Liquid Argon Technologies for Neutrino Physics: the Deep Underground Neutrino Experiment

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on behalf of DUNE Collaboration

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI MILANO BICOCCA

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Outline

- Liquid Argon features and properties
- DUNE Scientific Program and Phase-I Far Detectors
  - Focus on Photon Detection System
- Selected Results from the DUNE prototypes at CERN

Liquid Argon: ionization

LAr is a powerful media for precise calorimetry and particle identification, as well as for radiogenic background shield

W-value for ionization: W_i	23.6(3) eV/pair
Density; Z	1.4 g/ml ; 18
Radiation length: X_0	14 cm
Mininum specific energy loss: $(dE/dx)_{MIP}$	1.5 MeV cm^2 /g

2.7 eV for Ge

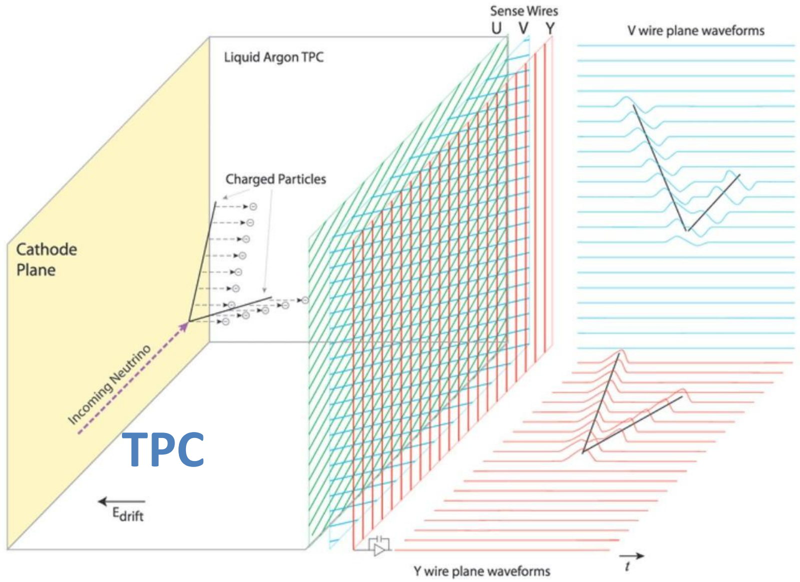
Ionization electrons

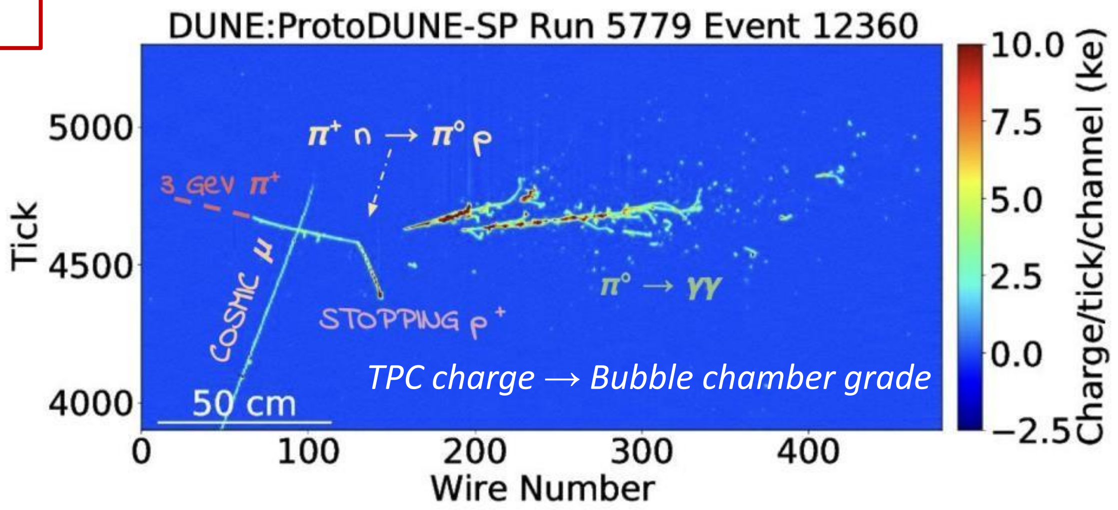
~27000 e^-/MeV

(Recombination included)

$$\tau_e \sim \frac{300}{[O_2\, ppb]} \mu s$$

Electron mobility μ_d	320.2 cm^2 V^{-1} s^{-1}
Electron drift velocity v_d (500 V/cm)	0.16 cm/μs
Attachment rate constant (O_2) k_A	3.34 × 10^{12} s^{-1}
Electron lifetime (for 0.1 ppb O_2)	τ_e =2.99 ms





LAr Scintillation

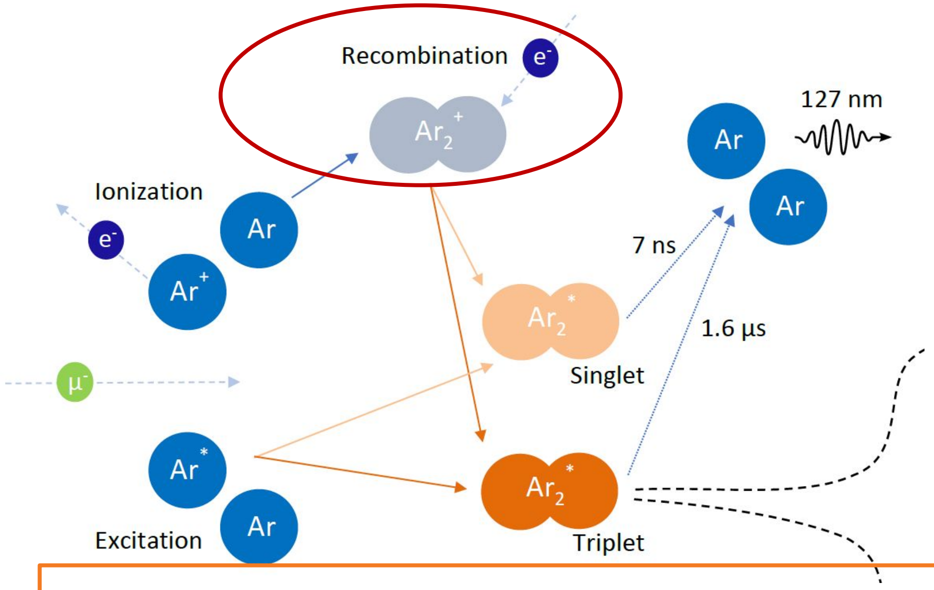
Mean energy per scintillation γ (w_s)	19.5 eV/ph.
Mean energy per Cherenkov γ (w_c)	2700 eV/ph.
Scintillation emission peak	128(10) nm
Decay time (fast component τ_f)	6(2) ns
Decay time (slow component τ_s)	1590(100) ns
Index of refraction at 128 nm	1.38
Rayleigh scattering length at 128 nm	95 cm
Absorption length at > 128 nm	200 cm

$$l(t) = A_s(e^{\frac{-t}{\tau_s}}) + A_t(e^{\frac{-t}{\tau_t}})$$

$$\int l(t)\,dt = A_s + A_t$$

$$\frac{A_s}{A_t} = depends\ on\ the\ particle\ nature$$

→ **PID by Pulse shape Discrimination**



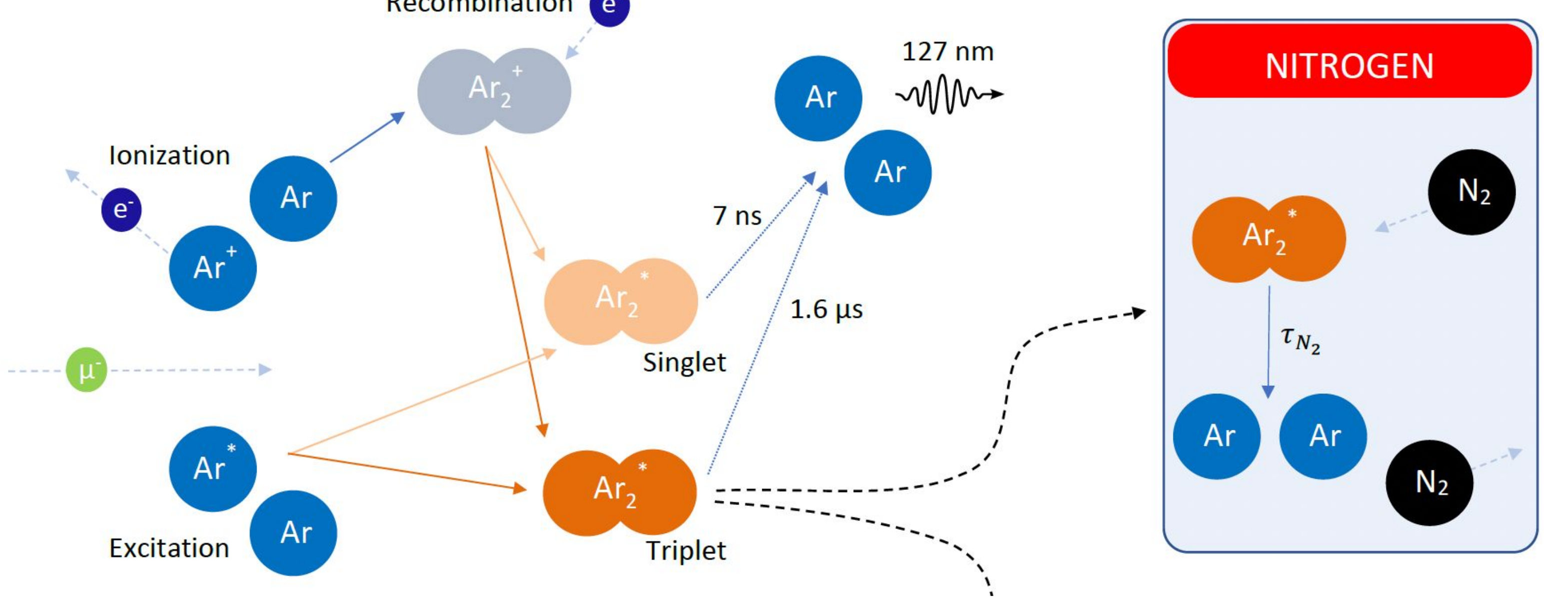
LAr LY (V = 0 V/cm)
~ 51000 ph/MeV (vs 40000 NaI)

LAr LY (V = 500 V/cm)
~ 24000ph/MeV

LAr Photons can propagate over large distances

LAr Scintillation quenchers

A. Abed Abud *et al* 2024 *JINST* **19** P08005



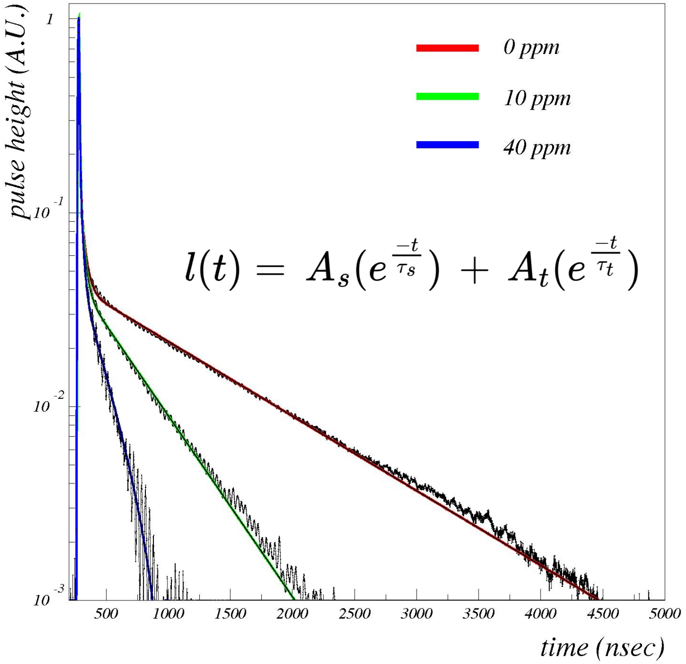
Both nitrogen and oxygen quench the Ar_2* radiative decay.

- 1 ppm of N_2 ~ 20% reduction of the scintillation light,
- 1 ppm of O_2 ~ 40% reduction.

Increasing concentrations of contaminants leads to

shorter scintillation lifetime & lower relative amplitude of the slow component

Study of the LAr light pulse shape vs the [N_2]



R. Acciarri *et al* 2010 *JINST* **5** P06003

DUNE: Long-Baseline Neutrino Experiment

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Far Detector

Phase I: 2 x LAr-TPC

-1300 km from Fermilab

-Measurement of oscillated neutrinos

Near Detectors

-Monitor of the un-oscillated neutrino beam energy & composition

-Control of beam related systematic errors

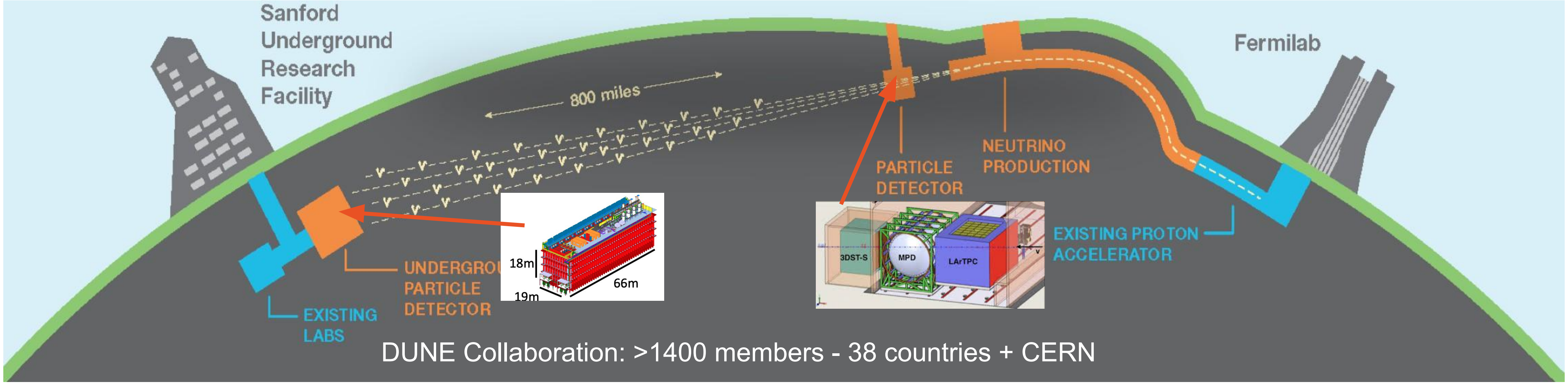
-ν-Ar cross-section measurements

Muon neutrino beam

LBNF at Fermilab

1.2 MW beam power

Upgradeable to > 2.0 MW



DUNE Collaboration: >1400 members - 38 countries + CERN

DUNE Physics

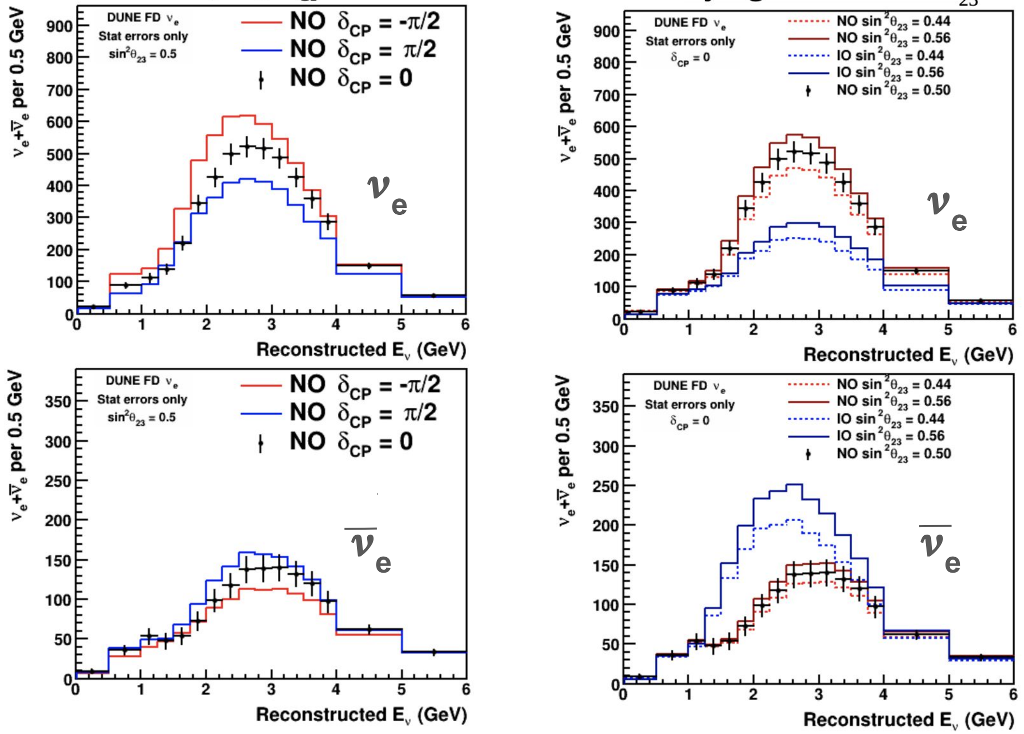
Measurement of ν_e appearance and ν_μ disappearance over a wide range of ν_μ energies at 1300 km will enable:

- Definitive measurement of neutrino Mass Ordering
- Define the octant of θ_{23}
- Discovery potential for CP violation for wide range of δ_{CP}
- Precise measurement of neutrino mixing parameters

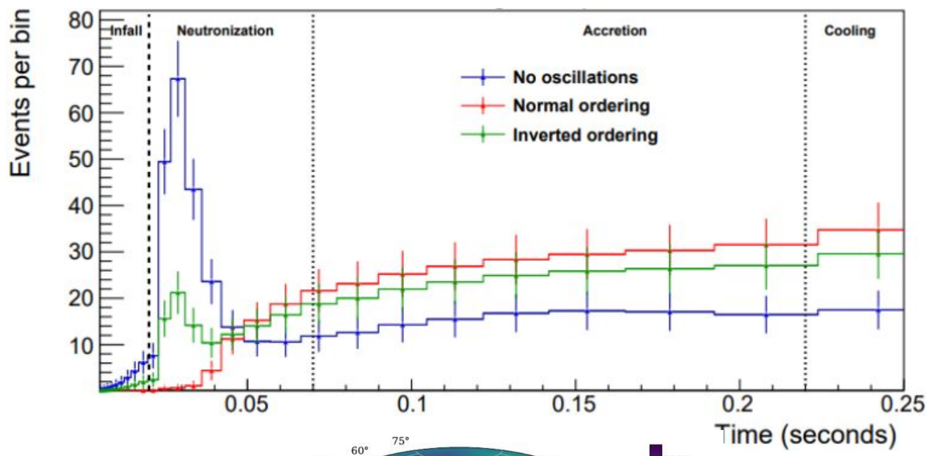
No Beam ν Physics

- Supernova Neutrino Burst
- Proton Decay searches
- BSM physics

Varying δ_{CP} | Varying MO and $\sin^2\theta_{23}$



ν Time profile from SNB in the Galaxy

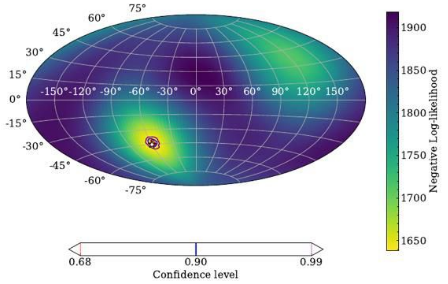


Eur. Phys. J. C **81**, 423 (2021)

pointing capabilities of ES 5°

ES: $\nu_x + e^- \longrightarrow \nu_x + e^-$

CC: $\nu_e + {}^{40}Ar \longrightarrow e^- + {}^{40}K^*$

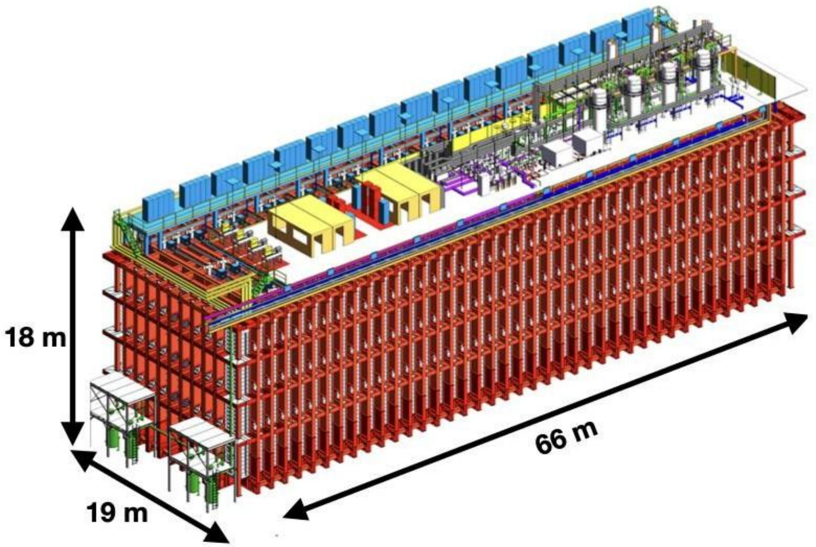


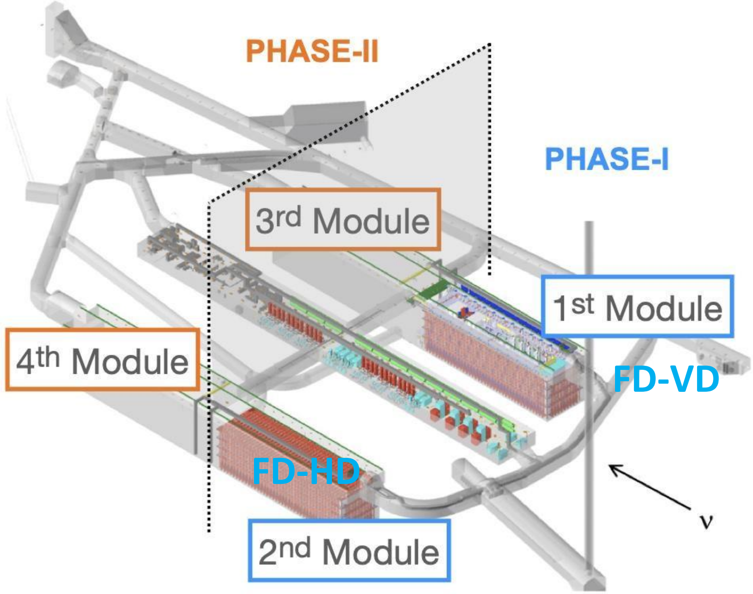
DUNE Far Detectors

- Detector located 1.5 km underground at SURF
- Staged approach of detector deployment:
  - ➢ DUNE PHASE-I (Modules 1st & 2nd): 2 x 17 kton LarTPC
  - ➢ DUNE PHASE-II (Modules 3rd & 4th): t.b.d

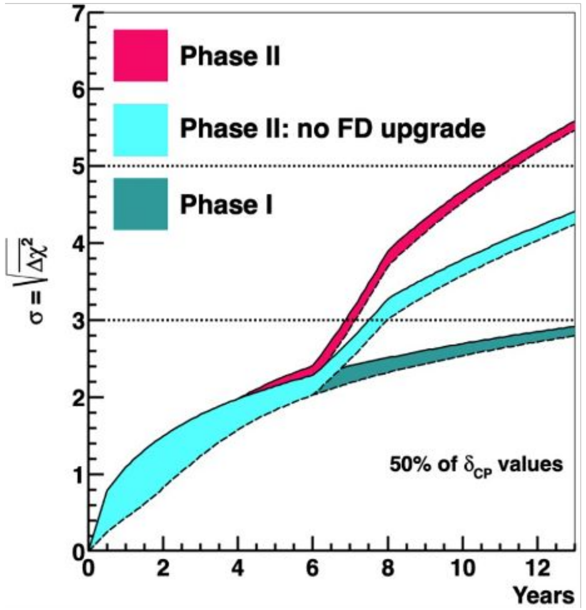
Two-phase approach

Improvements in technology implemented in Phase-II



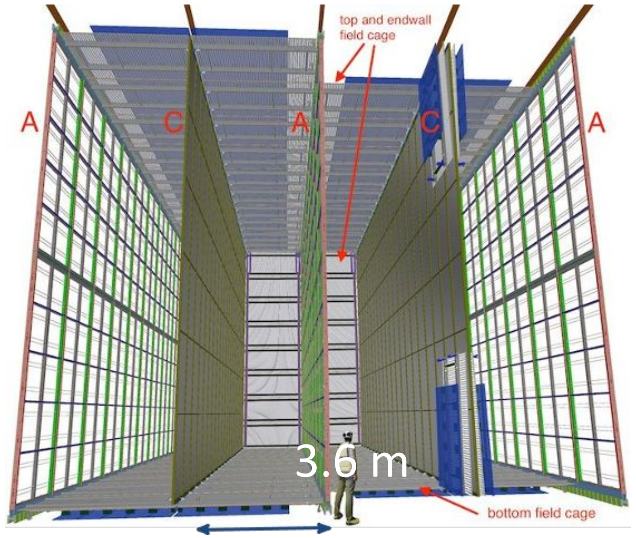


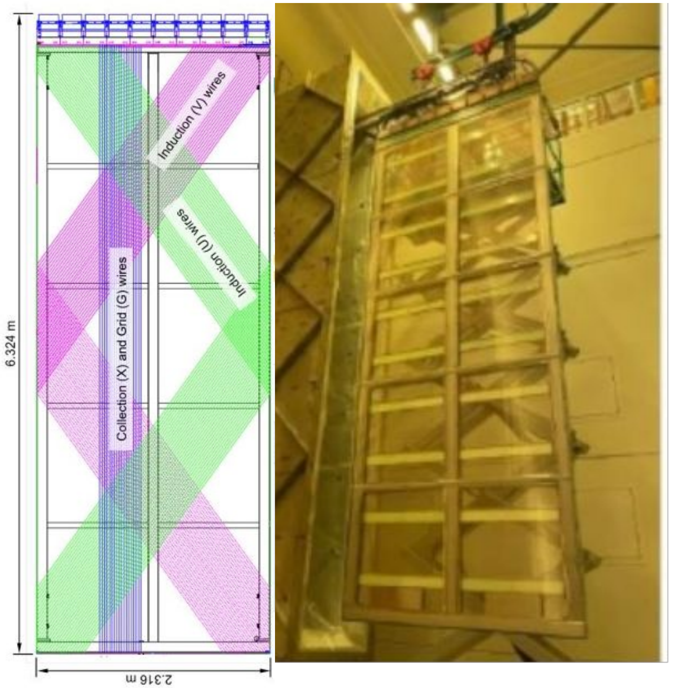
DUNE Snowmass
arXiv: 2203.06100



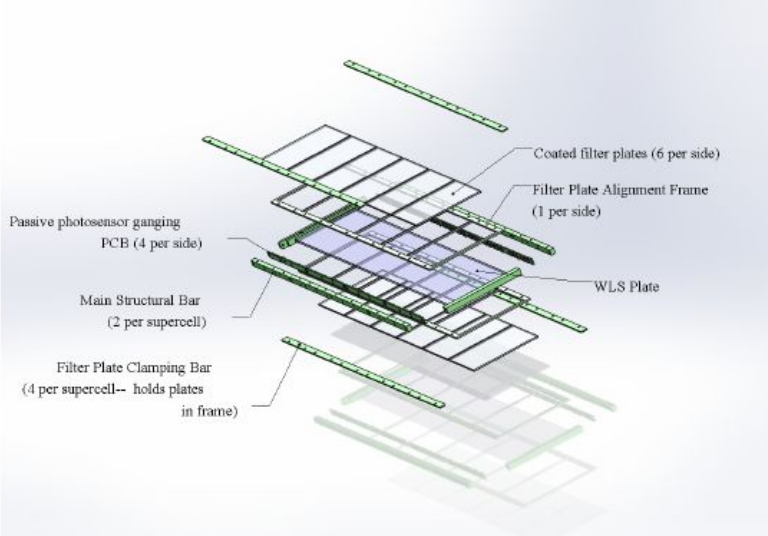
DUNE FD1: Horizontal Drift

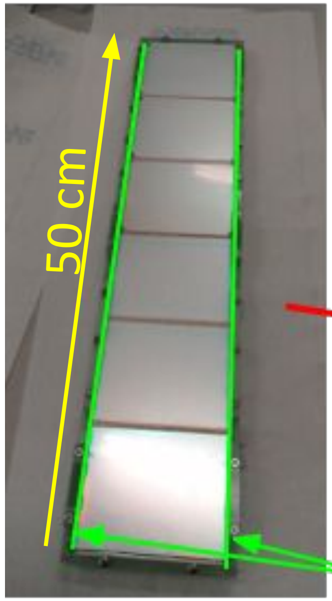
- **10 kton fiducial Volume (17 kton total)**
- **4 horizontal drift volumes x 3.6 m drift length**:
- **2 cathode** (180 kV) and **3 anode planes**
- **500 V/cm** electric drift field
- Charge readout:
  - ➢ **4 sets of wires (1 x grid, 2 x induction, 1 x collection)**
  - ➢ **transparent to scintillation light**
- **PDS embedded in the APA**
- **Mean LY > 20 PE**
- **Anode Plane Assembly (APA)** is the base module of the anodic plane
  - ■ **6.3 m** (H) x **2.3 m** (W)
  - ■ **150 APAs** total

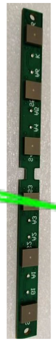


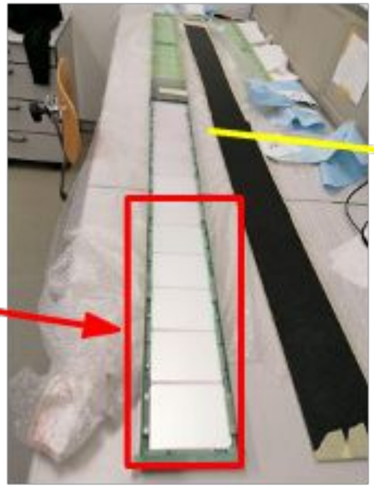


DUNE FD1- Horizontal Drift PDS









Sides populated with SiPMs, 24 each

SiPMs on FR4 rigid boards

FD1 optical cells named X-Arapucas: (50 x 10 cm^2)

- 4 SuperCells/module
- 10 module/APA
- 1500 Total Modules
- 1000 Double sided 500 single sided
- 48 SiPM/module for one readout chanel (**SiPM/WLS coverage: 3.9 %**)
- 288000 SiPM (Hamamatsu and FBK) *more on SiPMs in M.Guarise Talk!*
- SiPMs have been individually extensively tested at room and cryogenic T after multiple T cycles→ 0.3% mortality for HPK SiPMs or bad functioning has been found

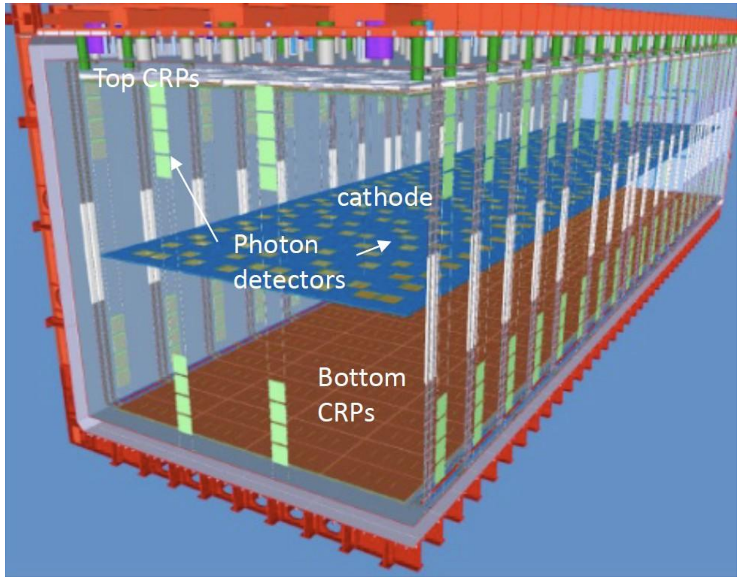
M. Andreotti et al, 2024 JINST 19 T01007

DUNE FD2- Vertical Drift

- **10.5 kton active volume (14.75 kton tot)**:
- **2 x 6.5 m drift volumes**
- **1 cathode** and **2 anode planes**
- **500 V/cm** electric drift field

Anode planes are modular:

- **Charge Readout Planes (CRP)** is the base module
  - **3.0 m x 3.4 m**
  - **160 CRPs** total
  - perforated PCBs
    - ➢ **not transparent to scintillation light**
- **Light is detected** by modules placed **on the cathode**
  - non conductive biasing and readout required
  - ➔ **Enabled by PoF technology, first-ever in HEP**



arXiv:2405.16816

Characterization and Novel Application of Power Over Fiber for Electronics in a Harsh Environment

M. A. Arroyave[a], B. Behera[b], F. Cavanna[a], A. Feld[a], F. Guo[c], A. Heindel[b], C. K. Jung[c], K. Koch[a], D. Leon Silverio[b], D. A. Martinez Caicedo[b,1,‡], C. McGrew[c], A. Paudel[a], W. Pellico[a,1,*], R. Rivera[a], J. Rodríguez Rondon[b], S. Sacerdoti[e], P. Shanahan[a], W. Shi[c,1,†], D. Torres Muñoz[b], D. Totani[d], C. Uy[b], C. Vermeulen[b], and H. Vieira de Souza[e]

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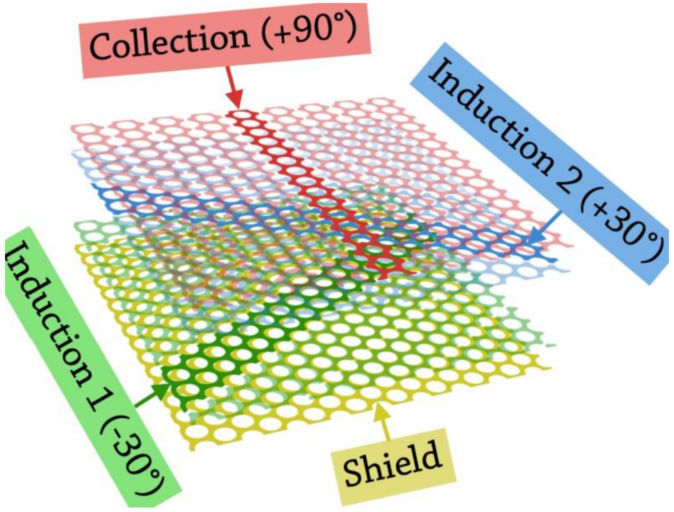
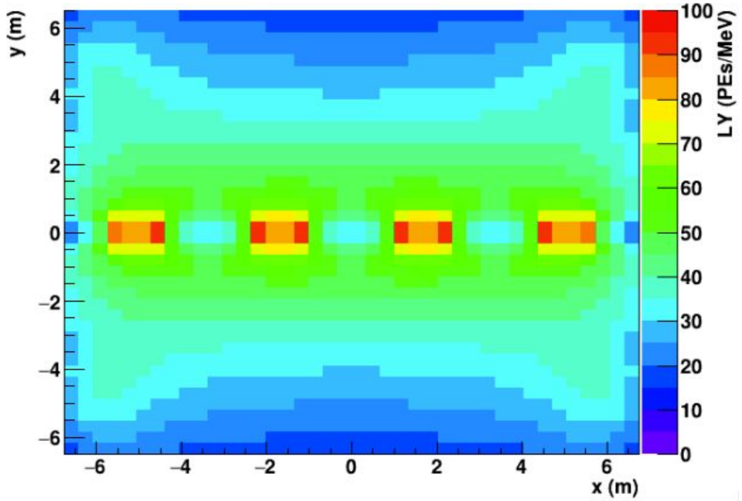


Charge Readout Plane



VD PDS Light Yield
(VD TDR arXiv: 2312.03130)

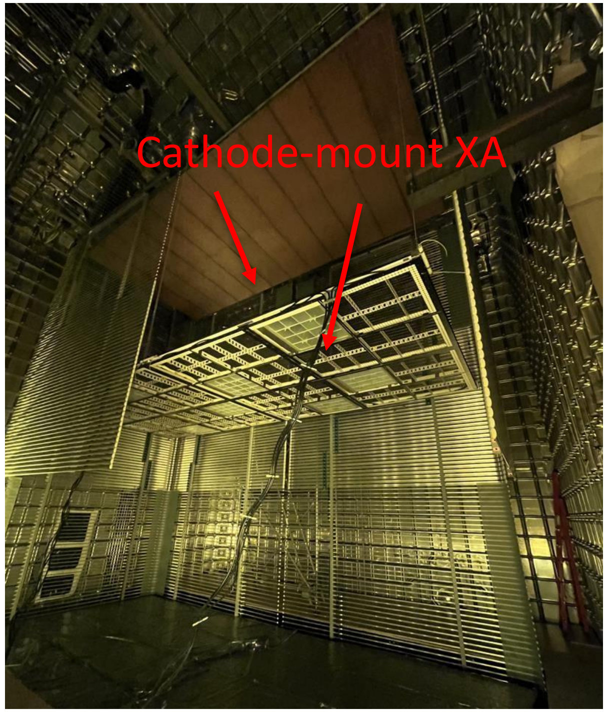
DUNE-VD - Vertical Drift PDS

60 cm x 60 cm photodetectors (X-Arapuca) on cathode and membrane

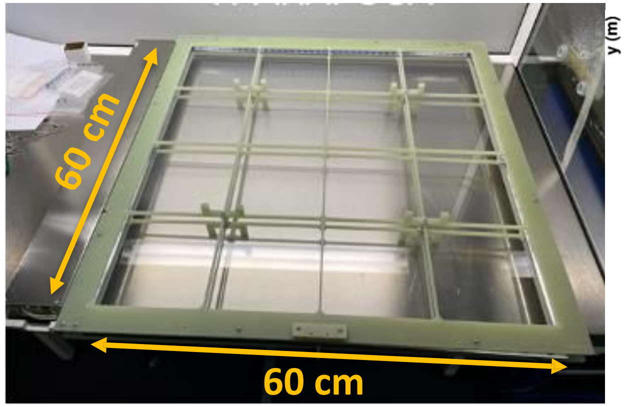
- **Mean light yield ~ 40 PE/MeV**
- **320 X-Arapucas on -300 kV** cathode to improve **light yield uniformity. POF & SOF technology**
- **320 XA on the long walls + 52 on the short walls** outside the semitransparent Field Cage. Bias and readout on copper cables.
- **108000 SiPMs overall on flex cables**

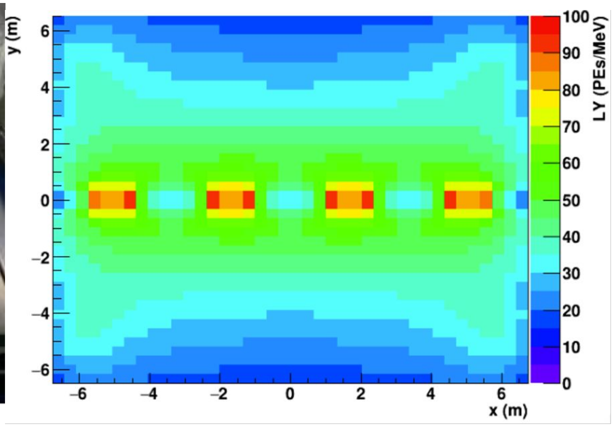
– 60 x 60 cm^2
– 16 entrance windows (144 x 144 mm^2)
– 1 WLS plate (x 8.2 area w.r.t. FD1)
– 160 6x6 mm^2 SiPMs. (**SiPM/WLS coverage: 1.6 %**) grouped in two readout channels

Wall-mount XA



X-ARAPUCA VD

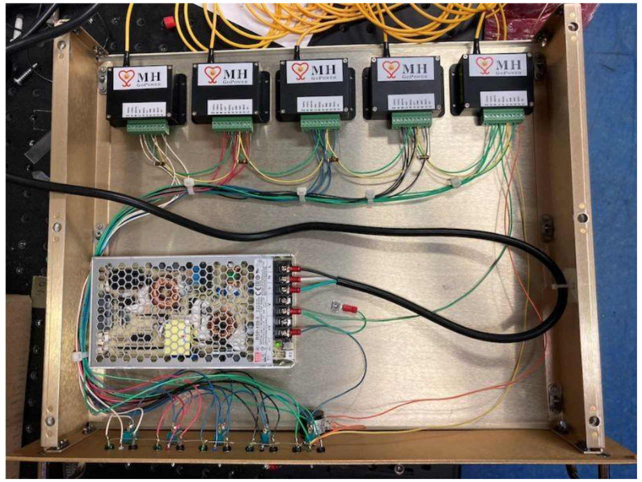




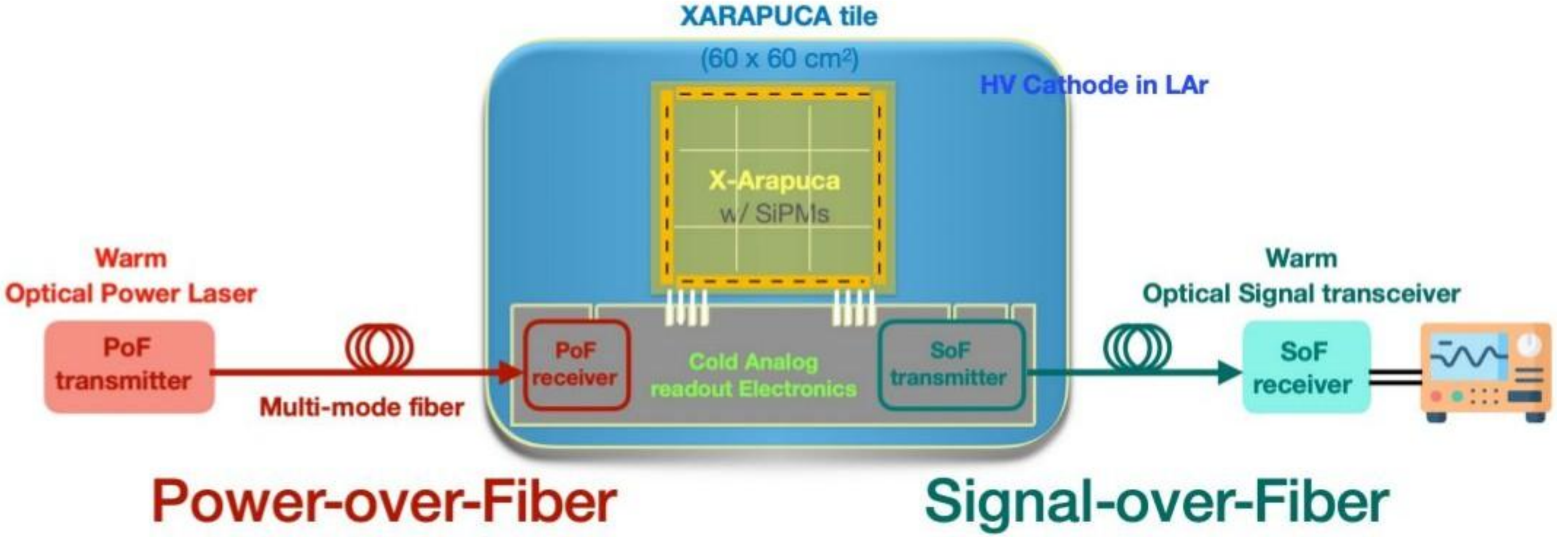
VD PDS Light Yield
(VD TDR arXiv: 2312.03130)

Power and Signal over Fiber (PoF-SoF)

- To power and read SiPMs biased at 300 kV (**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



partnership betweenFNAL, Broadcom, UIUC and GoPower



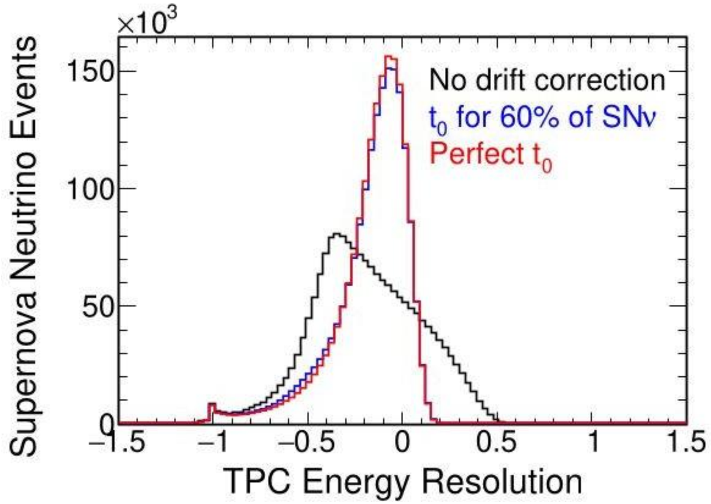
Photon-Detection System

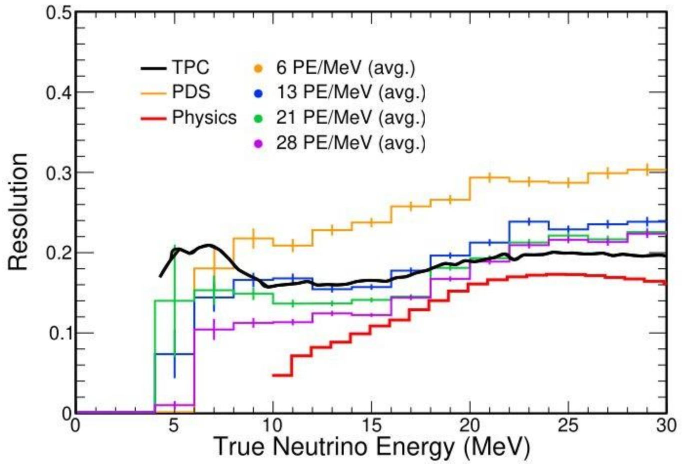
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Goals:

→ Increase energy resolution
→ Trigger for non beam events
→ Improve time precision
→ Measurement of t_0
→ Cross check with charge measurements
→Charge correction

- electron drift speed: ≅ 1.6 mm/μs
- photon speed: ≅ 2.5 x 10^5 mm/μs





LY requirement to boost the trigger (p-decay) and energy resolution (SN ν) capabilities of the DUNE PDS::

- LY_{min} > 0.5 PE/MeV
- LY_{ave} > 20 PE/MeV

Required performances of the photon detectors

- **PDE: 2%-3%**
- S/N > 4
- DCR/ch < 1 kHz

The 3rd and 4th Phase-II modules will have advanced PDS to extend the scope of DUNE non-beam physics (e.g.Solar)

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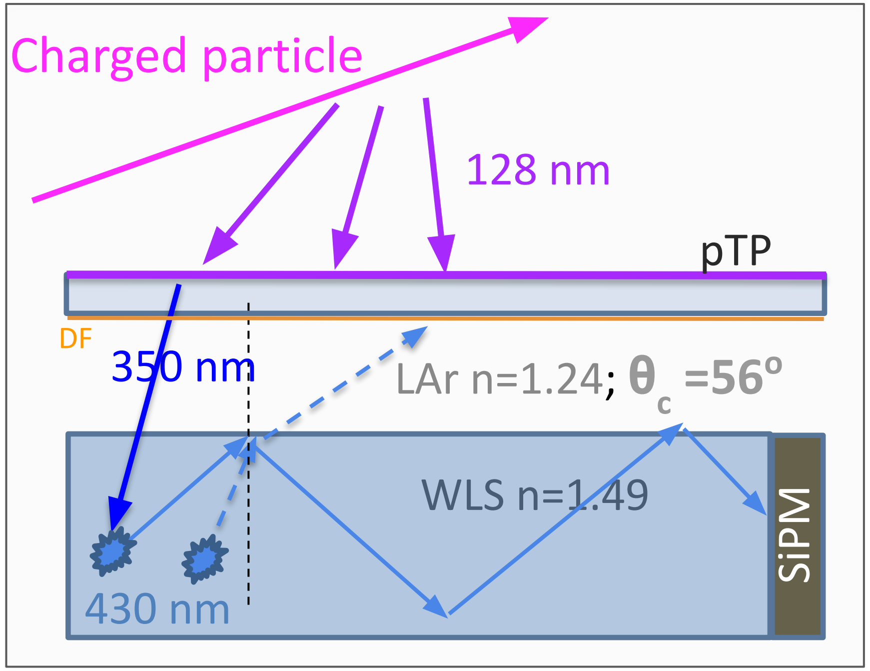
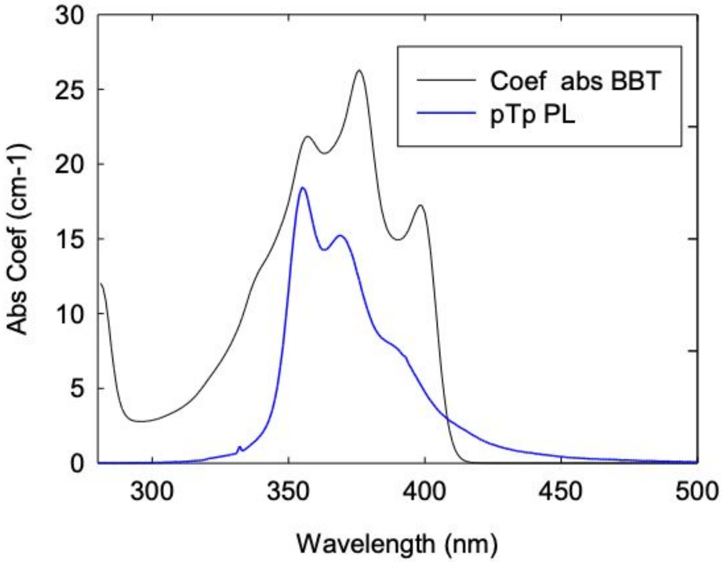
Photon-Detection Unit : X-ARAPUCA device

Large area Photon Collector constitutes of two light downshifting stages and photosensors:

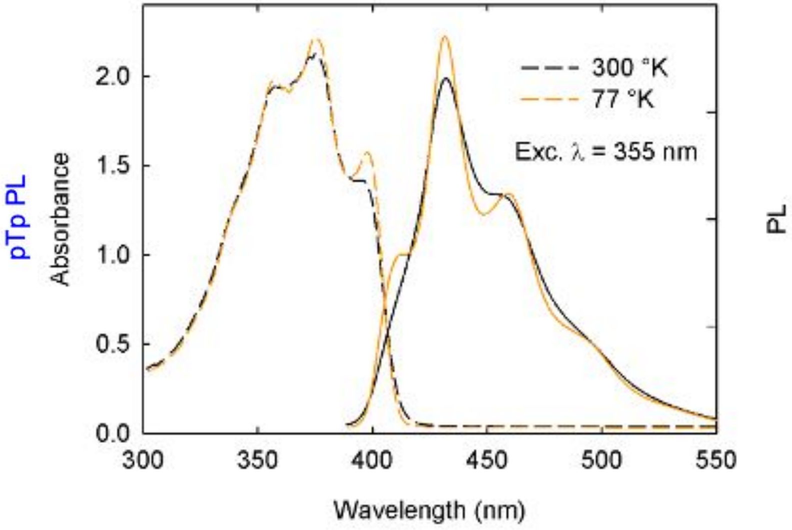
1. The pTP coated entrance window: LAr VUV light converted to 320-370 nm
2. The **wavelength shifter light guide (WLS-LG) plate** further downshifts the 350 nm light to 430 nm, and eventually guide photons > θ_c =56° to the **SiPMs** coupled to the plate edges
3. THE WLS-LG plate is a DUNE customised product, developed by INFN-MiB & ScMat UniMiB



pTP emission & WLS-LG Absorbance Spectral matching



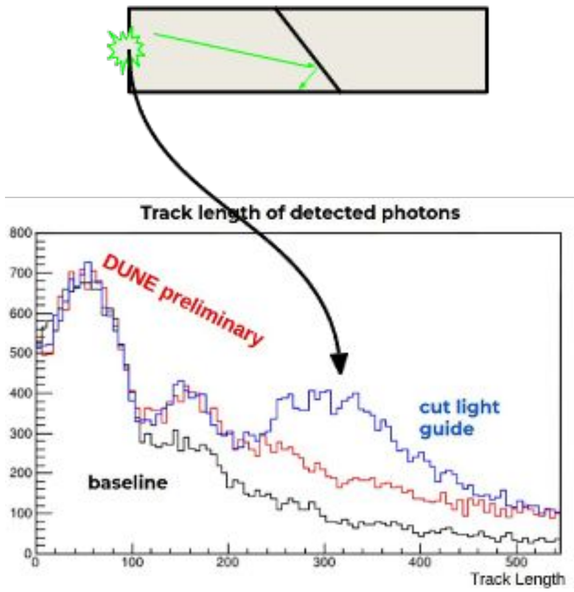
The Abs and PL spectra of the WLS-LG dye measured at room and cryo T



X-ARAPUCA HD Absolute Efficiency

C.Alvarez-Garrote et al. Eur. Phys. J. C 84

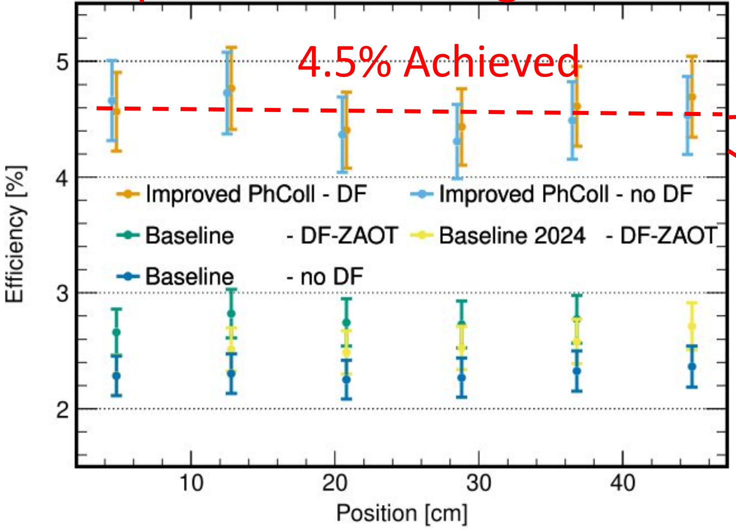
Tested configurations	XA absolute efficiency (%)	
SiPMs / plate	CIEMAT	INFN-MiB
FBK –TT / Ej-286PS-1	1.34 ± 0.24	1.80 ± 0.15
HPK 75HQR / Ej-286PS-1	1.59 ± 0.29	-
FBK –TT / G2P	-	2.22 ± 0.19
HPK 75HQR / G2P	2.13 ± 0.38	2.40 ± 0.20

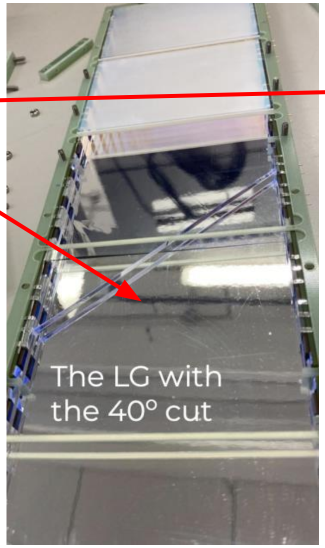


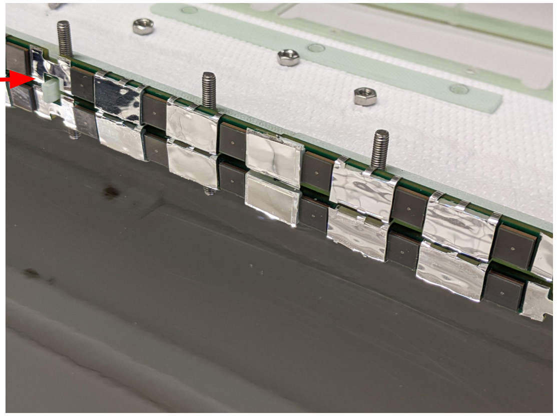
Further measurements ongoing at CIEMAT to validate MiB results and Impact of DF

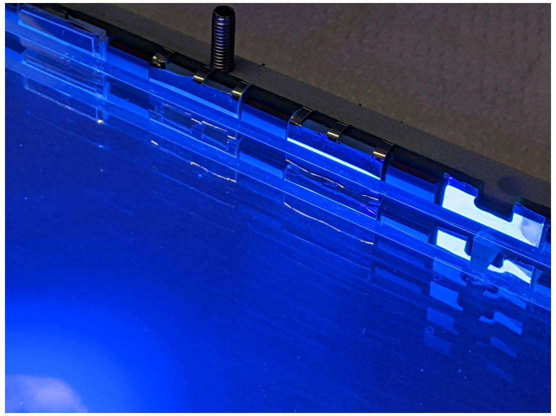
Improved FD1-XA light Collection

C.Cattadori LIDINE 2023



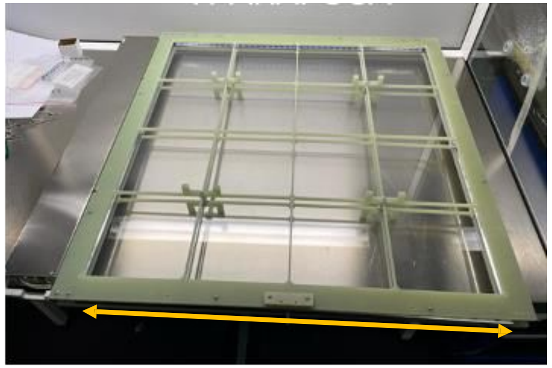


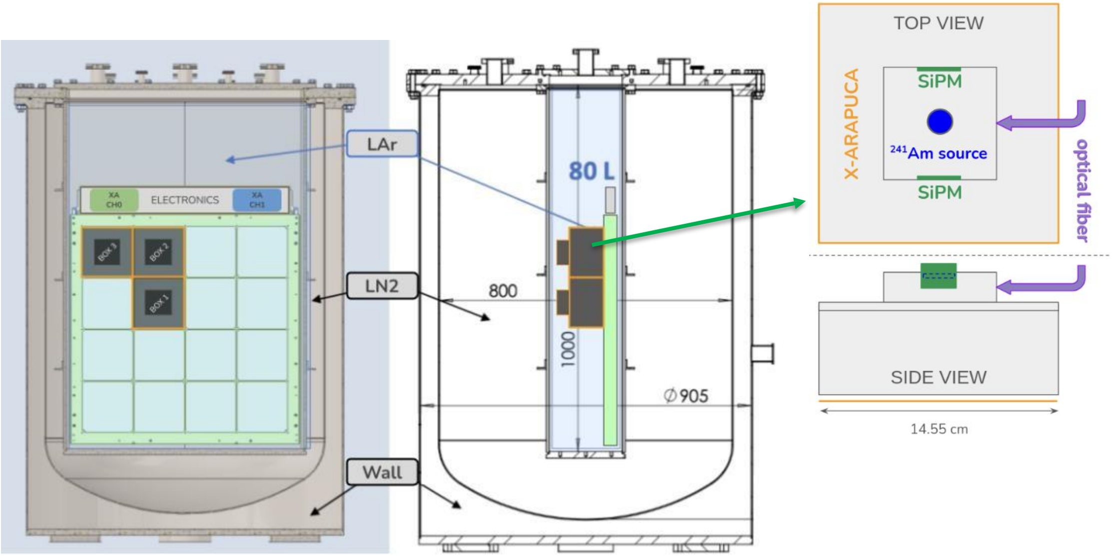




$$\text{Efficiency} = \frac{\text{N. of detected photons}}{\text{N. of photons impinging XA}}$$

X-ARAPUCA – Vertical Drift Absoulte efficiency

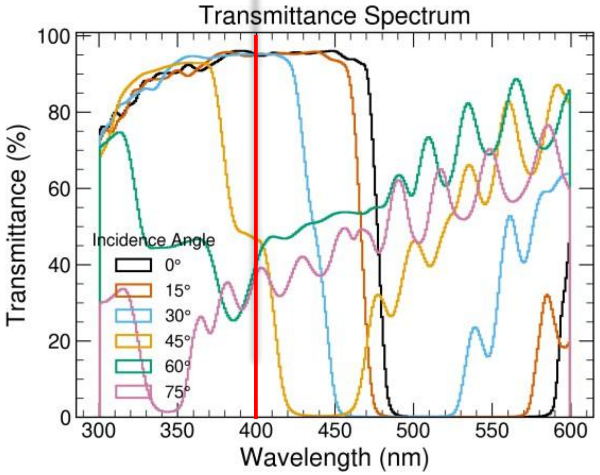




Tested configurations	XA Absolute efficiency (%)	
SiPMs & WLS: HPK 75HQR and G2P	CIEMAT	Uni Naples
Single-sided	**3.7 ± 0.3**	**3.1 ± 0.5**
Double-sided	4.0 ± 0.4	-
Single-sided no-DF	**4.5 ± 0.4**	-
Double-sided no-DF	4.5 ± 0.4	-

S. Mnthey-Corchado LIDINE 2023

Dichroic filter Transmittance



- An improvement (~15%) is observed when the Dichroic Filter is replaced by a pTP coated Glass
- No difference observed between single and double sided

ProtoDUNE program at CERN

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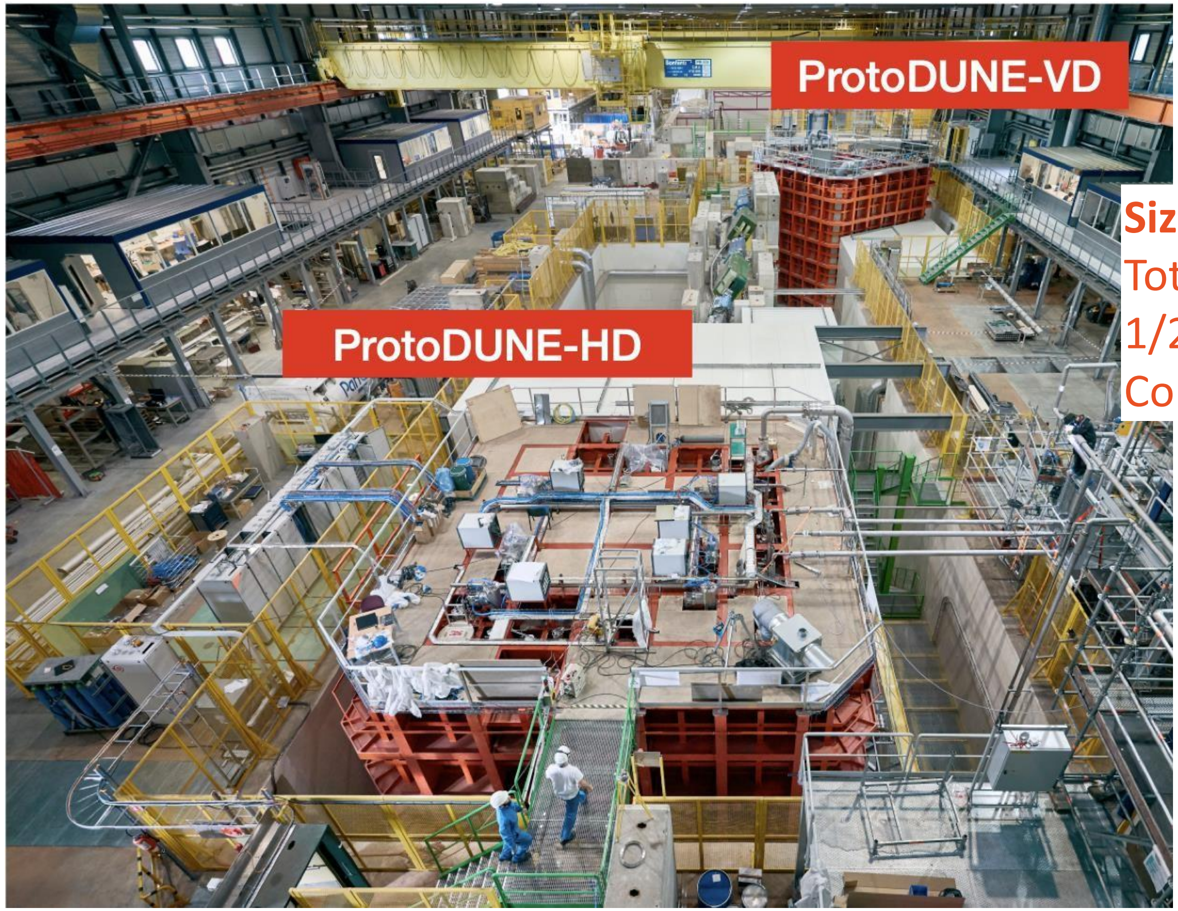
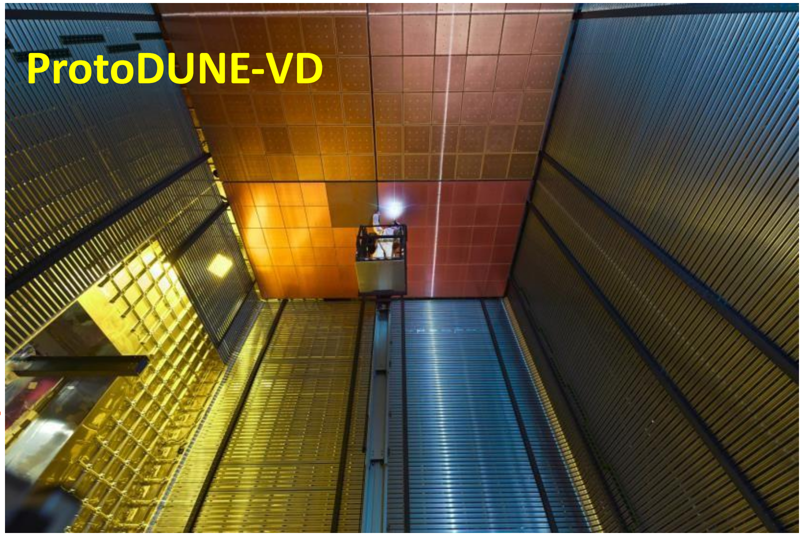


Size:
Total mass: 800 t of LAr
1/20 of a FD Module
Components 1:1 scale



ProtoDUNE program at CERN

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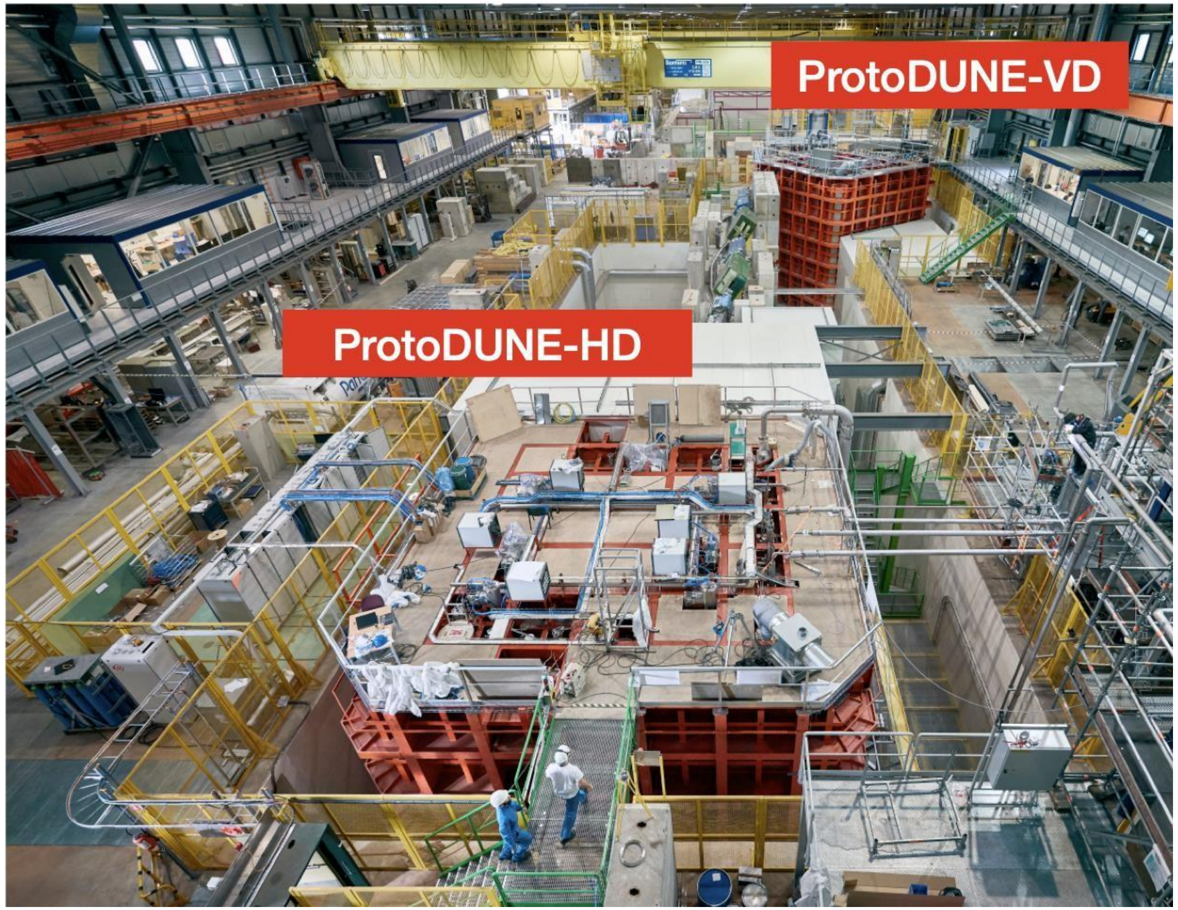

Successful run of ProtoDUNE-HD 2018 – 2020

-*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

-***JINST* 19 (2024) 08, P08005, Xe doping after N2 contamination**

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 → Success!

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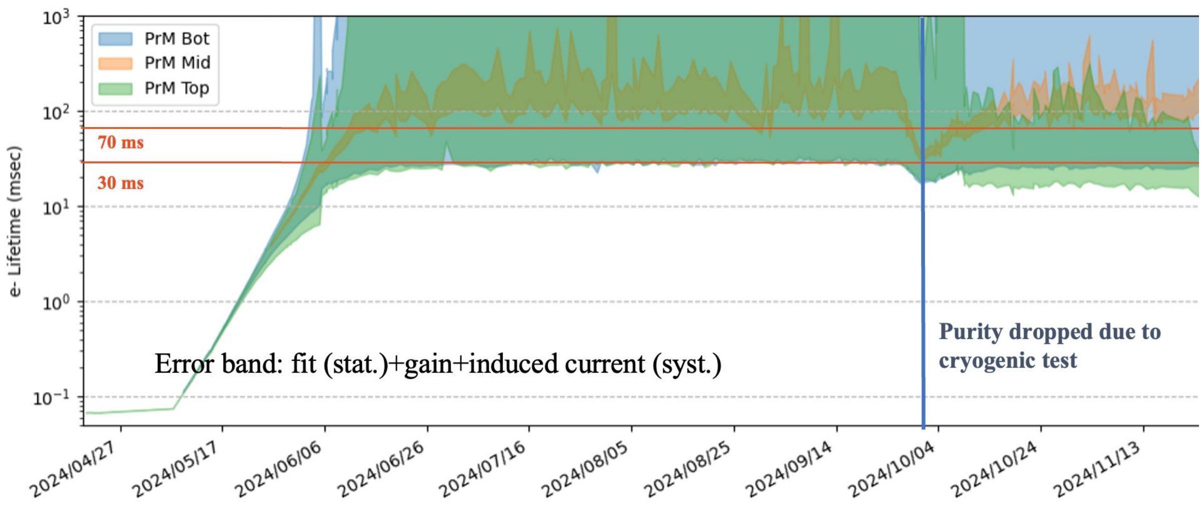
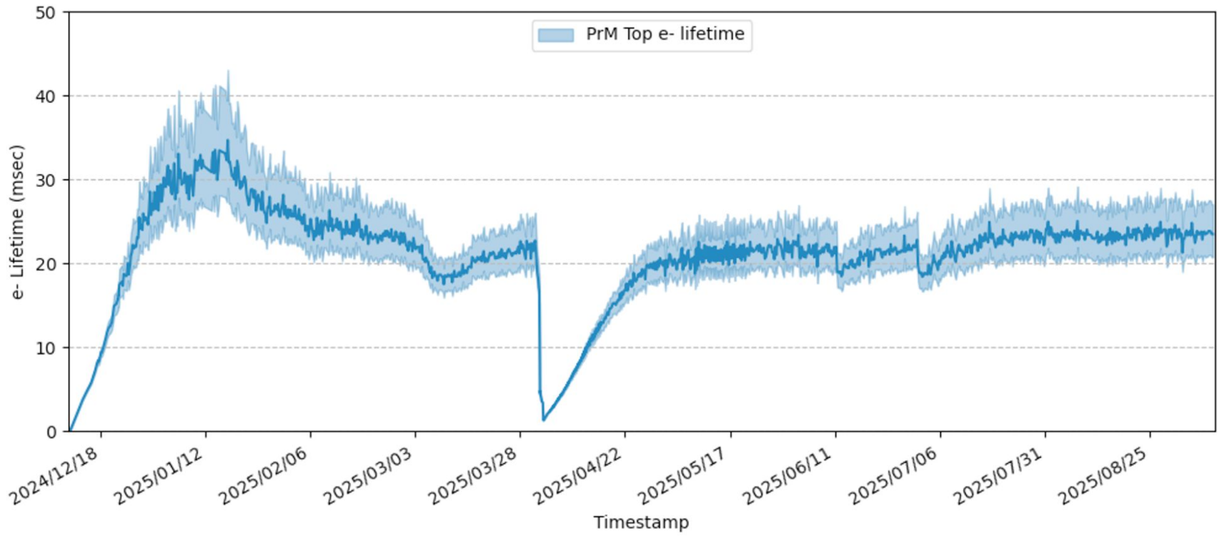
Performances of the NP04 and NP02 detectors: LAr purity

NP04 (pDUNE-HD)



NP04⟶ $[O_2] < 10$ ppT

NP02 (pDUNE-VD)



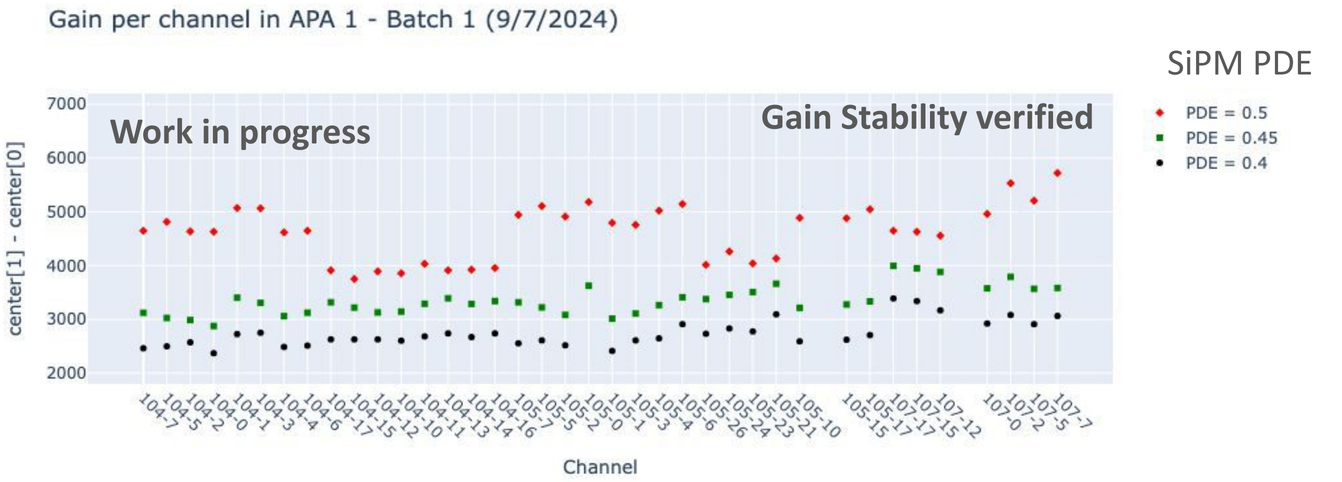
NP02⟶ $[O_2] \cong 15$ ppT

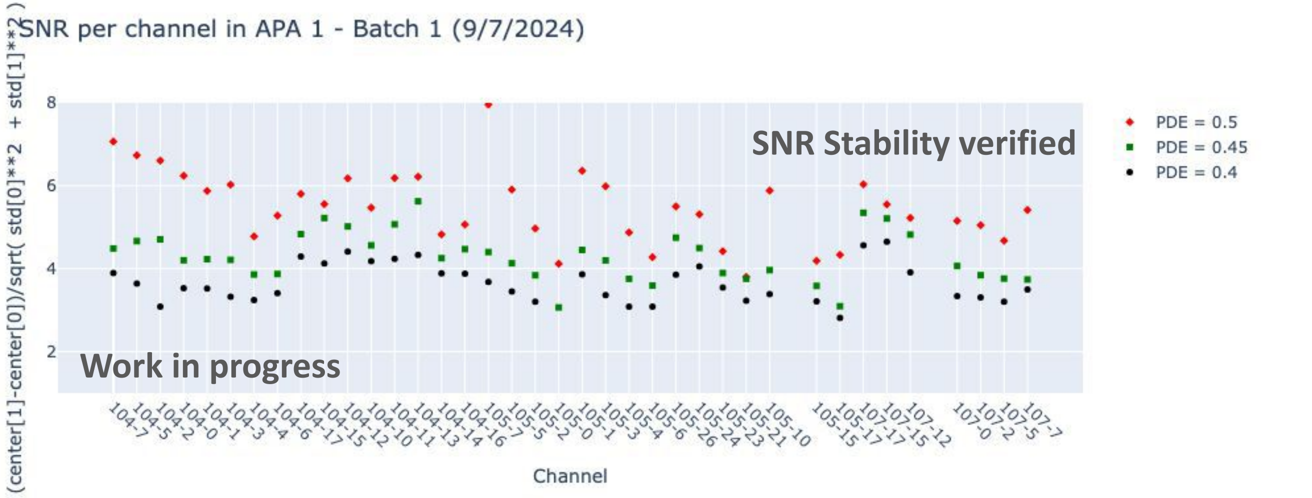
No leaks, excellent performances of purification system, low release of electronegative impurities

Gain and S/N studies in protoDUNE-HD NP04

DEEP UNDERGROUND NEUTRINO EXPERIMENT

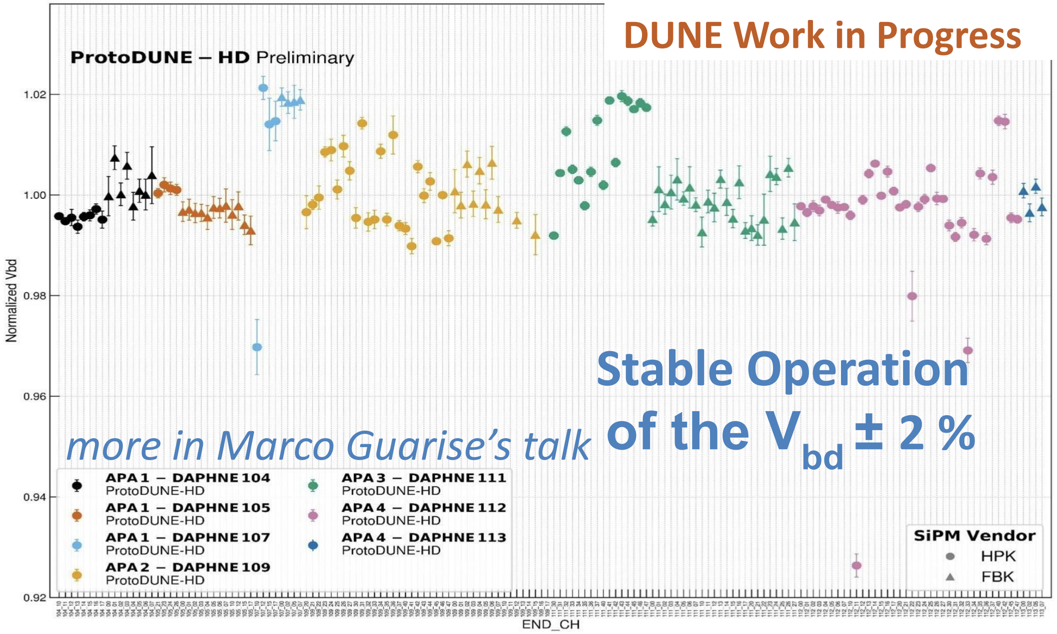
Gain and S/N studies in LED calibration runs

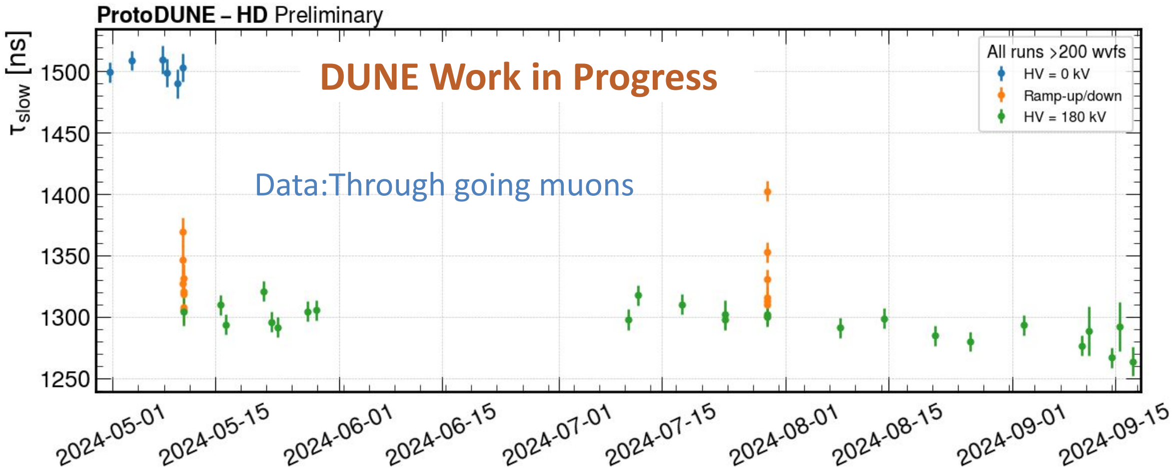


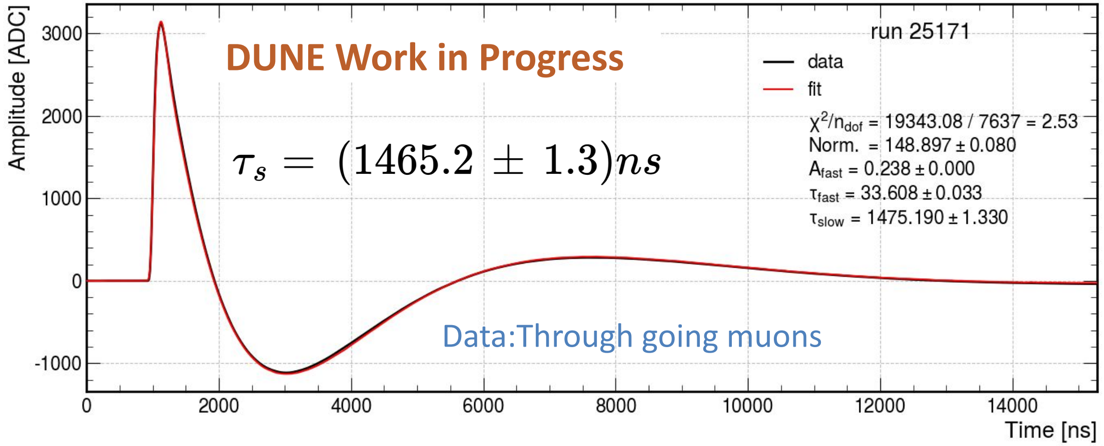


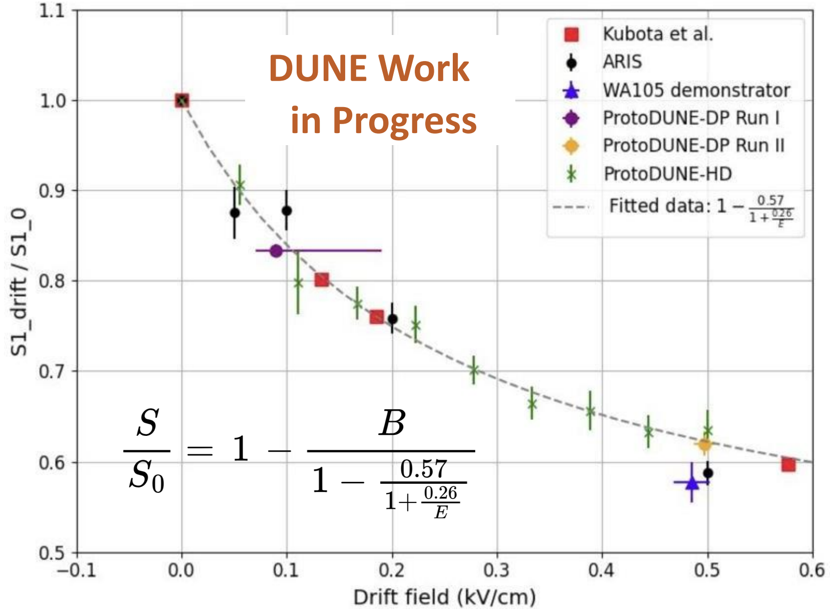
ProtoDUNE-HD: Performances of PDS and physics results

DEEP UNDERGROUND NEUTRINO EXPERIMENT









Detection of Michel electrons in ProtoDUNE-HD

- The muon track is required to cross either the cathode or anode plane, allowing the TPC to assign a T0 to the track.
- The responses of PDS in the same 5 ms readout window are then studied by computing the difference T0_TPC – T0_PDS for each track.

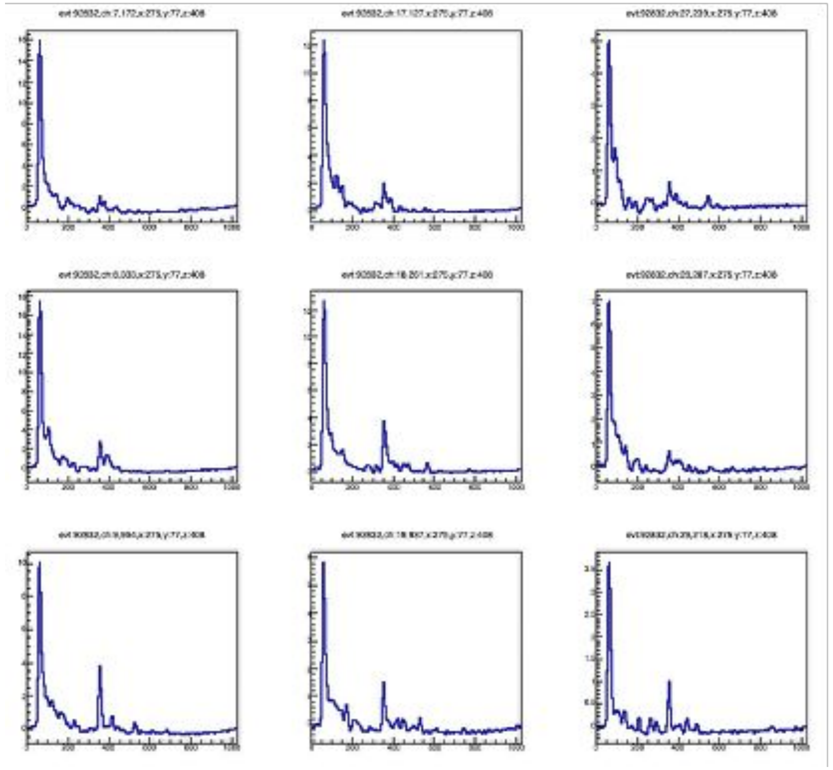
$$\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$$

$$\mu^- + p \rightarrow n + \nu_\mu$$

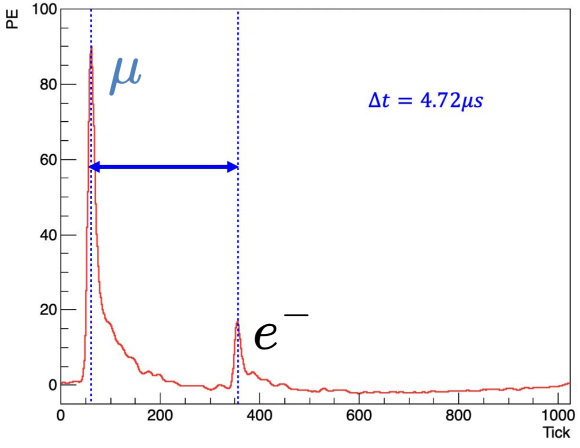
$$\tau'_\mu = \frac{1}{\Lambda_t} = \frac{1}{\Lambda_\mu + \Lambda_{capture}}$$

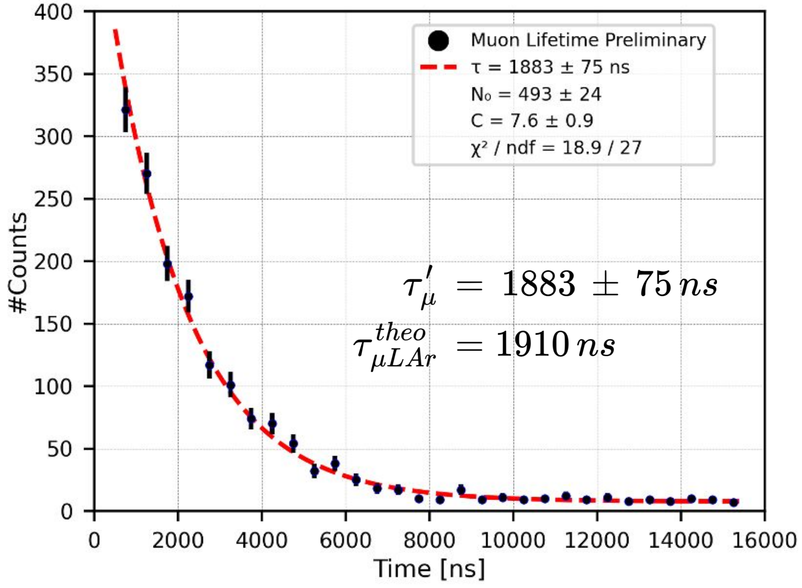
$$\frac{1}{\tau'_\mu} = \frac{1}{\tau_\mu} + \Lambda_{capture}\,;\ \tau_\mu = 2.197\,\mu s$$

$$\Lambda_{capture} \propto C\,Z^4\,(1-\delta)\,;\ (1-\delta)\ \text{nuclear effects}$$



Michel-electrons detected in mu decay

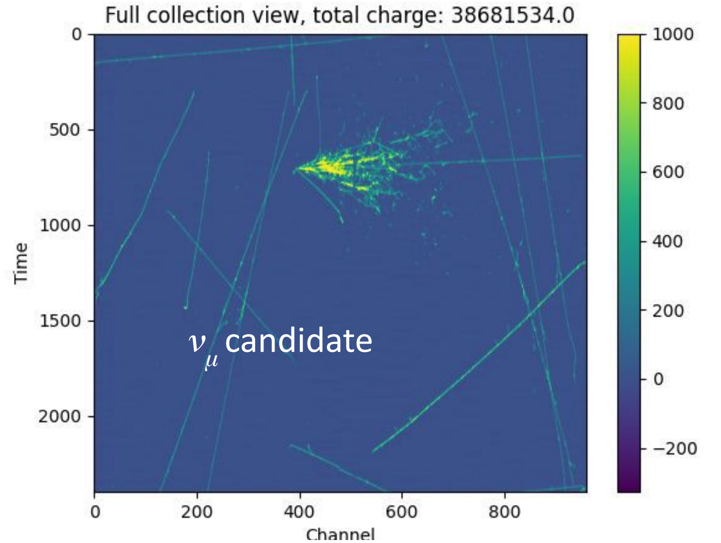


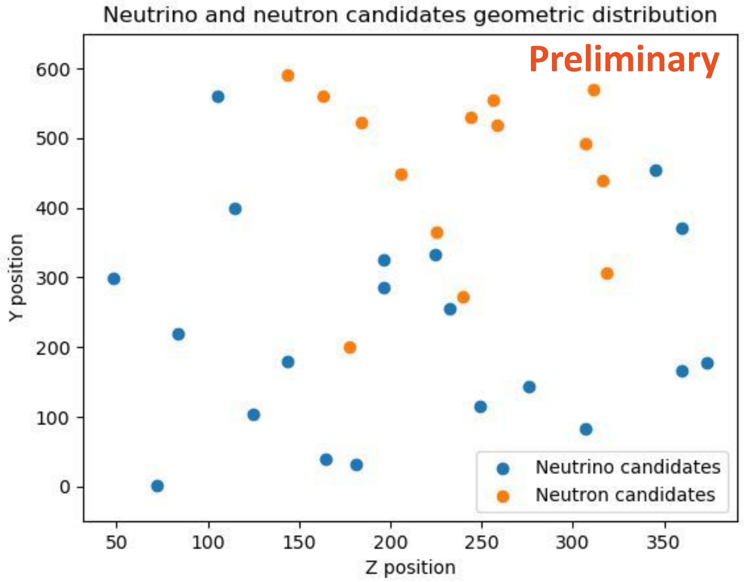


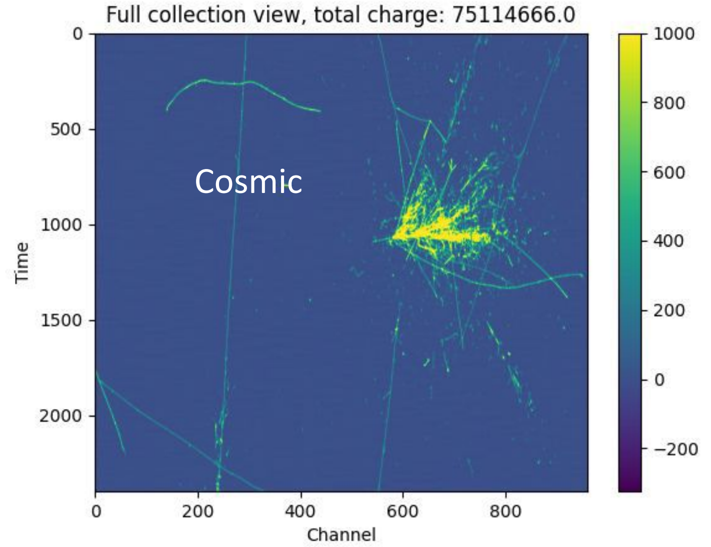
Neutrino interaction observed in pDUNE-HD

Work in progress

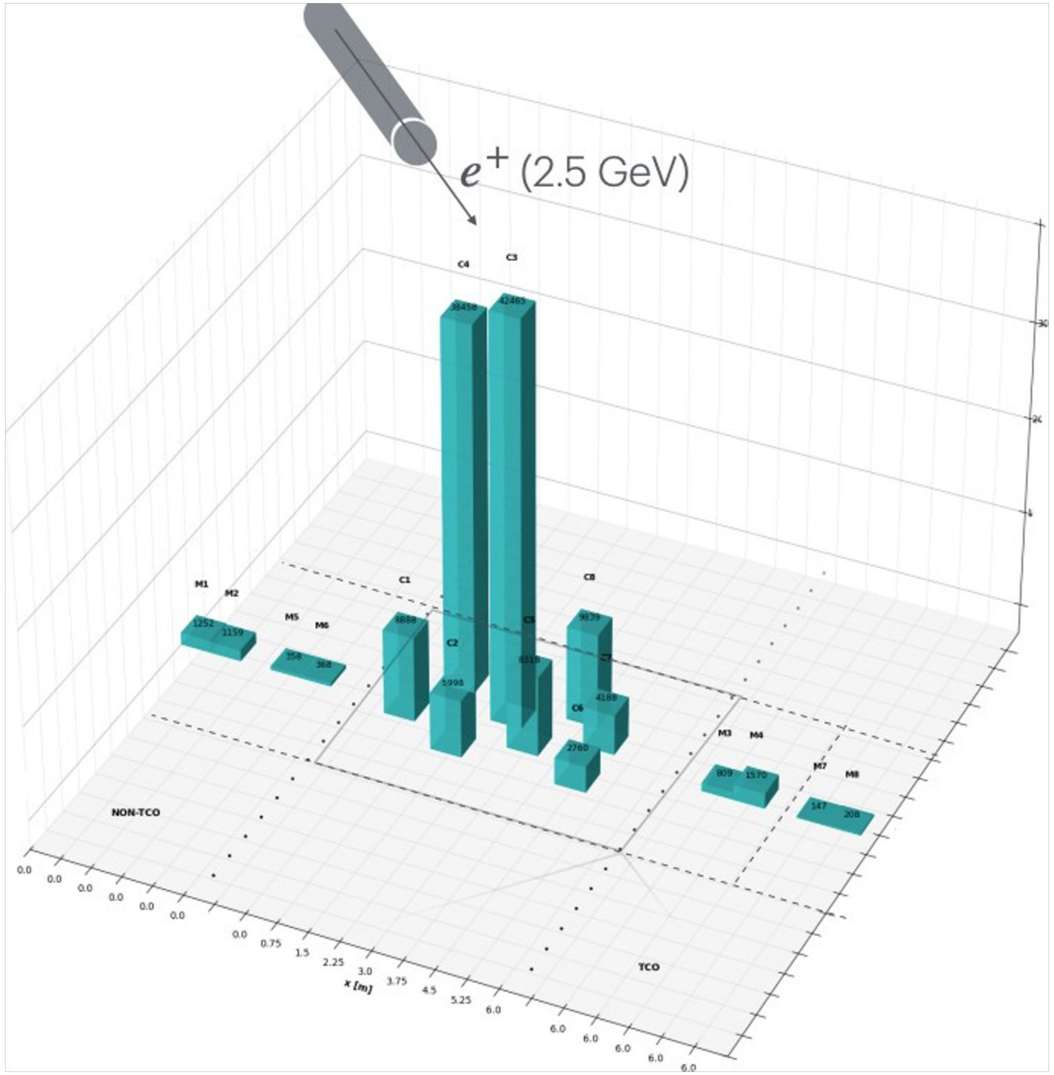
- The events must pass 4 differents cuts: the position, the cahrge distribution, the presence of a μ in the "tail", and its angle.
- Then a manual scanning follows
- Overall 29 events have been found in hadron SPS runs while none has been found with the same cuts when SPS is off

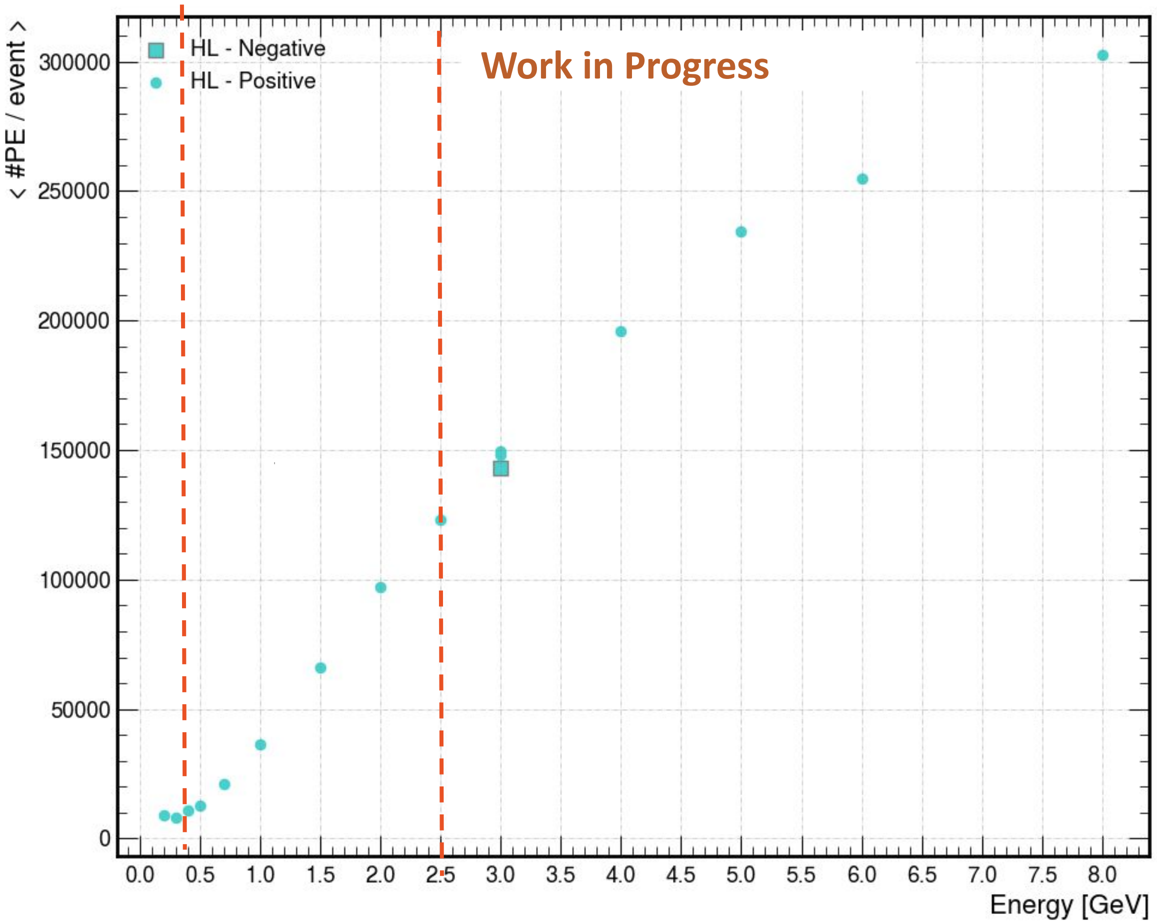






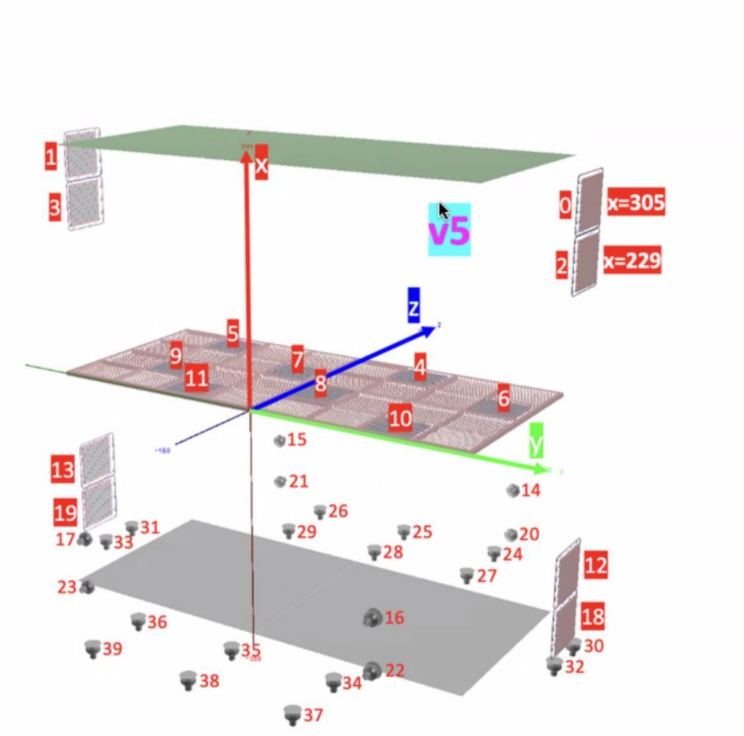
Beam Commissioning protoDUNE VD





protoDUNE-VD PDS Commissioning

- PD-DAQ integration and CTB Timing synchronization
- **SPE Calibration [ADC/PE] w/ LED** and Warm R/O DAQ Configuration
  - Min SPE Amplitude - Max Dynamic Range for High En Beam Run
- SNR characterization (all 32 PD Channels)
- **Collected Light to Deposited Energy Calibration [PE/MeV] w/ *e*-Beam**



☑ All 32 Channels from Cold alive and responding, with

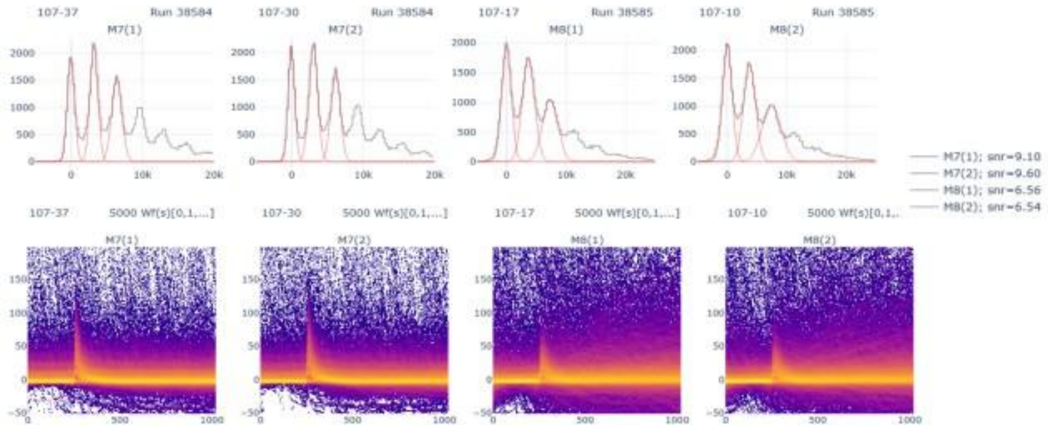
2 more noisy and 1 into bad DAPHNE channel excluded from DAQ

☑ $A_{SPE} \simeq 10\ ADC$ for all Ch.s, ***Dyn Range*** ~12,000 ADC

☑ $SNR = 4 \div 8$ (all Ch.s)

☑ PoF (Lasers) ON, stable

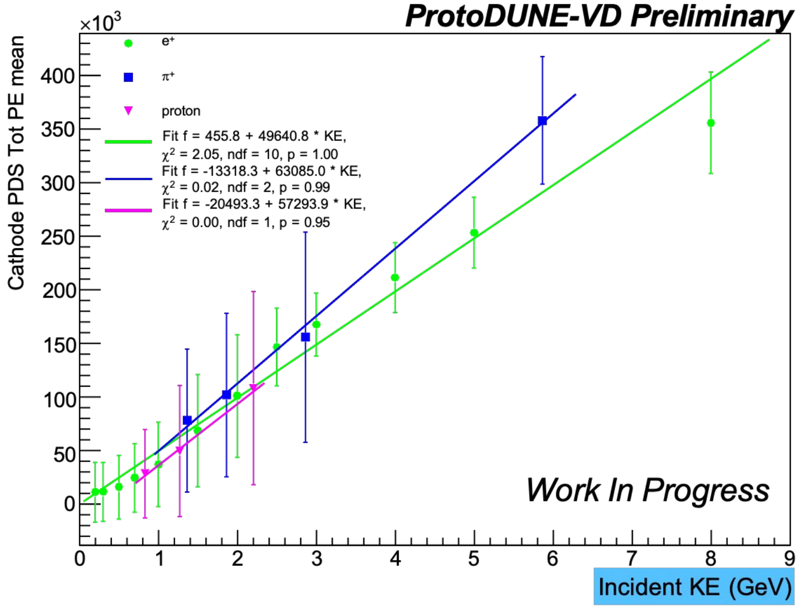
Success!



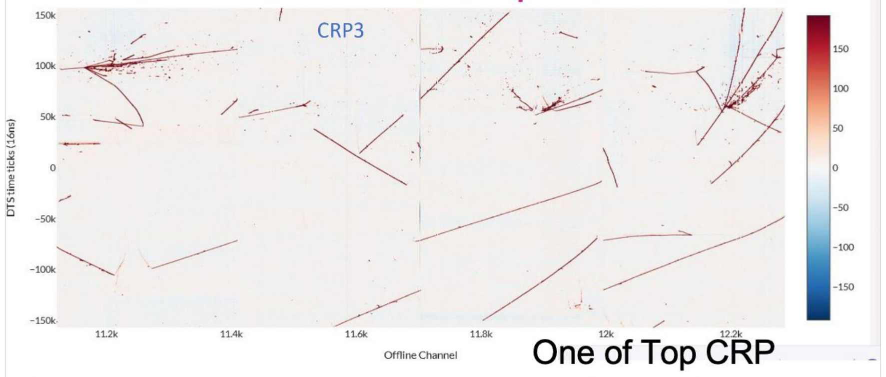
From S. Wei Presentation at CPAD 2025

Preliminary findings in protoDUNE VD

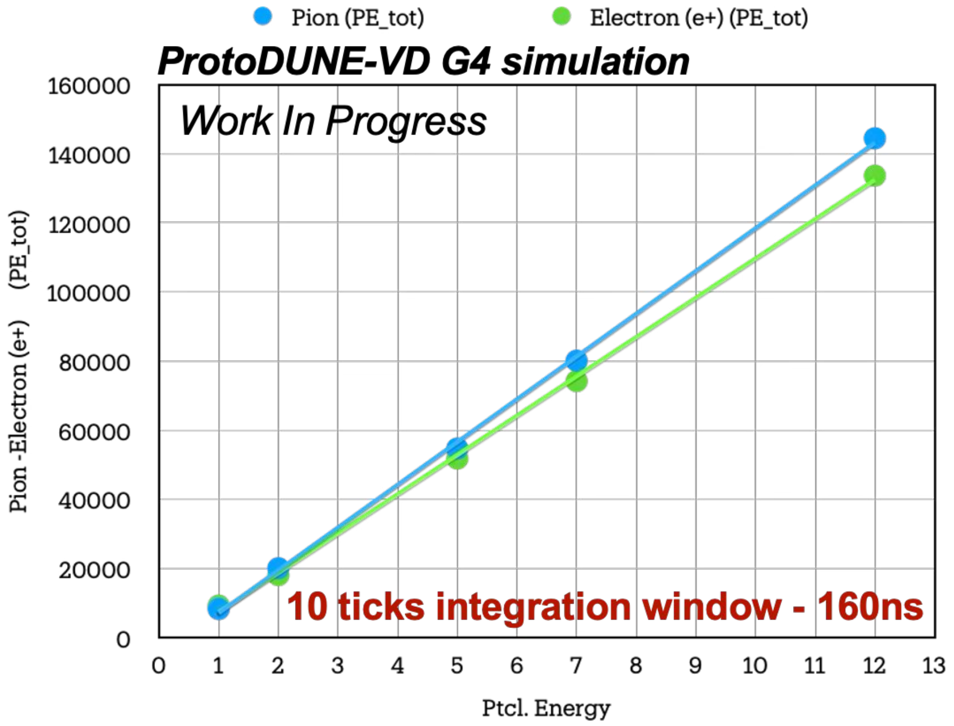
Cathode PDS tot PE vs KE



Beam event selection to be improved with TPC data



A beam pion interaction seen in CRP3 with a pion interaction from a cosmic track in the same drift window

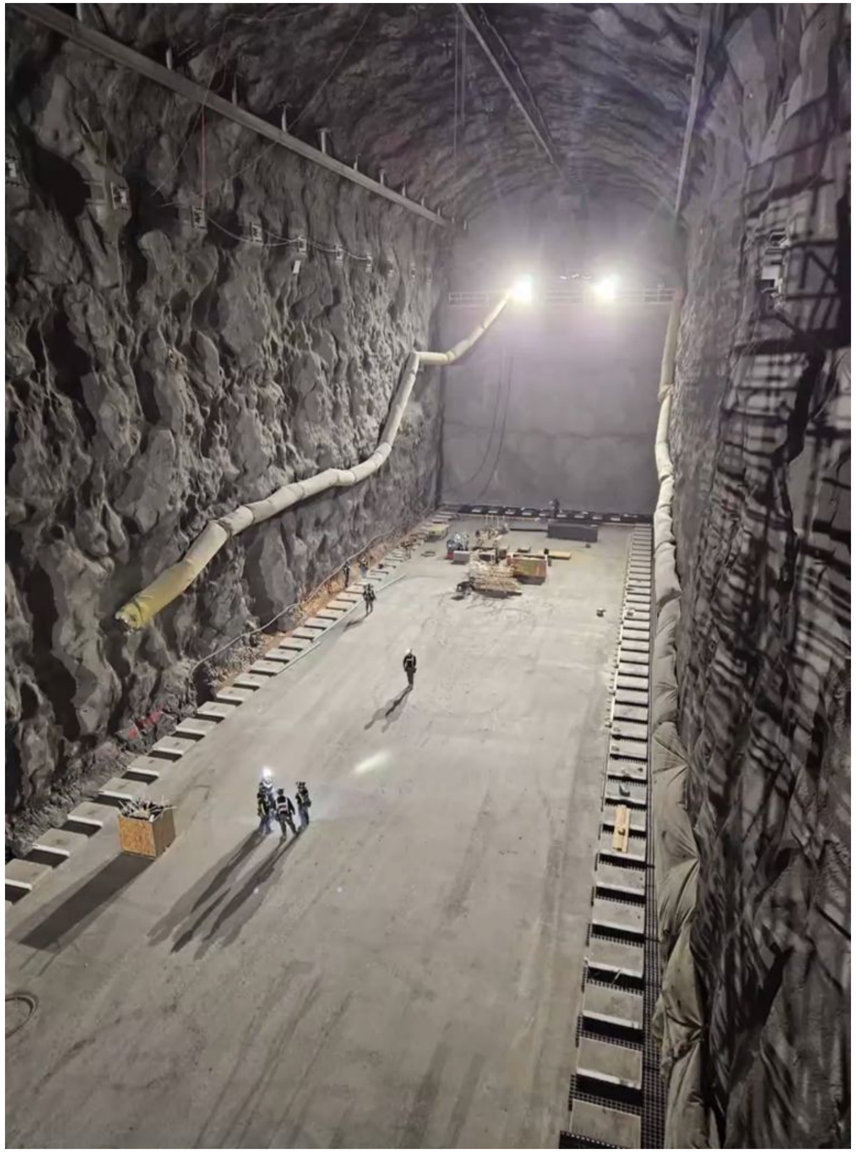


Detailed beam simulation under progress

Summary

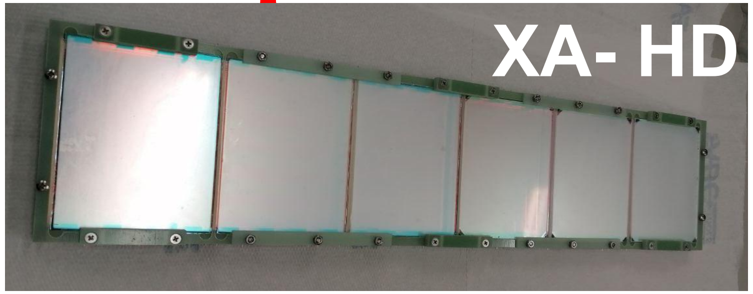
- DUNE experiment relies on LArTPC technology complemented with a SiPM based PDS to make precise measurements of neutrino mixing parameters and to detect neutrinos from SN burst
- The X-ARAPUCA design has being improving and adapted in two flavours to the different TPC layouts.
- Each X-ARAPUCA flavour & configuration (two SiPMs, two WLS plate & three Dichroic Filters technologies) have been fully characterized in two institution labs. For both HD and VD XA flavour an absolute efficiency of ≅ 4 % has been measured after years lasting optimization work.
    - Two SiPMs technologies, one WLS plate material (PMMA), no DF (for VD, still under evaluation for HD)
- The ProtoDUNEs (HD & VD) at CERN provided an opportunity to test and compare the X-Arapucas, the readout and biasing electronics, under real operation conditions. They are excellent bench tests in scale 1:20 of the final detectors
    - Exciting results in term of detector performances, reliability, sensitivity to beam energy
    - Michel electrons, Neutrino interactions have been identified in pDUNE-HD
- Outlook: Xe doping of protoDUNE-VD ranging 1-10 ppm is foreseen in 2025-2026

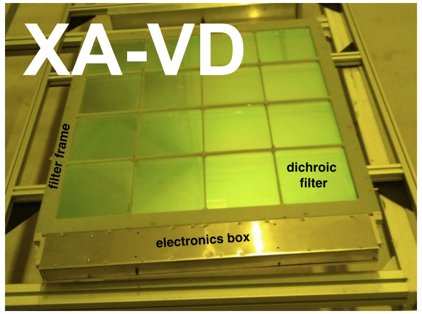
Status of the FD cavern at underground Sanford Laboratory



BACKUP

X-Arapuca & WLS-coated LG FOM





	Size	n. SiPM	Si/LG area[%]	PDE* [%] (*50% SiPM PDE)	**FOM [PDE/(Si/LG)]**
XA - FD1 [C. Cattadori et al.]	480 x 93	48 ganged	3.9	2.5 - 5 (0.2)	**0.64 -1.2**
XA - FD2 (No DF) *LIDINE 2024 S. Manthey*	607 x 607	160 gang 2x80	1.6	4.0 - 4.5 (0.4)	**2.49 - 2.67**
pDUNE-I (double shift) *B. Abi et al. 2020 JINST 15 P12004*	2007 x 83	12	0.3	0.2	**0.66**
pDUNE (single shift) (pure PMMA TPB coated)	2007 x 83	12		0.08	**0.27**

DUNE Physics

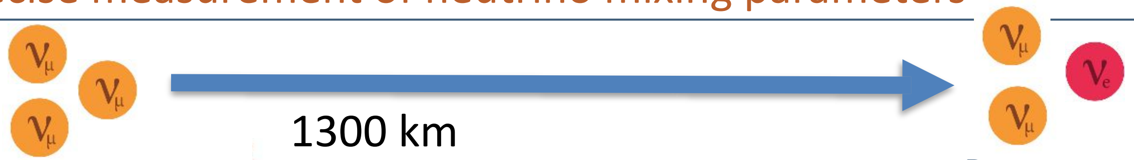
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Measurement of ν_e appearance and ν_μ disappearance over a wide range of ν_μ energy , at 1300 km would allow

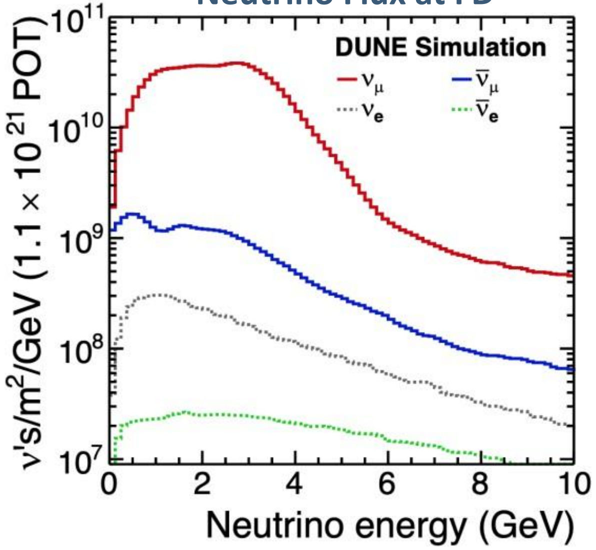
- Long BL enables definitive measurement of neutrino Mass Ordering
- Define the octant of θ_{23}
- Discovery potential for CP violation for wide range of δ_{CP}
- Precise measurement of neutrino mixing parameters

FD: No Beam ν Physics

- Supernova Neutrino Burst
- Proton Decay
- BSM physics

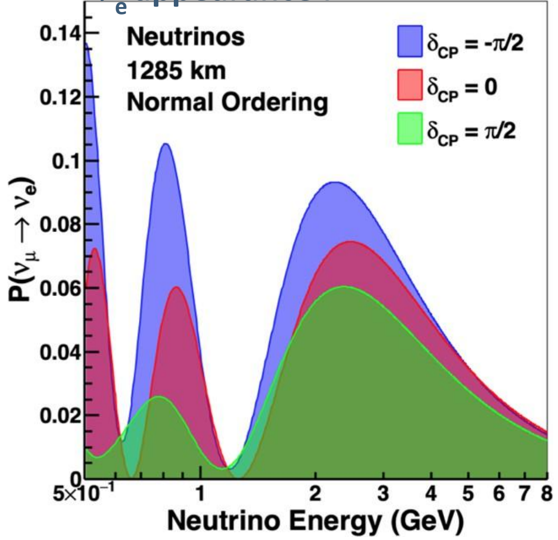


Neutrino Flux at FD

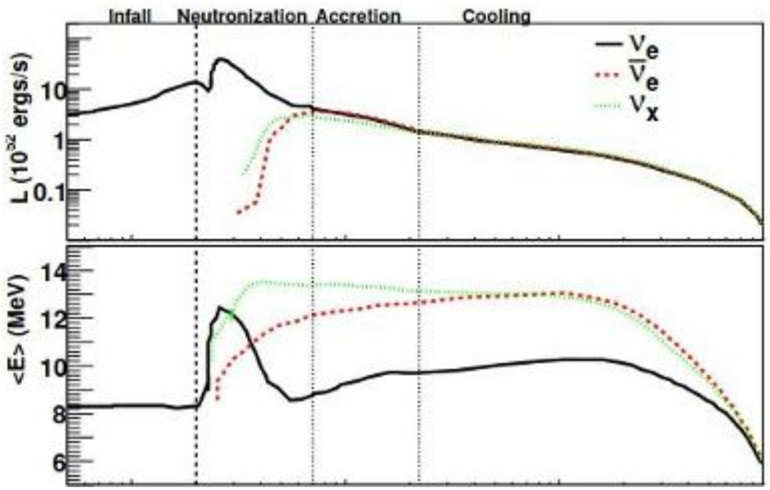


Eur.Phys.J.C 80 (2020) 10, 978

ν_e appearance P



L & ν Time profile from SNB



Eur. Phys. J. C **81**, 423 (2021)

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LAr Scintillation: Nitrogen and Oxygen quenching

DEEP UNDERGROUND NEUTRINO EXPERIMENT

The rate constants of the light quenching process have been found to be

a. $k(O_2)$=0.54 $\mu s^{-1}ppm^{-1}$ →1 ppm of N_2 ~ 20% reduction of the scintillation light,
b. $k(N_2)$=0.11 $\mu s^{-1}ppm^{-1}$ → 1 ppm of O_2 ~ 40% reduction.

$$\frac{1}{\tau'_j}([X_2]) = \frac{1}{\tau_j} + k[X_2]$$

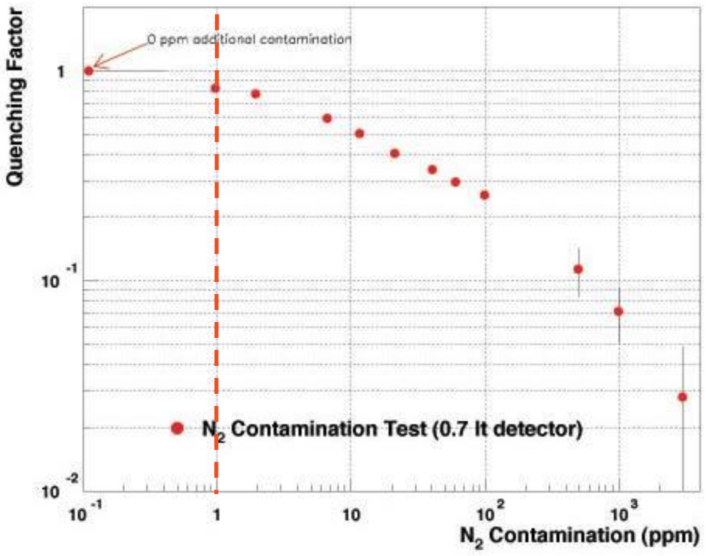
$$A'_j([X_2]) = \frac{A_j}{1+\tau_j k X_2};$$

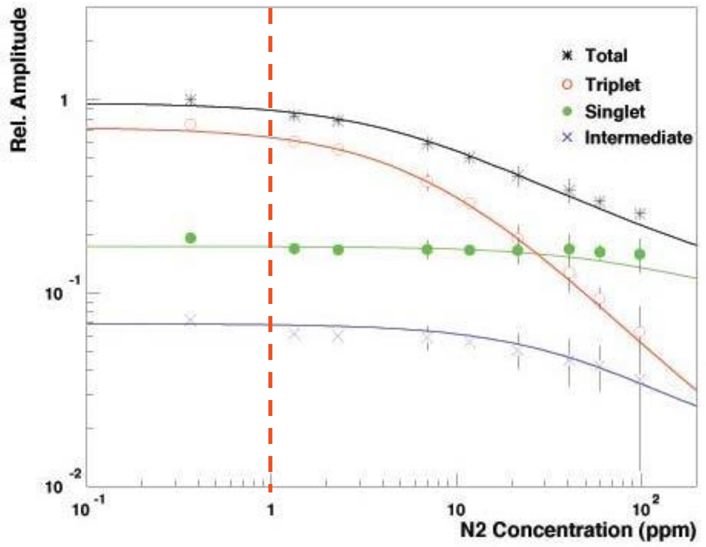
τ'_j is the effective decreased lifetime

A'_j is the effective quenched amplitude

$Q_F = A'_s + A'_t;\ 0 \le Q_F \le 1$

R. Acciarri *et al* 2010 *JINST* **5** P06003





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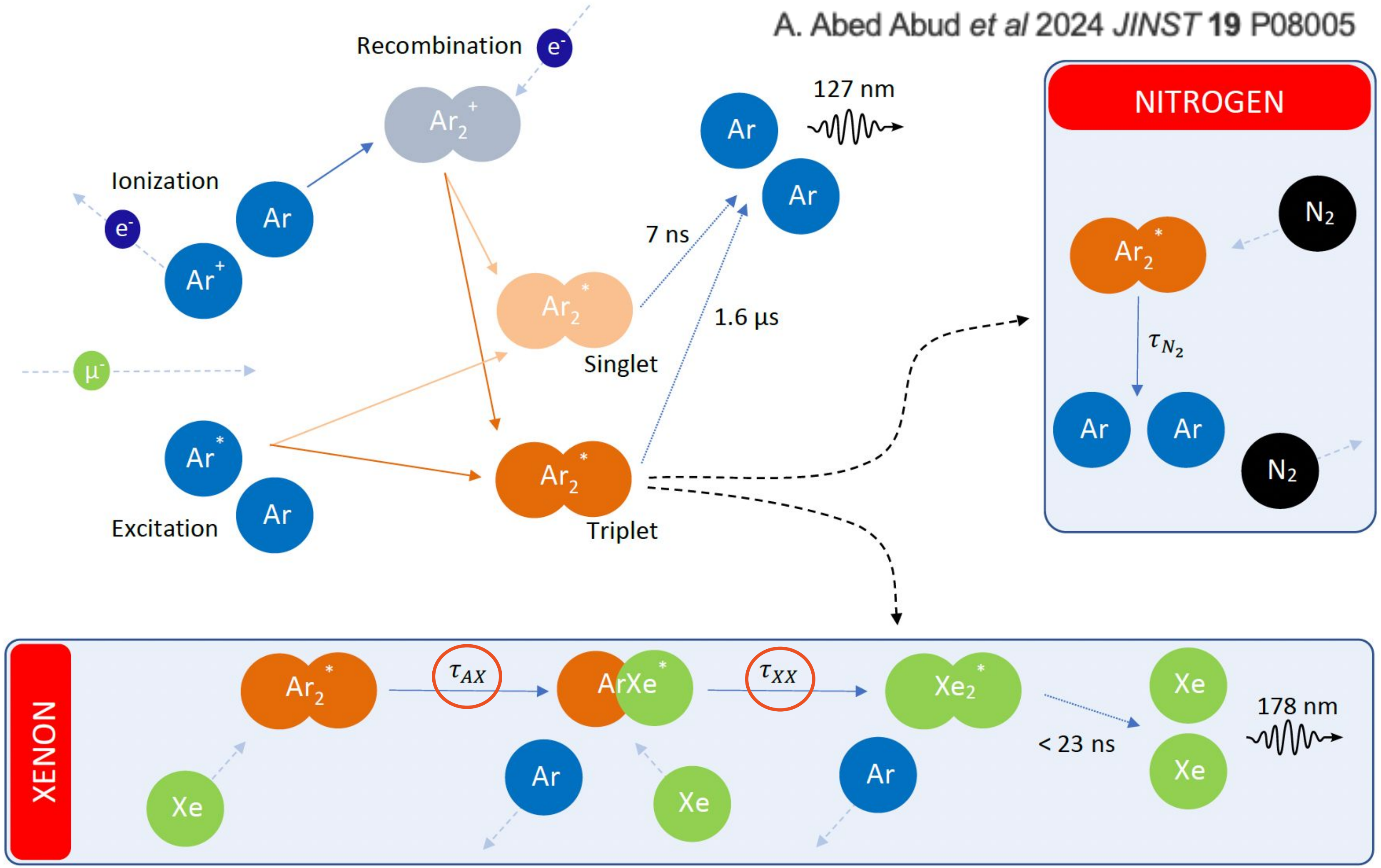
LAr Scintillation: Xe doping

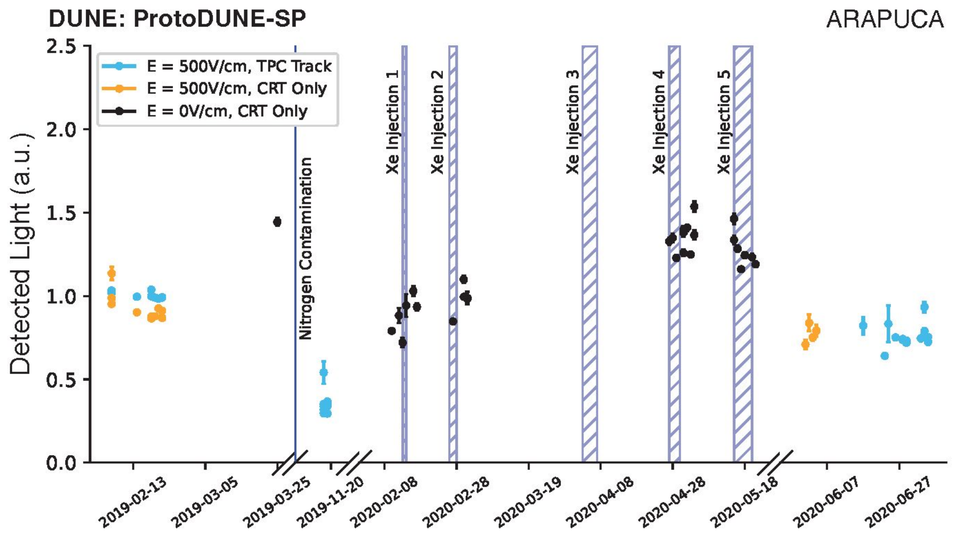
A. Abed Abud *et al* 2024 *JINST* **19** P08005

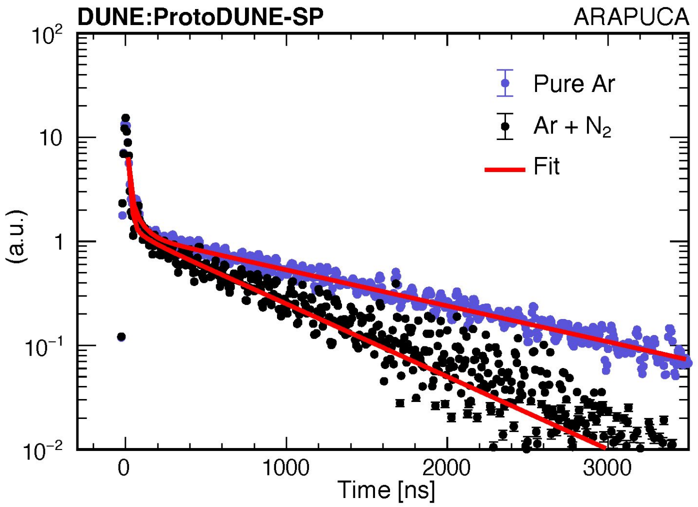


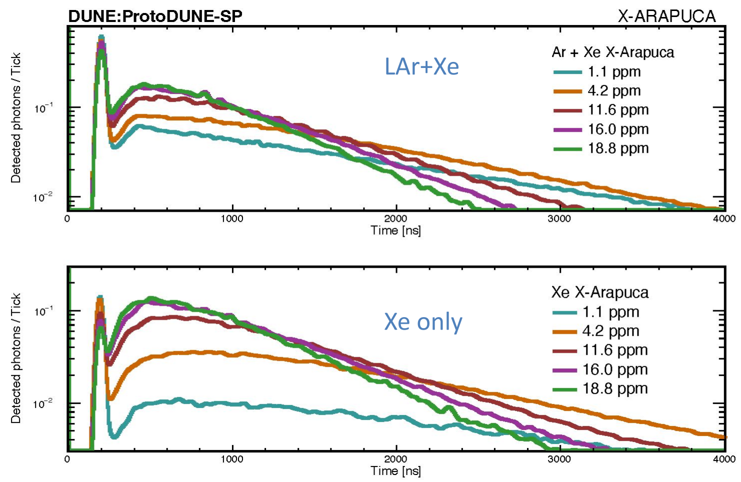
Nitrogen is a quencher of Ar_2*
radiative decay.
..e radiative decaying

gates its effects.
..ncentration in LAr

Results from pDUNE Run2 Xe doping (year 2020).







Evolution of the LAr light yield in pDUNE-SP, in years 2019-2020, as detected by the ARAPUCAs before and after the N_2 contamination

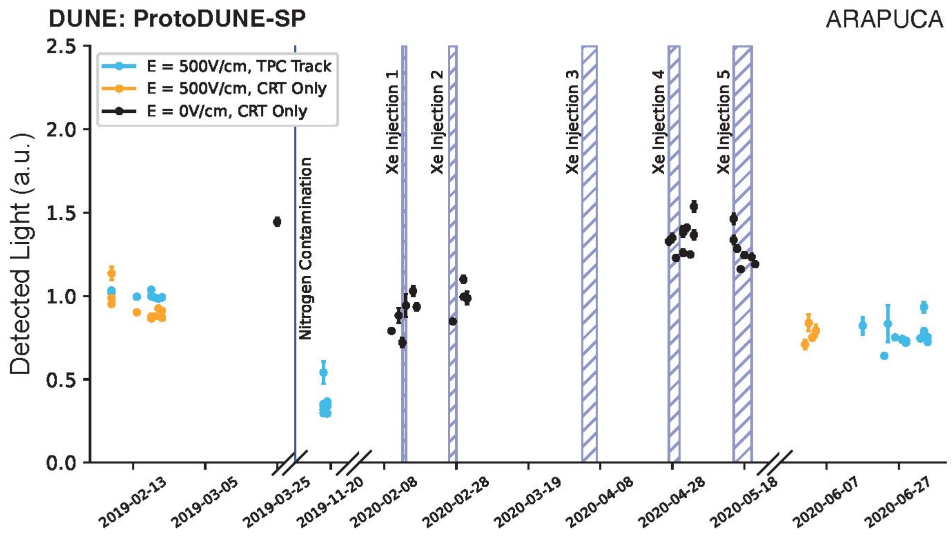
- with increasing Xe_2 doping

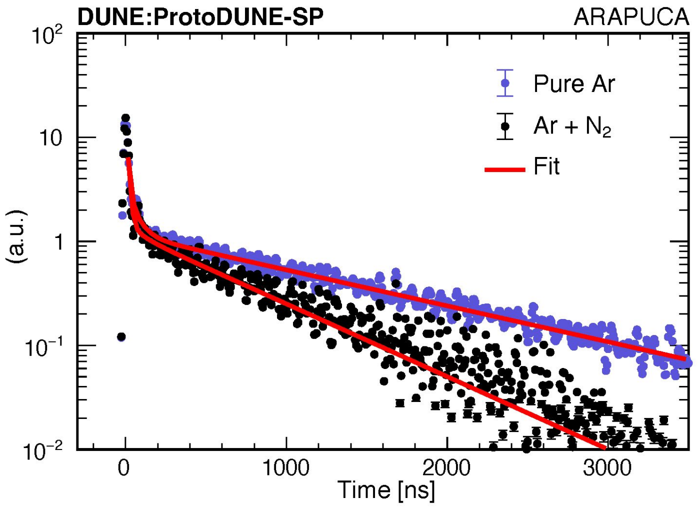
Evolution of the LAr light pulse shape in pDUNE-SP, detected by the ARAPUCAs, before and after the N_2 contamination event

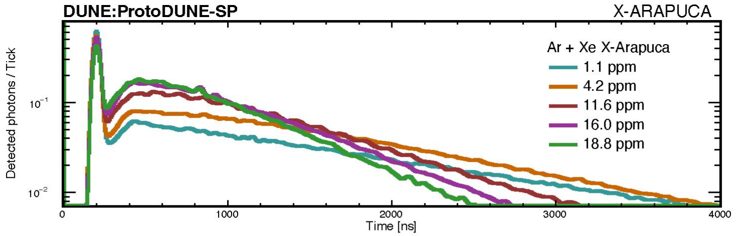
Evolution of the LAr light pulse shape detected by the X-Arapuca devices in pDUNE-SP, with increasing Xe_2 doping

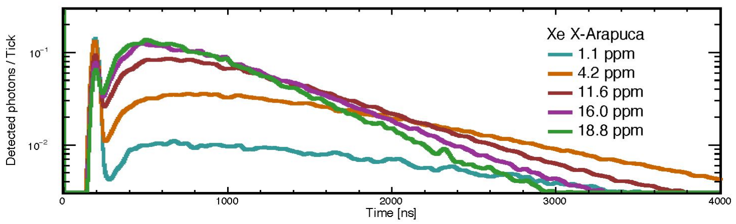
Results from pDUNE Run2 Xe doping (year 2020).

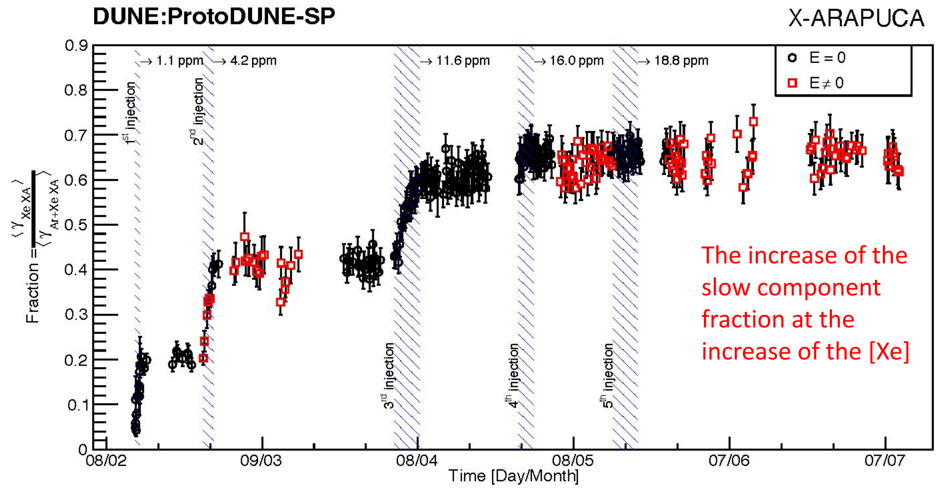
DEEP UNDERGROUND NEUTRINO EXPERIMENT

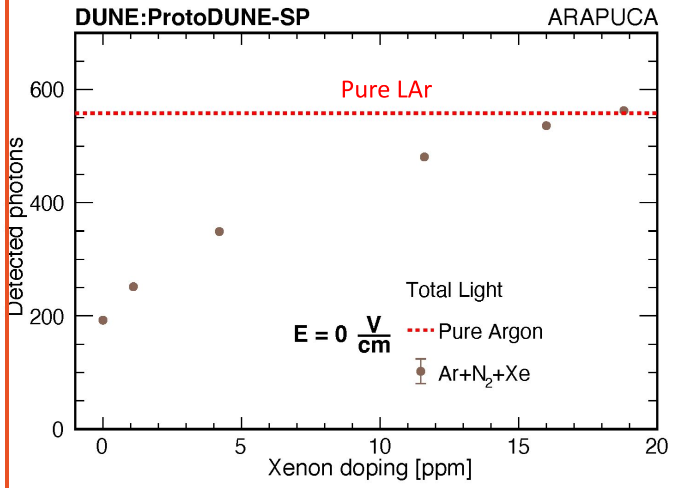


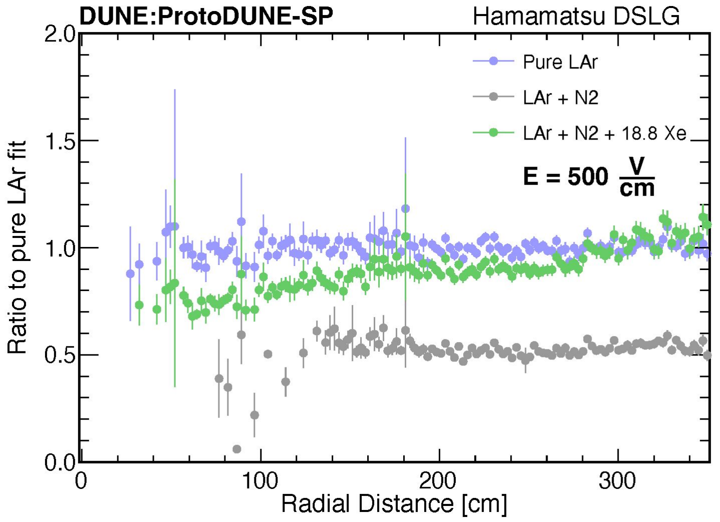












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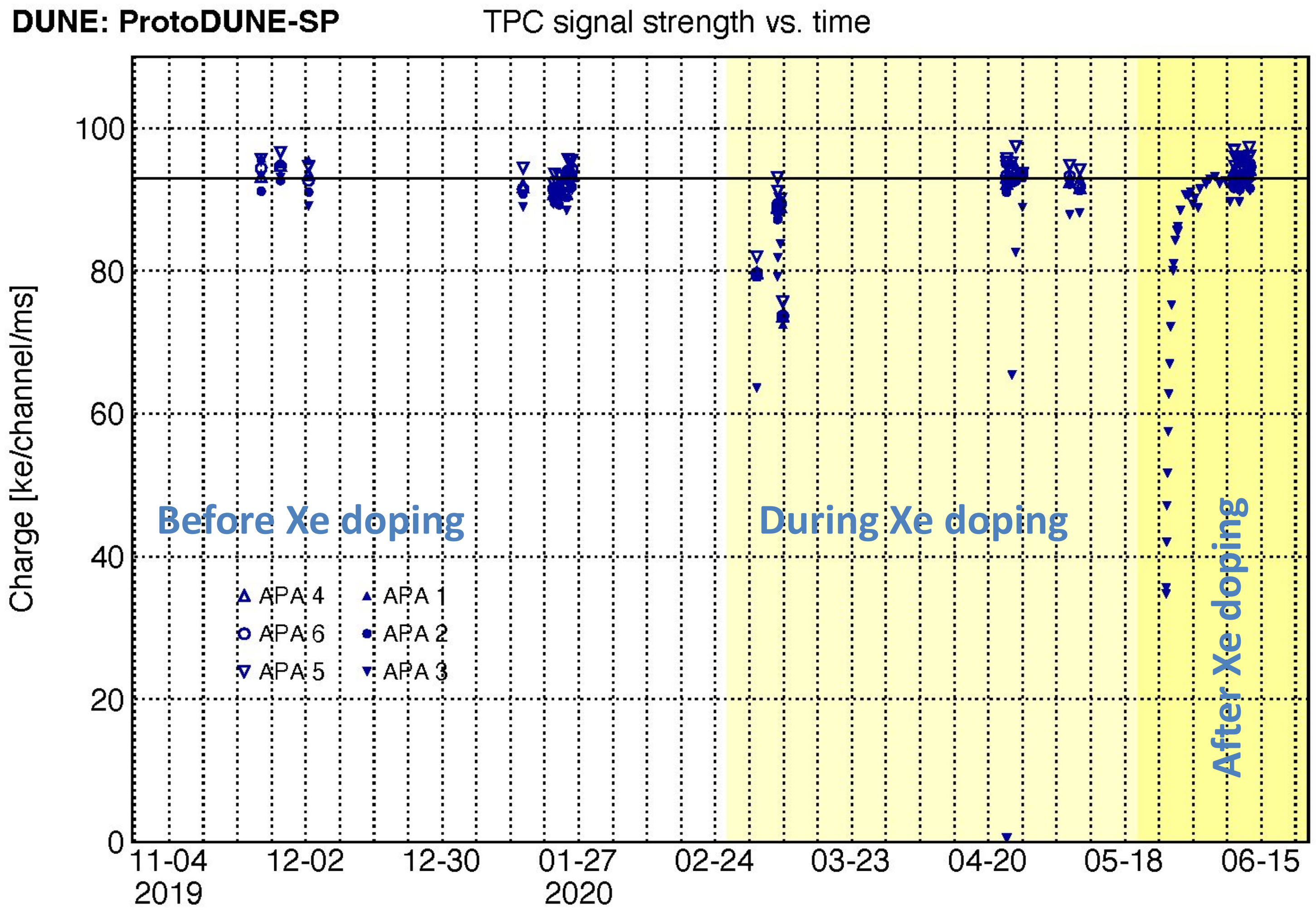
Results from pDUNE Run2 Xe doping (year 2020).

DEEP UNDERGROUND NEUTRINO EXPERIMENT



pact on the TPC charge