPMs connected in parallel in groups of 6 on G10 boards, 8x6 ganged together through 1 Ω resistors
- 48 SiPMs total per XA = 1 channel
- HD-XA sensitive area: 0.046 m^2
- HD-XA SiPM total area: 6x6 mm^2 x 48
- HD-XA SiPM/area coverage: **0,038**

- SiPMs passively passively ganged in groups of 20 on Kapton flex boards spring loaded, 4x20 actively ganged, successfully read by a single readout channel with S/R~6 (FermiLab)
- 160 SiPMs total per XA = 2 channels
- VD-XA sensitive area 0.36 m^2
- VD-XA SiPM total area: 6x6 mm2 x 160
- VD-XA SiPM/area coverage: **0,016**

The ratio between SiPMs area and detector sensitive area is 2.4 times higher in HD-XA w.r.t. VD-XA

VD-XA PDE measurements

Tests ongoing/performed at **CIEMAT (Madrid)** and **University of Naples**.
Membrane (no PoF) XA equipped with:

- G2P WLS plate with 80 mg/kg chromophore concentration (as in HD-XA), 3.8 mm thick
- SiPM by FBK

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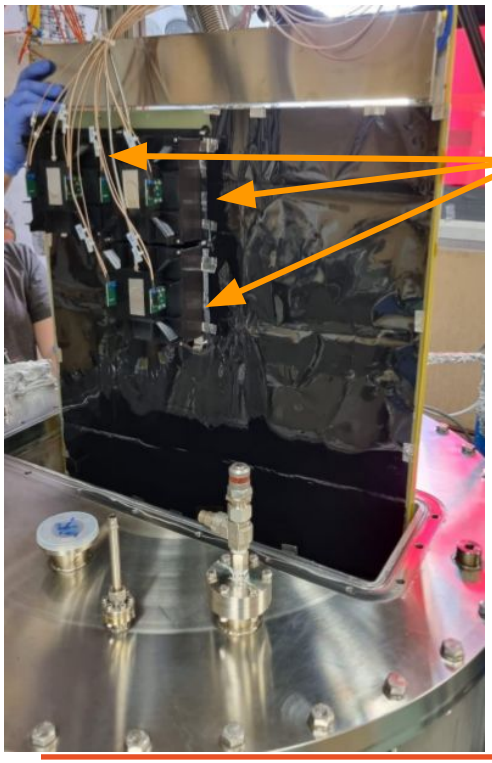
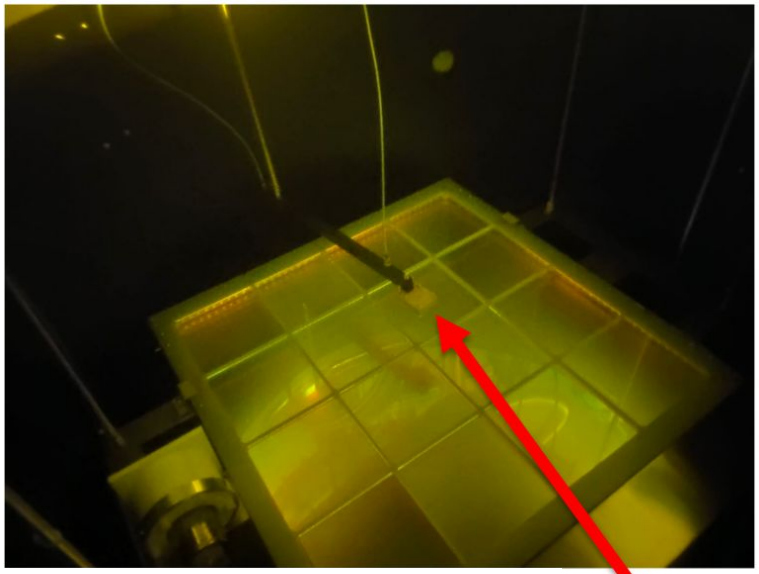


3 calibration boxes each with 2 reference VUV SiPMs triggering on scintillation from an ^{241}Am α source (3 α sources in total). Megacell tested in vertical.

Measurements and analysis currently ongoing.



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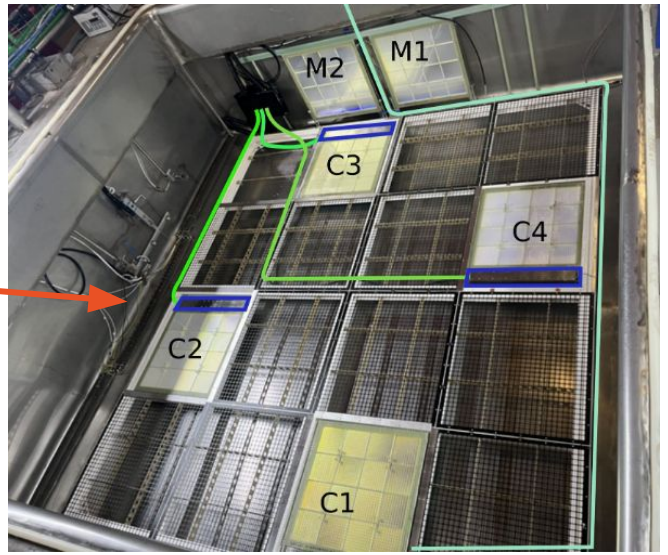
Preliminary lower limit
ε=2.15 ± 0.20%
at 45% SIPM PDE. Analysis ongoing.

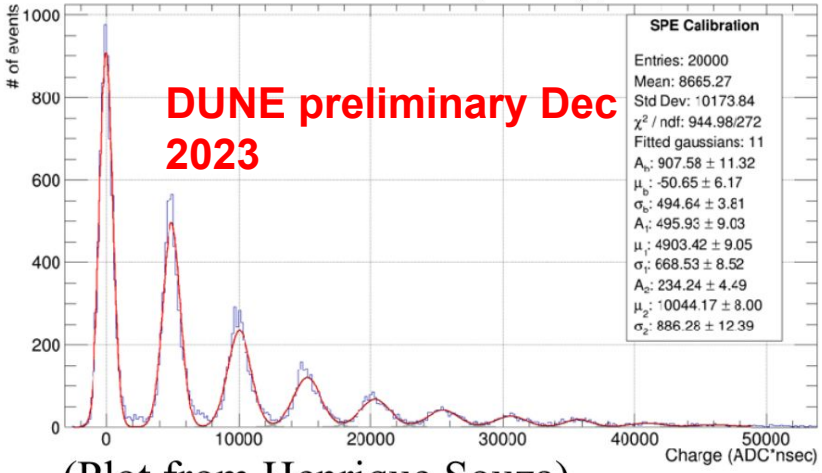
α source (^{241}Am) mounted on a rotating arm to scan different positions. Megacell tested in horizontal.

VD COLD BOX and NP02 ProtoDUNE updates

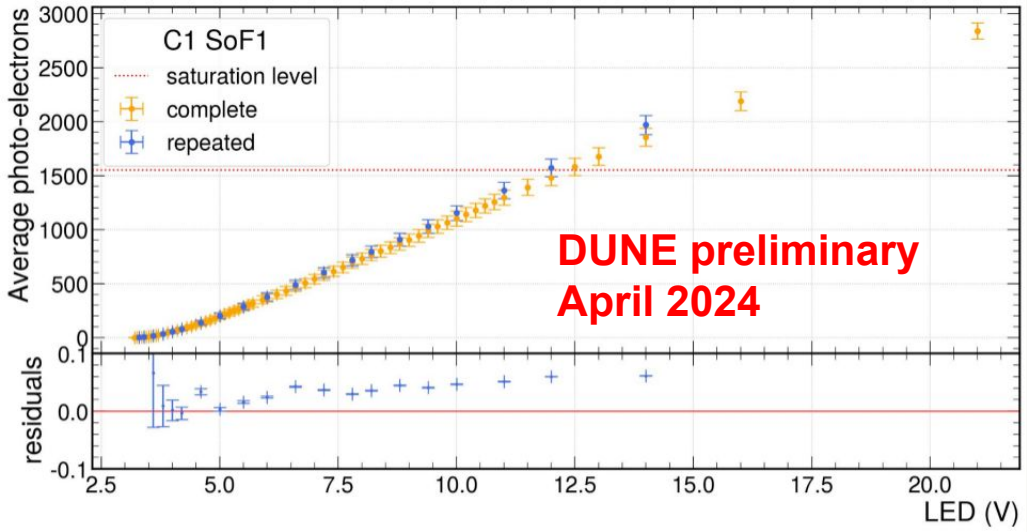
- NP02: 8 Memb-XA +8 Cath-XA deployed in 2023
- NP02 LAr filling scheduled for end of 2024
- Ongoing tests in nearby test facility ("**Cold Box**") on Power and Signal over Fiber technologies. Currently calibrating the cathode modules and assessing the linearity of the signal with SoF. LED scan from 3.2V to 21.0V



Cathode module "C1" (FBK), channel 1

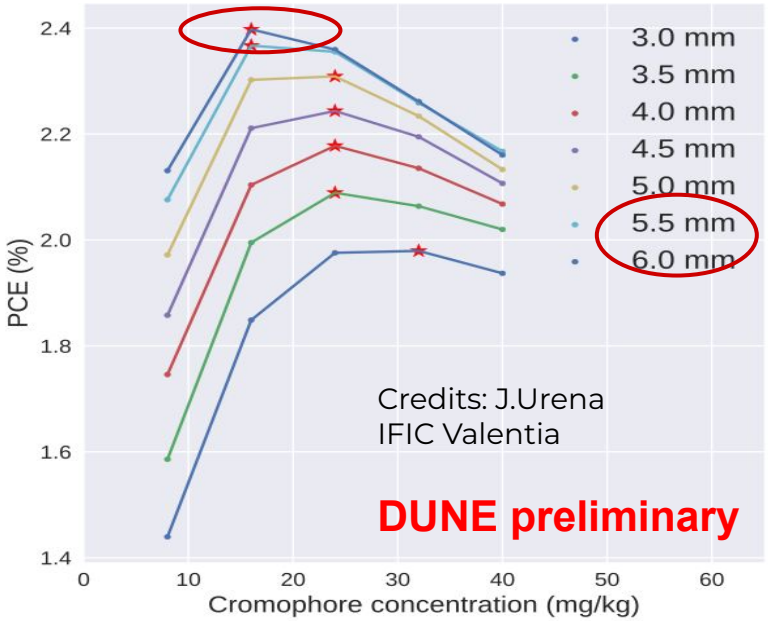


(Plot from Henrique Souza).



VD-XA PDE enhancement and assessment of components contribution

- Due to multiple reflections the optical path inside large size WLS may reach a couple of meters → dye concentration tailored to VD-XA size and optical path → optimization driven by simulations
- The max. PDE is found for WLS-plate: 5.5-6.0 mm thick 16-24 mg/kg chromophore concentration



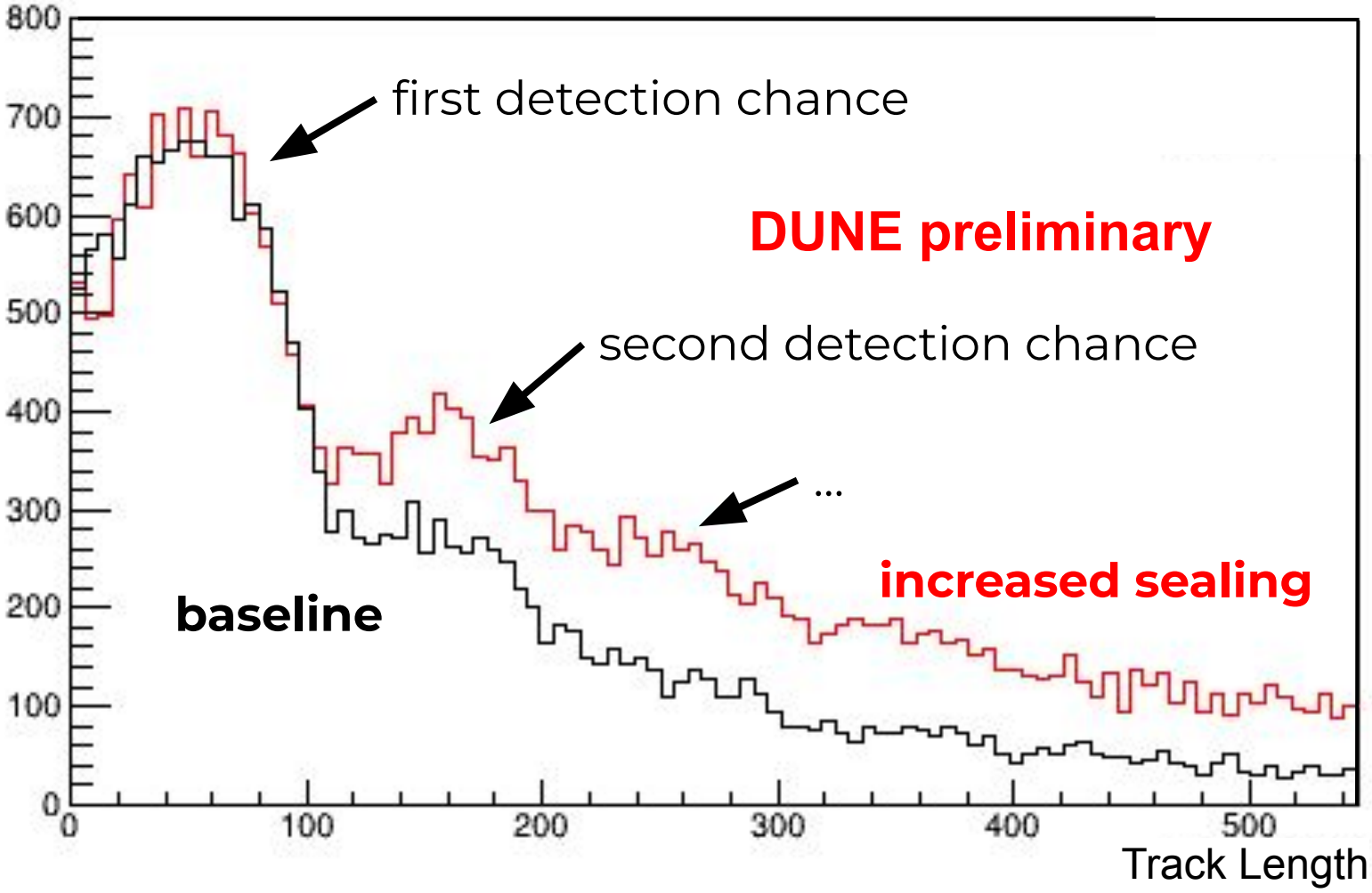
Measurements and analysis in program/ongoing at CIEMAT:

- **5.4 mm** thick plate + **24 mg/kg** chromophore concentration
- Neutral pTP coated filters

Summary

- ProtoDUNE-HD NP04 @ CERN installed and filled with LAr, V_{bd} assessment in progress
- **Horizontal Drift X-Arapuca PDE: 1.34-2.50%** depending on the SiPM-WLS combination. **Possible improvement to 4-5%** by improving light sealing of the light guide and adding a 40° cut for light collection
- ProtoDUNE-VD NP02 @ CERN installed, to be filled with LAr at end of 2024. Ongoing tests in nearby facility for Power and Signal over Fiber
- **Vertical Drift X-Arapuca PDE** under evaluation, **preliminary lower limit at ~2%**

Track length of detected photons



Track length of detected photons