Progress on the Dual Phase Liquid Argon TPC prototype for DUNE

Laura Zambelli (LAPP - CNRS/IN2P3)
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Enigmass The enigma of mass

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Neutrino oscillation : knowns

Neutrino mass (i=1,2,3) and flavor (α=e,μ,τ) eigenstates are linked by the PMNS unitary matrix U:

Atmospheric — Reactor/Accelerator — Solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$

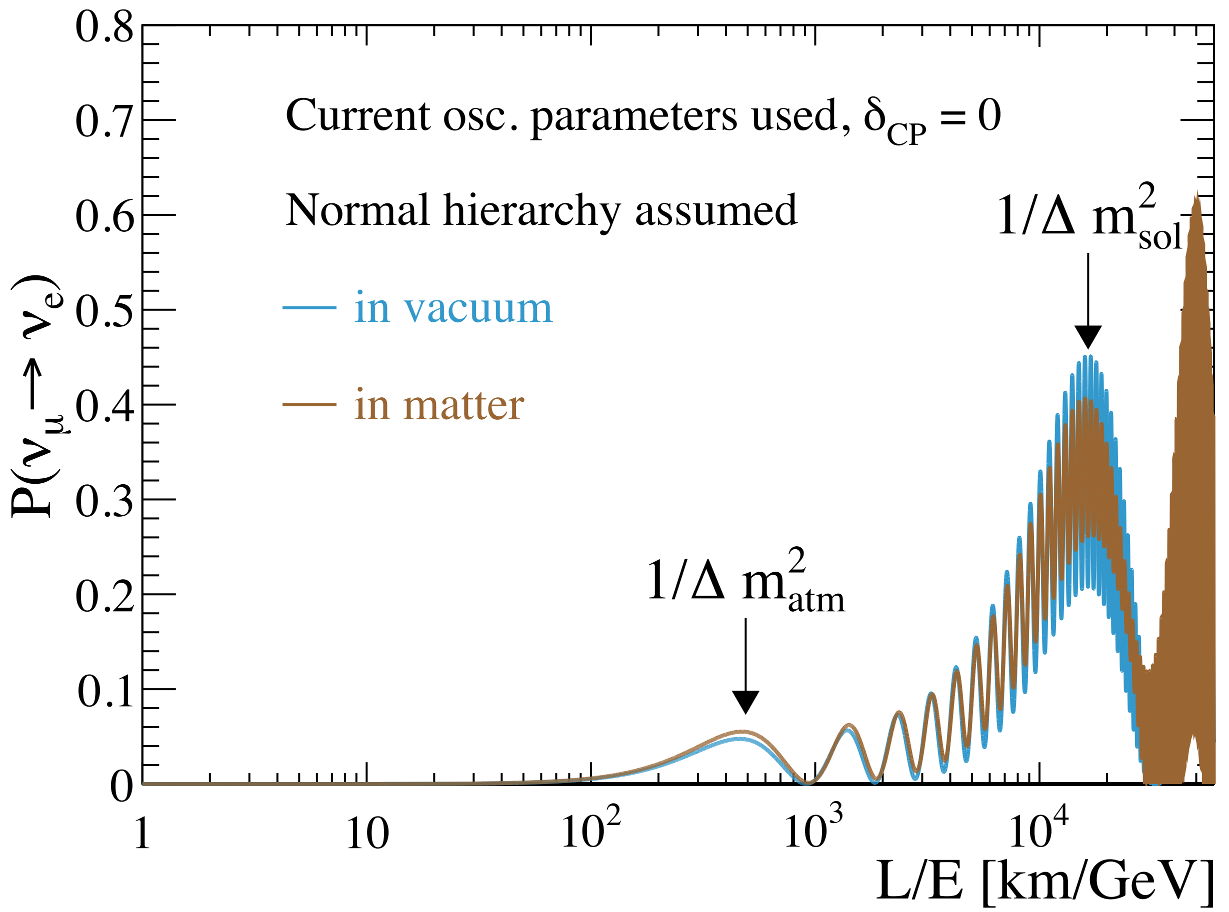
1. Neutrinos can oscillate: A produced ν_α at energy E can be detected as a ν_β after travelling a distance L.

In a 2 ν-flavor scenario :

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta m^2 = m_1^2 - m_2^2$$

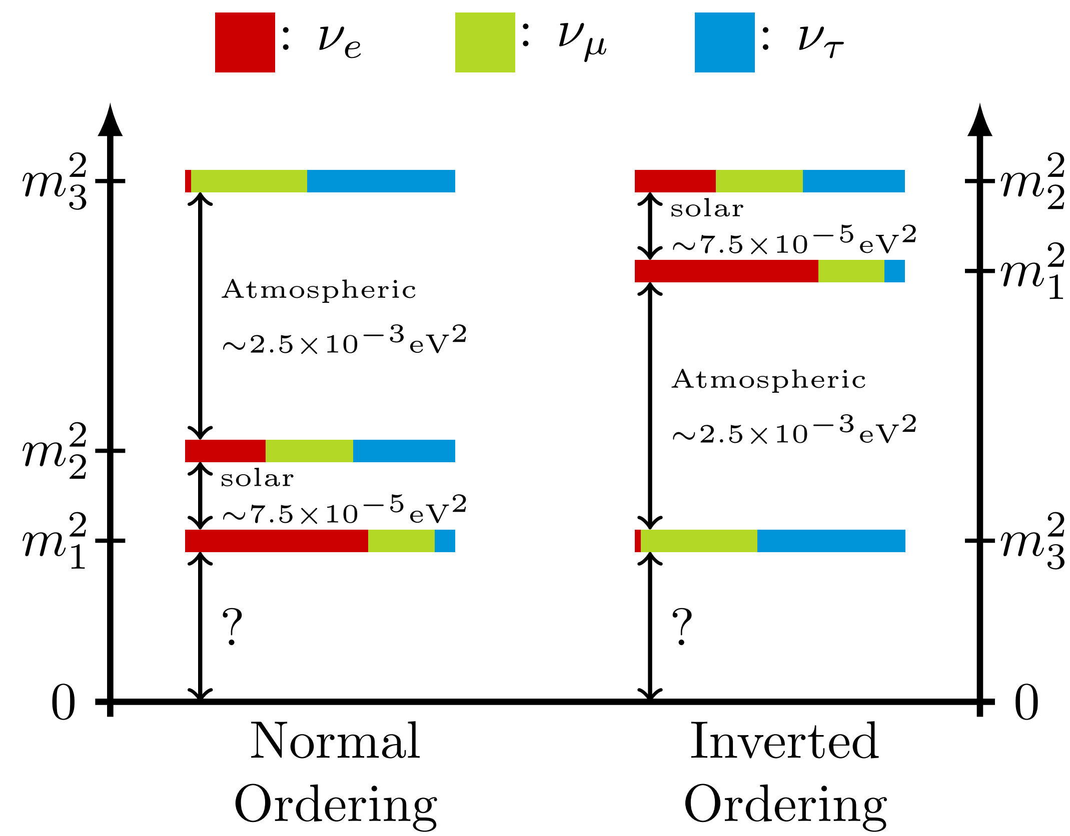
2. Neutrinos are massive
3. Can lead to CP violation in the leptonic sector
4. The oscillation probabilities are modified in matter

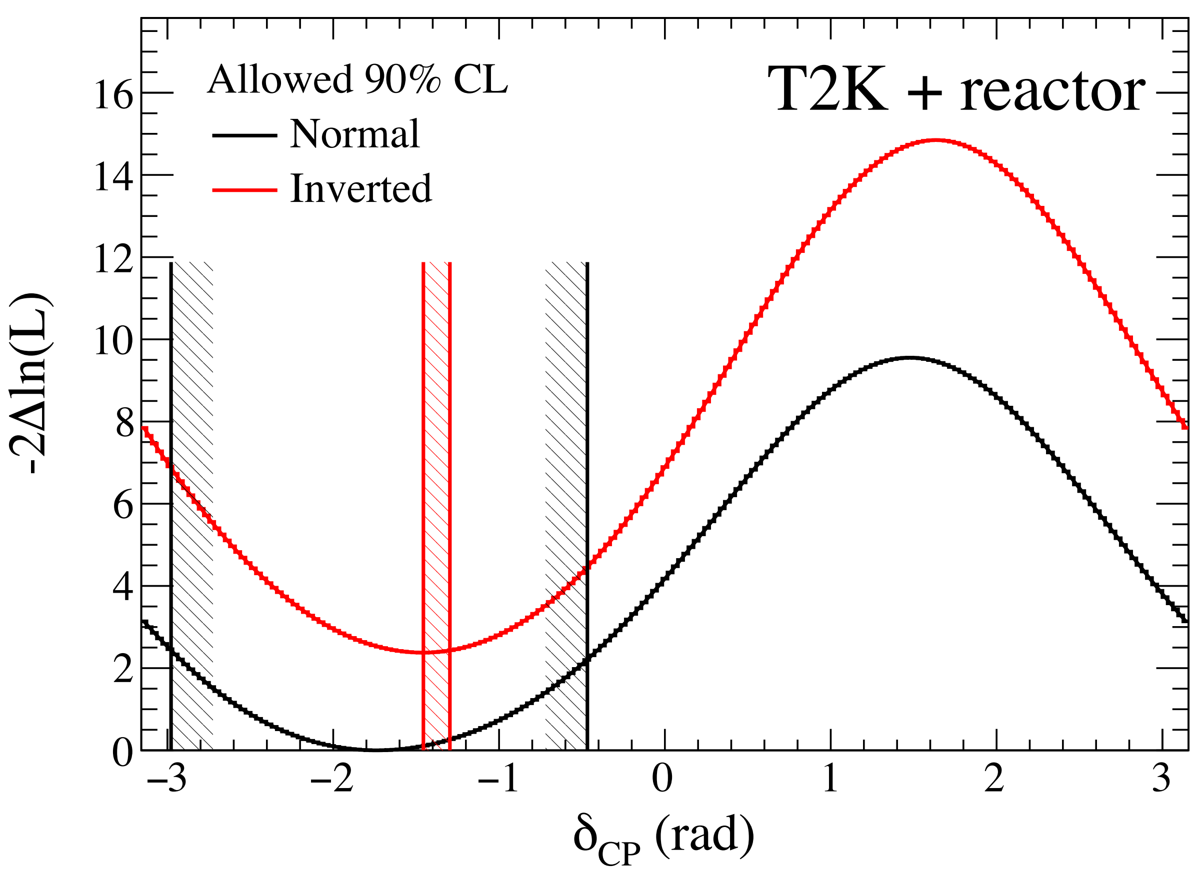


Neutrino oscillation : unknowns

The full 3-ν oscillation phenomena are governed by:

- 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
  - ↳ *measured with 2-8% precision*
- 2 mass splittings: Δm^2_{sol}, $|\Delta m^2_{atm}|$
  - ↳ *measured with 1-3% precision*
  - ▹ *Mass ordering not yet known*
- CP violation phase
  - ▹ *Exact value not yet known*

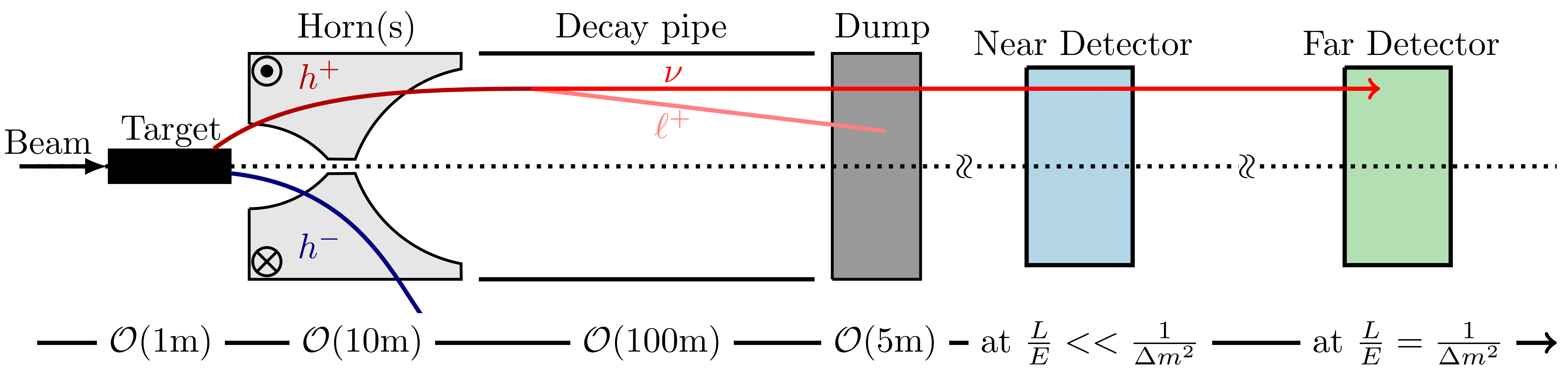




- Current experiments (T2K, NOνA) have a small preference for the normal hierarchy and δ_{CP} = -π/2
- They will not be able to reach the 5σ precision on these parameters

Towards the measurement of CP violation & MH

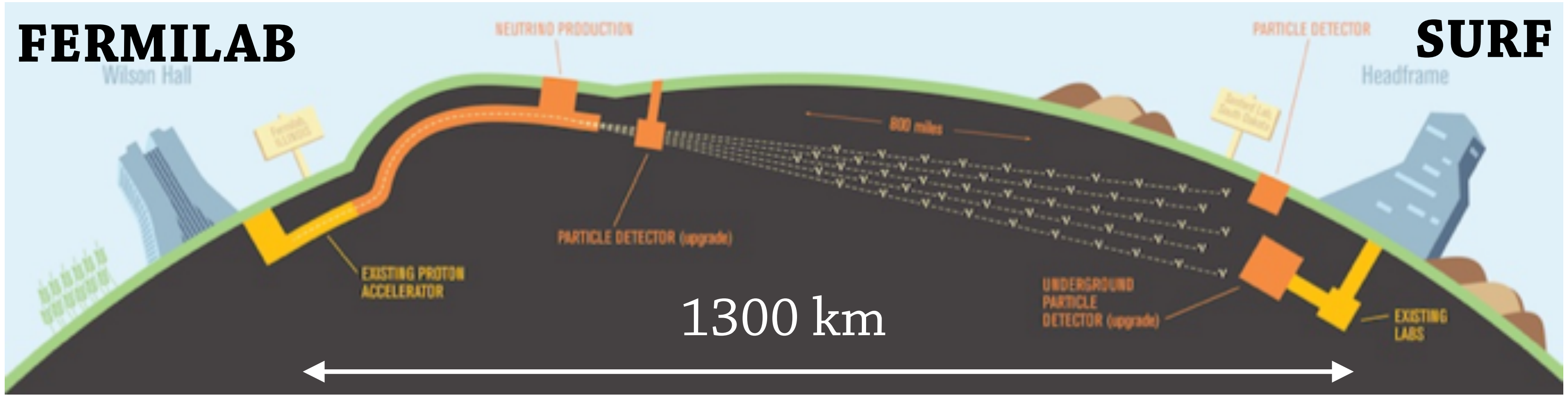
Both measurements can be conducted in accelerator-based long baseline neutrino experiments



Main advantages :

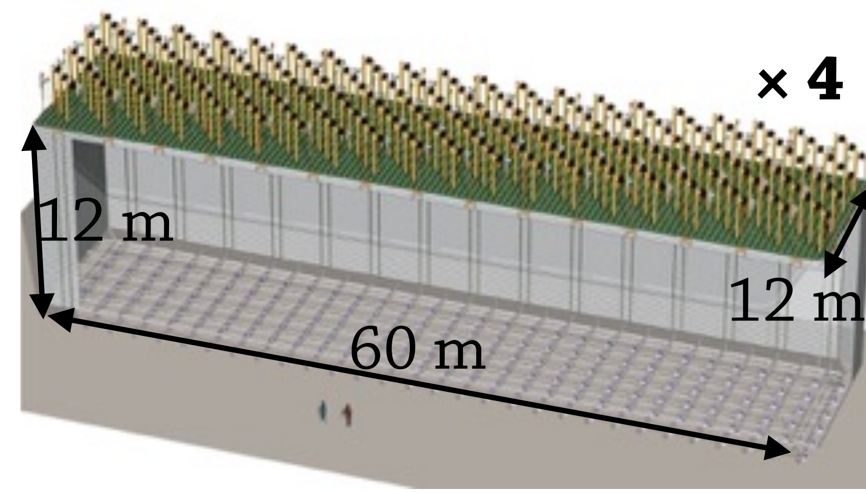
- Neutrinos are produced from secondary hadron decay
  - → Intense flux of ν_μ or $\overline{\nu}_\mu$ at a controlled energy
- Near detector placed before oscillations
  - → Flux content and spectrum measurement, and cross section studies
- Far detector at a distance maximizing of observation of oscillations
  - → L ~ O(300-1300 km) to enhance the matter effects
  - → Appearance of ν_e or $\overline{\nu}_e$
  - → Disappearance of ν_μ or $\overline{\nu}_\mu$

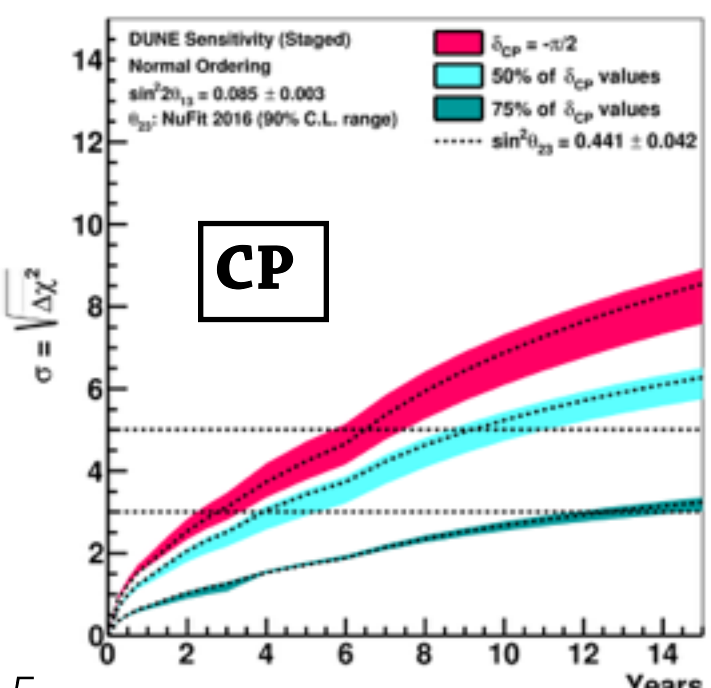
The DUNE experiment



- International project
- Located in the US
- Construction starts in 2021
- 1st neutrino event in 2026

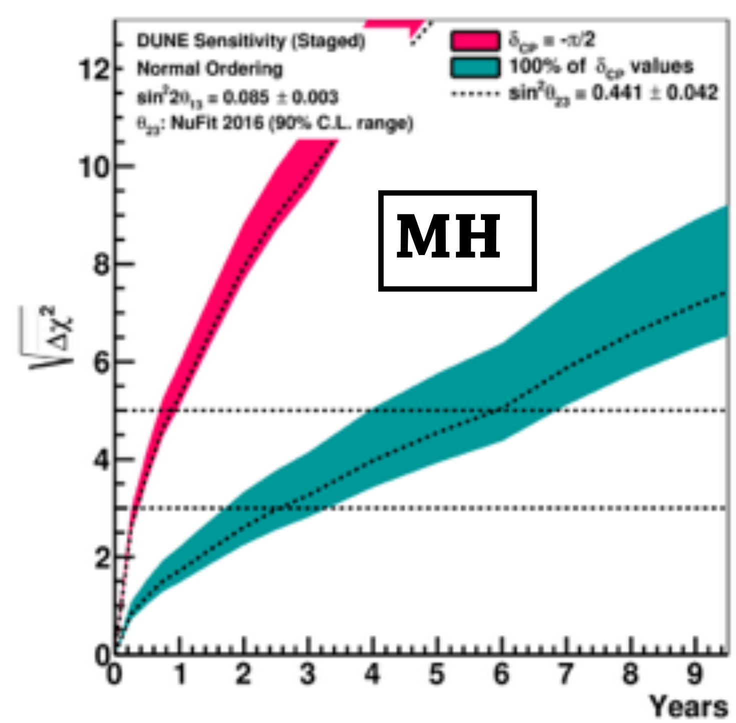
DUNE Far detector consists of 4×10 kt Liquid Argon TPC, 1.5 km underground in the SURF mine in South Dakota, 1300 km away from FERMILAB.





DUNE sensitivities are:

- CP conservation excluded at 5σ for 75% of the δ_{CP} values in 14 years
- Mass hierarchy established at 5σ in 6 years for any values of δ_{CP}

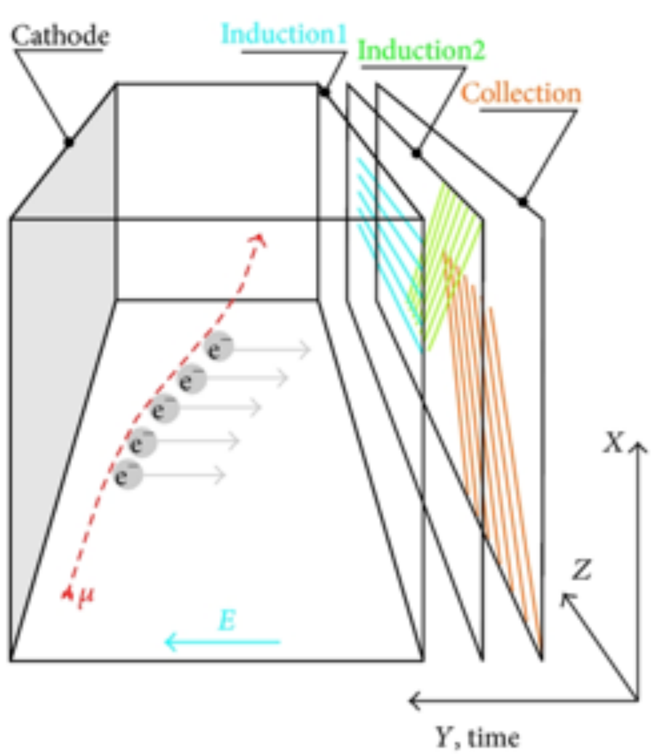


Liquid Argon TPC technology

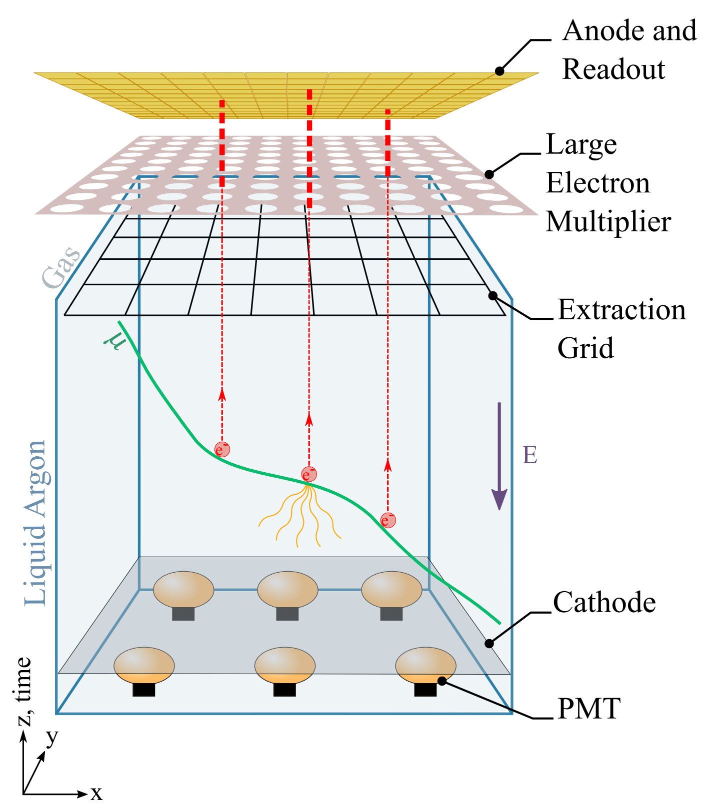
- Liquid Argon is inert, dense and naturally abundant.
- Strong electric field applied across the TPC to collect electrons produced by energy loss.
- LAr is transparent to its own scintillation light which can be used as an internal trigger and for complementary calorimetry measurement.

— Two LArTPC technology foreseen for DUNE —

Single Phase



Dual Phase



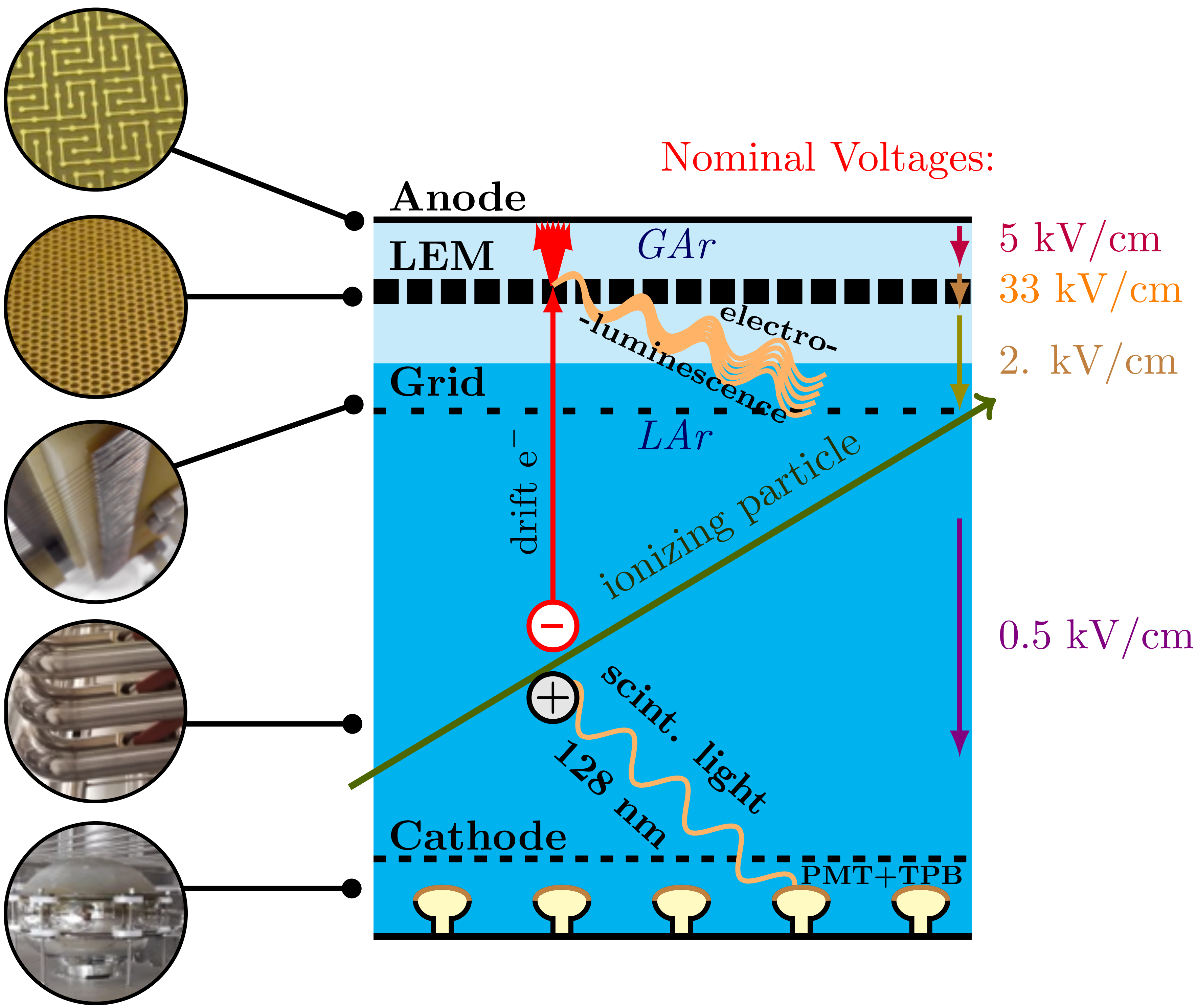
Advantages of the dual phase design :

- Charge amplification in gas
- Higher signal/noise
- Lower energy threshold
- Fewer readout channels with better resolution
- Accessible cold front end electronics

The feasibility of both technologies at large scale is being tested with prototypes.

The dual phase charge and light signals

From the energy deposited by a charged particle in LAr



— *Charge signal* —

Ionization electron are extracted to the gas, amplified in the LEM and induced to the collection plane on the anode.

— *Light signal* —

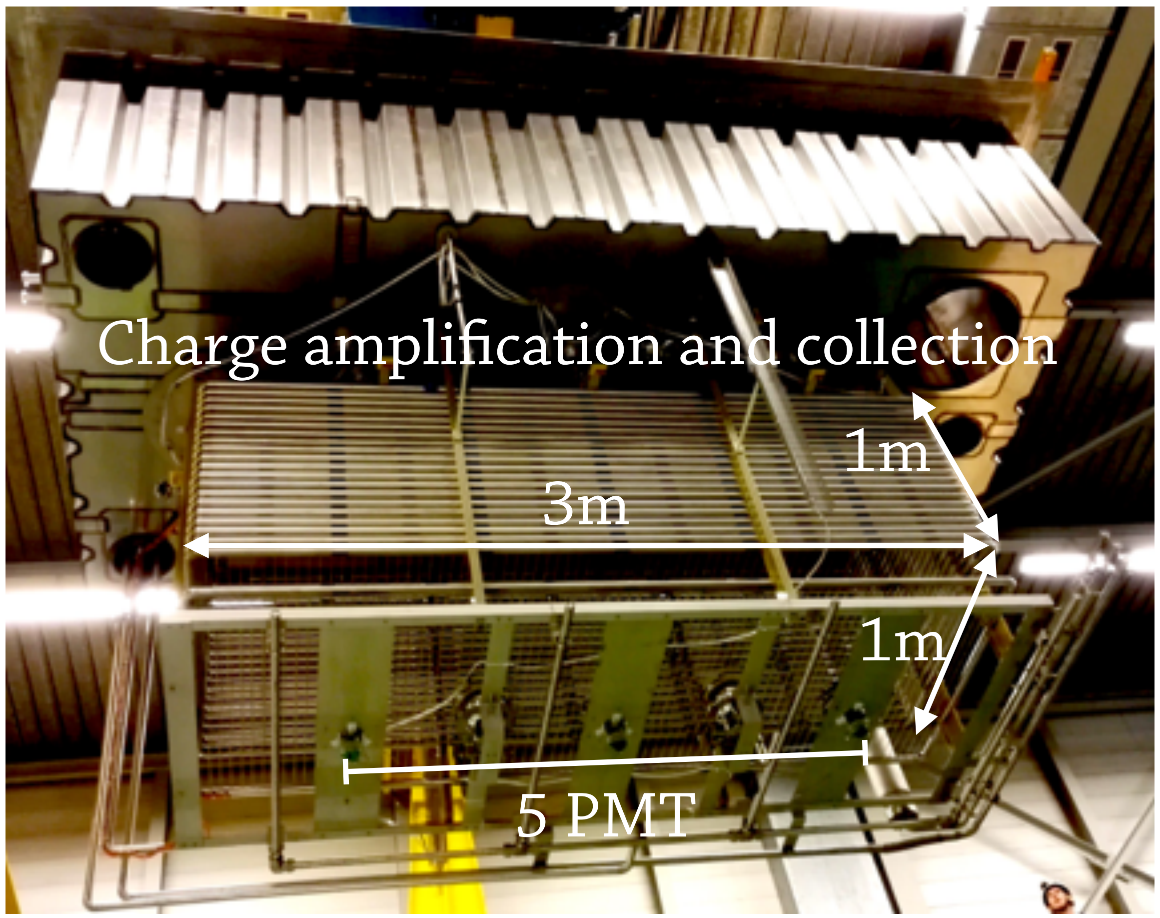
From scintillation in LAr [S1] and electro-luminescence in GAr [S2].

Time constants at 6 ns and 1.6 µs.

Produced in VUV range, has to be shifted to be detected by PMTs

The dual phase LArTPC demonstrator (3×1×1)

First large scale LArTPC-DP with 4.2 tons of active volume (3×1×1 m³) at CERN.
Construction started in 2015, and was operated in 2017 for 5 months recording cosmics.

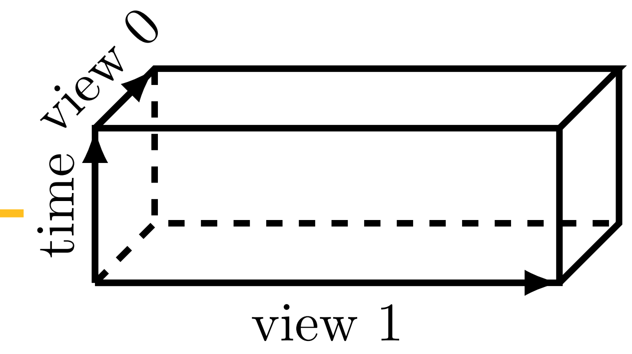


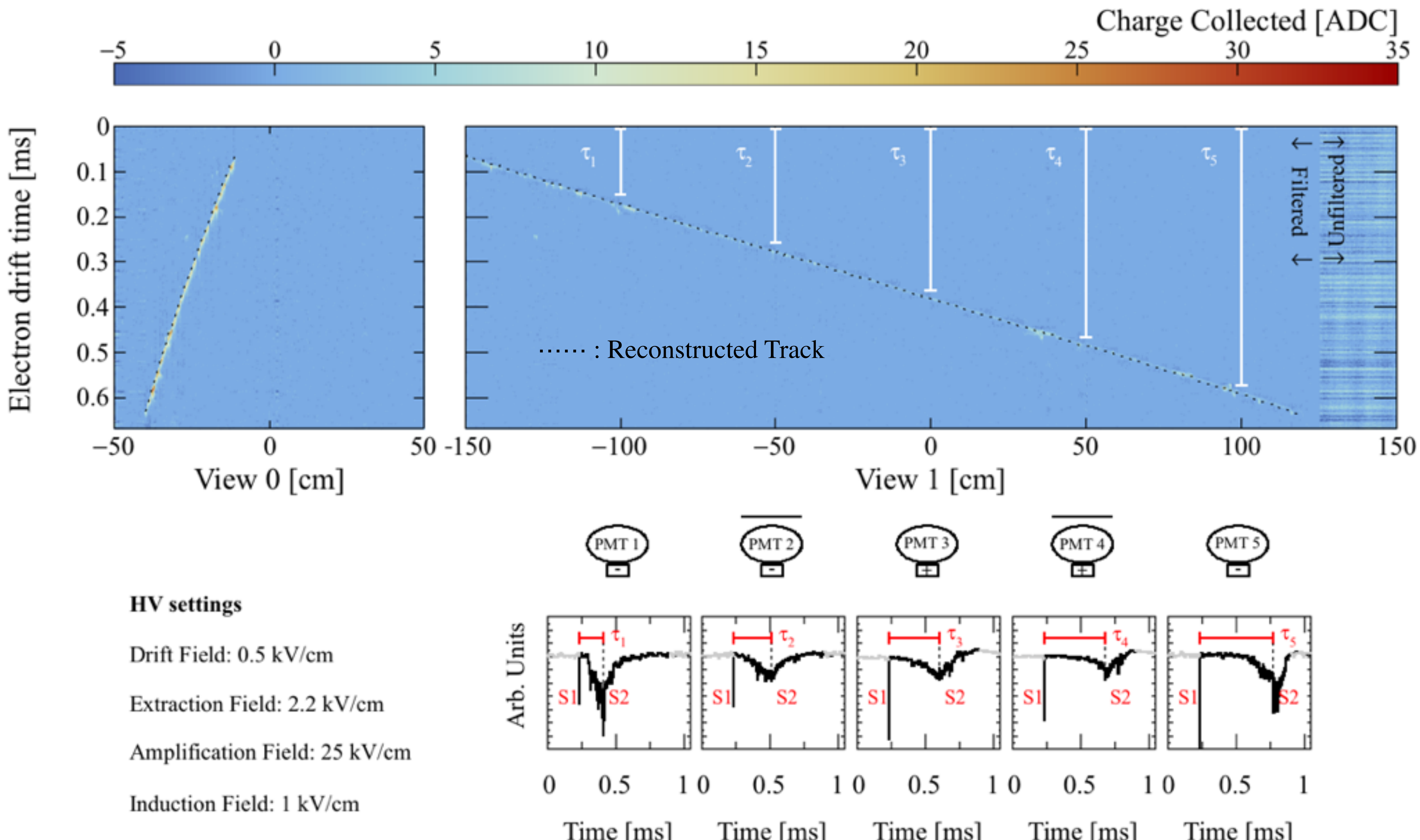
The demonstrator was mainly built for the validation technical aspects of the DP design:

- Construction and operation of stable cryogenic installation
- Liquid Argon purification system
- Charge extraction, amplification and collection on a 3 m^2 surface
- Stable operation of PMT in LAr

- More than 5×10^6 cosmic tracks recorded with the charge and light signal
- Two trigger settings tested : PMT-self trigger and external trigger with scintillator planes
- Many HV configurations tested (at drift, extraction, amplification and induction fields level)

Typical event recorded in 3×1×1





HV settings

Drift Field: 0.5 kV/cm

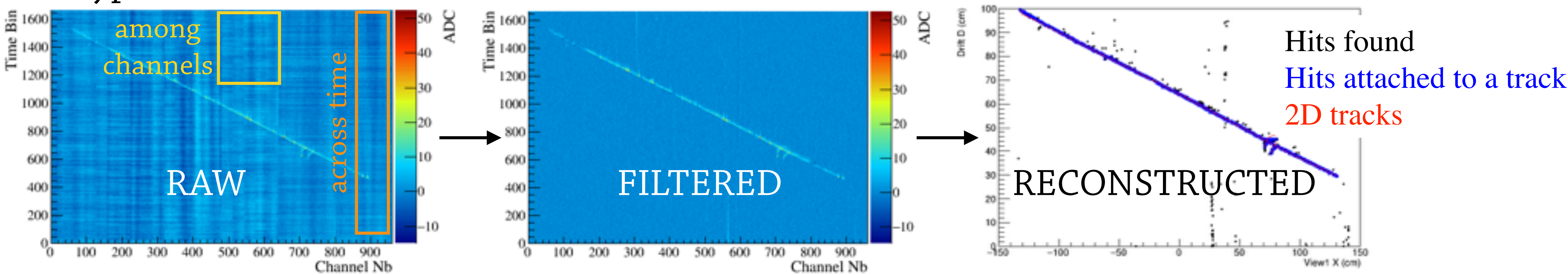
Extraction Field: 2.2 kV/cm

Amplification Field: 25 kV/cm

Induction Field: 1 kV/cm

Track selection and reconstruction in 3×1×1

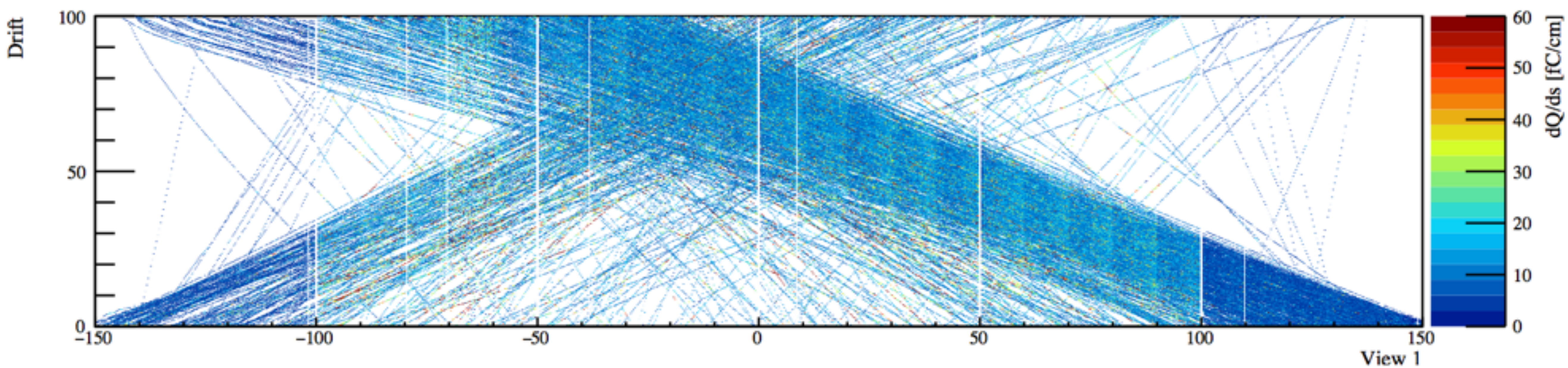
2 types of electric noise



Hits found by means of threshold.
2D track reconstructed using Kalman filter algorithm.
3D tracks built using timing informations.

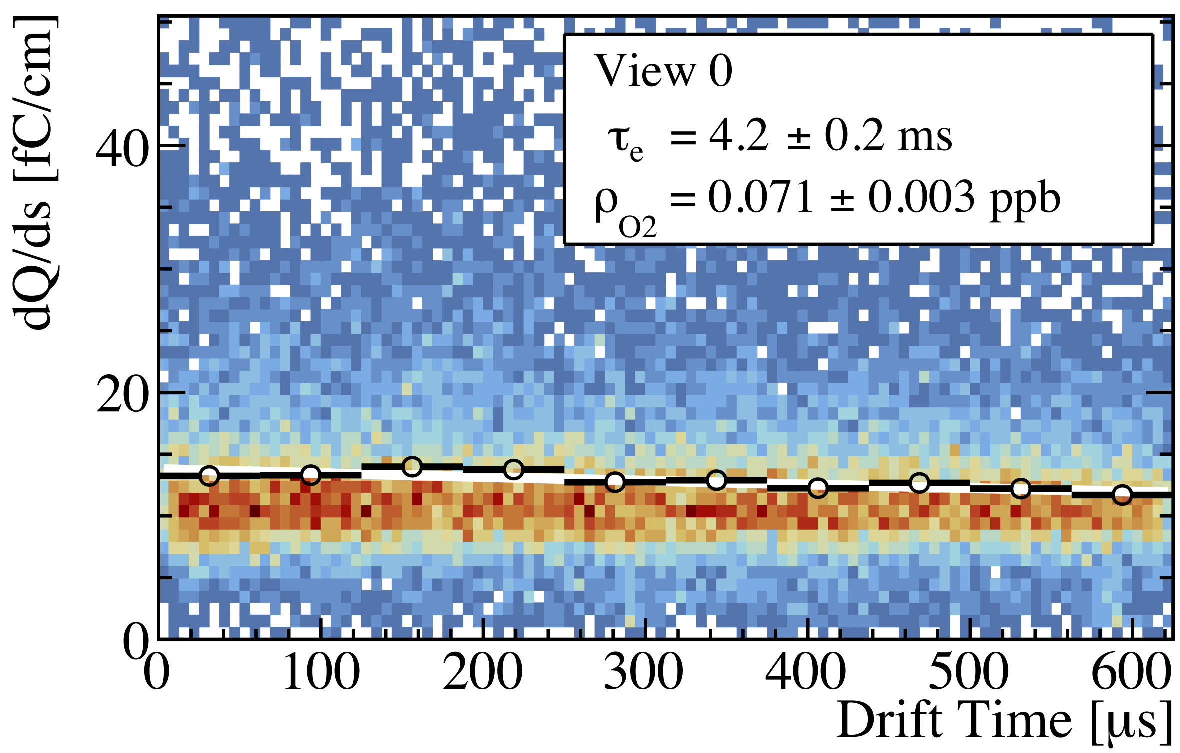
HV configuration :
Drift Field = 500 V/cm
Extraction Field ≥ 1.85 kV/cm
Amplification Field: 24-28 kV/cm
Induction Field = 1.5 kV/cm

All reconstructed through going tracks viewed from the long side

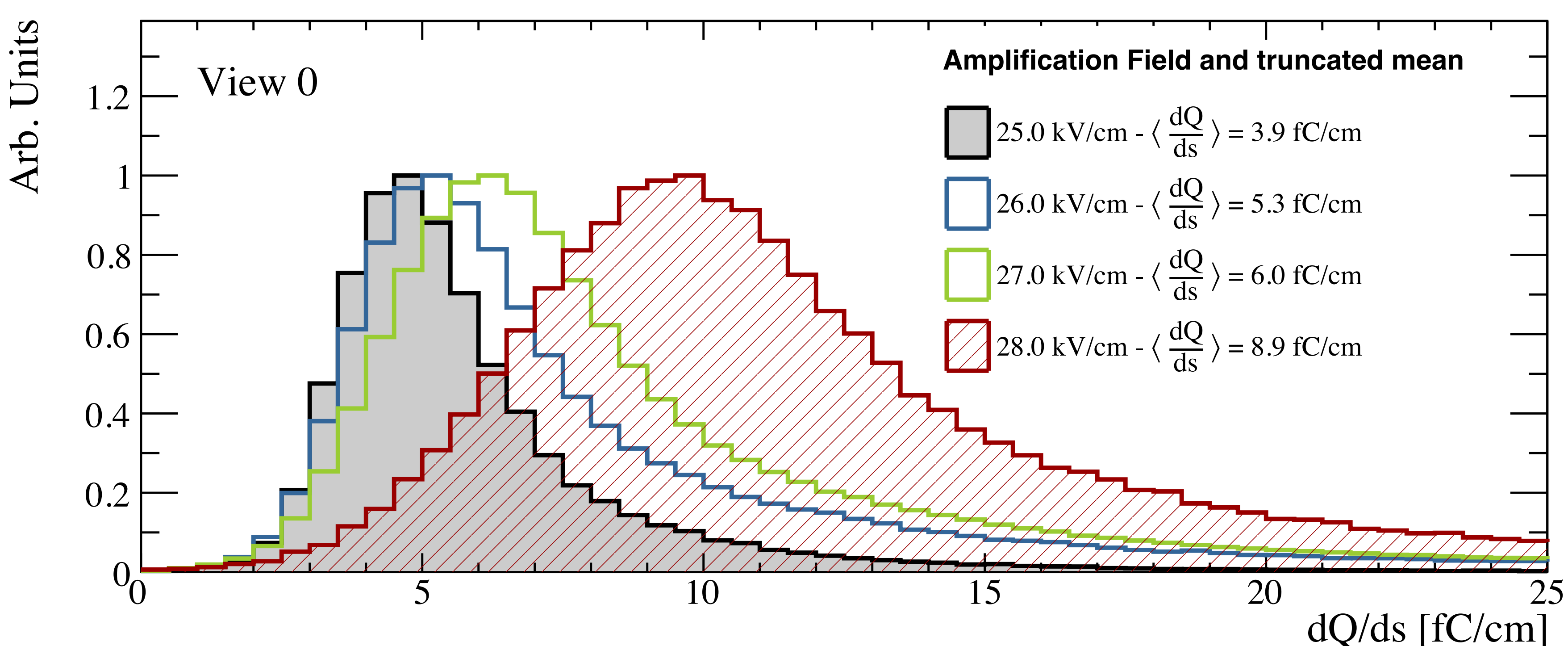


Preliminary 3×1×1 results using the charge signal

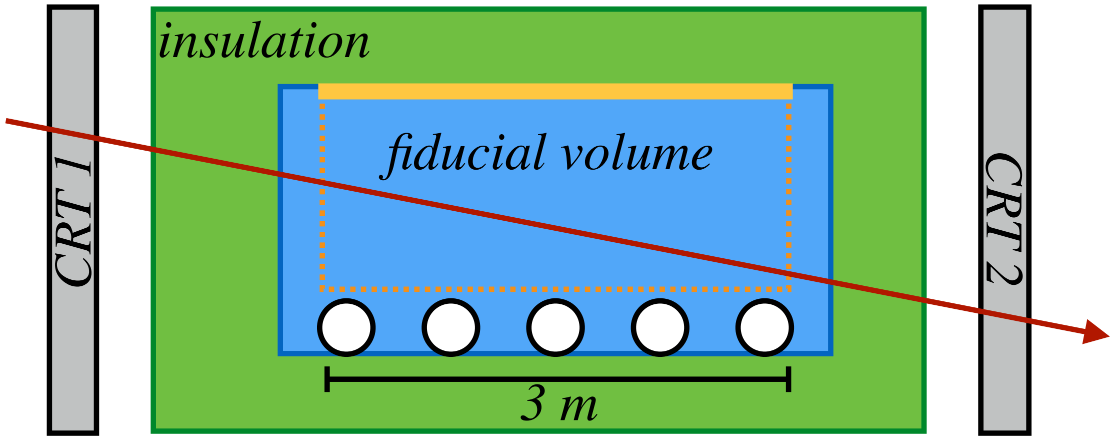
Measurement of the LAr purity through the electron lifetime



Effect of the LEM amplification



Scintillation light studies in the 3×1×1



For the study of the scintillation light, more than 32×10^6 events were recorded ; most of it with no drift field (<-> no charge signal).
The CRTs (Cosmic Ray Taggers) can provide track parameter informations.

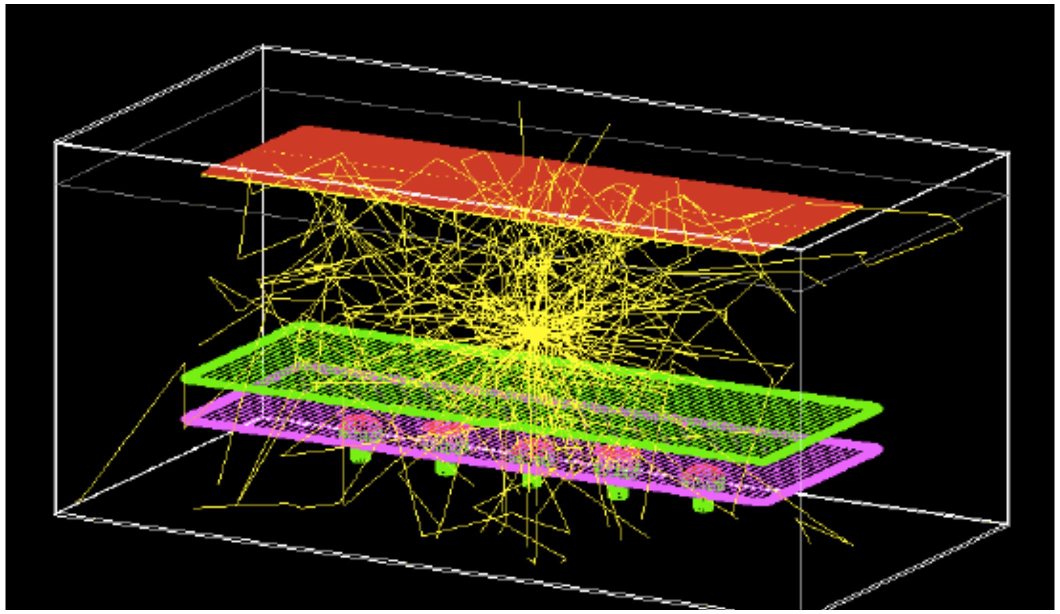
— Main light analysis ongoing —

Study of the light ***production*** :
- Amount of light produced through argon excitation and ionization processes
- Measurement of the time constants and evolution with electric fields
- Amount of S2 light produced with the effective gain

Study of the light ***propagation*** :
- Effect of the impurities on the light collected
- Measurement of the Rayleigh diffusion length
- Electron drift velocity

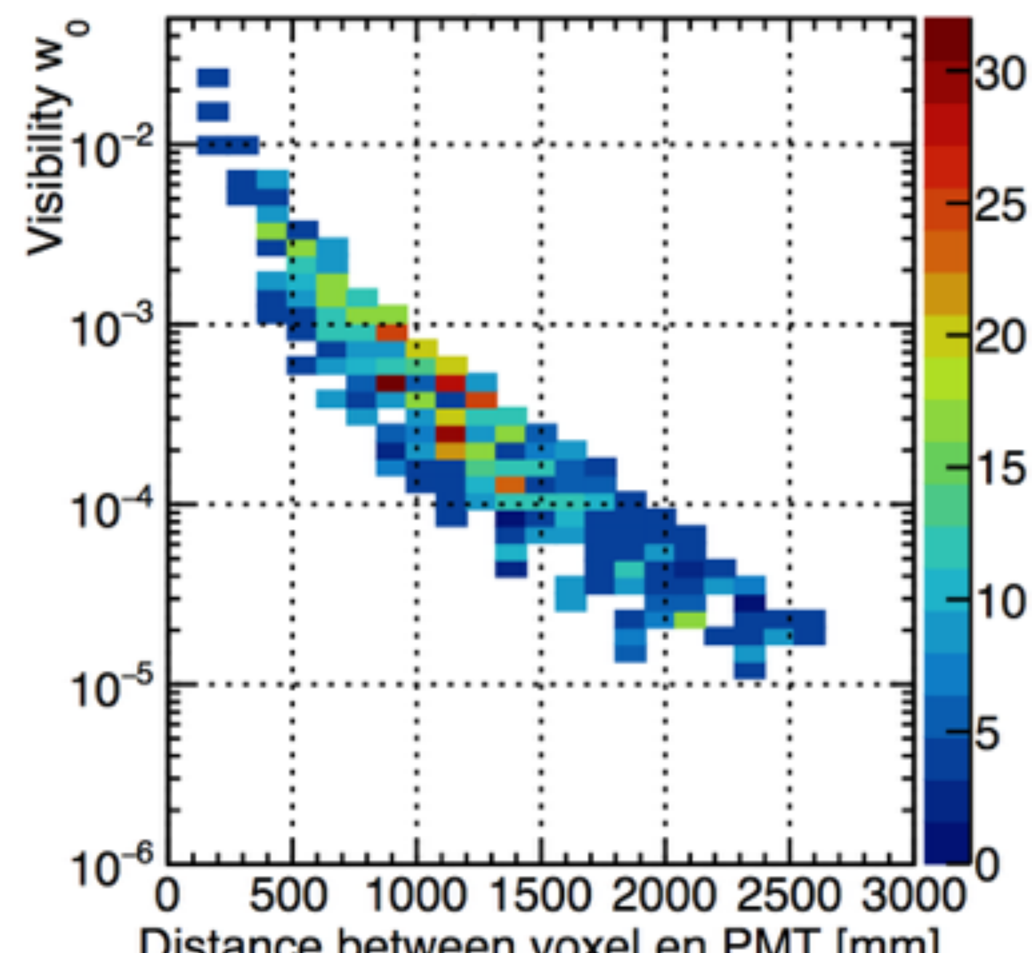
Charge and light ***combination*** :
- Track timing
- Event classification

Scintillation light simulation



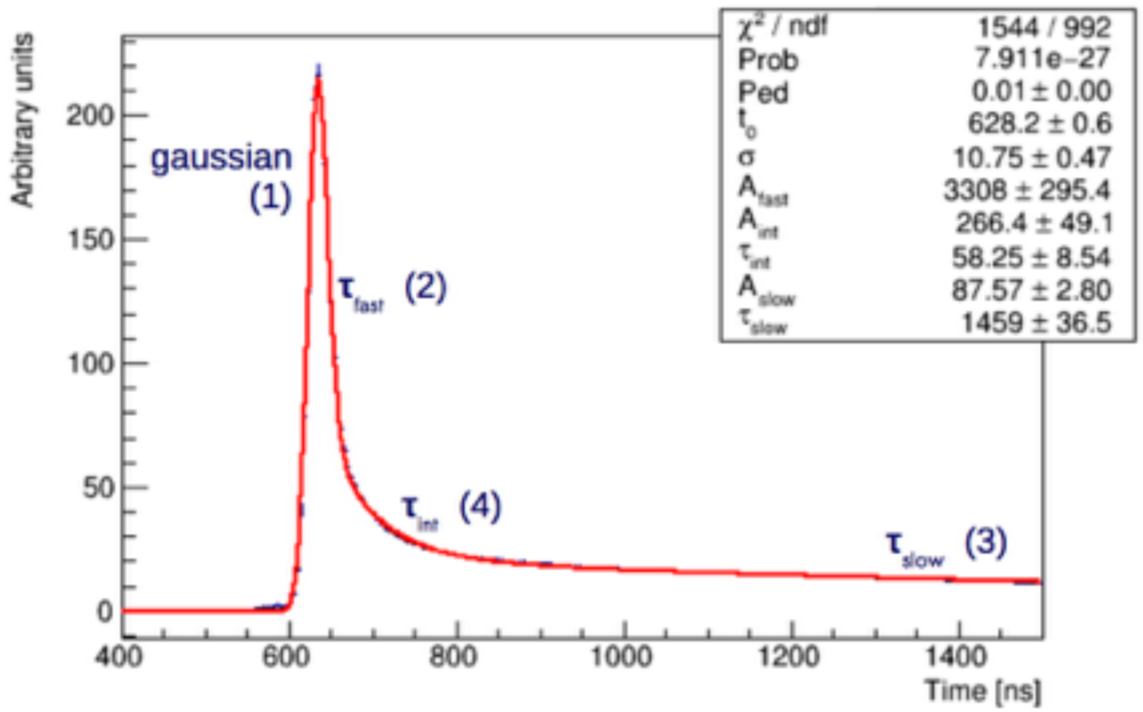
About 40 000 photons/MeV deposited are produced, but:
- the probability for a photon to be detected is low (<1%)
- the exact photon trajectory is not needed
- tracking all photons requires a lot of CPU

For the simulations, we have developed ***light maps:***
- In a detailed Geant4 dedicated geometry, the fiducial volume is divided into 3D voxels.
- In each voxel, 10^8 photons are generated and propagated to the PMTs.
- For each voxel-PMT pair, we store the photons visibility (w_0 = Ncoll/Ngen) and parametrize the time distributions



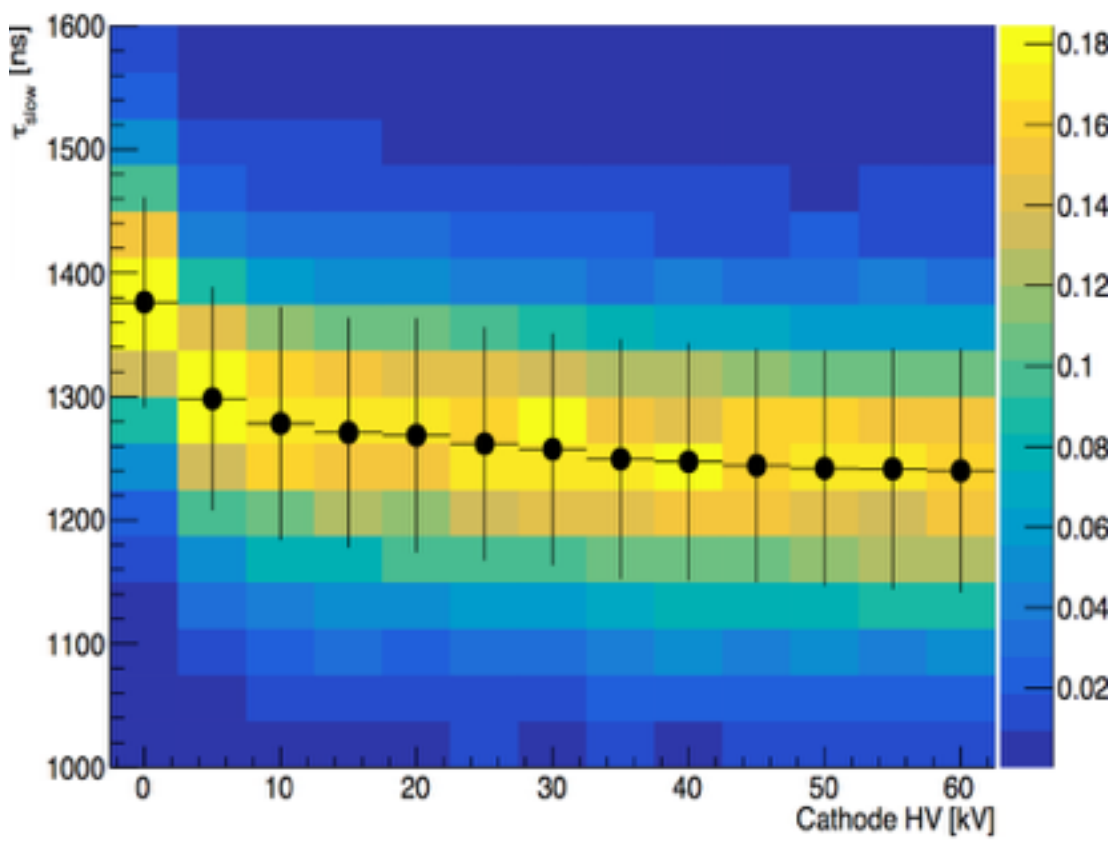
▹ *In the detector simulation, we generate the scintillation signal from the interpolation of the light maps parameters*

Preliminary 3×1×1 results - S1 light production



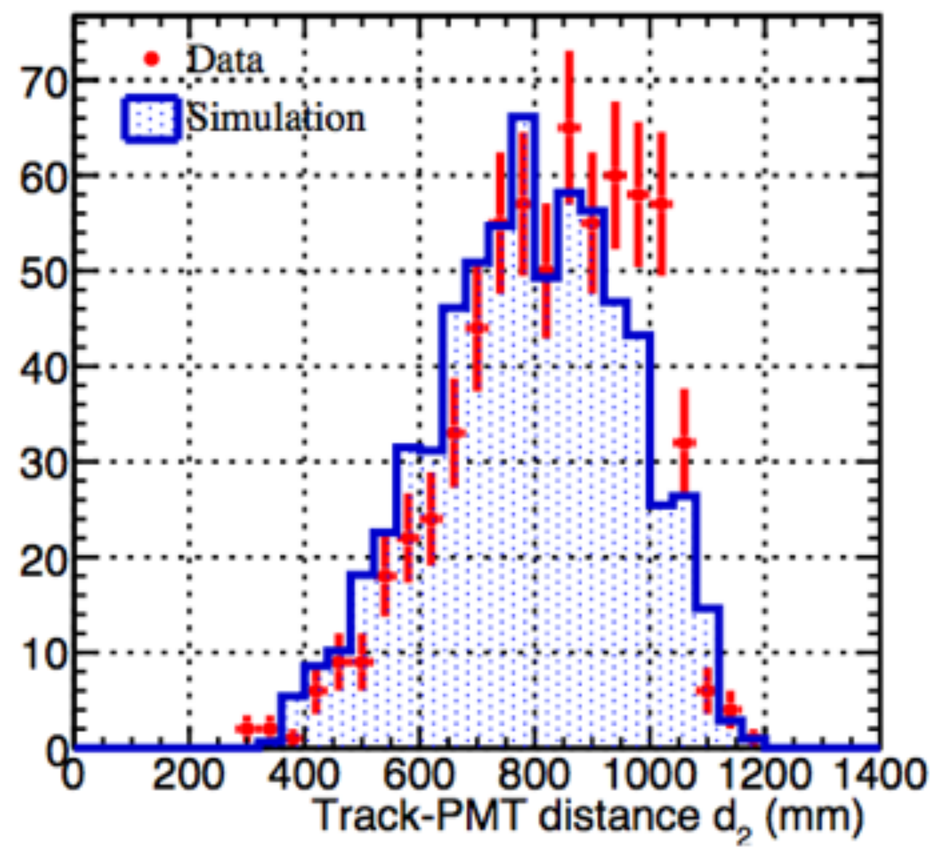
Average light waveforms are fitted with 3 exponentials convoluted with a gaussian.

- The fast component is fixed to 6 ns (data has a 4 ns resolution)
- The slow component is compatible with the literature and the amount of impurities in LAr
- The intermediate component has an unknown origin, our extracted value agrees with other observations in LArTPC



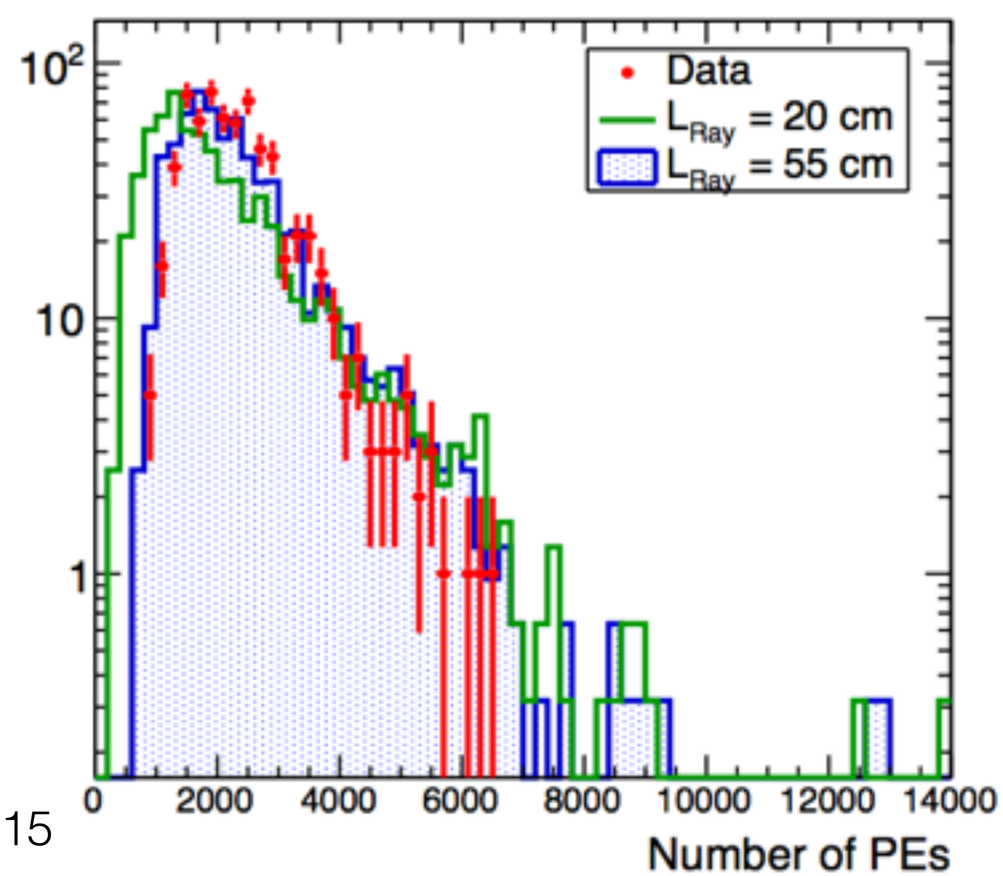
We observe a reduction of the slow component with increasing drift field. For this study, all data was collected a few minutes apart.
This effect has been observed in Liquid Xenon TPC, but not yet extensively studied in LAr (to our knowledge)

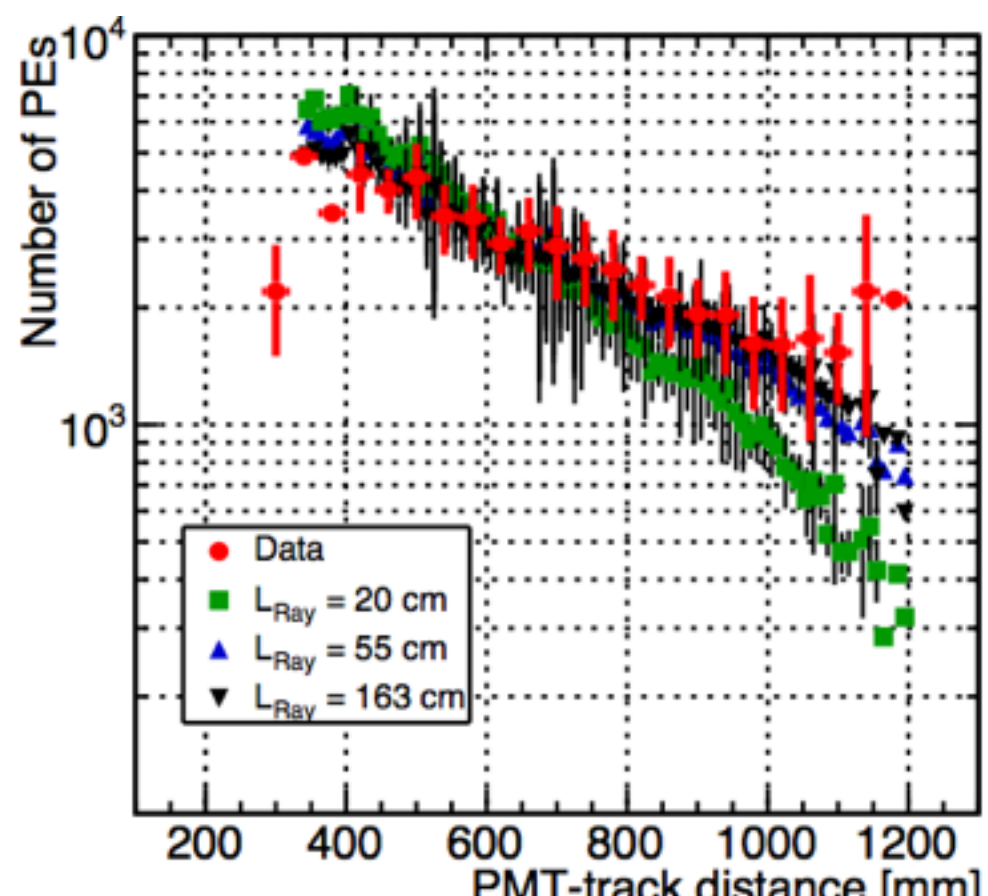
Preliminary 3×1×1 results - S1 light propagation



Generating simulation of similar events as what we have recorded in data, for different assumptions of the Rayleigh diffusion length.
Data/MC comparisons of track to PMT distances are similar, as well as the amount of charge collected per PMT.

The preliminary result highlight a better data/MC agreement for large Rayleigh scattering values.

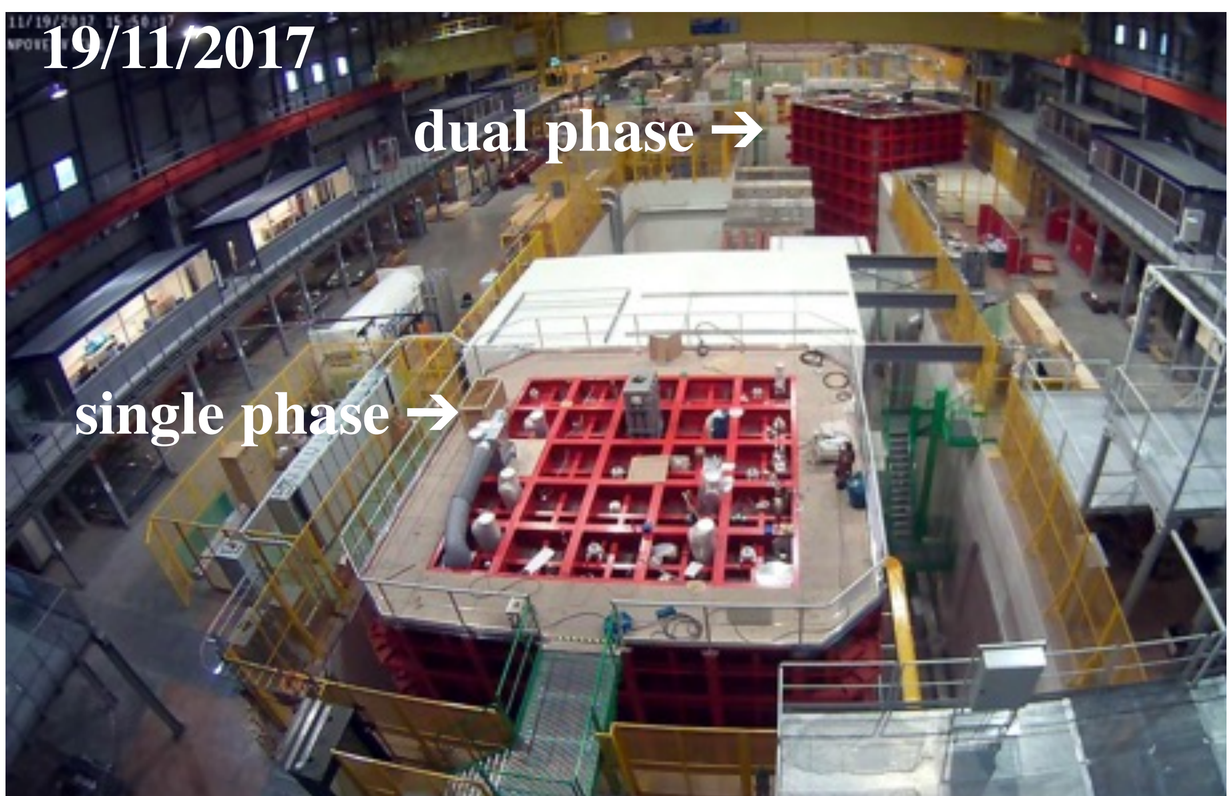


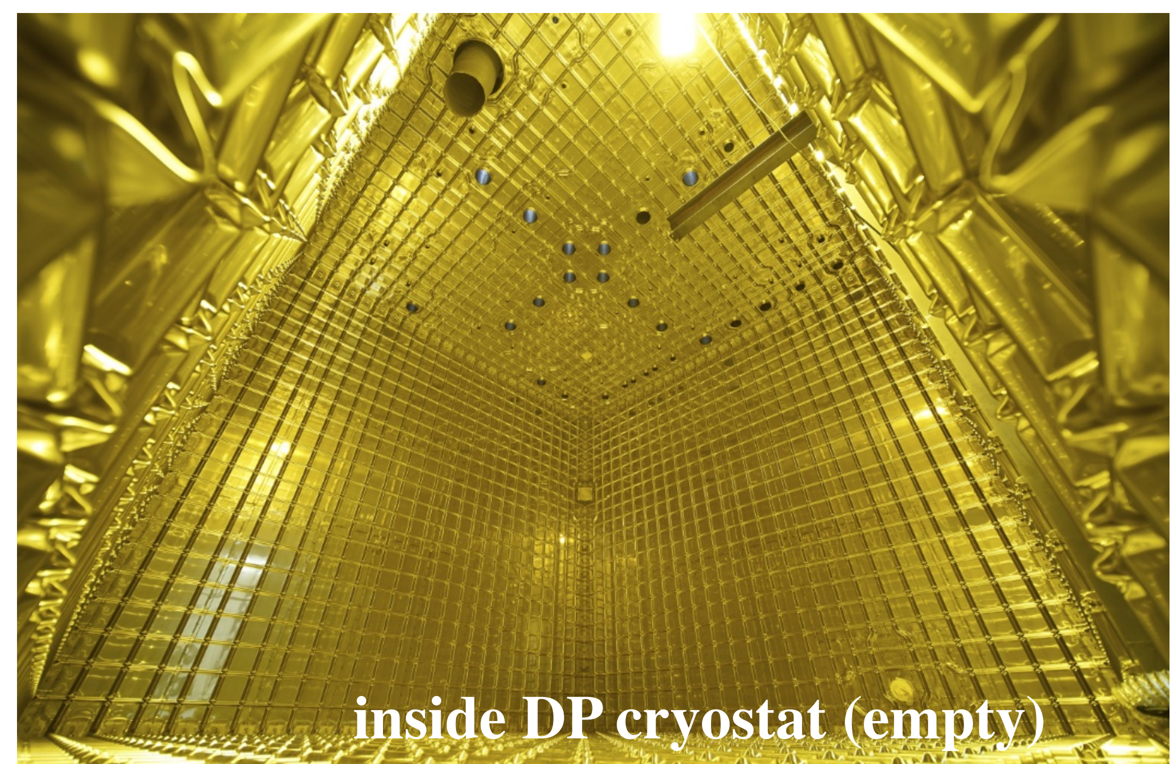


Beyond the 3×1×1 demonstrator

- A technical paper on the 3×1×1 demonstrator has been published:
"A 4 tonne demonstrator for large-scale dual-phase liquid argon time projection chambers"
B. Aimard *et al,* JINST13 P11003 (2018), arXiv: 1806.03317
- Two analysis papers (charge, light) are in preparation, publication foreseen in 2019

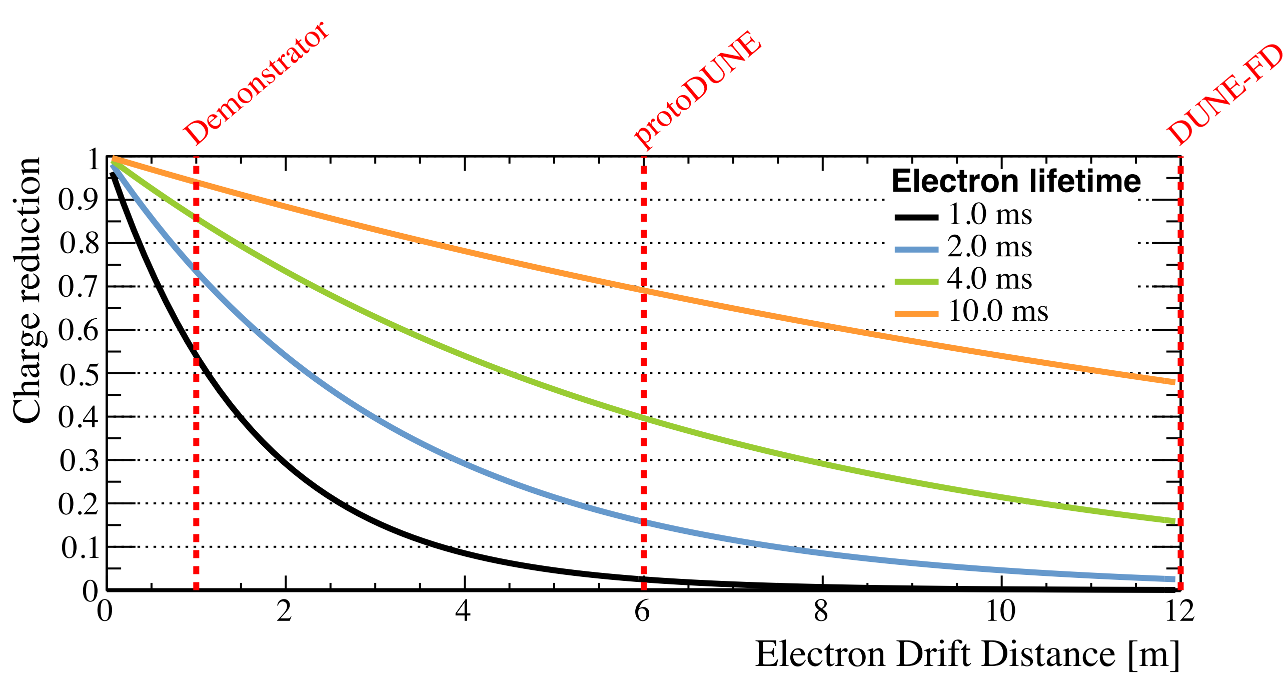
The dual phase community is now preparing for the next stage : the construction and operation of the DUNE prototype of 6×6×6 m^3 at CERN



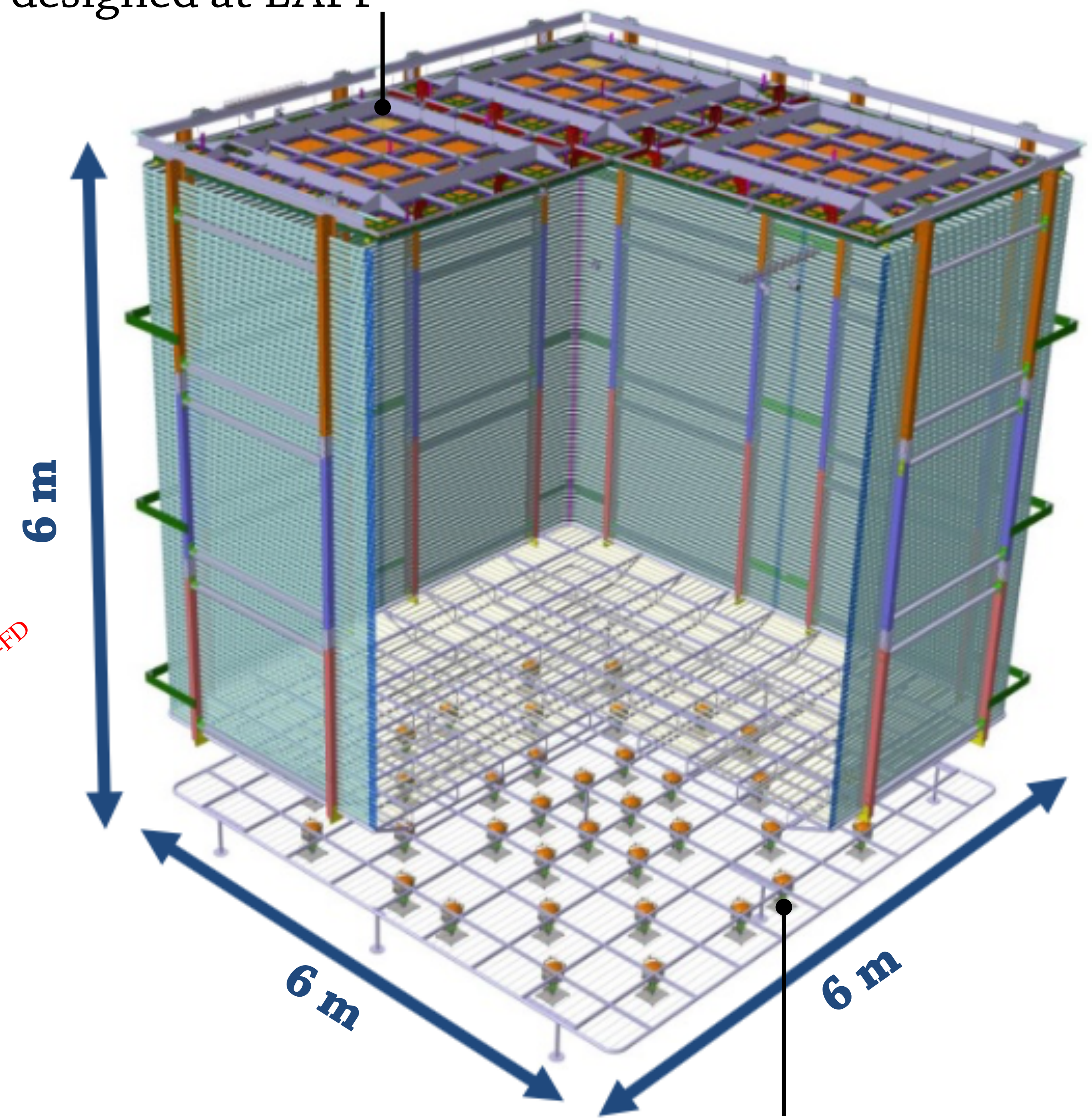


protoDUNE-DP

- Collection area of 36 m^2
  - ▹ 1920×1920 channels
- Maximum drift length of 6 m
  - ▹ max drift time of 3.7 μs
  - ▹ V_{cath} = 300 kV
- 36 PMTs
- Electron lifetime goal at 7 ms (corresponding to 40 ppb of impurities)



Charge readout plane structure and support designed at LAPP



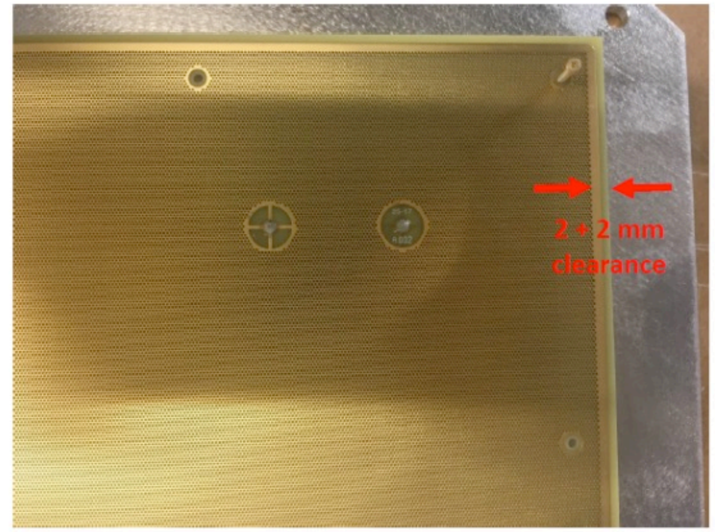
PMT Layout optimized using light simulations

Anne Chappuis' PhD (19/10/18)

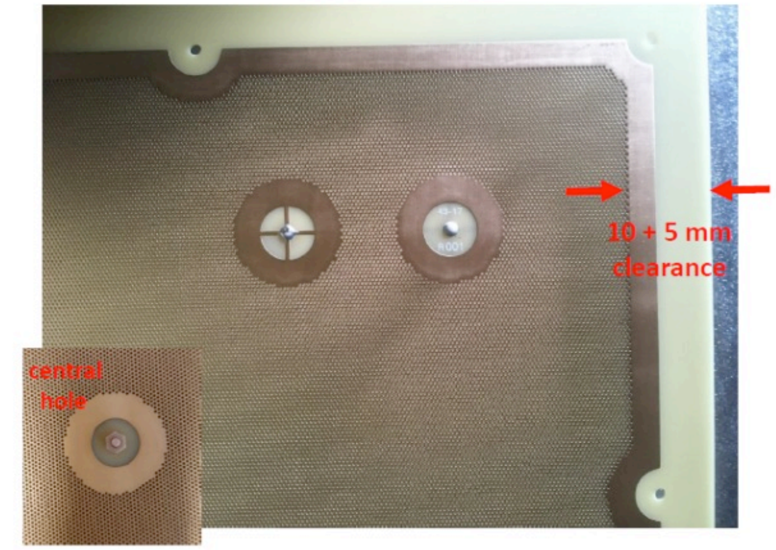
Design upgrade and status of the construction

From the operation of the demonstrator, the design of the LEMs was improved with a wider guard ring on the edges.
The new design allows a larger gain and stability (tested in a small vessel at CEA Saclay)

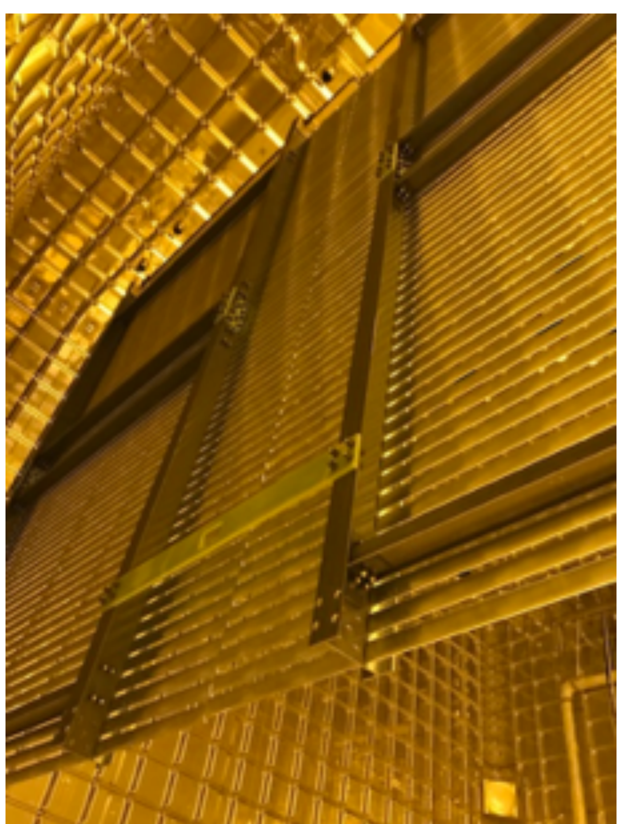
Current



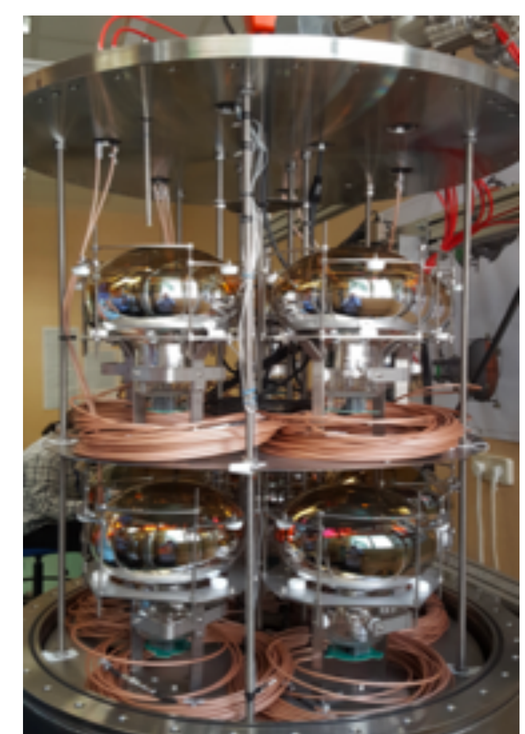
Modified



The field cage is fully mounted

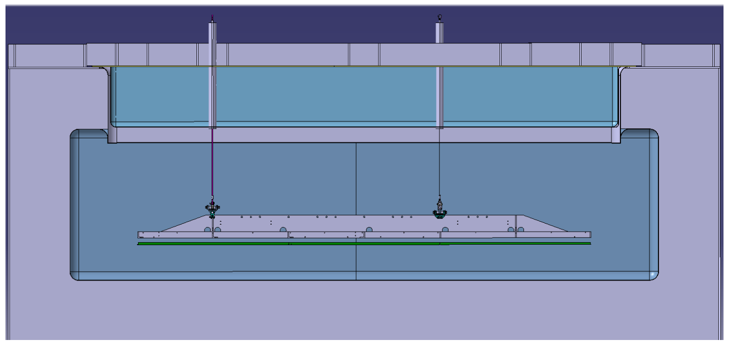


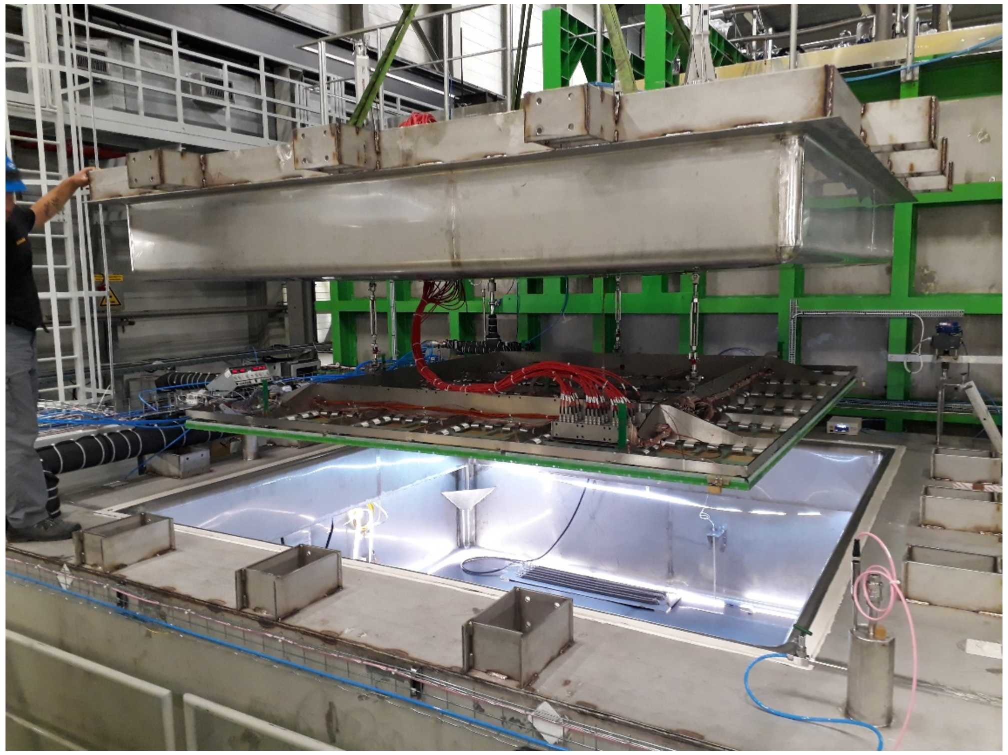
The 36 PMTs has been TPB coated and calibrated. The positive based (single cable) design has been chosen



Cold box tests

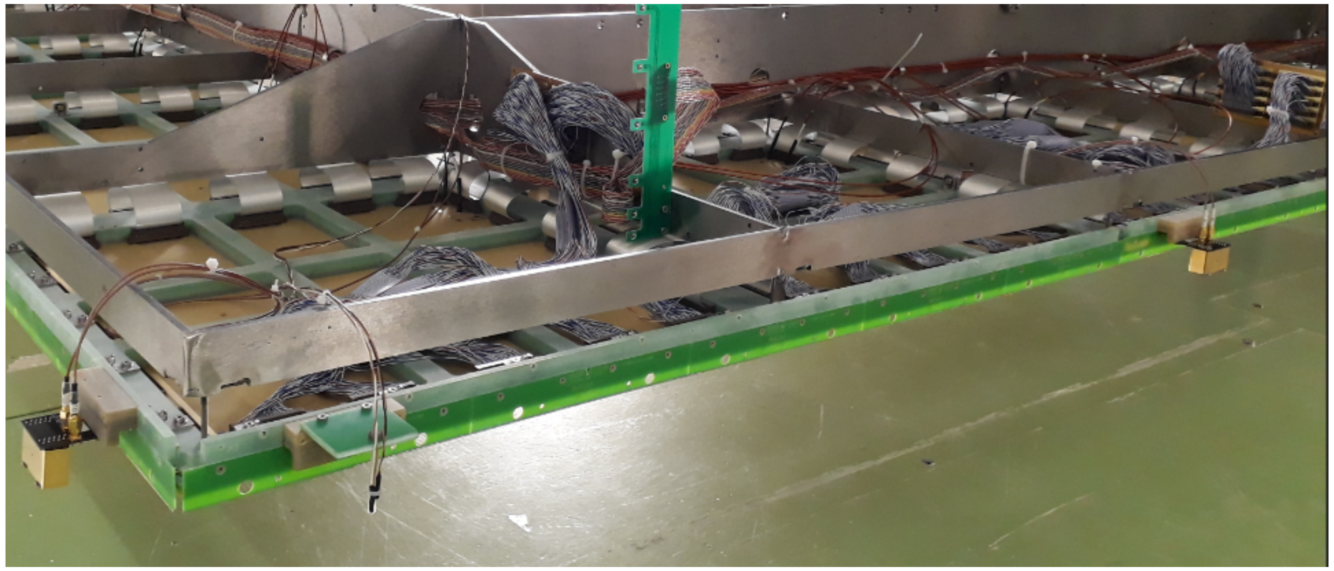
Each CRP modules (of 3×3 m^2) is extensively tested in LAr in a dedicated cold box system





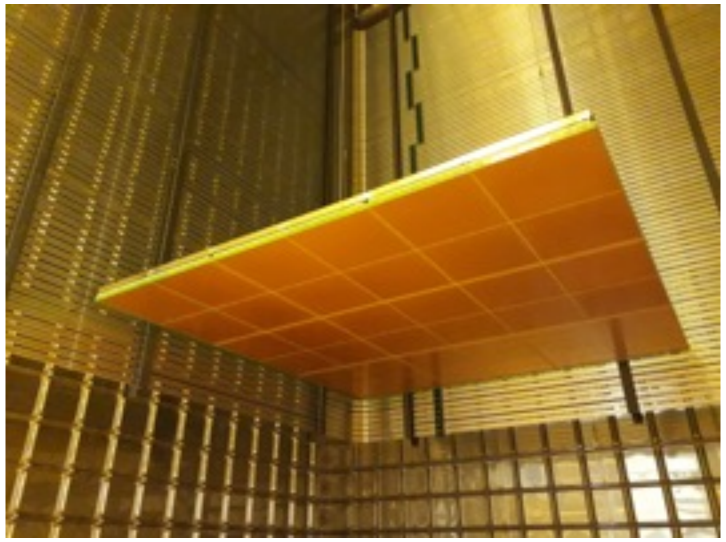
The grid, LEM and anode panels are immersed and powered in LAr. The setup allows to study:

- The electronic connections
- The capacity of the system to sustain high voltages over a long period of time in cryogenic temperatures
- Study the mechanical behavior of the frame
- Calibrate the level meter monitors in real conditions

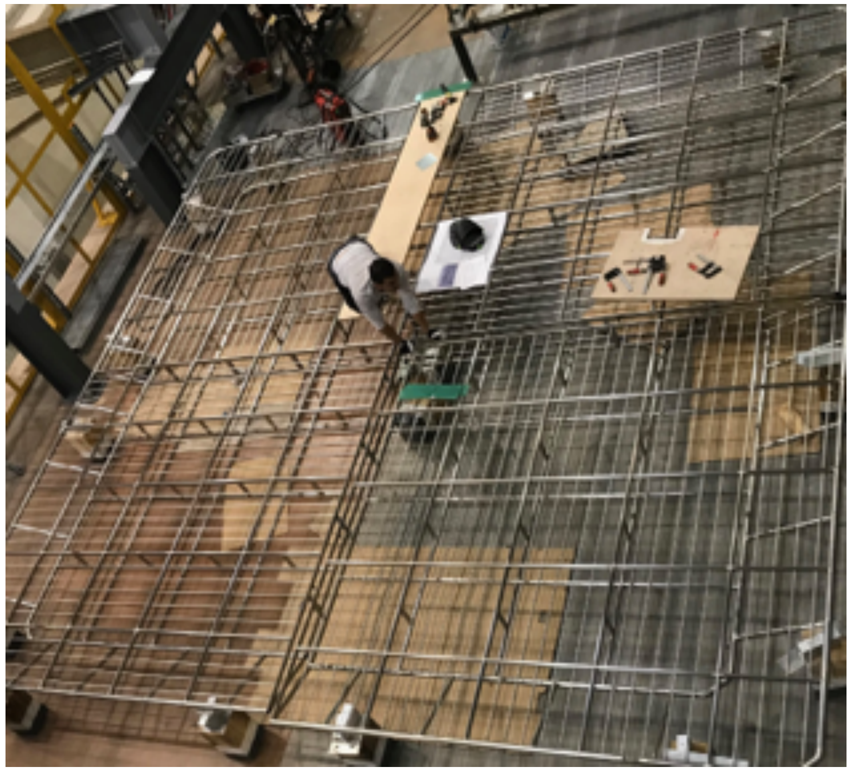


protoDUNE-DP schedule for the next months

Up to end of 2018 : CRP of cold box test
January 2019 :Installation of the CRP in the cryostat



Cathode modules assembly



February : Cathode, ground grid and PMT installation

March :
TCO closing

DP Cryogenic system

April - June : Cryostat purge and LAr filling

June - July : Detector commissioning

Conclusions and Perspectives

- 1^{st} protoDUNE-DP PhD thesis defended in October 2018
- Dual phase demonstrator LArTPC (3×1×1) constructed and operated
  - Technical paper published
  - Data analysis ongoing
- Construction of the dual phase DUNE prototype (NP02) ongoing at CERN
  - First data expected for mid 2019
- DUNE Far Detector design optimization in progress
  - DUNE Interim Design Report released in 2018
  - DUNE Technical Design Report to be written in 2019