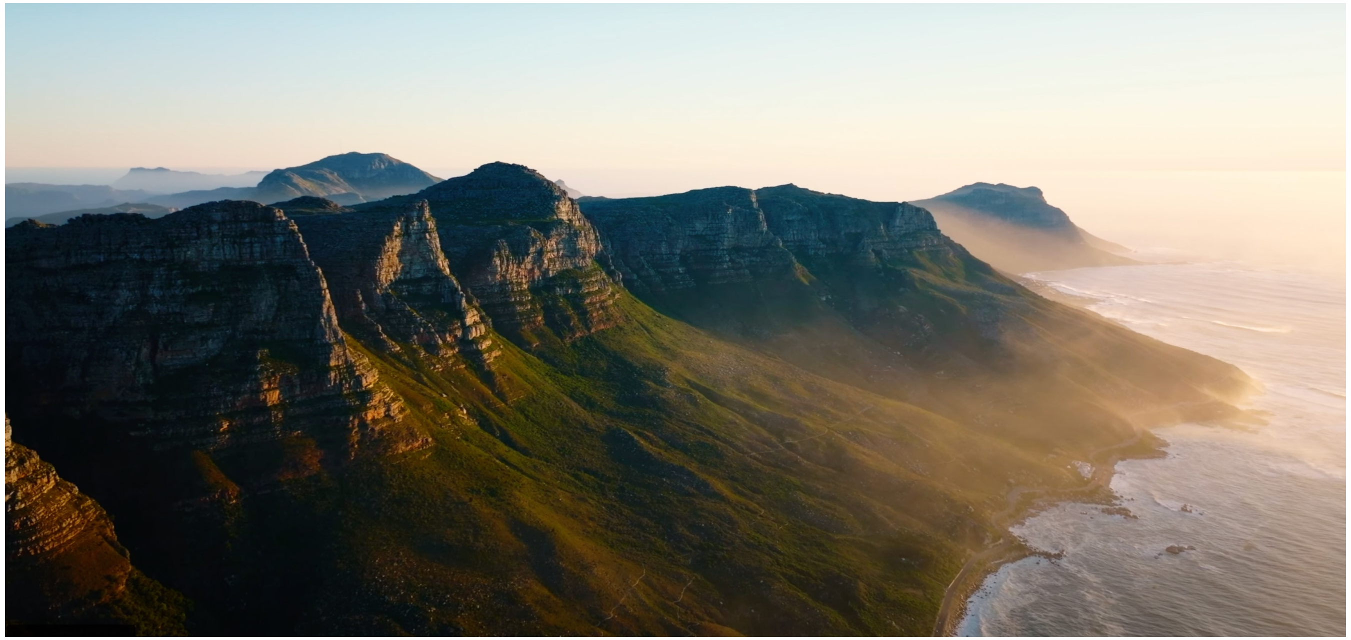
Photon Detection System in the far detector module of the DUNE experiment

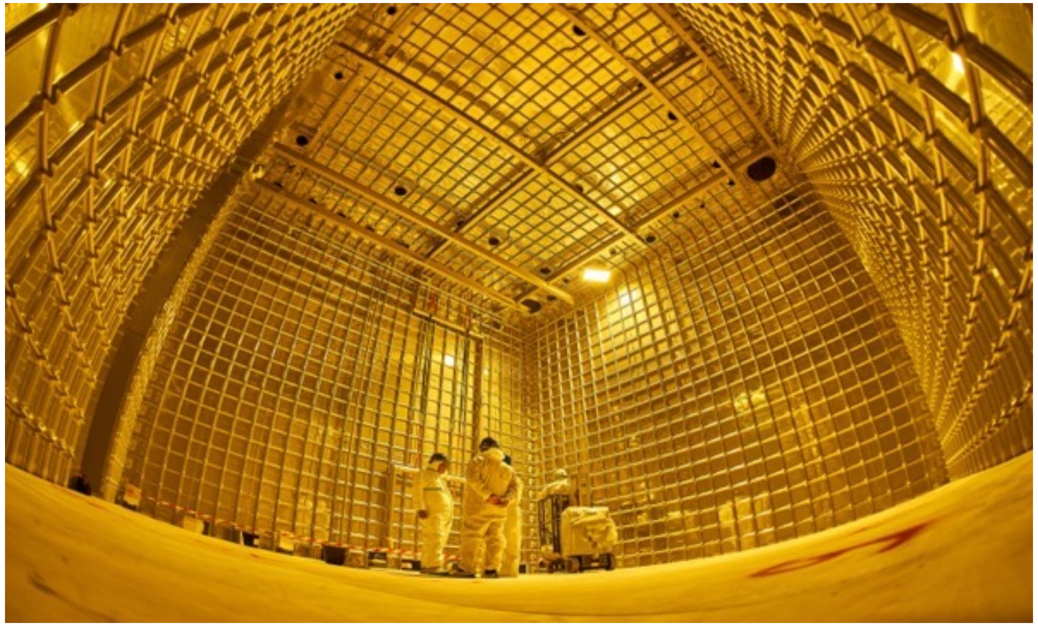


F. Di Capua - **Università di Napoli and INFN**

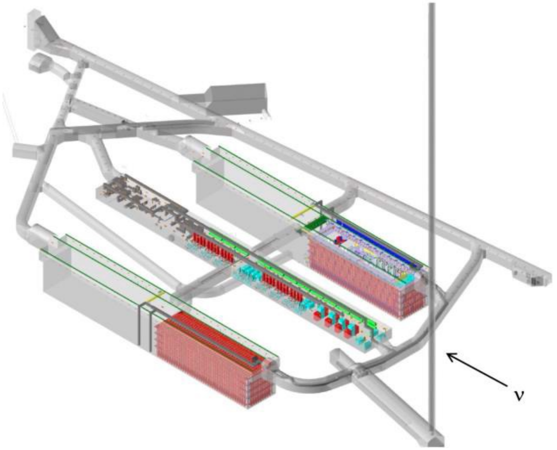
on Behalf of the DUNE Collaboration

Overview

- DUNE Experiment and physics program
- DUNE Far Detector: LAr technology
- Photon Detection System (PDS) in first and second Far Detector modules
- Preliminary Photon Collection Efficiency (PCE) measurement of the PDS

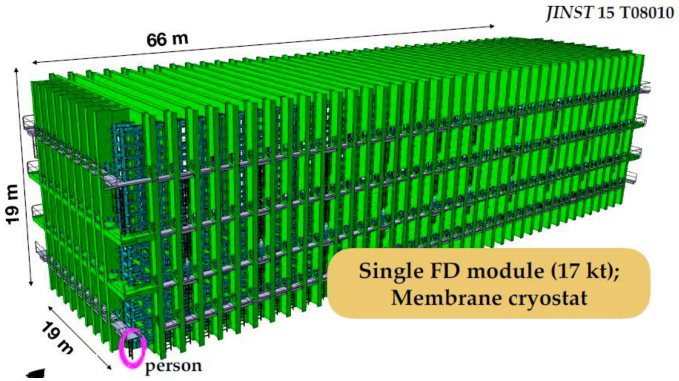


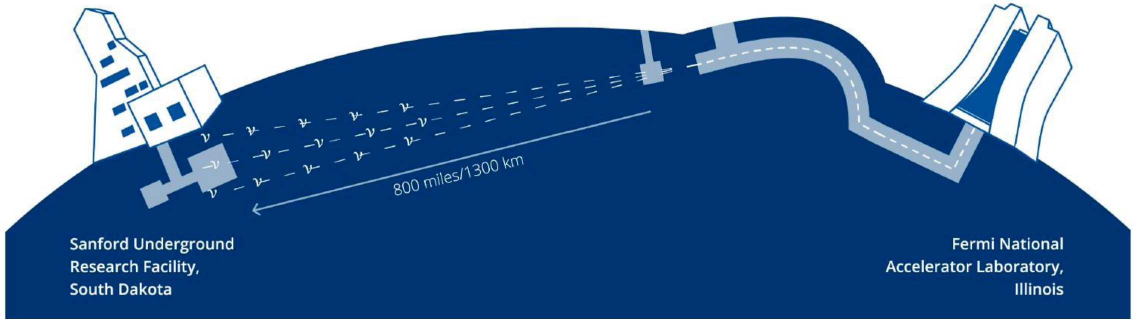
Deep Underground Neutrino Experiment (DUNE)

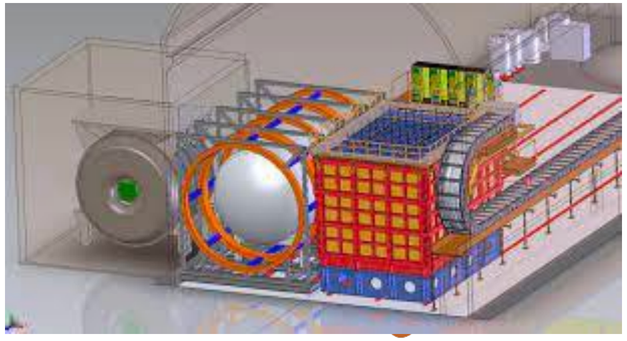


A new generation long-baseline neutrino oscillation experiment (1300 km – large matter effect):

- High power wide-band neutrino (ν_μ or $\overline{\nu}_\mu$) beam originating from the upgrade of the Fermilab accelerator complex (1.2MW in Phase I upgradable to 2.5MW in Phase II)
- Huge far detector volume(~70 kton) divided in 2 (Phase I) + 2 (Phase II) modules, 1.5 km underground
- Multi technology Near Detector (movable NDLAr, TMS + on axis SAND detector) for beam characterization and to constraint systematic uncertainties (same nuclear target)



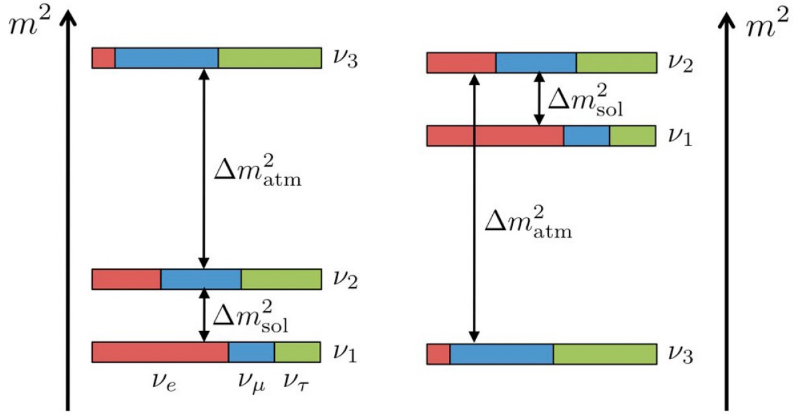




DUNE: A Wide Physics Program

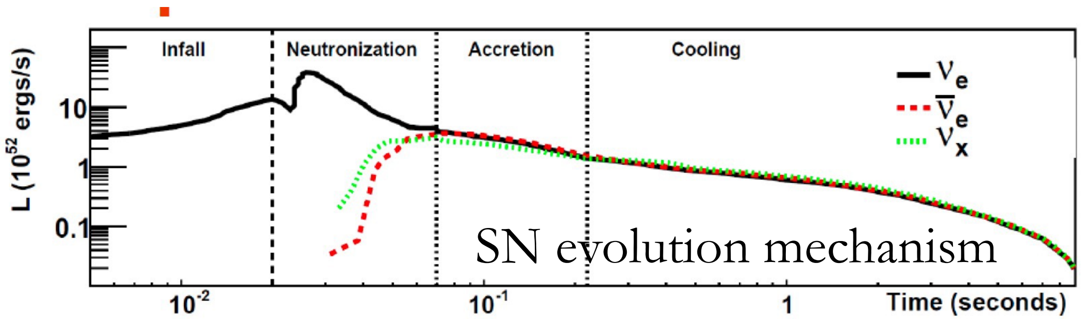
Beam Physics

- Discovery of *CP* violation phase δ_{CP}
- Determine neutrino mass hierarchy
- Precise measurement of neutrino oscillation parameters (ϑ_{23}, Δm_{13}^2)

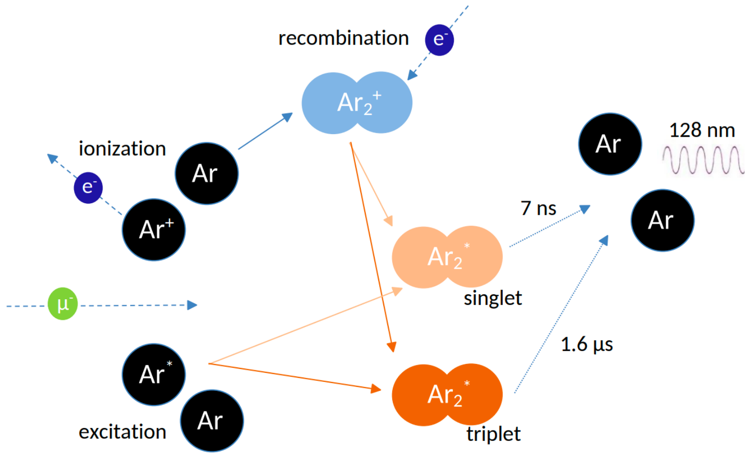


Astroparticle Physics

- Detection of low energy neutrinos bursts from galactic supernova (sensitive to ν_e)
- Detect solar neutrinos (first possible observ. hep neutrinos, best meas. ϑ_{12})
- BSM physics: proton decay…
- Dark matter



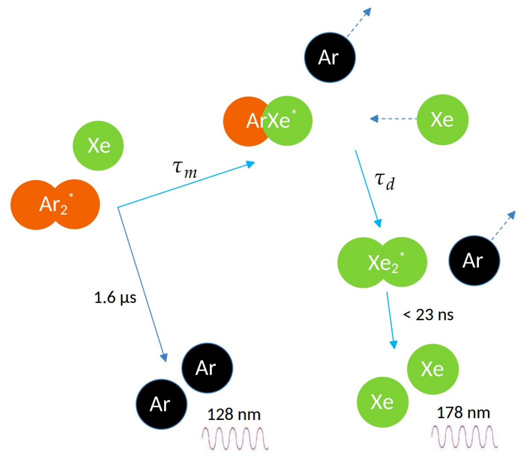
LAr VUV Light Detection



LAr VUV scintillation:

- Excited argon interacts creating excited molecules in singlet and triplet states
- De-excitation emit 128 nm light photons
- 54k photons/MeV @0kV/cm
- Fast component (5 ns) crucial for triggering non-beam events
- Slow/Fast component relative contribution used for background rejection

Xenon doping



Xenon doped LAr will be used in DUNE VD far detector module

- Longer Rayleigh scattering length - enhanced light collection in large volumes
- Mitigation of light absorption from nitrogen contamination

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TIPP 2023
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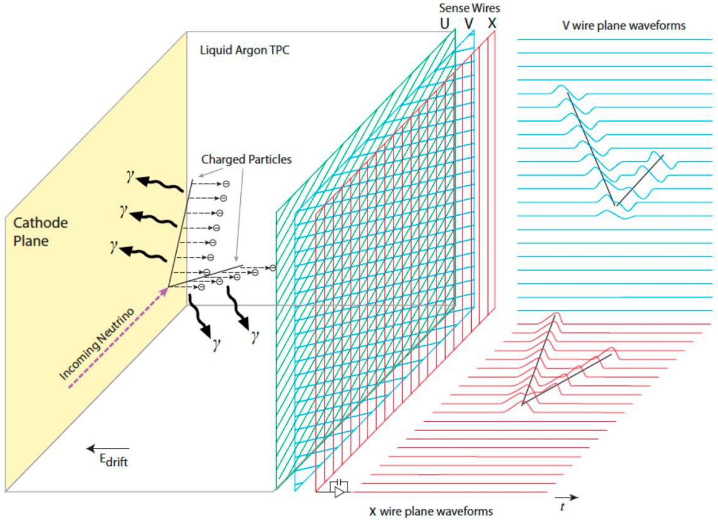
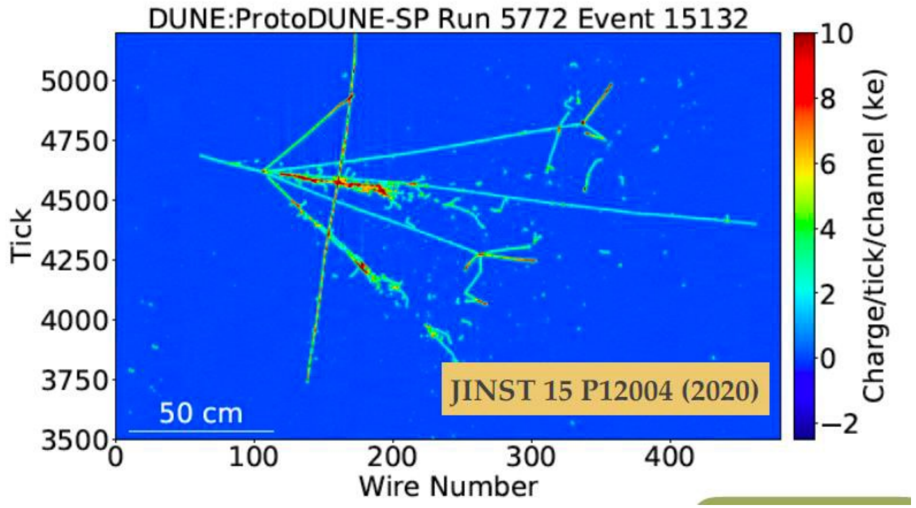
DUNE

DUNE Far Detector Technology



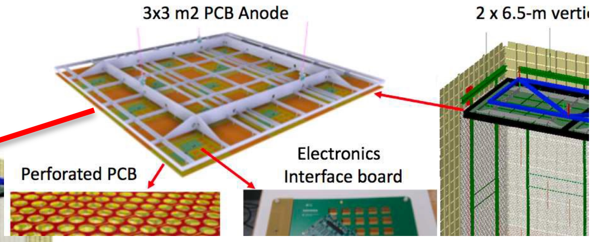


Charged particles In LAr TPC produces two signals (Charge/Light production and collection)

- Electrons produced by ionization are drifted by a strong electric field applied across the TPC allowing for an excellent 3D imaging – few mm scale over large volume detector
- VUV scintillation photons (128 nm) provide precise event timing (LAr transparent to its own VUV scintillation)
- Excellent energy measurement capability – totally active calorimeter
- Particle ID by dE/dx, range, event topology

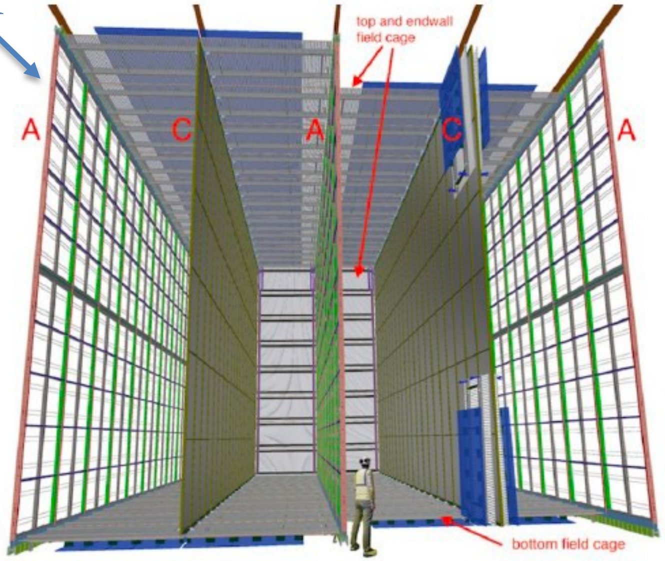
DUNE Far Detector: HD & VD

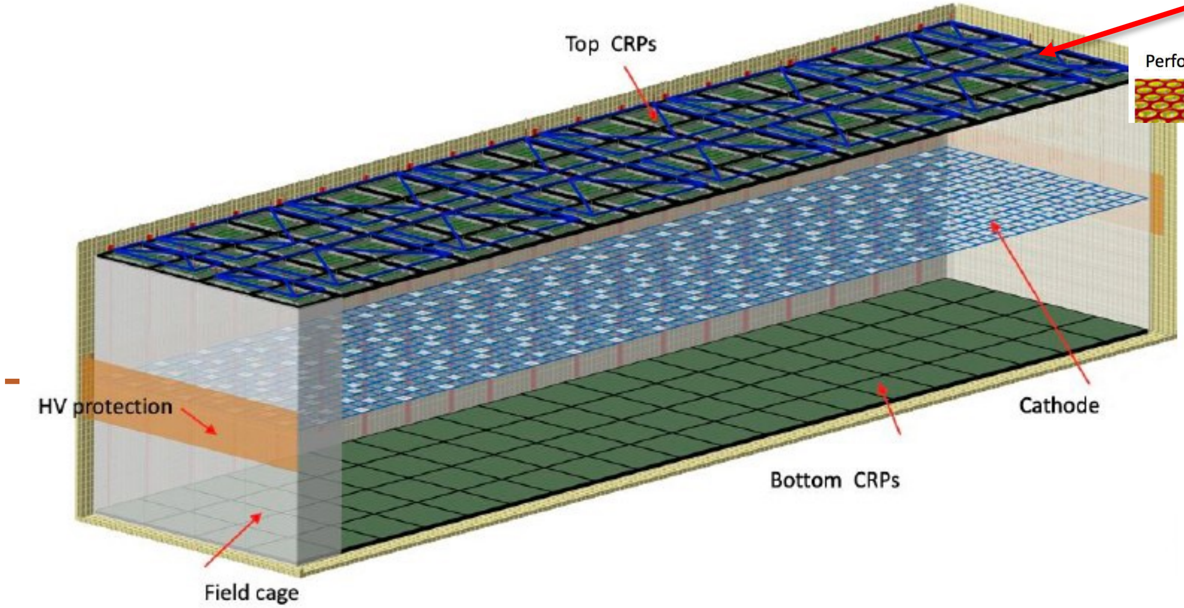
- First FD module will use Horizontal Drift technology: four 3.5 m drift regions, charge readout with wires in Anod Planes Assembly (APA). Similar to ICARUS, MicrobooNE, SBND.
- Second FD module will use Vertical Drift technology (two volumes 13.5 m x 6.5 m drift x 6.0 m), readout with strips (perforated PCB). Larger active volume, cheaper than FD-1 and similar performances



Charge Readout Planes (CRP)

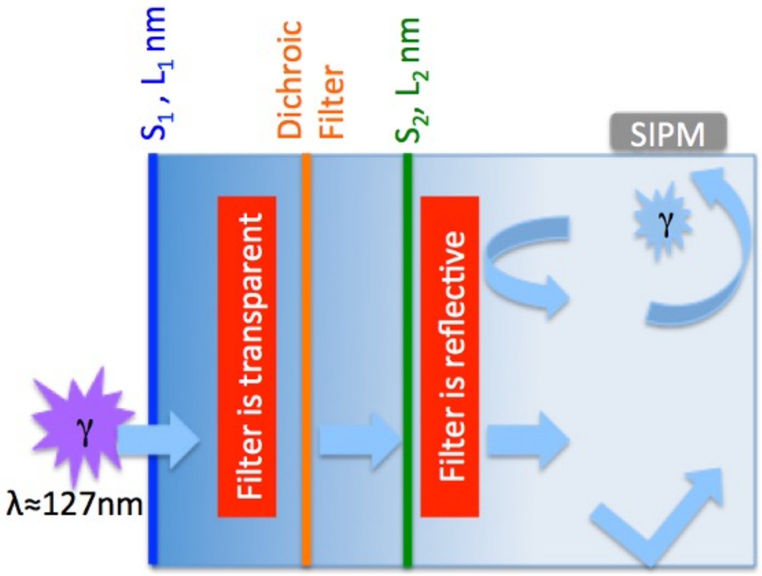
APA

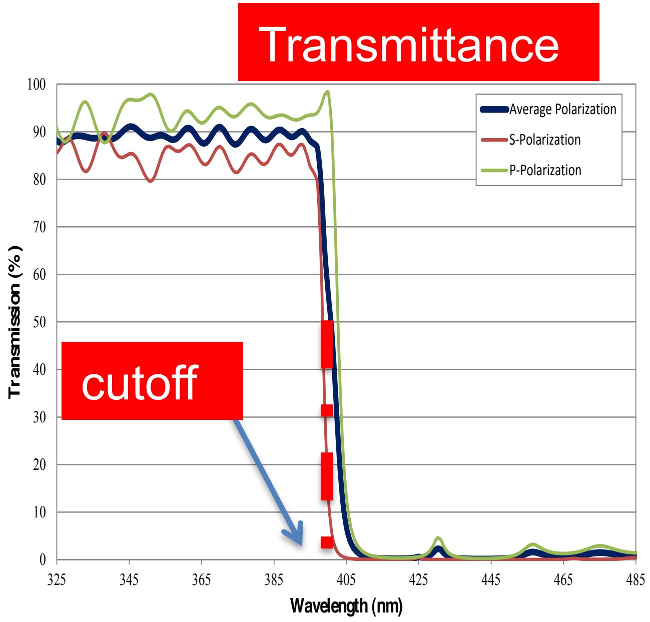


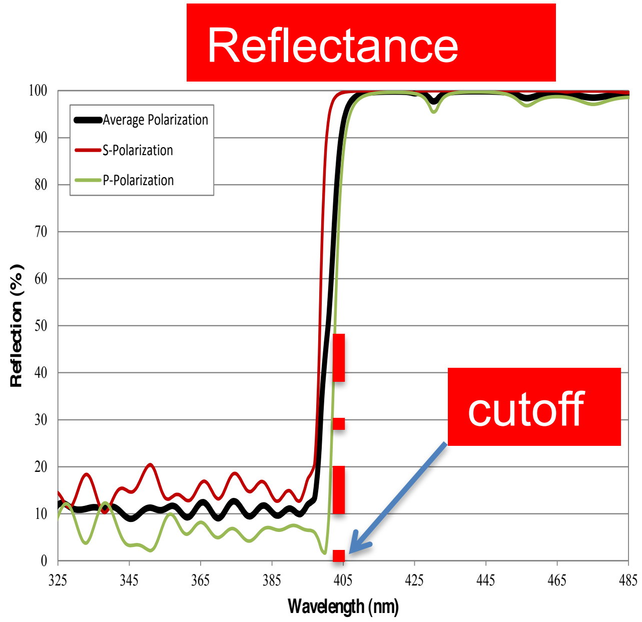


Photon Detection System: the ARAPUCA concept

- Basic idea (Machado, Segreto) is to trap photons in a box with **highly reflective internal surfaces**
- Develop an **efficient photon collector** system which allows to increase the effective area of the active SiPM devices
- The core of the device is the **dichroic filter**: a multilayer interference film which is **highly transparent** for wavelength **below a cutoff** and **highly reflective above it**

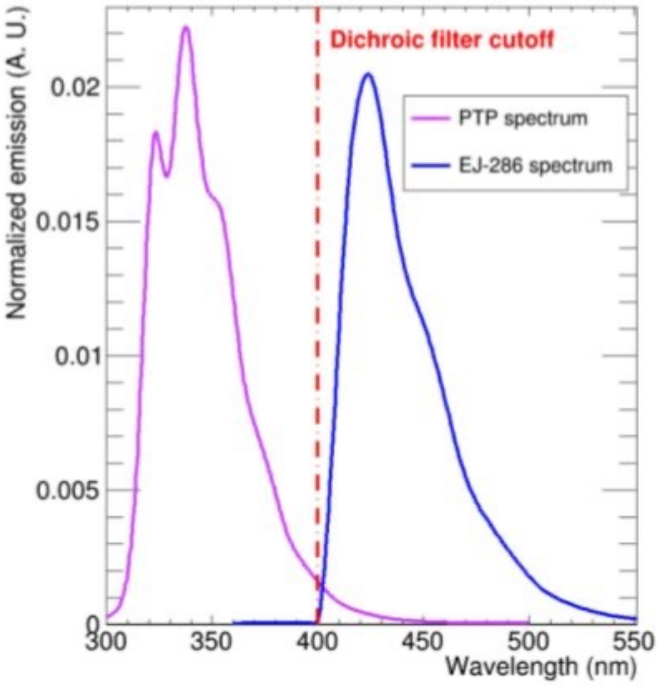


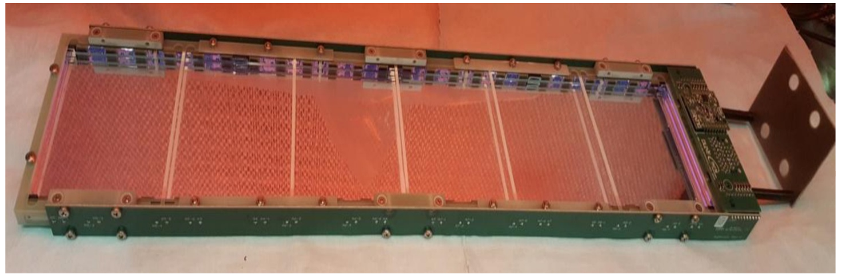


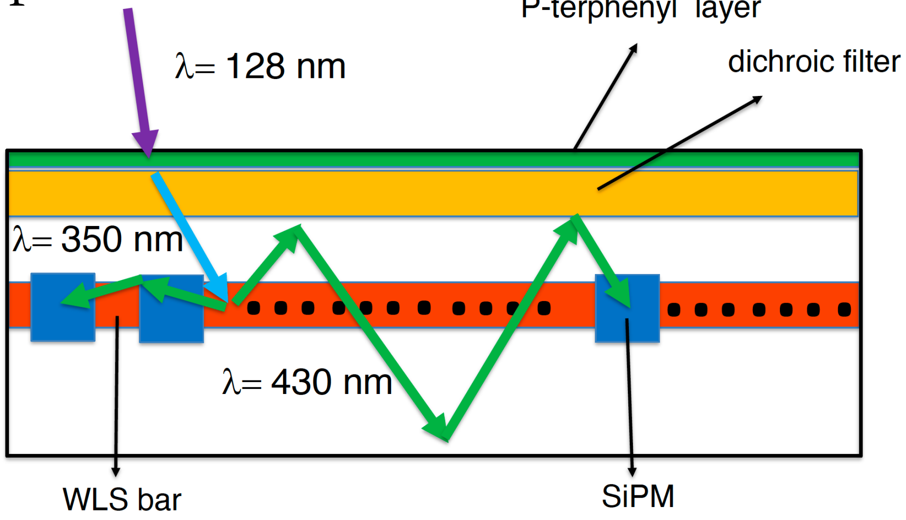


Photon Detection System: the X-ARAPUCA

- VUV scintillation light produced in LAr
- PTP shifter deposited on the dichroic external side converts VUV light to a wavelenght < dichroic cutoff **(light transmitted)**
- The internal WLS bar converts the primary shifted photons to a wavelenght > dichroic cutoff **(light is trapped)**
- After reflections the photons can be detected by SiPM positioned laterally with respect to the WLS plane

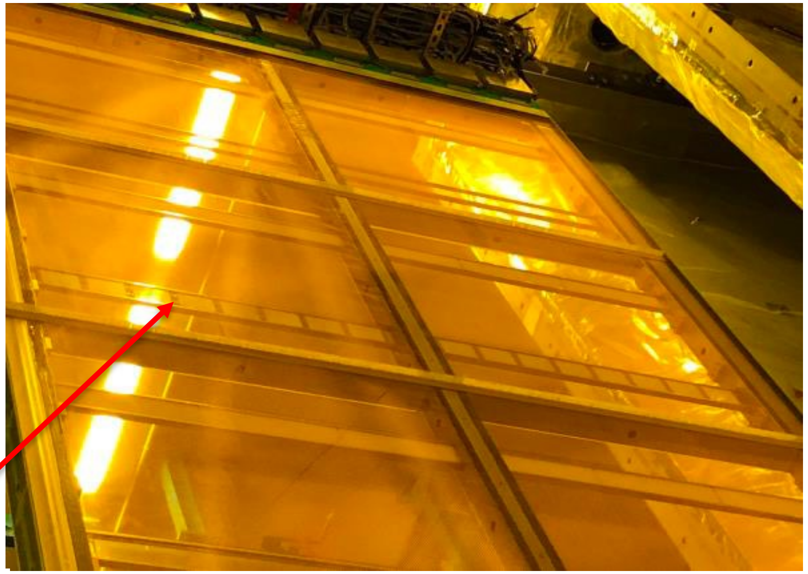


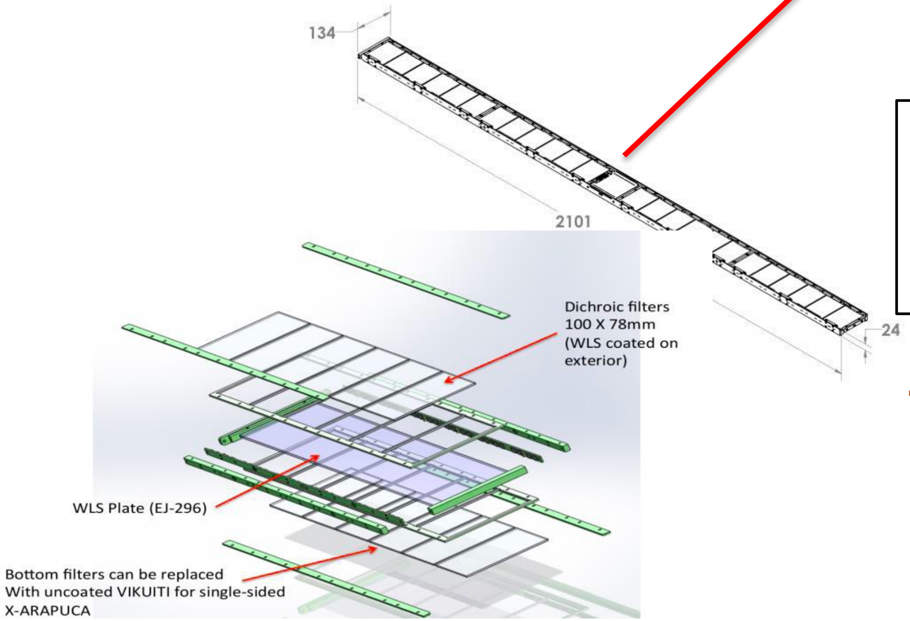




Photon Detection System in HD Detector

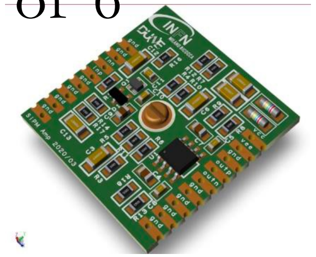
- **Supercell:** 488 x 100 x 8 mm^3
- **Module**: 4 supercell 2092 x 118 x 23 mm^3
- 10 modules for APA
- in total 1500 modules in FD-1
- 4 channels per module





SiPM readout

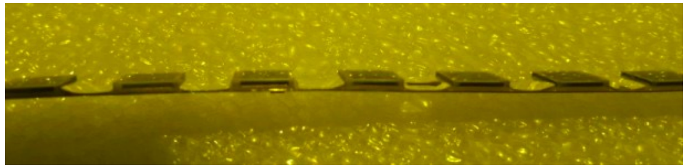
- 48 SiPM ganged to a single readout channel
- Active ganging amplifiers collect 8 groups of 6 parallel SiPMs

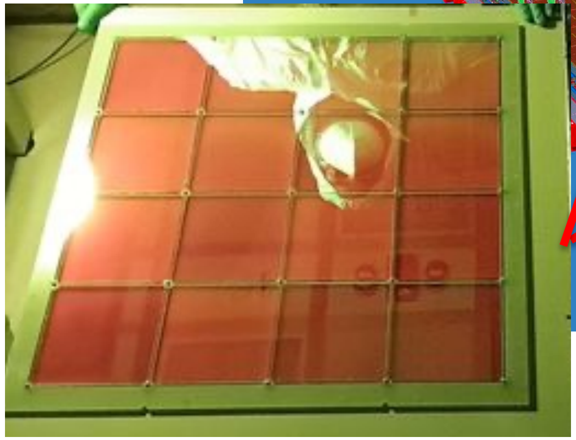


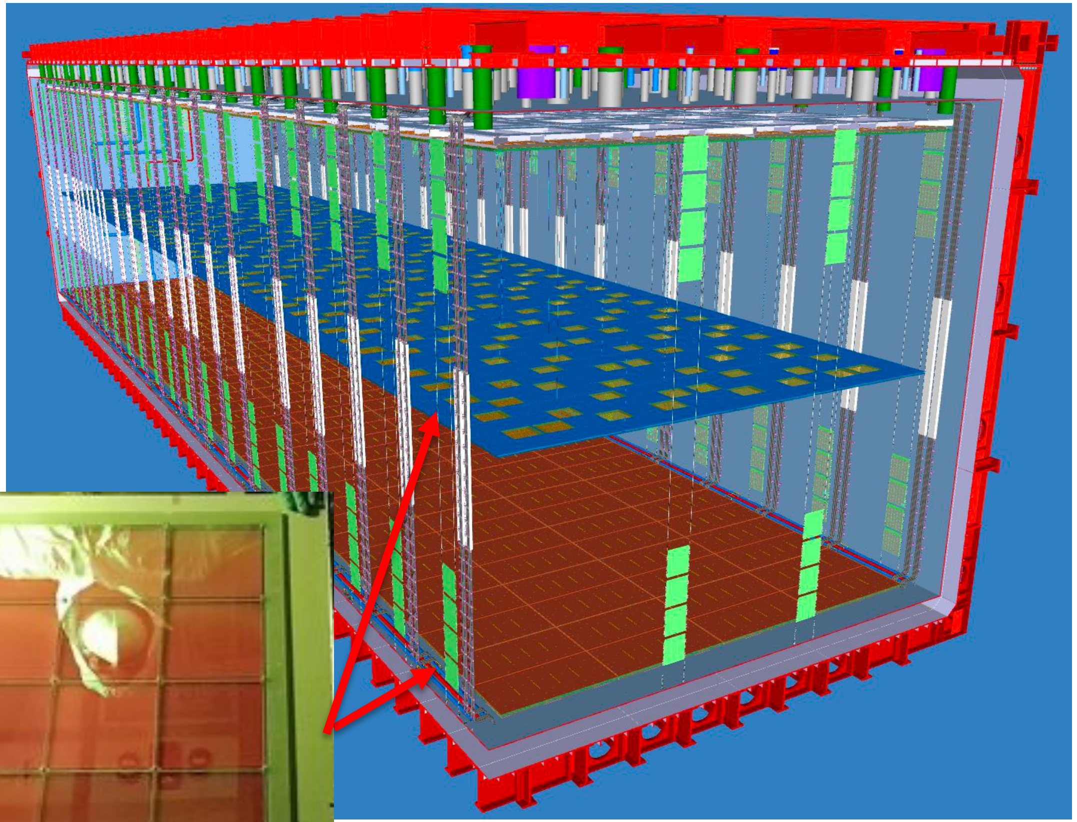
The Photon Collection Efficiency of the HD-PDS has been measured in several laboratories and is between 2.0-2.5%

Photon Detection System in VD Detector

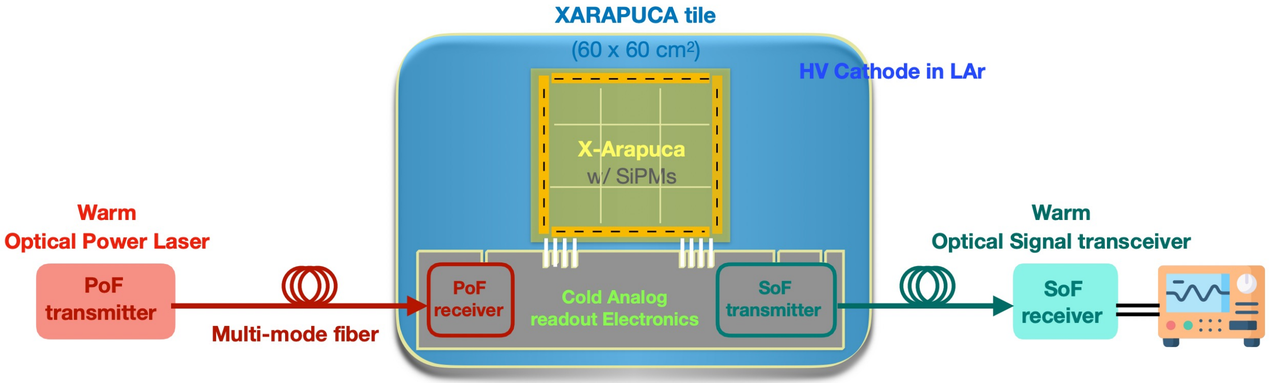
- **PD modules** mounted on the cathode (at 300 kV) and on the cryostat walls (membrane) behind the transparent (70%) field cage
- 320 double side (cathode) + 352 single side (membrane)
- **Square geometry**: dimension 65 x 65 cm^2
- A single large **WLS light guide** plane
- Light readout by **160 SiPMs** mounted on flexible strips





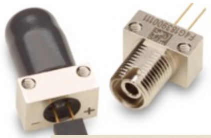


PDS-VD Electronics (Power over Fiber and Signal over Fiber)

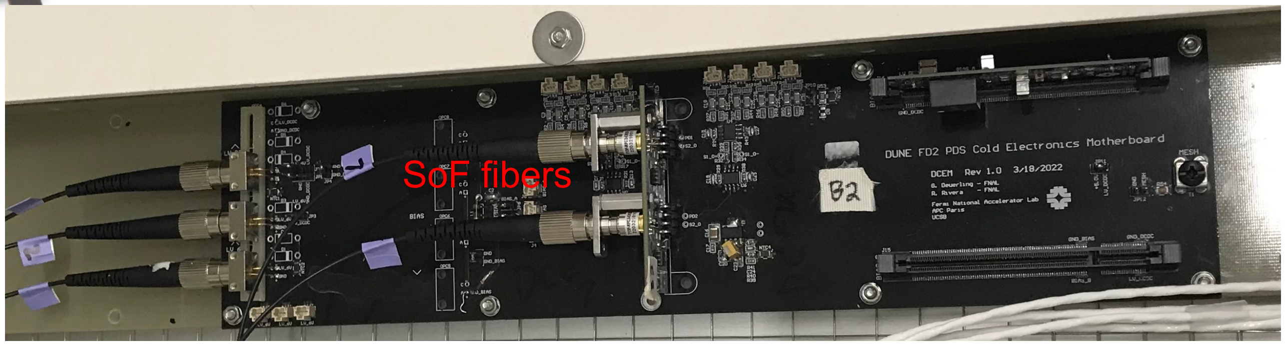


Power-over-Fiber

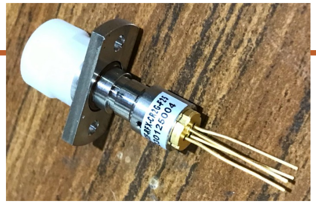
Signal-over-Fiber



PoF: High efficiency GaAs OPC

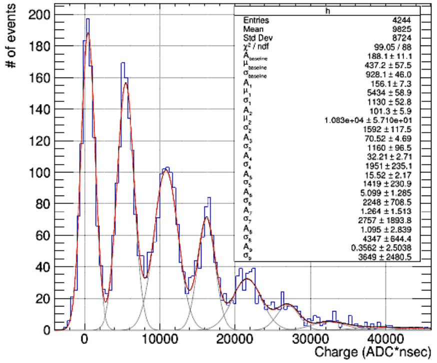


PoF fibers

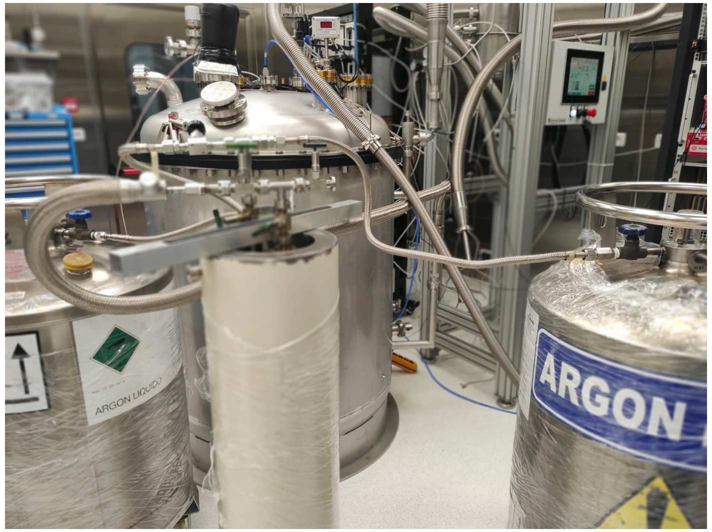


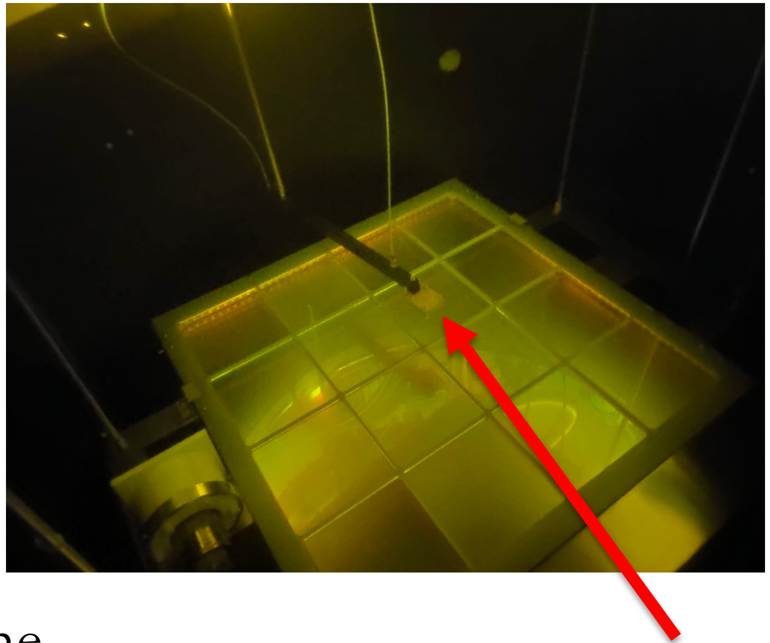
SoF defocused FP laser diode

- **Membrane** modules have standard electronics
- 4 groups of 20 SiPM passively-ganged in two stages, two output channels
- For **Cathode** modules a dedicated R&D have been carried out
- **Power over Fiber:** Laser toward a Photovoltaic Power Converter (PPC)
- **Signal Over Fiber:** analog signal transmission using IR laser light



Photon Collection Efficiency determination of PDS-VD module at Naples cryogenic laboratory

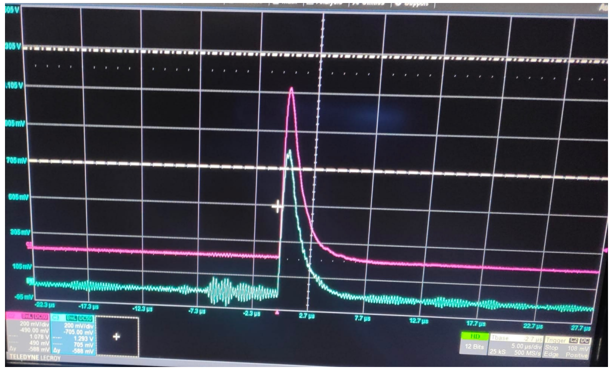




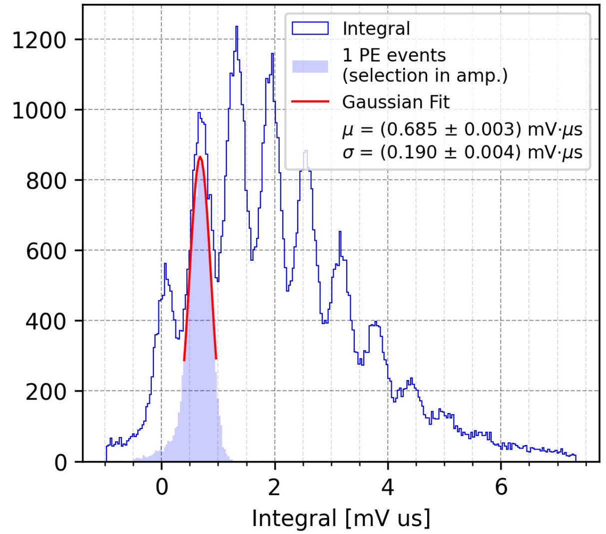
^{241}Am source

- PDS module mechanical structure connected to cryostat dome
- ^{241}Am source connected to rototranslator
- Cryostat walls covered by black delrin light shield

Measurement of the Photon Collection Efficiency

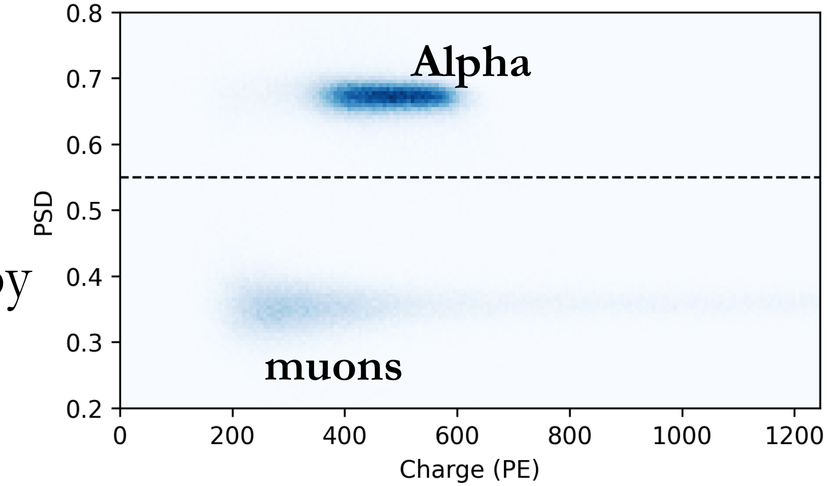


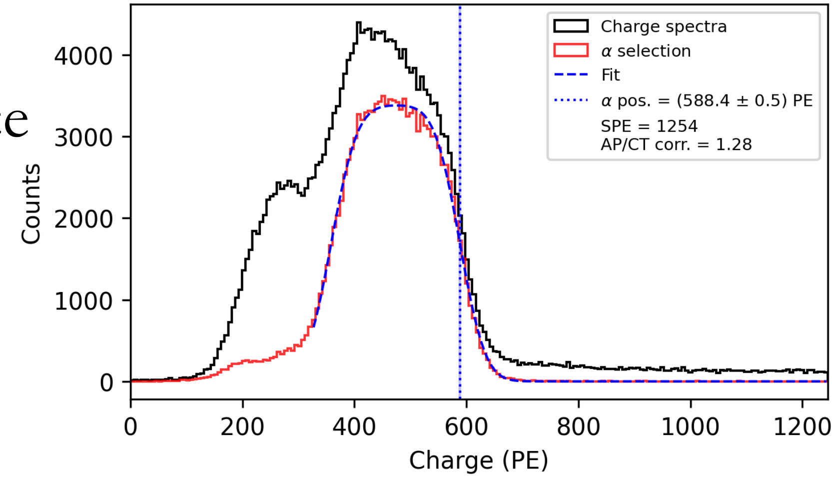
SPE response



$$PCE = \frac{N^{PE}}{N^{Ph}_{SIM}}$$

- Scintillation VUV photons produced by alpha source
- SPE response determined with pulsed laser
- Clear signal selection from alpha source
- N^{PE} given by detected photoelectrons produced by alpha particles and corrected for SIPMs secondary pulses: afterpulse and cross-talk (AP/CT)

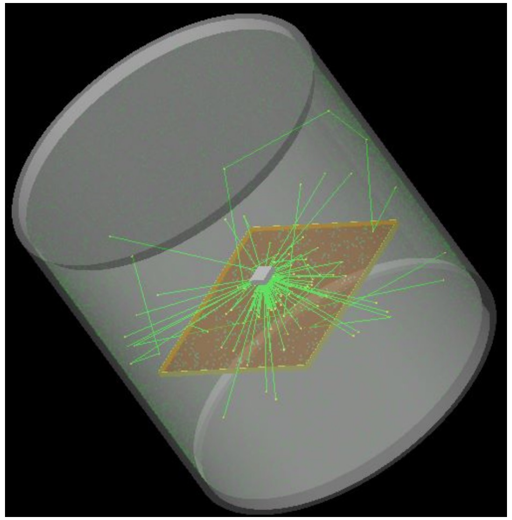


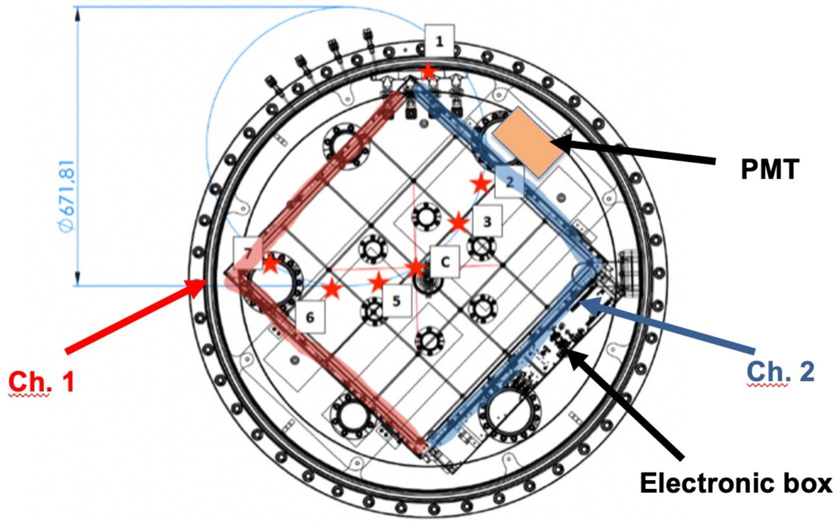


VERY PRELIMINARY

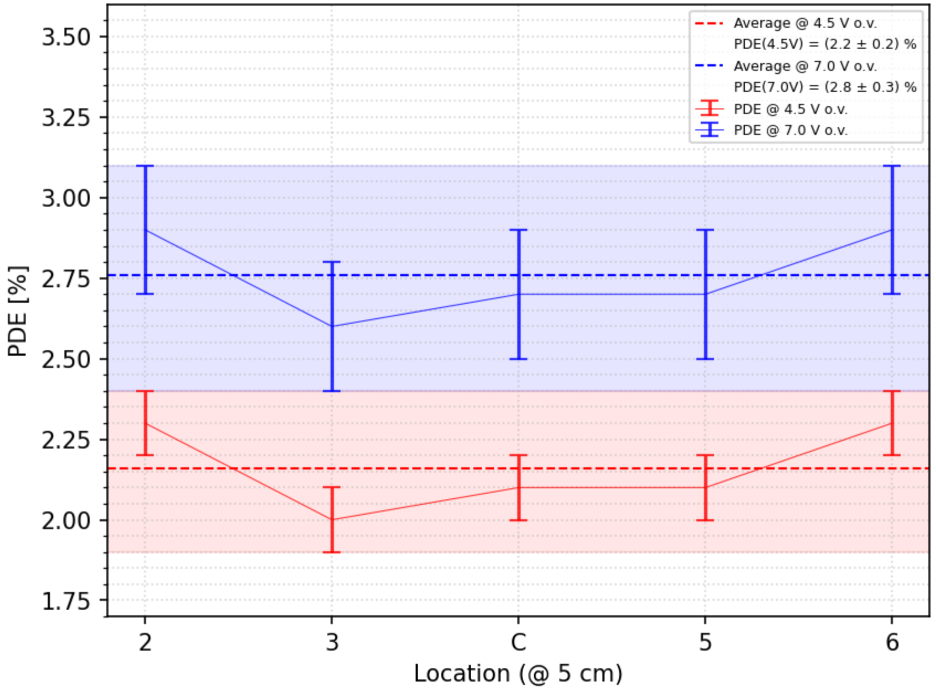
Photon Collection Efficiency

- ${N^{Ph}}_{SIM}$ is the expected number of photons impacting on PD module estimated with G4 simulation: alpha LY + geometrical acceptance
- Measured efficiency in different detector locations and at 4.5 V and 7.0 V overvoltage
- A **very preliminary** PCE estimation is about $2.2 \pm 0.2\%$ at 4.5V overvoltage
- This value allows to infer an overall experiment LY of ~30 PE/MeV





$$PCE = \frac{N^{PE}}{{N^{Ph}}_{SIM}}$$



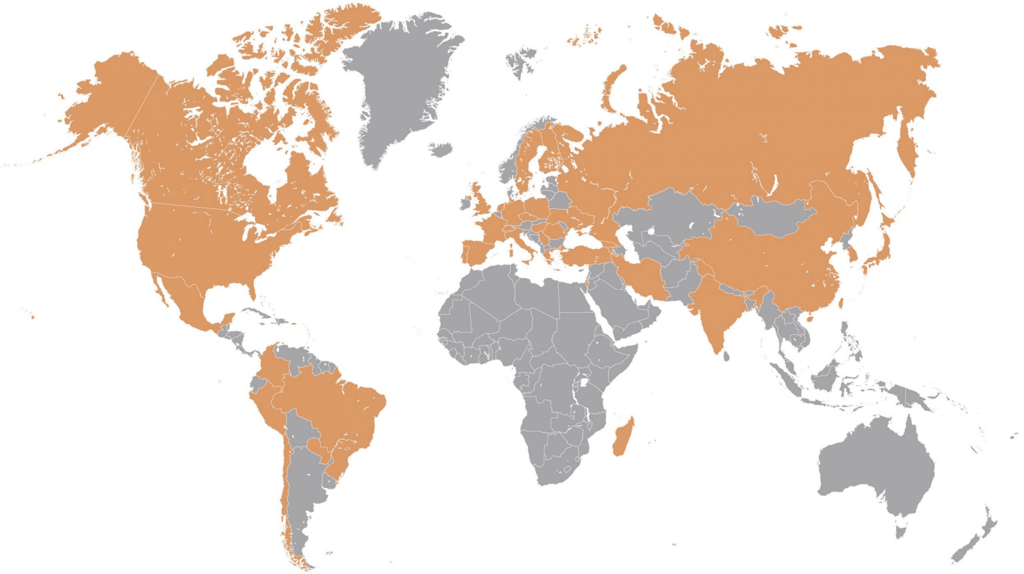
Conclusions

- DUNE will enable a rich and exciting physics program in next decades
  - CP violation and neutrino oscillation
  - MeV-scale neutrinos
  - BSM searches
- Far Detector Technology defined for FD-1 (HD) and FD-2 (VD)
- Photon Detection System: conceptual design based on X-Arapuca light collector
- PCE measurement of the X-Arapuca systems: HD and preliminary for VD
- R&D and improvements in PDS group: enhanced light collection performance enhances physics capability

Backup Slides

The DUNE Collaboration

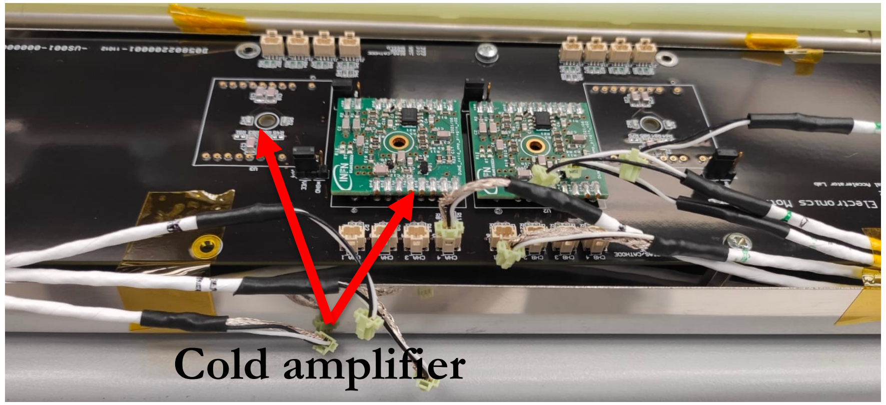
DUNE Collaboration meeting, FermiLab May 2023



DUNE Collaboration

- 1440 collaborators
- 37 countries
- 208 institutions including CERN

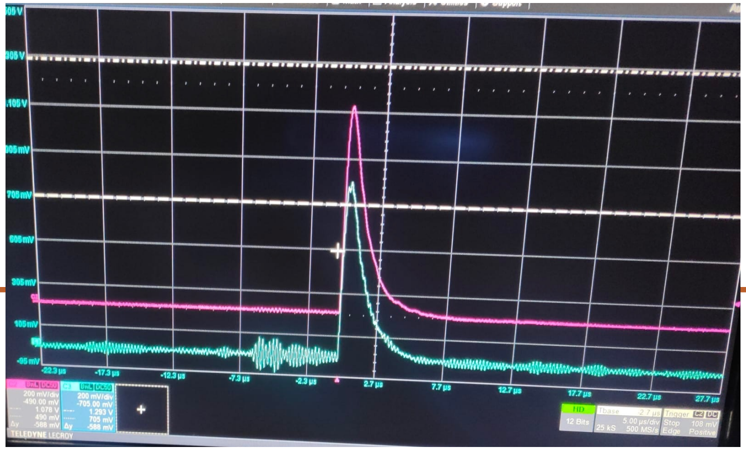
Electrical connection and DAQ



Cold amplifier

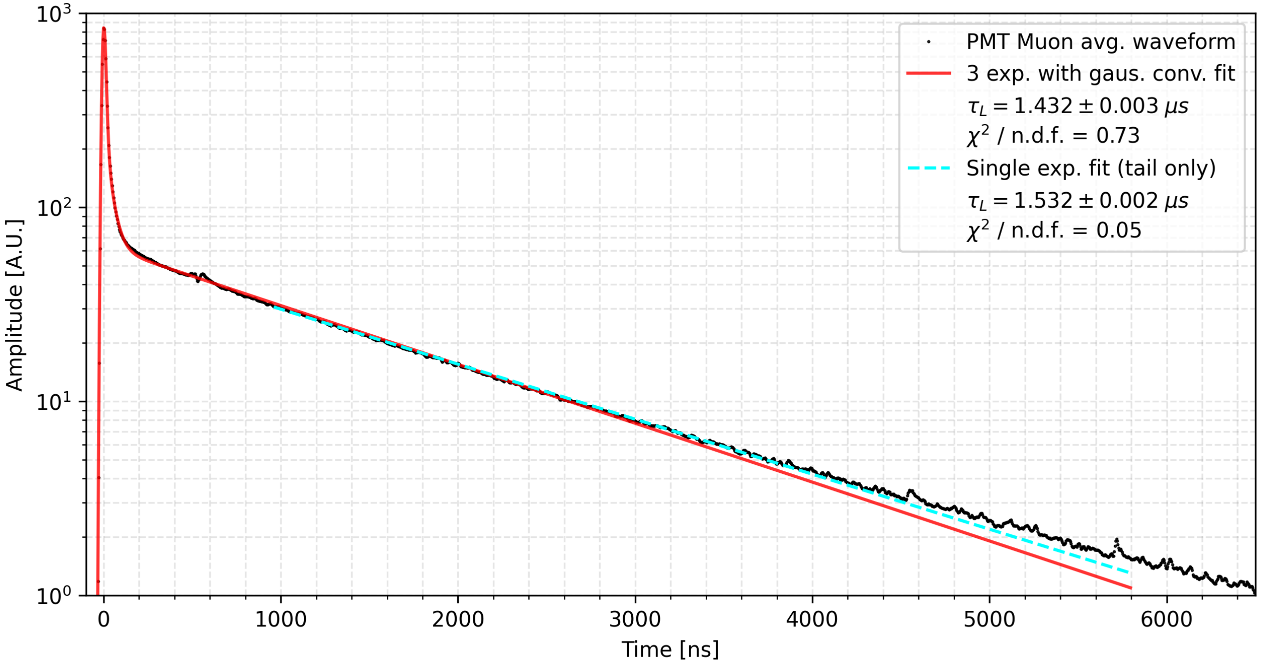
- DMEM with two cold amplifier: preliminary tested in LN_2 : both channels working
- just before to close the cryostat one of two signal is not present: we changed position of one cold amplifier
- After LAr filling discovered that one channel is very noisy
- Output signals from second stage amplifier sent to CAEN V1725B digitizer

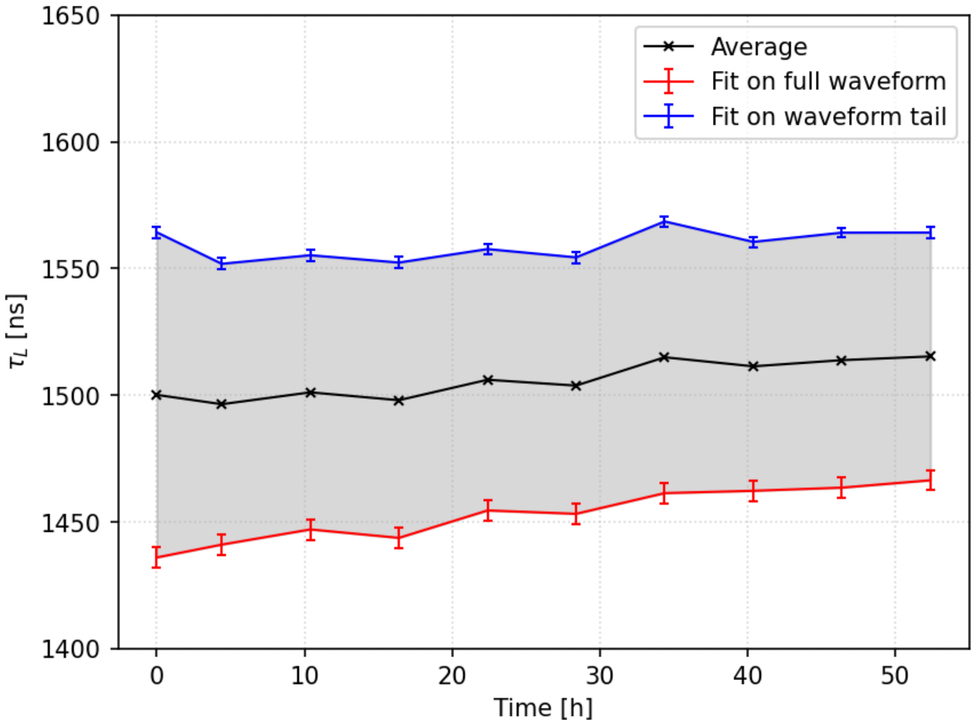
Warm second stage amplifier



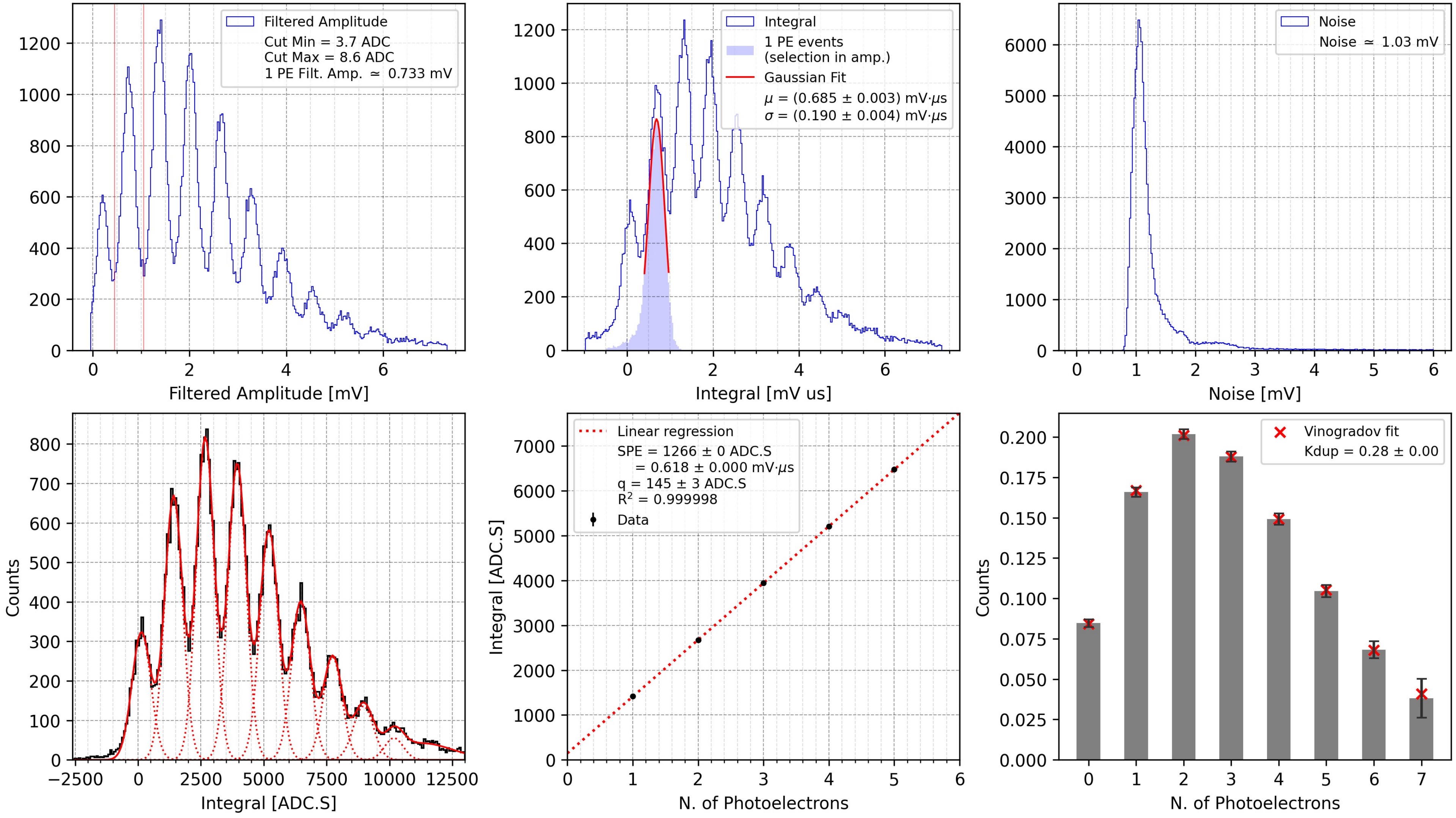
LAr purity estimated with PMT

- Two fitting procedures_
  - 3 exp. + gaussian
  - Single exp (tail only)
- **Result of long tau component between 1.4-1.5 us**
- Fit executed on muon sample





SPE response at OV=4.5V

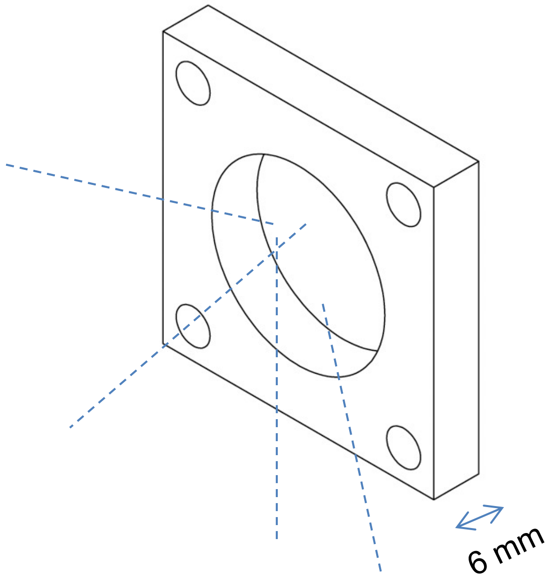


Channels: 1,2

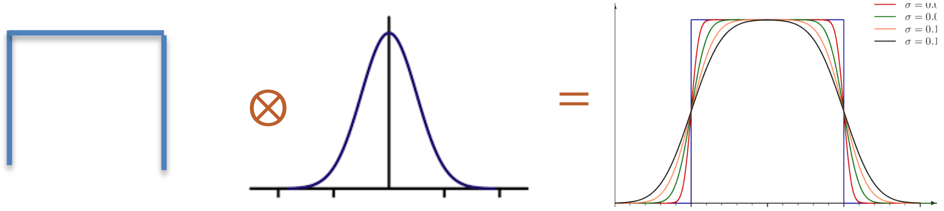
Filter moving average

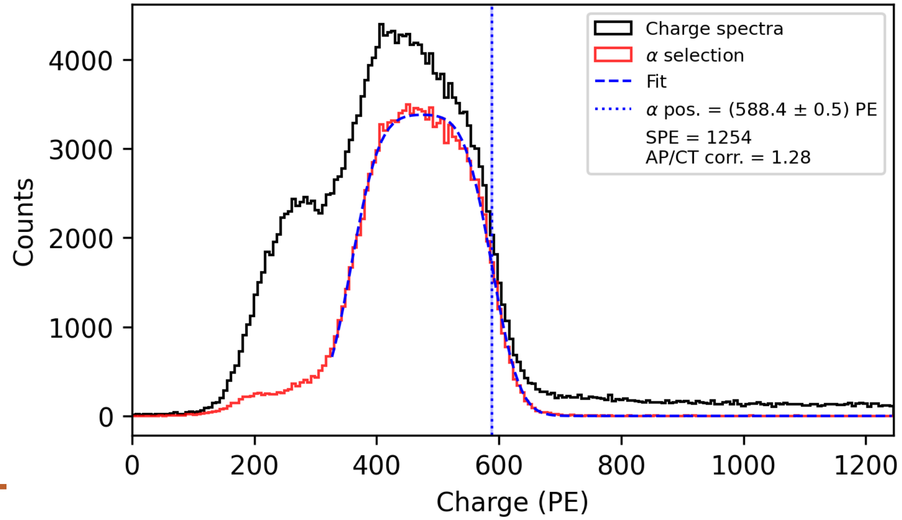
- Channel 1 very noisy → **impossible to retrieve SPE**
- Channel 2 is ok
- Vinogradov fit to photon statistics
- duplication factor 0.28
- f_{CTAP}=1.28

Source holder geometry

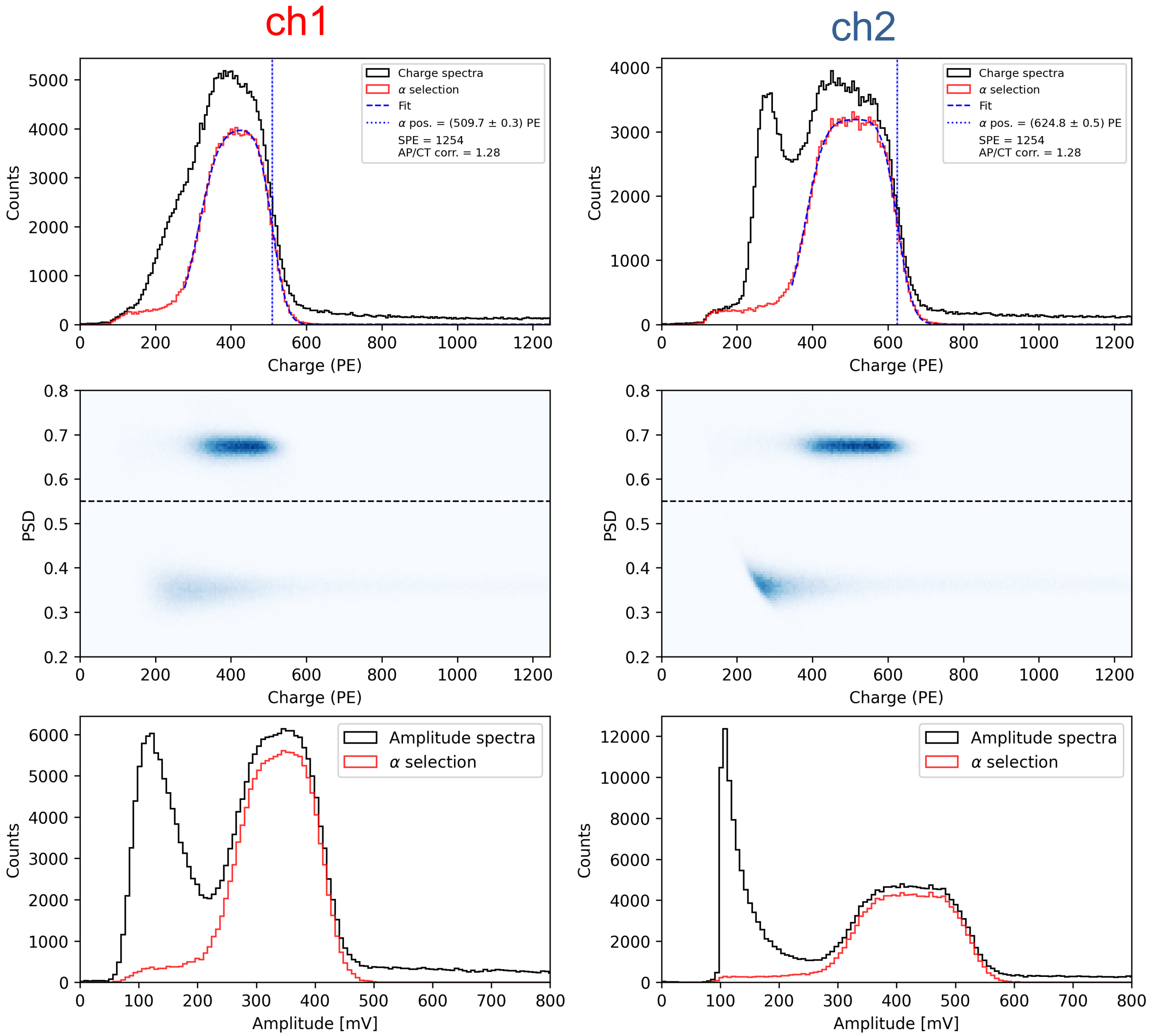


- Source holder window is 23 mm diameter
- Thickness of the holder edges is 6 mm: this induce a shielding of alpha particles
- Due to the holder shielding the alpha spectrum becomes flat
- **Charge spectrum** fitted with the convolution of a box function and a gaussian
- **Alpha yield: 50% of right tail**
- Alpha Spectrum has been corrected for secondary pulses (AP/CT)





Alpha spectrum: OV=4.5 V



- Trigger on ch2 due to lower noise
- Alpha events selected via prompt light (PSD)
  - Alpha distribution appears non-gaussian due to source holder shielding
  - Alpha yield = fitted tail with the convolution of constant + gaussian distributions=50% of the maximum on the right tail
- Measurement in six different locations for the source
- Error (systematic) estimated by varying cuts

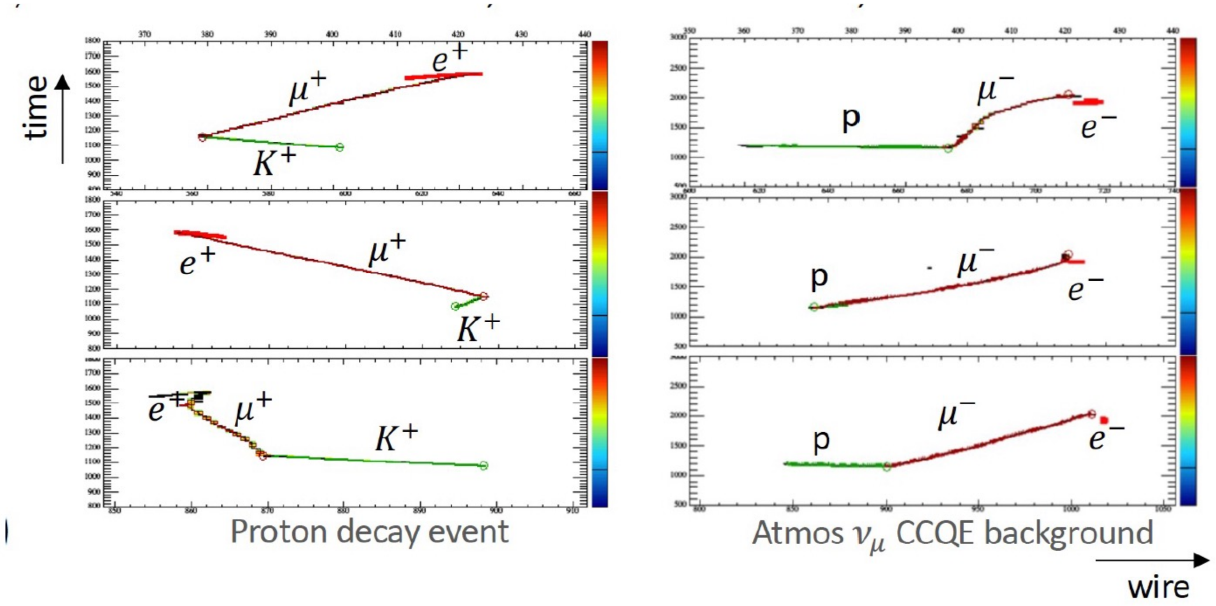
BSM Physics

Baryon number violation, dark matter searches, sterile neutrinos, etc.

Example: proton decay

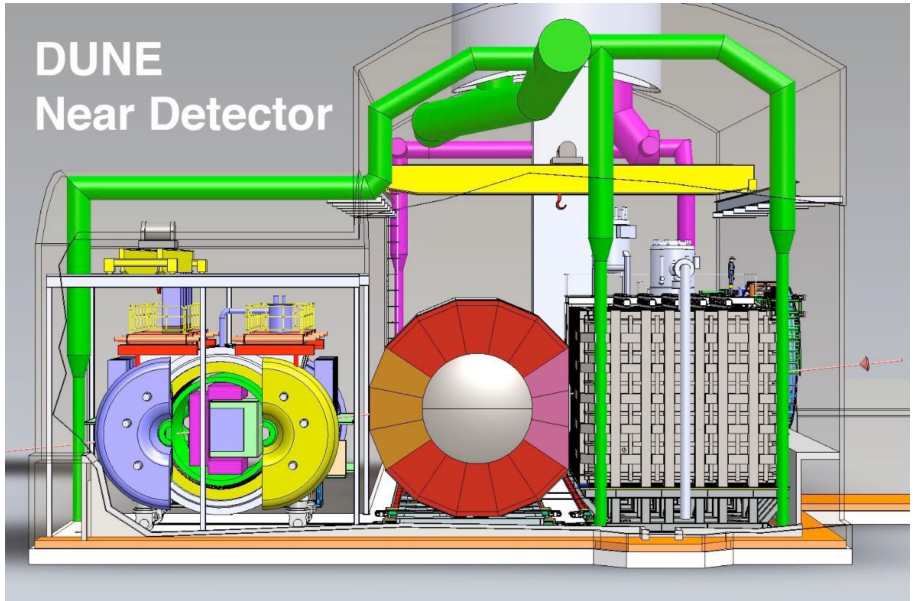
- Underground location
- Large fiducial mass
- Imaging capabilities

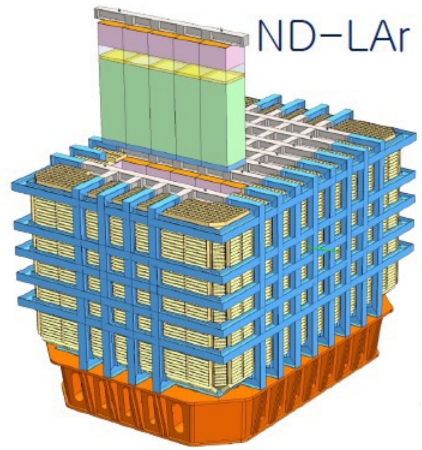
p → $K^+ \bar{\nu}$
(dominant SUSY GUT model)

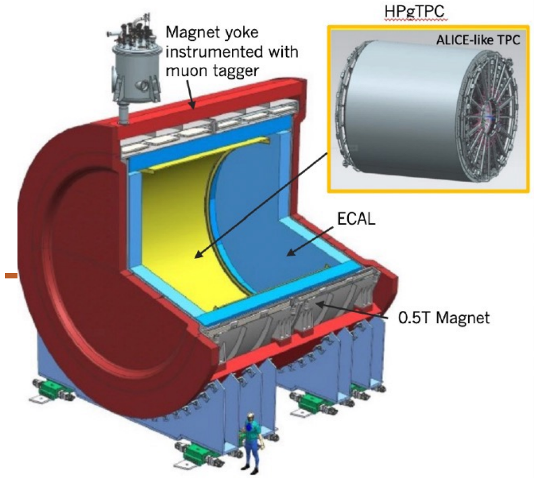


- Identify kaon by dE/dx and decay products
- Main background: atmospheric neutrinos

The Near Detector Complex







- Measures the neutrino beam rate and spectrum to predict un-oscillated event rate in the far detector
- Constraint systematic uncertainties (flux, cross-sections, detector response) for oscillation measurements
- NDLAr LAr-TPC with pixel readout
- TMS: Magnetized steel range stack for measurement of muon momentum and sign
- SAND: On-axis magnetized neutrino detector with LAr target (GRAIN), tracking (STT) and calorimeter (ECAL)