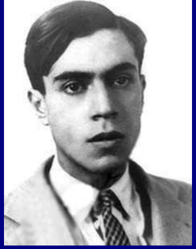
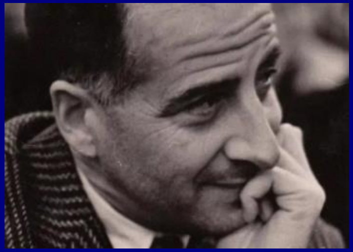
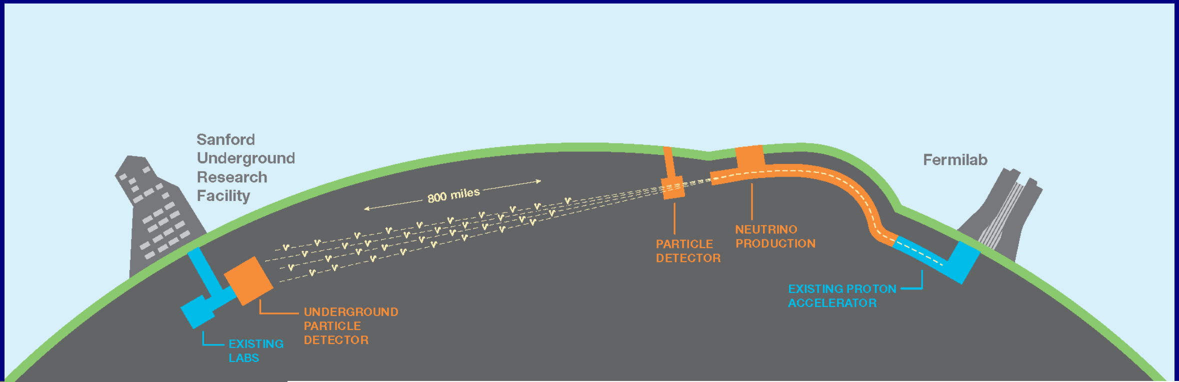
Neutrino Physics and the DUNE Experiment

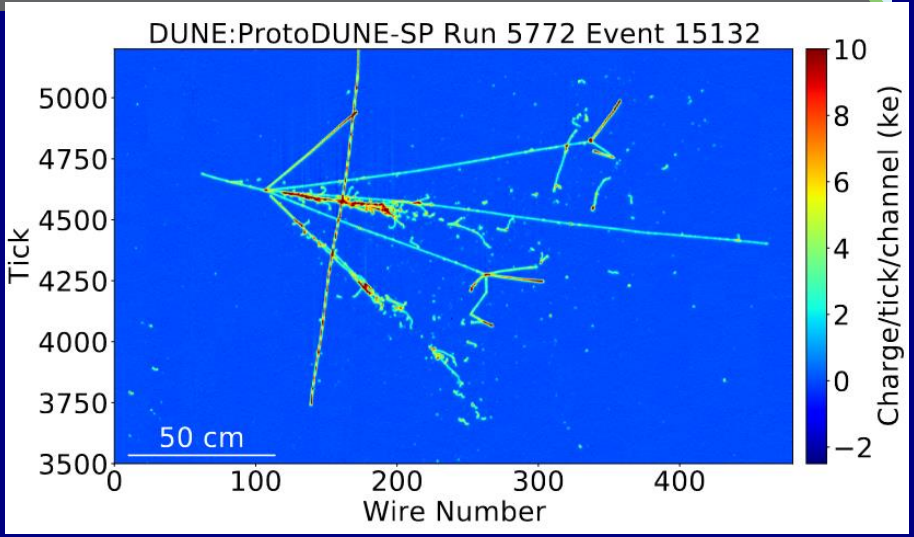

W. Pauli


E. Fermi


E. Majorana


B. Pontecorvo





30/10/2023

D. Autiero (IP2I)

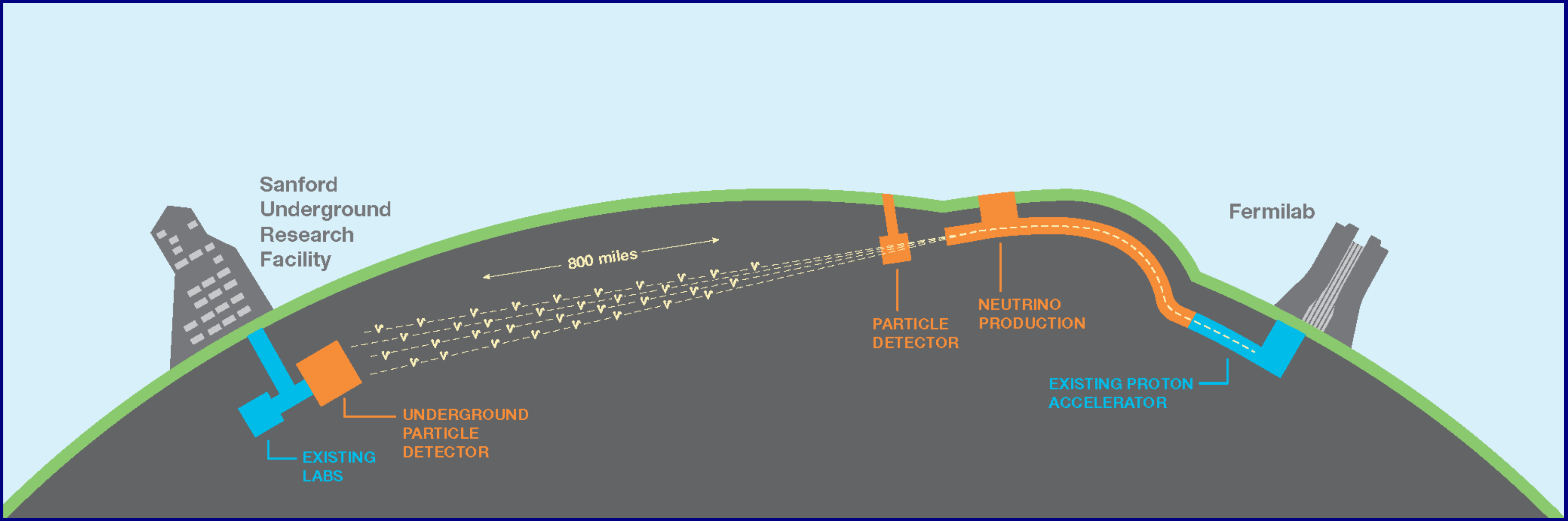
Journées des deux infinis

30-31/10/2023

Lectures:

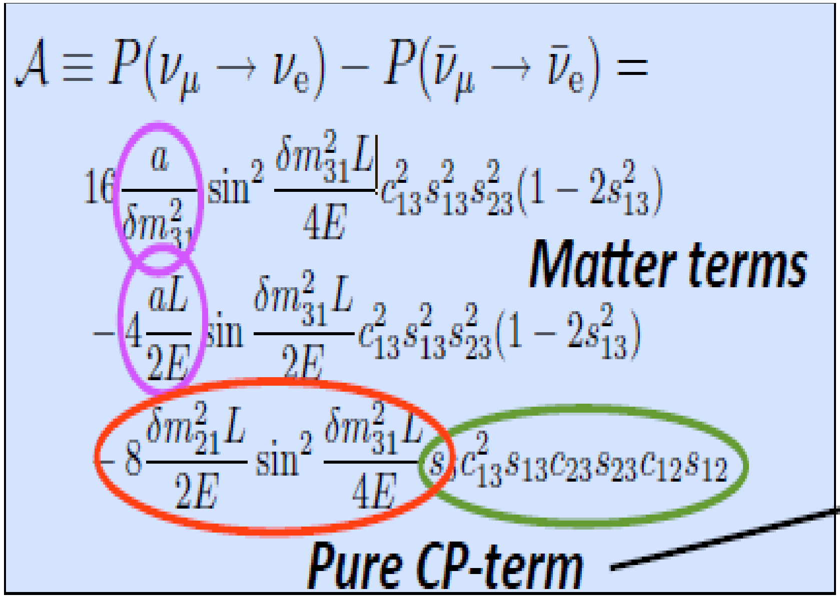
30/10 Lecture 1: Introduction to neutrino physics and neutrino oscillation searches

31/10 Lecture 2: The Deep Underground Neutrino Experiment (DUNE) at LBNF (Long Baseline Neutrino Facility)



CP asymmetry as a function of L/E

CP violation can be measured by comparing ν and anti-ν oscillation probabilities in an asymmetry variable



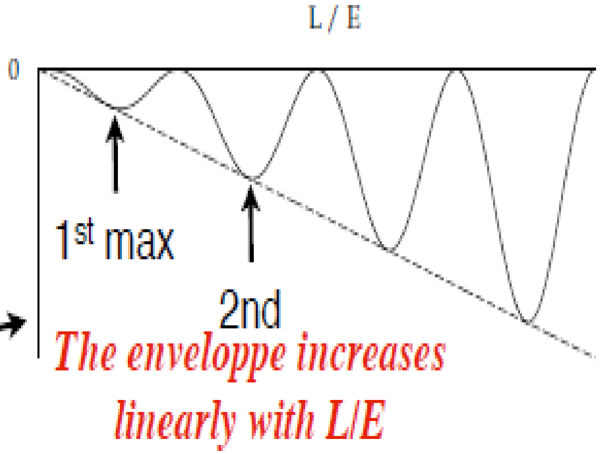
$$A \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

$$16\frac{a}{\delta m^2_{31}}\sin^2\frac{\delta m^2_{31}L}{4E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

$$-4\frac{aL}{2E}\sin\frac{\delta m^2_{31}L}{2E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

$$-8\frac{\delta m^2_{21}L}{2E}\sin^2\frac{\delta m^2_{31}L}{4E}s_\delta c^2_{13}s_{13}c_{23}s_{23}c_{12}s_{12}$$

$$\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2s_\delta c_{12}s_{12}}{s_{13}}\cot\theta_{23}\frac{\delta m^2_{21}L}{2E}$$



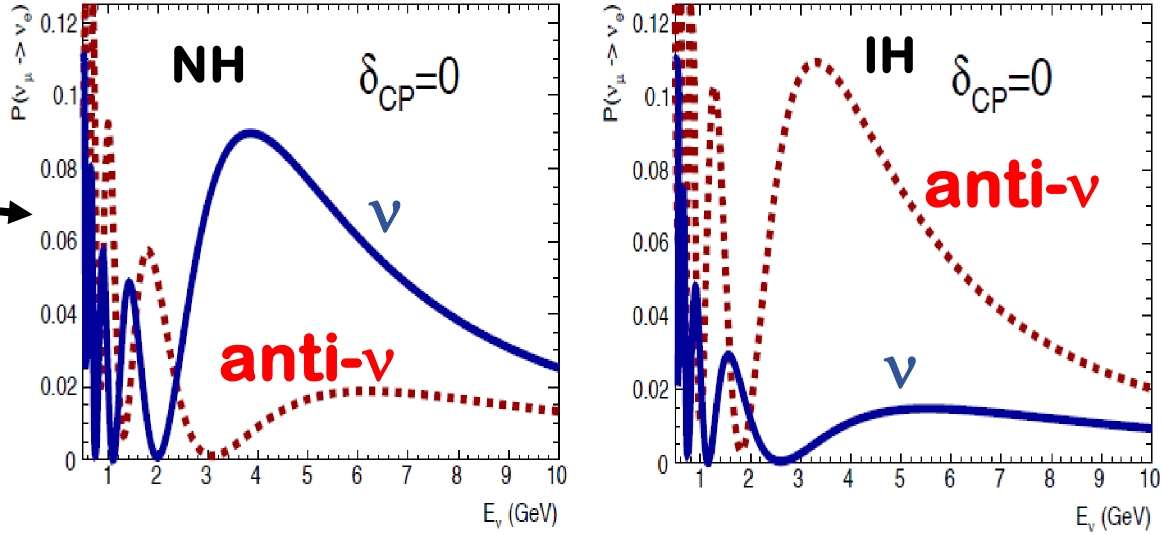
The envelope increases linearly with L/E

The amplitude of the pure CP term increases with L/E → this effect is stronger at the second oscillation maximum.

Measurements at the second oscillation maximum are very important and possible only with a detector with very good energy resolution

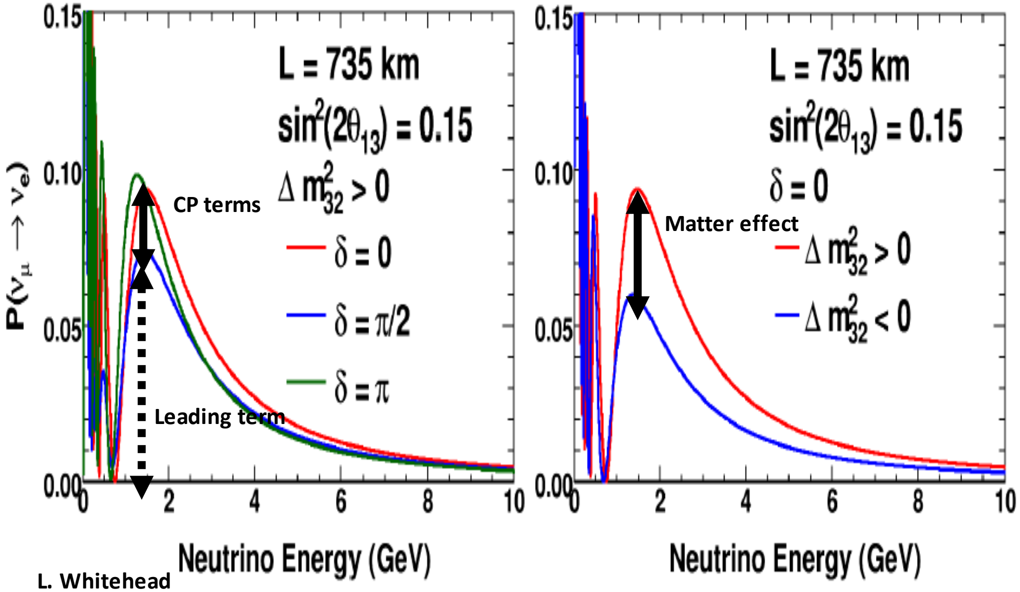
Matter effects and CP violation effects degeneracy

Matter effects on the oscillation probability at L = 2300 km for ν and anti-ν in the case of Normal (NH) or Inverted (IH) hierarchy



Since CP violation is also measured by comparing ν and anti-ν oscillation probabilities matter effects mimic CP violation if the mass hierarchy is not known

- **It is needed to accurately measure and subtract the matter effects in order to look for CP**
- **Matter effects dominate around the first maximum**



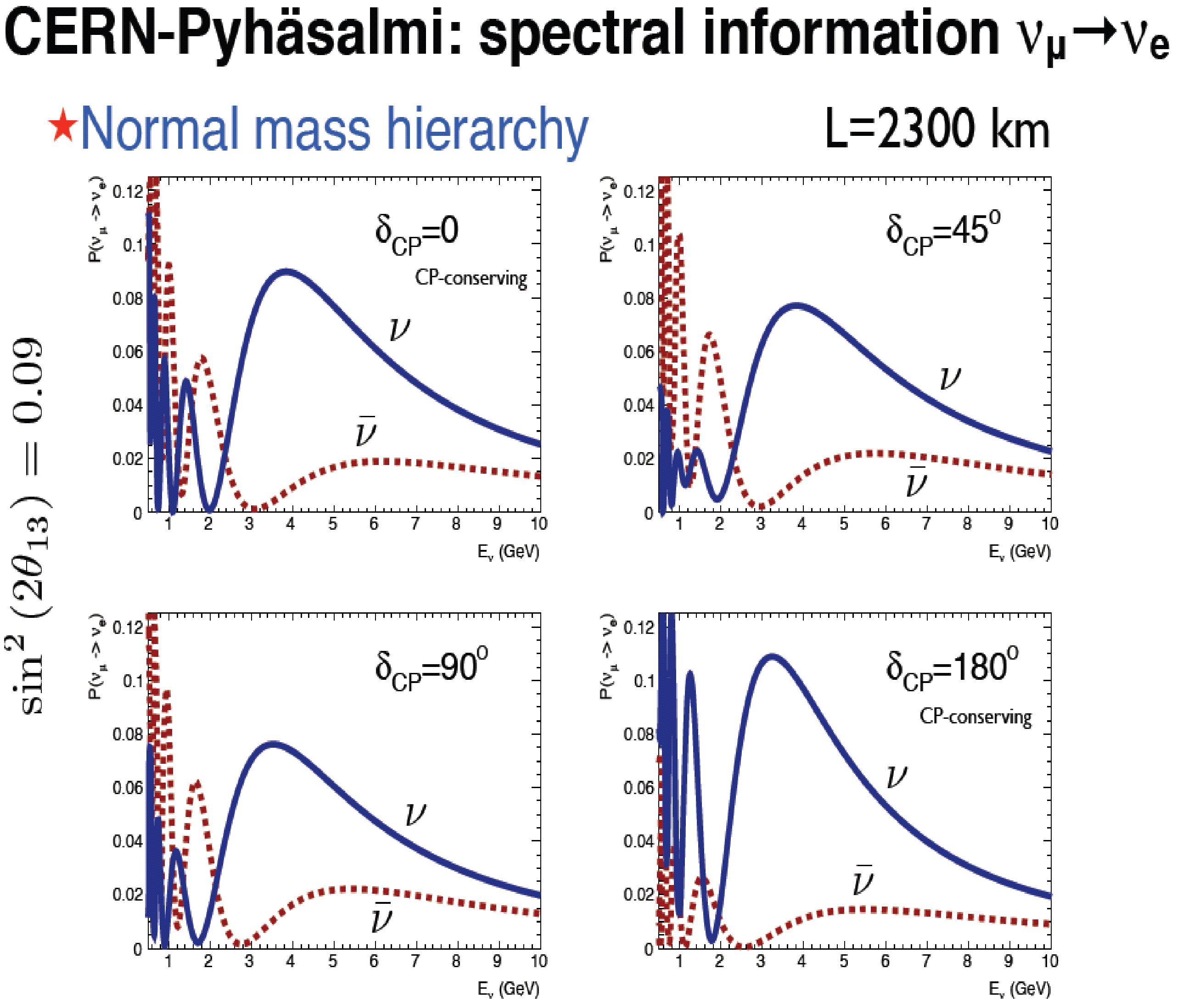
L. Whitehead

Effects on oscillation probabilities as a function of δ CP

Once the mass hierarchy is determined, it is possible to study the CP-violation and determine the value of δ by measuring the ν and anti-ν oscillation probabilities

A lot of information is contained in the shape around the first and second maximum

→Direct measurement of the energy dependence (L/E behavior) induced by matter effects and CP-phase terms, independently for ν and anti-ν, by measurement of events energy spectrum



CERN-Pyhäsalmi: spectral information $\nu_\mu \rightarrow \nu_e$

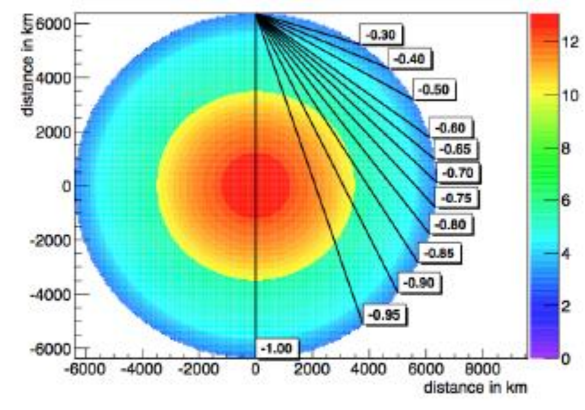
★Normal mass hierarchy L=2300 km

Addressing mass hierarchy with non-accelerator experiments:

Matter effects in atmospheric neutrinos:

Study upward going neutrino flux in bins of energy and cos(θ)

→ Different patterns at low energy

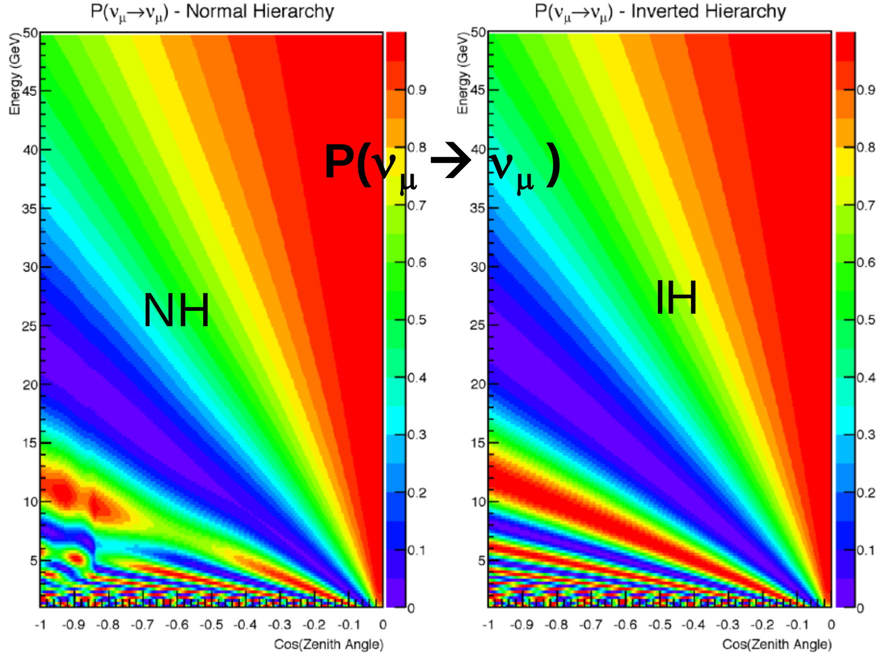


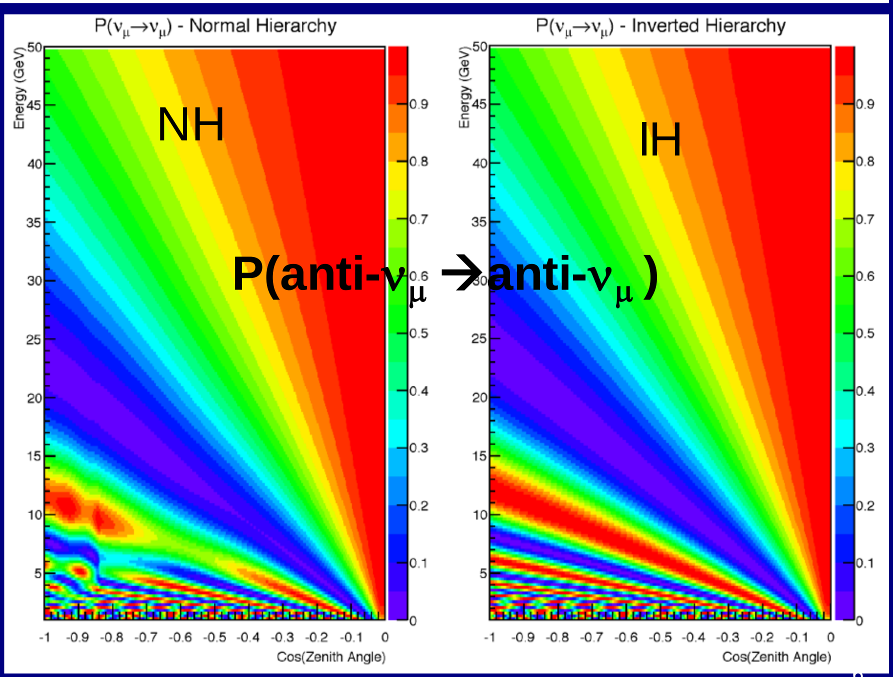
Oscillations probabilities for NH and IH are similar for neutrinos and antineutrinos → if the charge of the muons is not measured the effect is diluted

However there are differences in fluxes and cross sections for neutrinos and antineutrinos and a few % effects can be still measured

Adaptation of the high energy neutrino observatories Icecube and Antares at low energy → Pingu, Orca, higher density of photomultiplier strings

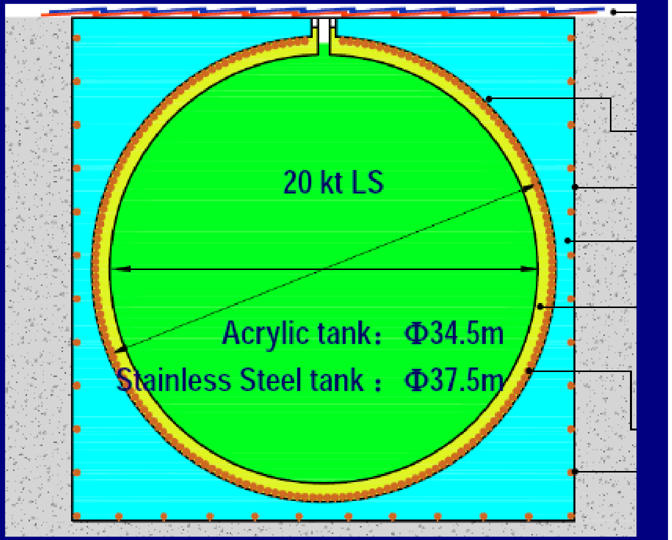
Difficult measurement for flux modelling and detector response to reach ~3σ significance



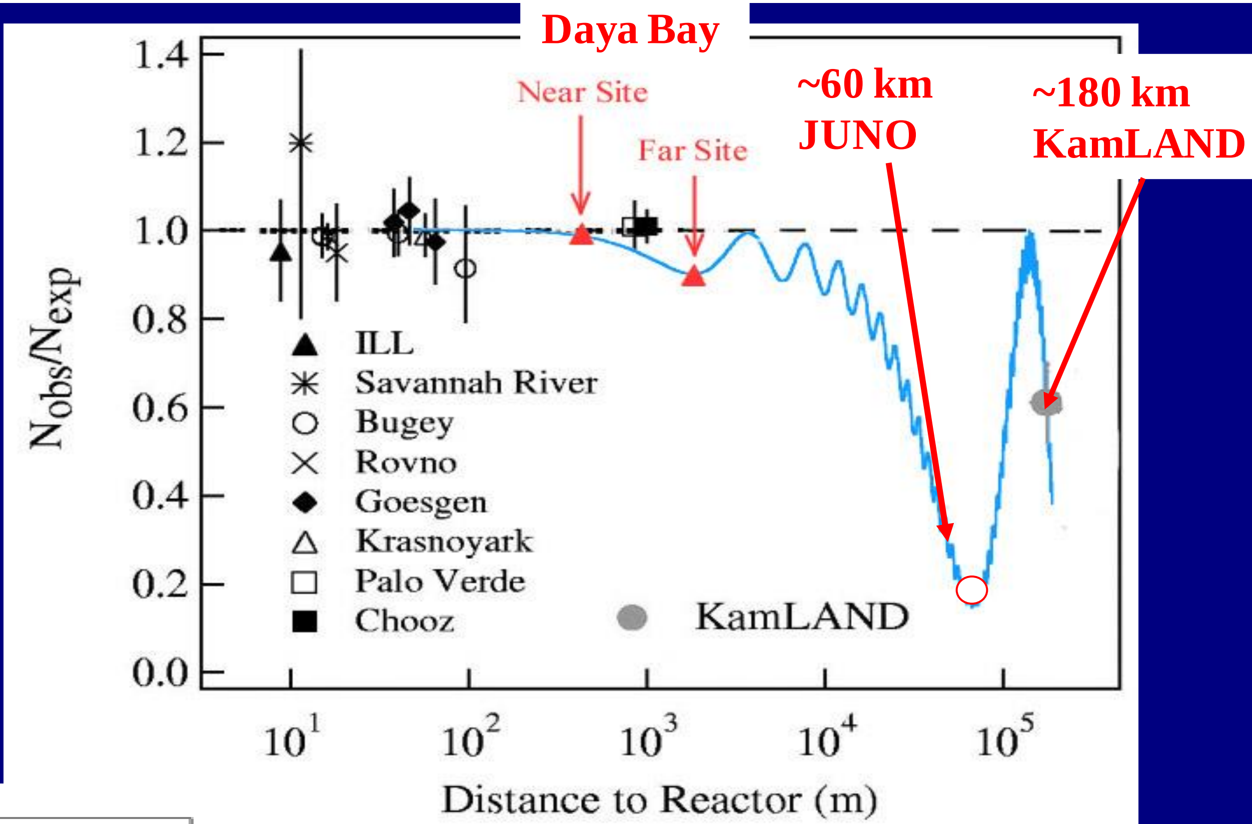


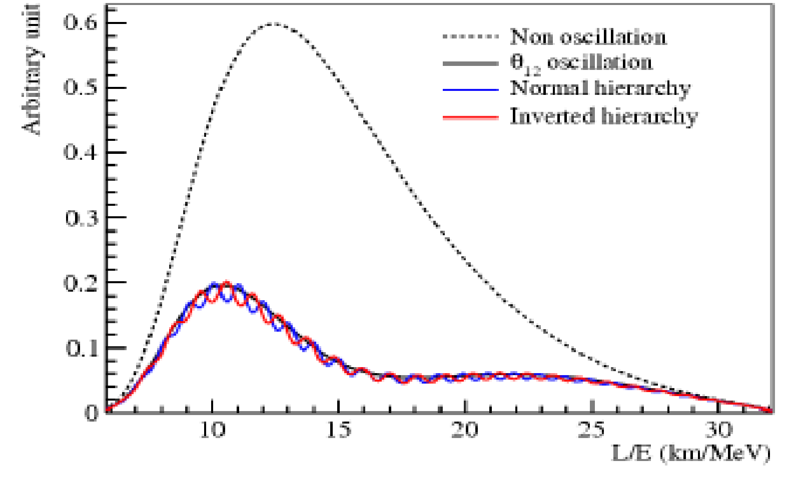
Reactor experiments tuned on solar oscillations wavelength $\Delta m^2_{12}+\theta_{12}$ (JUNO –RENO50)

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2 2\theta_{12}\sin^2\frac{\Delta m^2_{13}L}{4E} + \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{23}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12}L}{4E}$$



JUNO, expected start after 2021





Study of anti-nue disappearance exploiting the interference between the atmospheric and solar terms

→ Shifted patterns in measured neutrino energy spectrum

Requiring exceptional resolution and linearity (<1% precision) to reach ~3σ significance

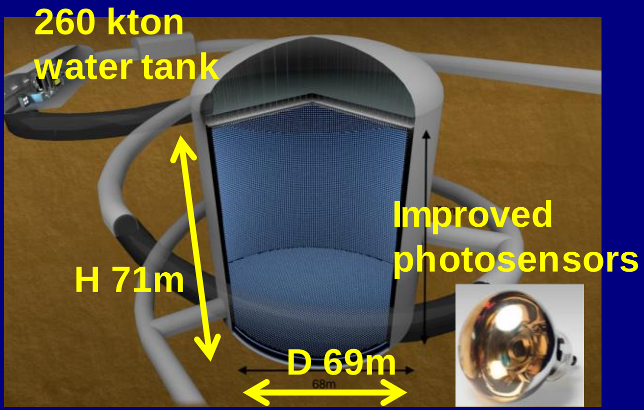
The Water Cerenkov approach (extrapolation of SuperKamiokande):

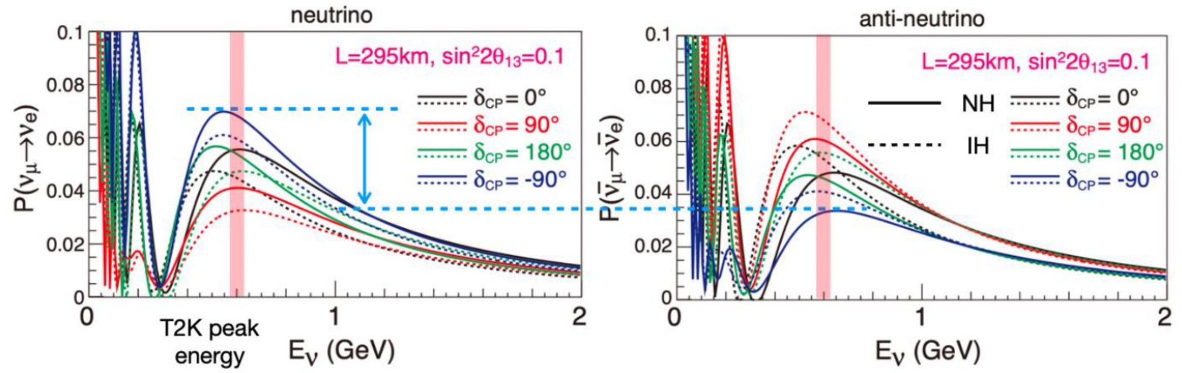
- ✓ Large water Cerenkov detector
- ✓ Low energy narrow beam (0.1-1 GeV), peak at 0.6 GeV → just lepton reconstruction in QE events
- ✓ Short baseline (100-300 km) → no mass hierarchy determination (*needs an external input (atm. neutrinos, other experiments)*
- ✓ New beam needed ~*1.3 MW*
- → Counting experiment on neutrinos-antineutrinos asymmetry at first oscillation maximum

- HyperKamiokande project in Japan

Initial project 2013 0.56 Mton, 99k PMT 20'', new beam from JPARC (295 km)
Beam neutrinos, Supernovae neutrinos, Search for proton decay

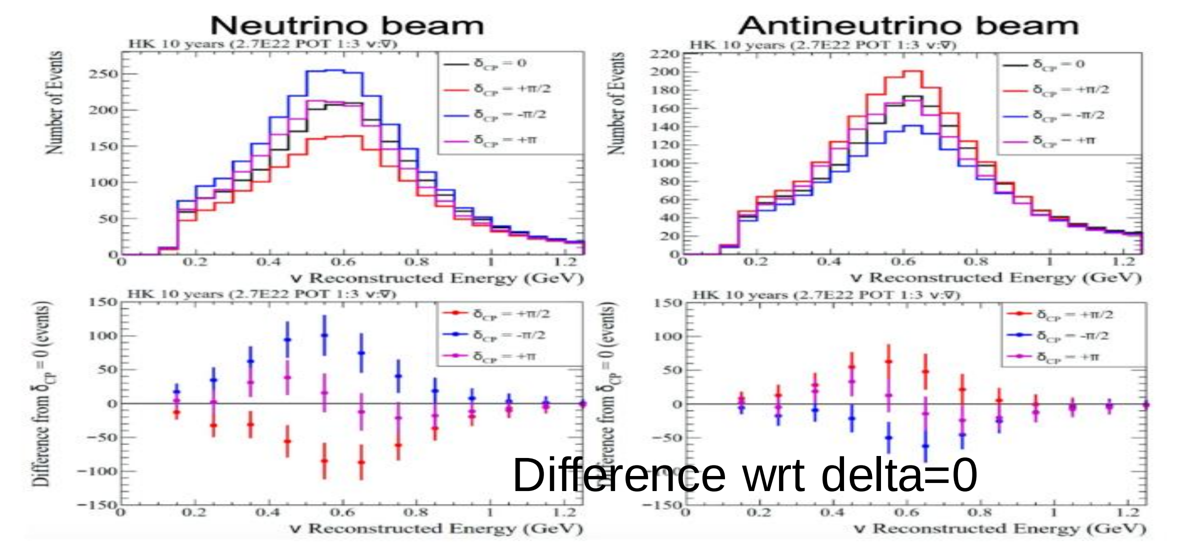
→ Project under construction since 2021:
188 kton fiducial mass (x8.3 SK) 20k PMT 20'', 800 multi-PMT modules





HyperK:

- **Continuation of measurements in sub-GeV region (peak at 0.6 GeV)**
- **Mostly « counting , statistics experiment » *O*(kevents)**
- **MH to be known to avoid a systematic bias**



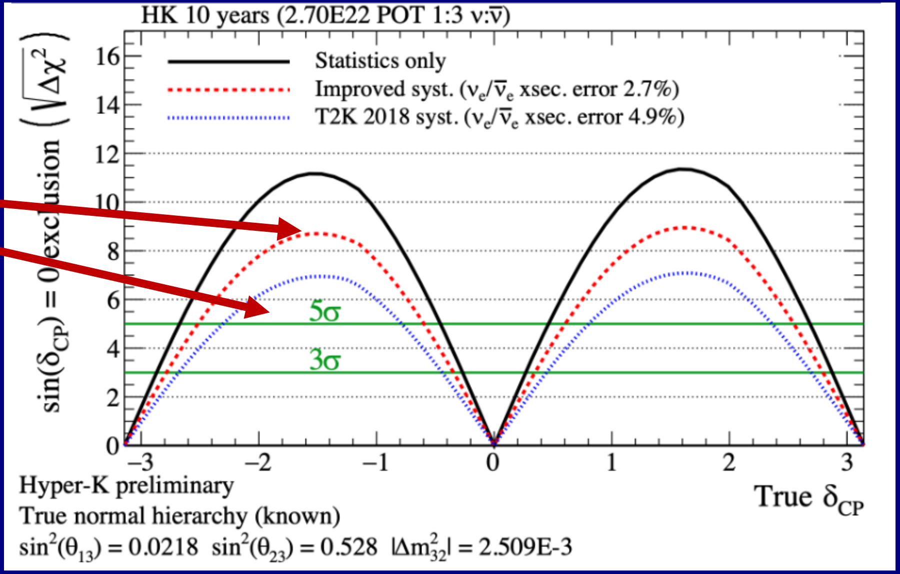
Difference wrt delta=0

HyperK 10 years at 1.3MW

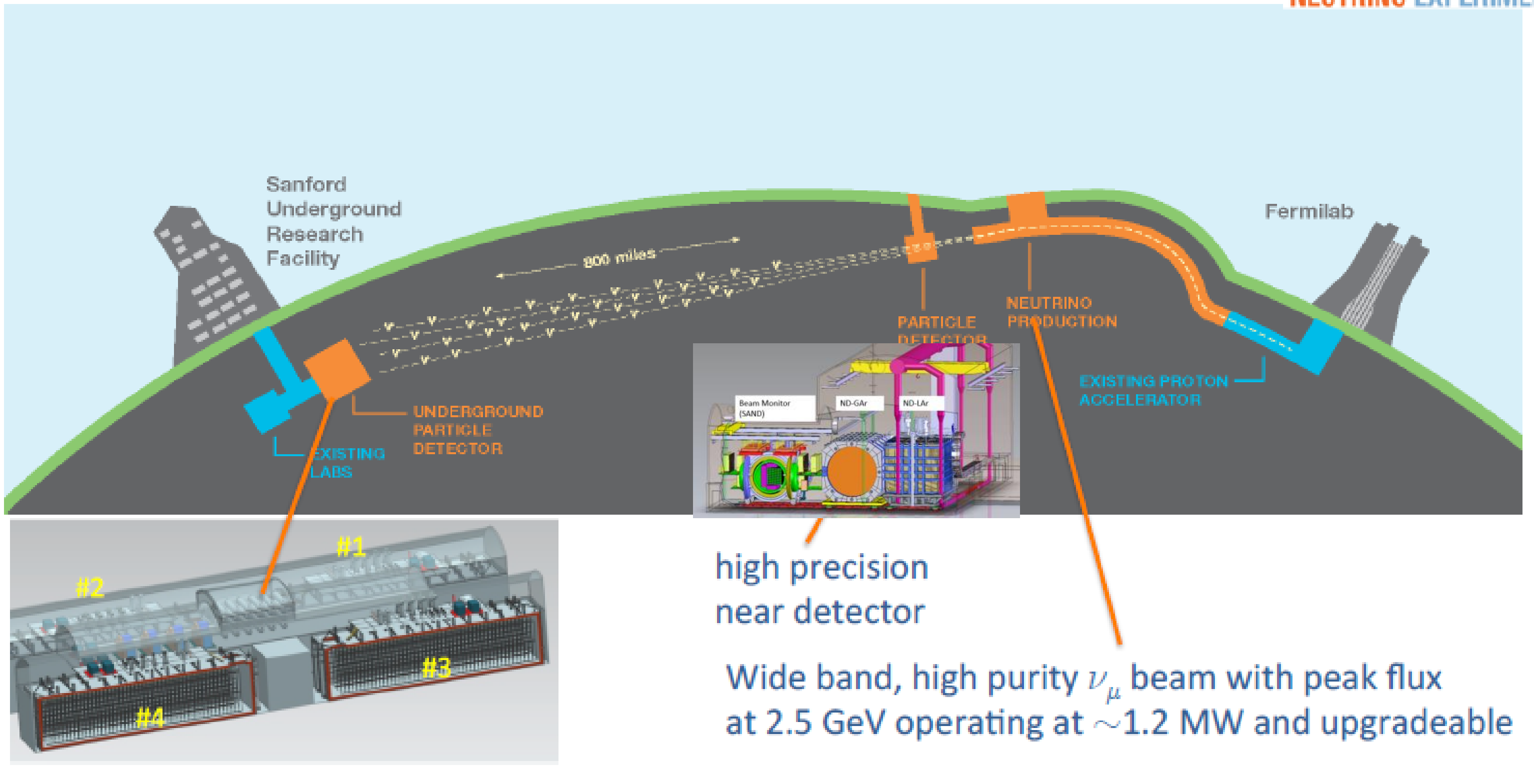
Systematic uncertainties based on:
- ✓ T2K experience
- ✓ Water Cerenkov Near Detector
- ✓ Study of atmospheric neutrinos control sample in Far Detector

T2K systematics on nue/nuebar cross sections at 4.8% planned to be reduced to 2.7%

→ 60% CP coverage (5σ) if MH know reachable in 10 years with 188 kton, 1.3 MW beam power to be upgraded from 515 kW, 3:1 antineutrino/neutrino running



Overall Experimental Layout



high precision near detector

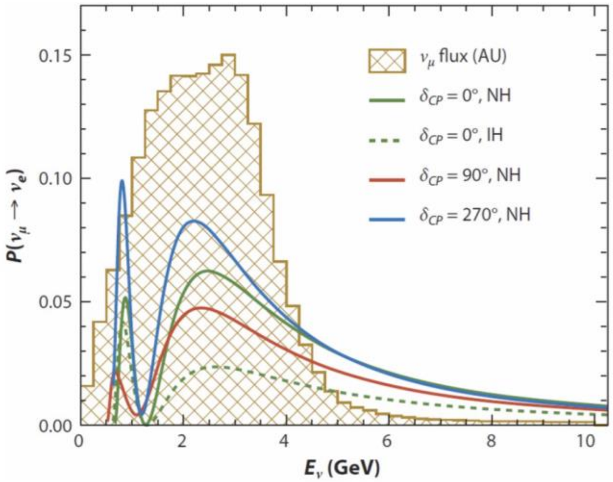
Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at ~1.2 MW and upgradeable

- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and double-phase readout under consideration

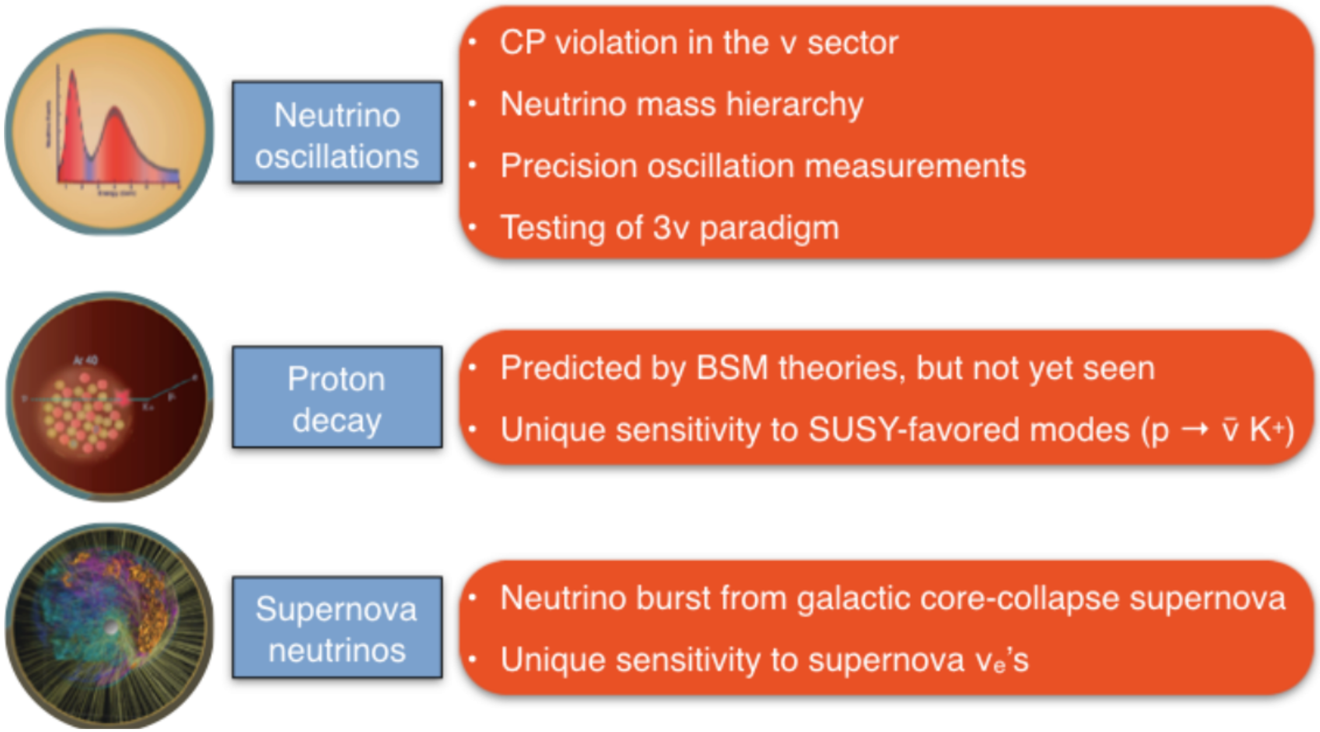
- Four liquid argon far detector modules of ~10 kton LAr mass each located in the mine at 1500m depth
- First two detector modules constructed by 2028

➢ Neutrino Beam: 1.2 – 2.4 MW proton beam intensity on target

➢ ~40 kton Far Detector mass



The Primary DUNE Scientific Goals



Neutrino oscillations

- CP violation in the ν sector
- Neutrino mass hierarchy
- Precision oscillation measurements
- Testing of 3ν paradigm

Proton decay

- Predicted by BSM theories, but not yet seen
- Unique sensitivity to SUSY-favored modes ($p \rightarrow \bar{\nu} K^+$)

Supernova neutrinos

- Neutrino burst from galactic core-collapse supernova
- Unique sensitivity to supernova ν_e's

High precision neutrino mixing measurements in a single experiment:

- Determination of the neutrino mass hierarchy in the first few years.
- Observation and measurement of CP Violation in the neutrino sector.
- Test of the 3-neutrino paradigm (PMNS unitarity).
- Observatory for astrophysical neutrino sources (solar, atmospheric, supernova).
- Search for BSM physics with ND and FD

Additional physics goals (ancillary program):

- ν_τ appearance
- Sterile neutrinos
- Search for Non Standard Interactions (NSI)
- Physics with atmospheric neutrinos: e.g. oscillations, mass hierarchy, BSM
- Searches for n–nbar oscillations
- Study of neutrino interactions in the near detector
- Searches for dark matter signatures

- Measurement of solar neutrino if threshold permits
- Potentially first observation of diffuse supernova neutrinos
- Detection of High Energy Neutrinos from astrophysical sources

Serendipity: intense LBNF neutrino beam and novel capabilities for both ND and FDs probing new regions of parameter space for both the accelerator-based and astrophysical frontiers

Some references:

Prospects for Beyond the Standard Model Physics Searches at the Deep Underground Neutrino Experiment https://arxiv.org/abs/2008.12769

Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment https://arxiv.org/abs/2008.06647

Long-baseline neutrino oscillation physics potential of the DUNE experiment https://arxiv.org/abs/2006.16043

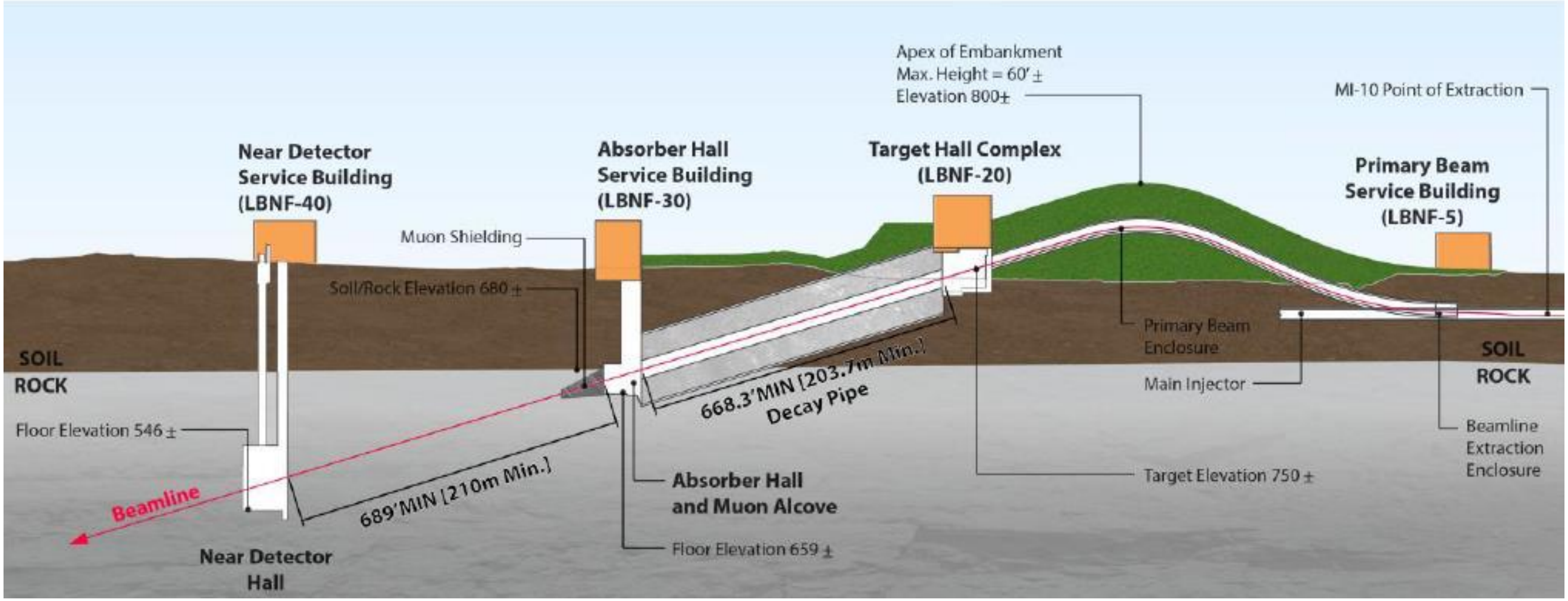
Neutrino interaction classification with a convolutional neural network in the DUNE far detector https://arxiv.org/abs/2006.15052

Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics https://arxiv.org/abs/2002.03005

Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I: Introduction to DUNE https://arxiv.org/abs/2002.02967

Long Baseline Neutrino Facility (LBNF)

- DOE/Fermilab hosted project with international participation
- **Horn-focused beamline** similar to NuMI beamline
  - 60 – 120 GeV protons from Fermilab's Main Injector
  - 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
  - Initial power 1.2 MW, upgradable to 2.4 MW

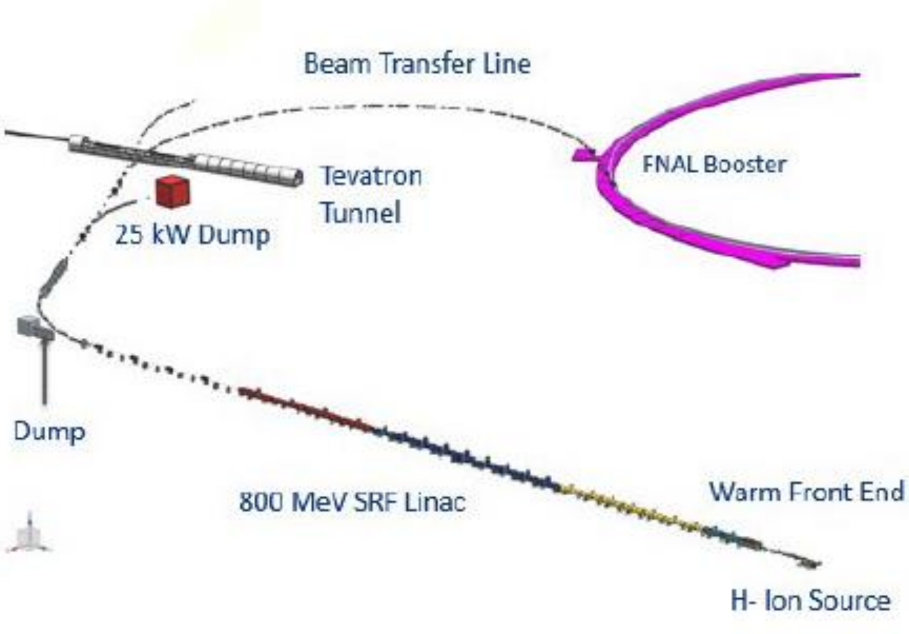


Proton Improvement Plan II (PIP-II)

PIP-II https://pip2.fnal.gov/
FERMILAB Proton Improvement Plan-II
→ Another O(1G$) program on top of LBNF-DUNE

PIP-II enables the accelerator complex to reach 1.2 MW proton beam on LBNF target.
Upgradable to multi-MW power

800 MeV LINAC + transfer line to Booster + Booster upgrade → Under construction

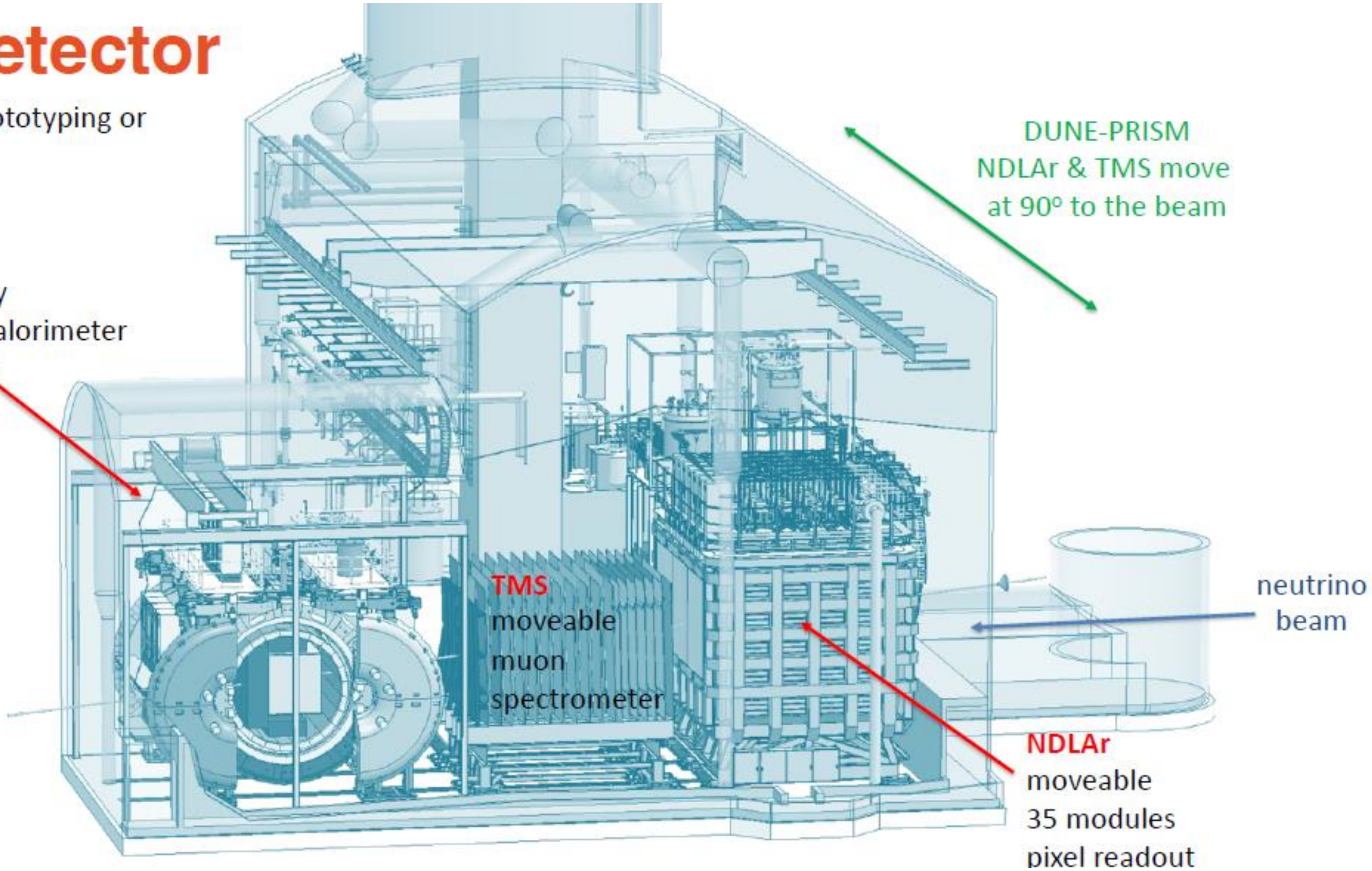


- Fermilab beams stop end 2026
- Beam commissioning: 2029-30
- Beam to DUNE: Fall 2031, ~ 1 MW
- 1.2 MW by end 2032

Near Dectector complex: Conceptual Design Report (CDR): https://arxiv.org/abs/2103.13910 March 2021, PDR (Day 1 configuration) in 2021

Near Detector

All systems in prototyping or preparation



SAND
on-axis, stationary
KLOE magnet & calorimeter
Straw Tubes
GRAIN: 1 ton LAr

DUNE-PRISM
NDLAr & TMS move
at 90º to the beam

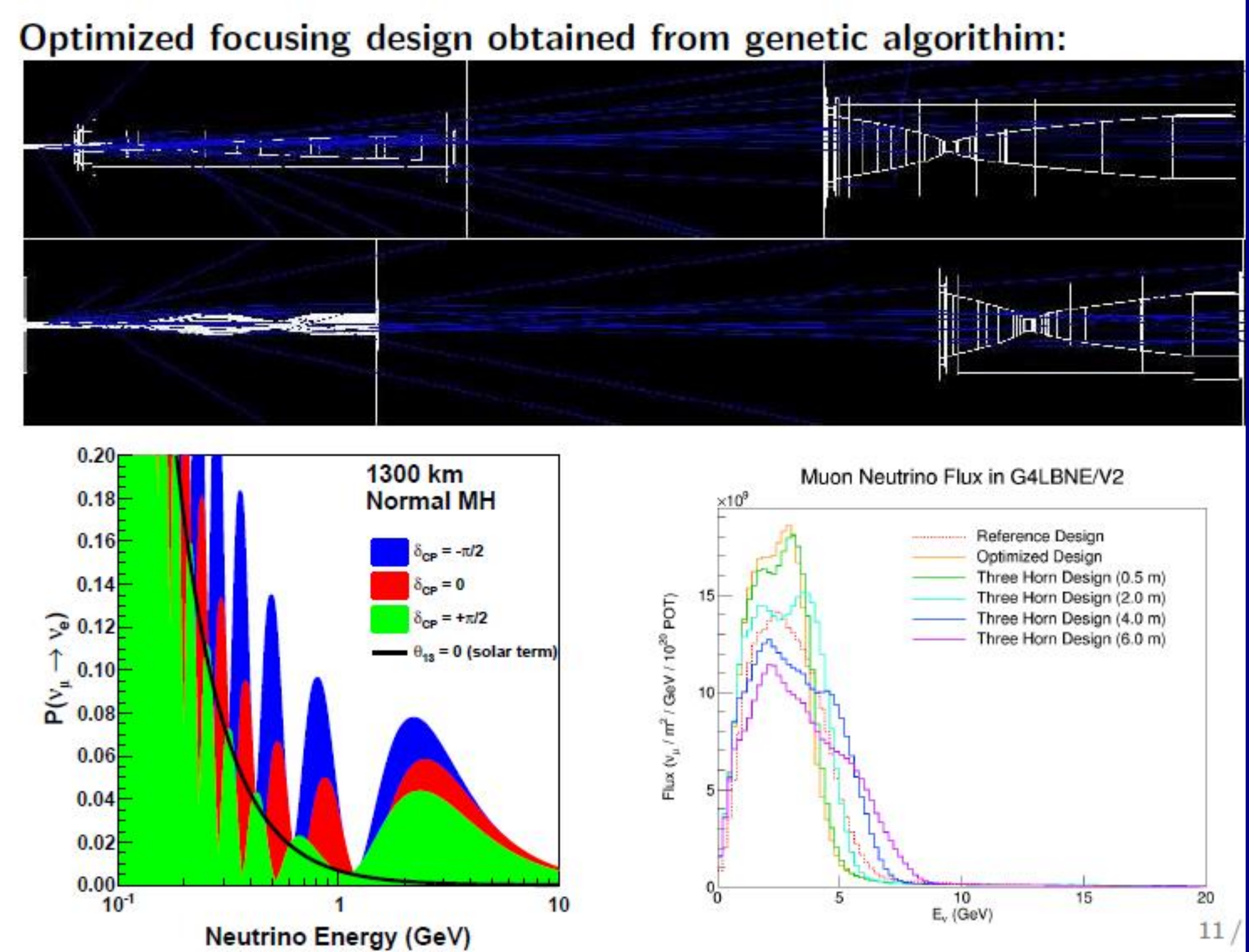
TMS
moveable
muon
spectrometer

neutrino
beam

NDLAr
moveable
35 modules
pixel readout

- Measures the neutrino beam rate and spectrum to predict un-oscillated event rates in the far detector
- Constrains systematic uncertainties for oscillation measurements

Optimized beam focusing design based on a genetic algorithm à la LBNO to define the all parameters of the horns geometry



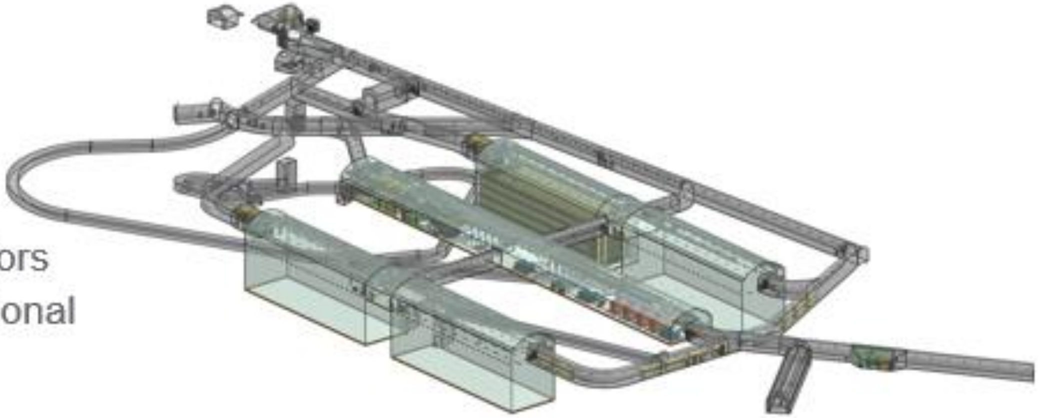
Optimized focusing design obtained from genetic algorithim:

11 /

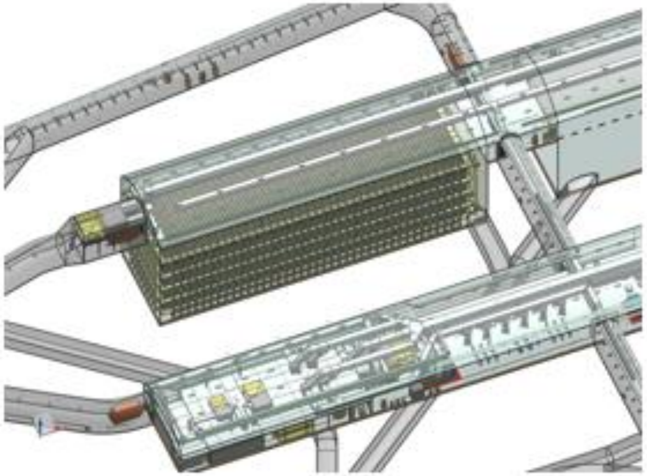
Overview – "Far Site" – LBNF at Sanford Lab, Lead, SD

- **Conventional Facilities**:
  - Surface and shaft Infrastructure including utilities
  - Drifts and two caverns for detectors
  - Central utility cavern for conventional and cryogenic equipment
- **Cryostats**:
  - Four membrane cryostats supported by external steel frames
- **Cryogenic Systems**:
  - LN2 refrigeration system for cooling and re-condensing gaseous Argon
  - Systems for purification and recirculation of LAr
- **Argon:**
  - 70kt LAr (~40kt "fiducial" mass)

LBNF facilities will support DUNE experiment



4850L caverns and drift layout



Single cryostat and portion of central utility cavern

Far Site Conventional Facilities Status

Pre-Excavation Scope

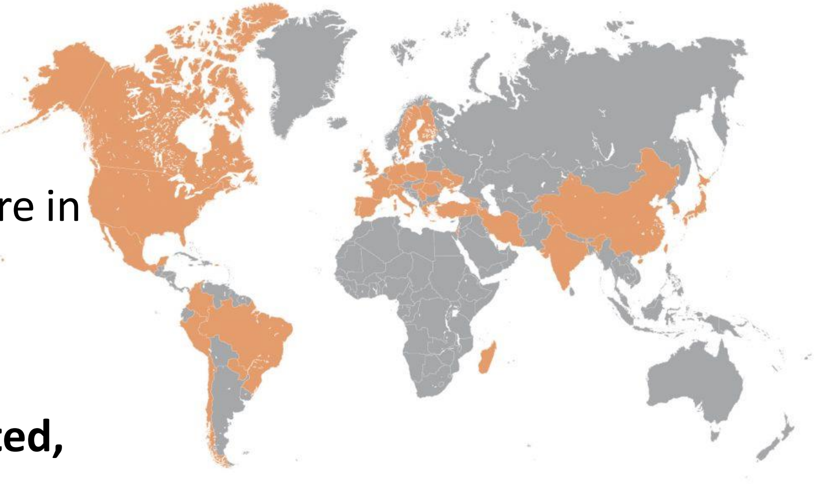
- ✓ Empty & Repair Ore Pass
- ✓ Replace Skip Loading System
- ✓ Replace/Restore Rock Crushing System
- ✓ Rehabilitate the Existing Tramway
- ✓ Install New Conveyor System
- ✓ Install additional Electrical Capacity at Ross Substation
- ✓ Structural Reinforcement of Ross Headframe
- ✓ Install Shaft Utilities
- ✓ Early Ventilation Improvements

Groundbreaking for pre-excavation work was held in August 2017

LBNF Groundbreaking held at 4850L (1.5km underground) at Sanford Lab. Participants included:

- International funding agencies: CERN, INFN, and STFC
- Congressional delegation and the Governor of South Dakota
- Executive Office of the President (Michael Kratsios, OSTP) and DOE
- Fermilab and Sanford Lab

➢ **DUNE experiment: started in 2014/5 by an international *worldwide* collaboration including EU countries and CERN (1500 collabiorators from 37 countries)**



➢ **Infrastructure based in the USA:**

- Neutrino Beam from Fermilab Chicago, Illinois
- Underground (1500m depth) far detector infrastructure in Lead, South Dakota, SURF laboratory (in former Homestake mine) at 1300 km from Fermilab

Underground exavation started in 2017 almost completed,
Far detectors under construction

➢ **Strong french participation supported by a TGIR/IR* program and 6 IN2P3 laboratories (APC, IJCLAB, IP2I, LAPP, LP2I, LPSC), IN2P3 and CEA also supporting via the IR* program the beam intensity uprade at Fermilab (PIP-2 program)**

➢ **DUNE TGIR kickoff in 2021: https://indico.in2p3.fr/event/24119/**

→DUNE needs sophisticated massive detectors **O(10 kton)** in order to study tiny effects :

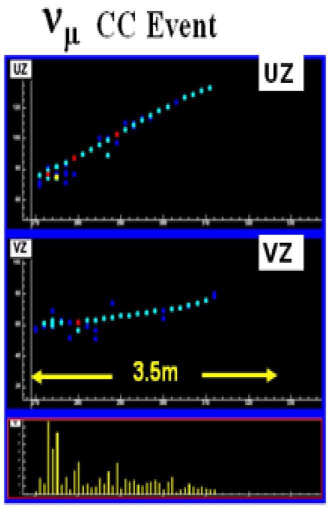
- Accurate identification of neutrino flavors via final state lepton (**muon, electron, tau: tau appearance via kinematical methods like in the NOMAD experiment**)

- Precise measurement of all particles in the final state and of the **neutrino energy**

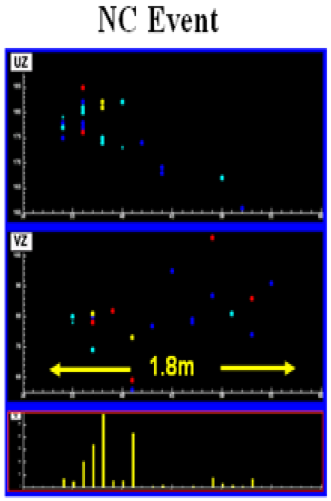
→ Electronic version of **Bubble Chambers**: **The Liquid Argon Time Projection Chamber (TPC)**

Typical neutrino interactions events in fine grained detectors

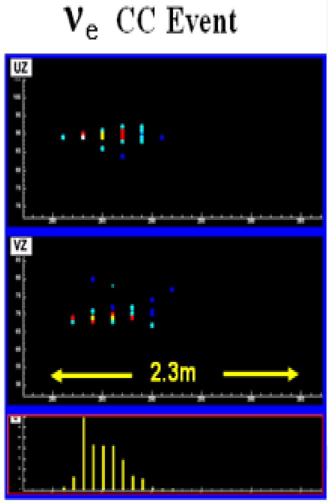
MINOS (sandwich of 2.54 cm magnetized steel and 1 cm scintillator plates)



- Long muon track + hadronic activity at vertex



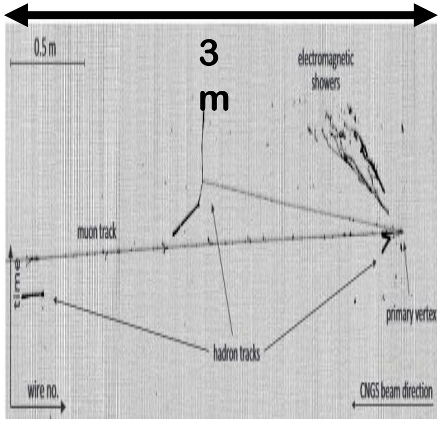
- Short showering event, often diffuse



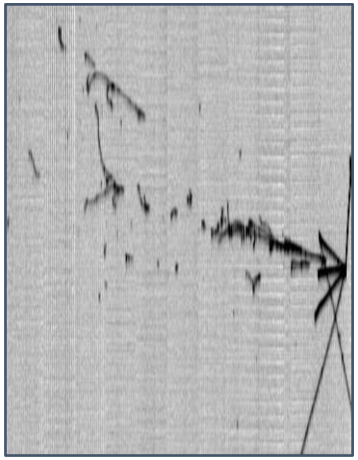
- Short event with typical EM shower profile

ICARUS **LAr TPC neutrino interactions from CNGS beam**

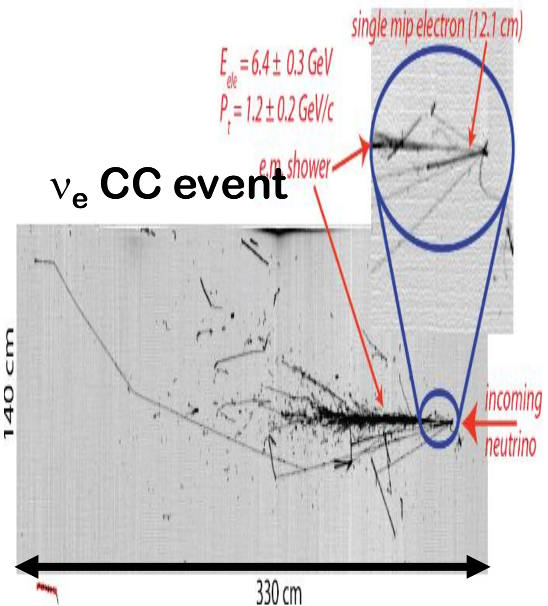
ν_μ CC event with π^0 production



ν_μ NC event with π^0 production

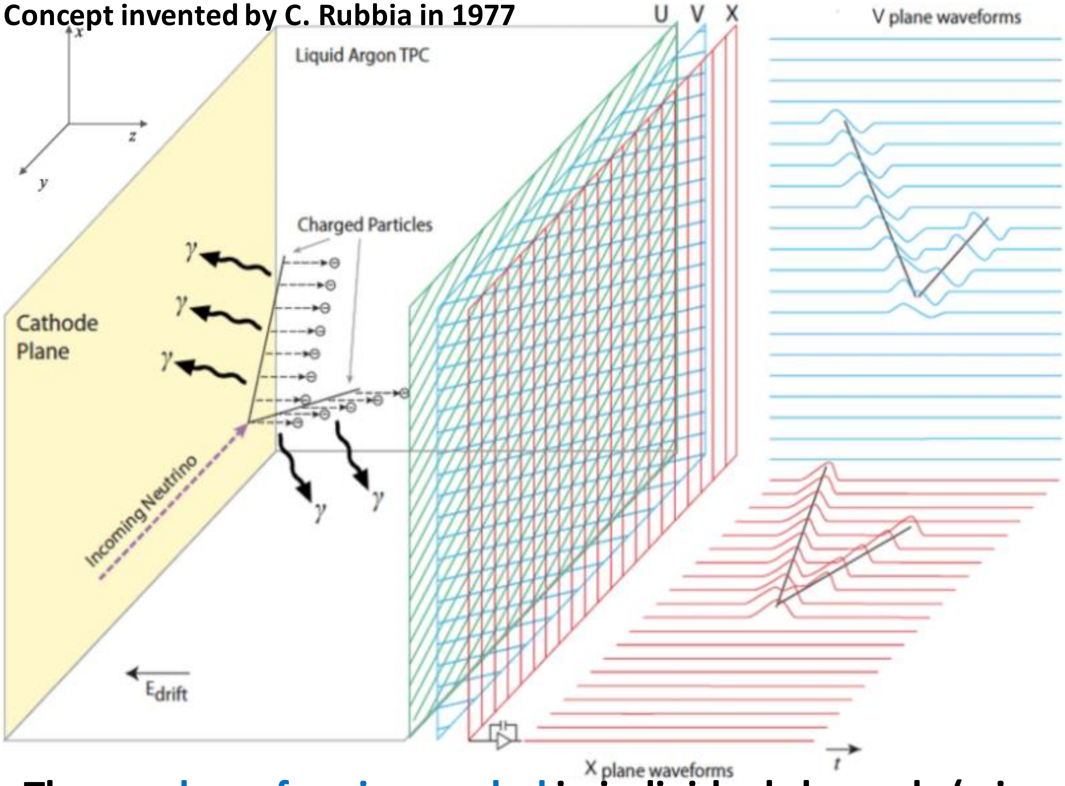


ν_e CC event



The Liquid Argon Time Projection Chamber (LAr TPC)

Concept invented by C. Rubbia in 1977



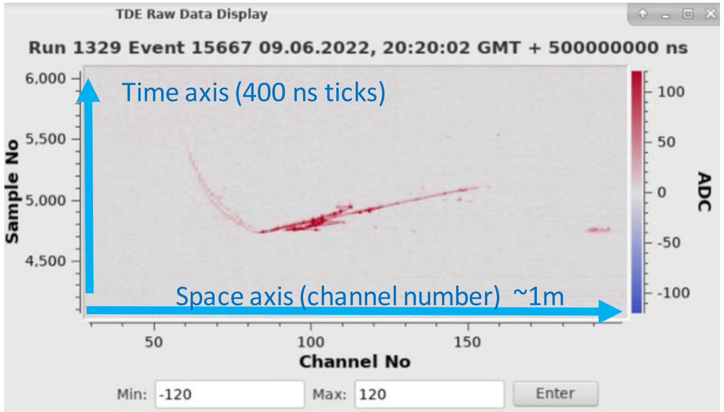
- **Ionization** by a charged particle produce in LAr a **cloud of electrons and positive ions along the trajectory of the particle** (~10k electrons/mm of path)
- **A strong electric field** separates electrons from Ar^+ ions, ~30% of them recombine producing UV light at 127 nm (Prompt signal)
- Remaining **electrons drift at constant speed ~1.5m/us to the anode** in ultra-pure LAr → 0.1 ppb remaining O_2 contamination in LAr
- **The image of the track of the particle is projected** to the anode

- The **anode surface is sampled** in individual channels (wires planes or segmented PCB) with a pitch of ~5 m and **3 independent views** (e.g. 90° +30° -30°)
- Single channels are **readout by low noise cryogenic amplifiers and the output waveforms are continuously digitized** (14 bit, ~2 MHz)

→ **3D images of particles interactions are reconstructed in great details**

Example of image from a single view

The number of electrons collected per unit of track lenght allows measuring the energy of the particle and indentifying the particle type



Run 1329 Event 15667 09.06.2022, 20:20:02 GMT + 500000000 ns

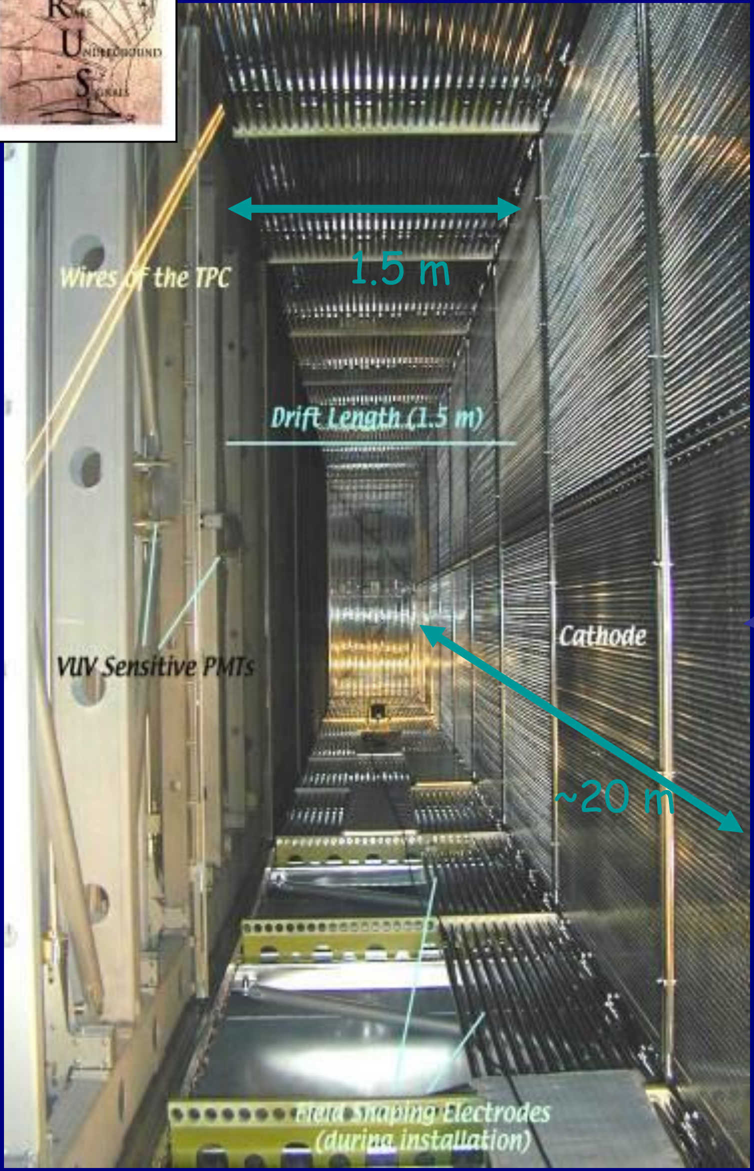
Time axis (400 ns ticks)

Space axis (channel number) ~1m

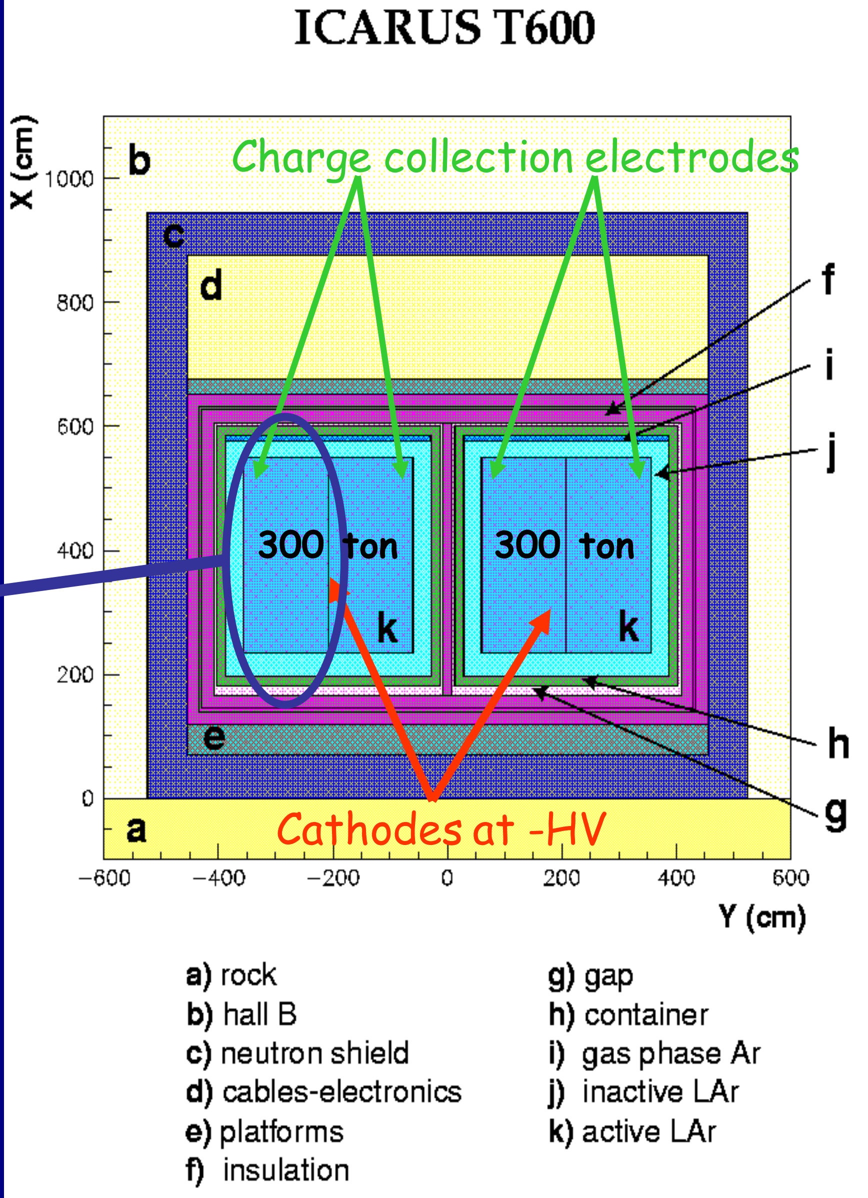
Min: -120

Max: 120

ICARUS T600 prototype (2001) exploited at LNGS and now at FNAL for the short-baseline program



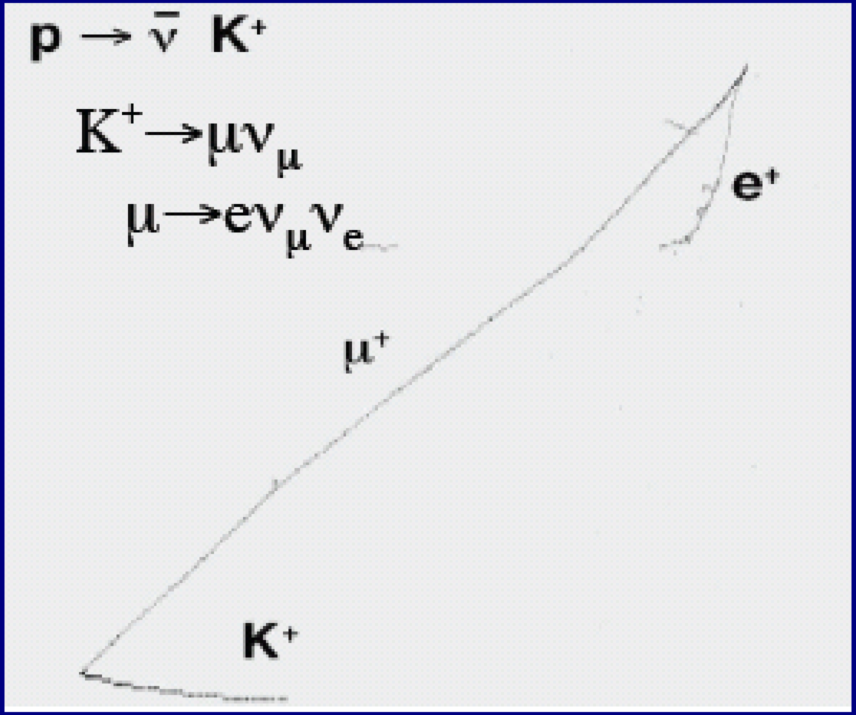
ICARUS T600

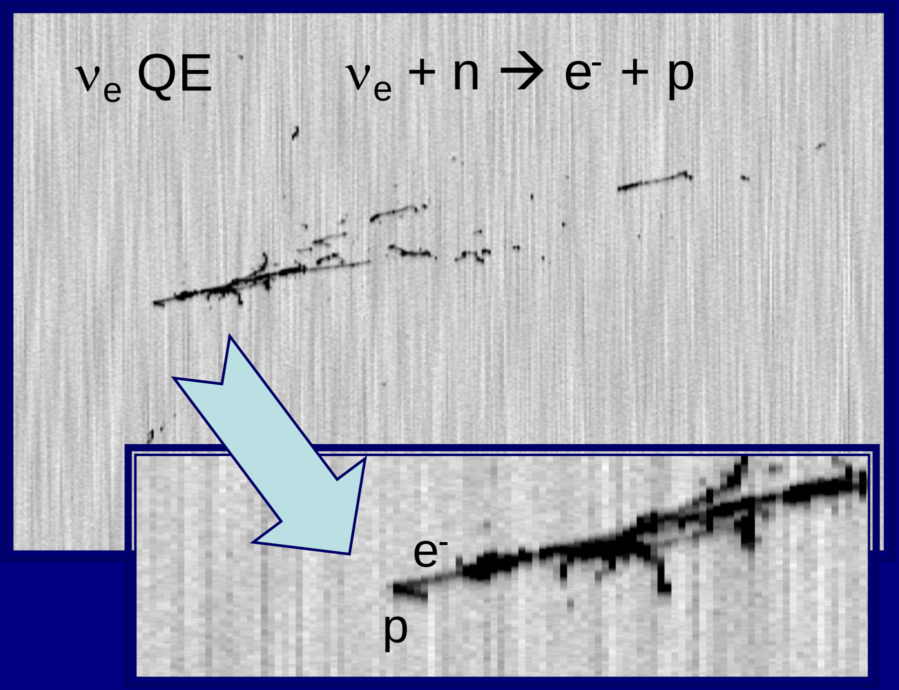


The liquid argon TPC as an electronic bubble chamber

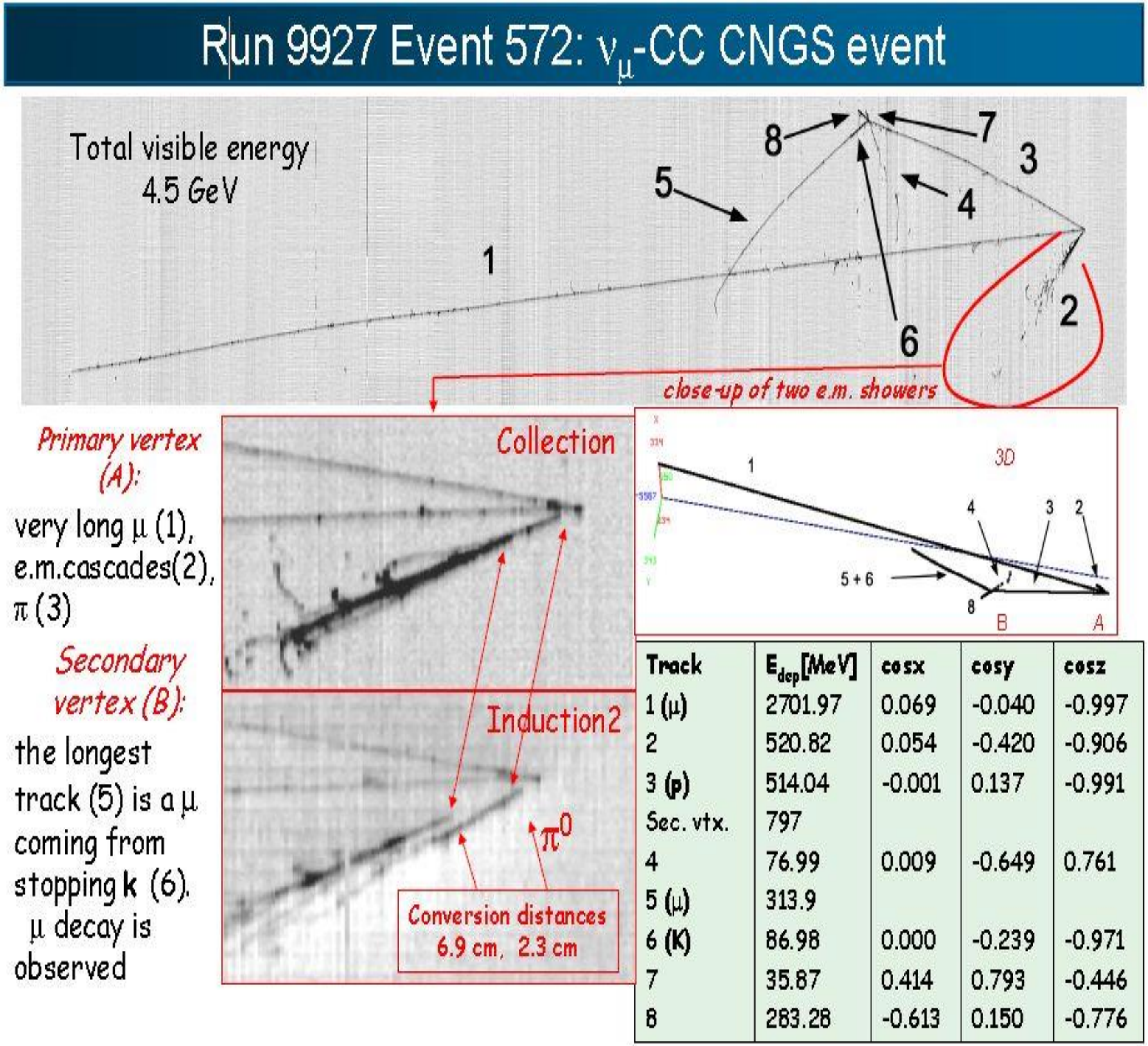
- Large mass, homogeneous detector, low thresholds, exclusive final states
- Tracking + calorimetry (0.03 X0 sampling)
- **Electron** identification, π^0 rejection, particles **identification with dE/dx**

→ Neutrino physics (electron identification, reconstruction of event kinematics, identification of exclusive states, excellent energy resolution from sub GeV to multi GeV)
→ Supernovae neutrinos
→ Proton decay search (large mass, particles id.)





The liquid argon TPC as an electronic bubble chamber



Run 9927 Event 572: ν_μ-CC CNGS event

Total visible energy
4.5 GeV

close-up of two e.m. showers

Primary vertex (A):

very long μ (1), e.m.cascades(2), π (3)

Secondary vertex (B):

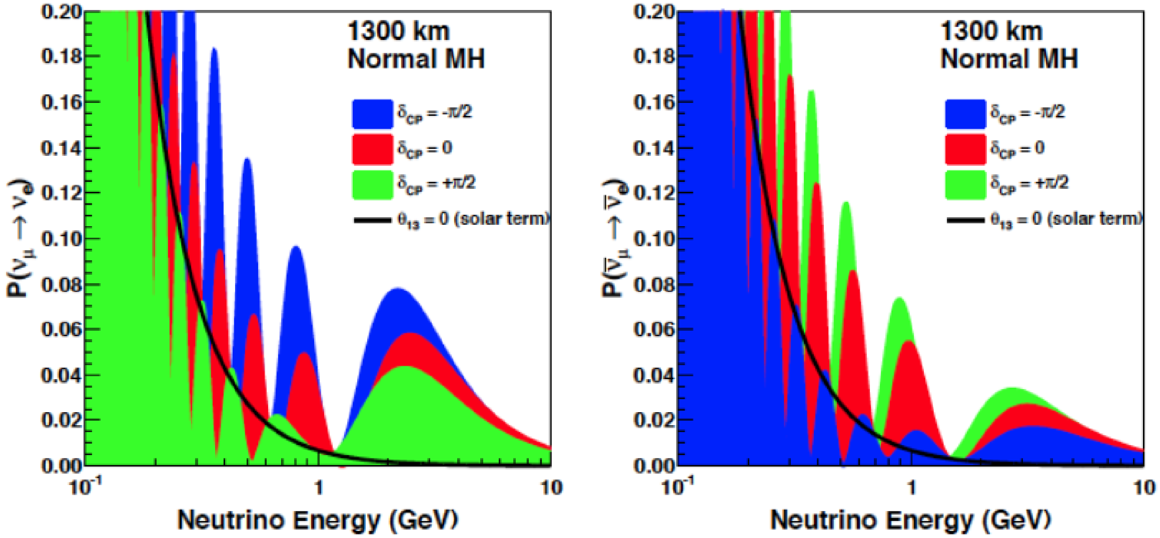
the longest track (5) is a μ coming from stopping **k** (6). μ decay is observed

Conversion distances
6.9 cm, 2.3 cm

Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

DUNE Neutrino Oscillation Strategy

Measure neutrino spectra at 1300 km in a wide-band beam



- ν_e appearance probability depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects. All four can be measured in a single experiment.
- Wide-band beam and long baseline break the degeneracy between CP violation and matter effects.

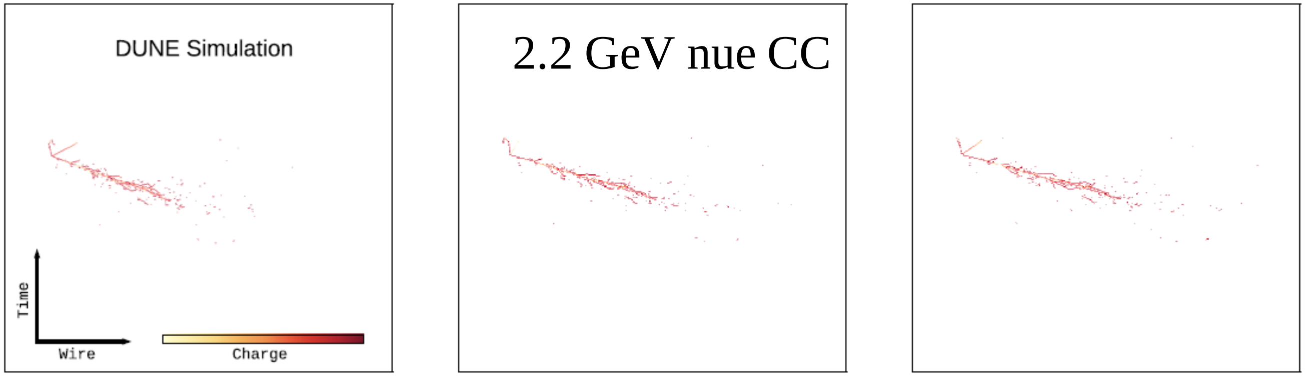
- ➢ Exploitation of spectral information and 2nd oscillation maximum
- ➢ DUNE is a unique experiment allowing performing all these measurements (CP search, mass hierarchy, 3 neutrinos phenomenology with also τ appearance, precision measurements) <u>within the same set-up and with high significance for discovery.</u> Checking of CP vs NSI with spectral info.
- ➢ It also provides a complete neutrino interactions final state reconstruction information

DUNE use of the visual neural network (CVN) for the events classification

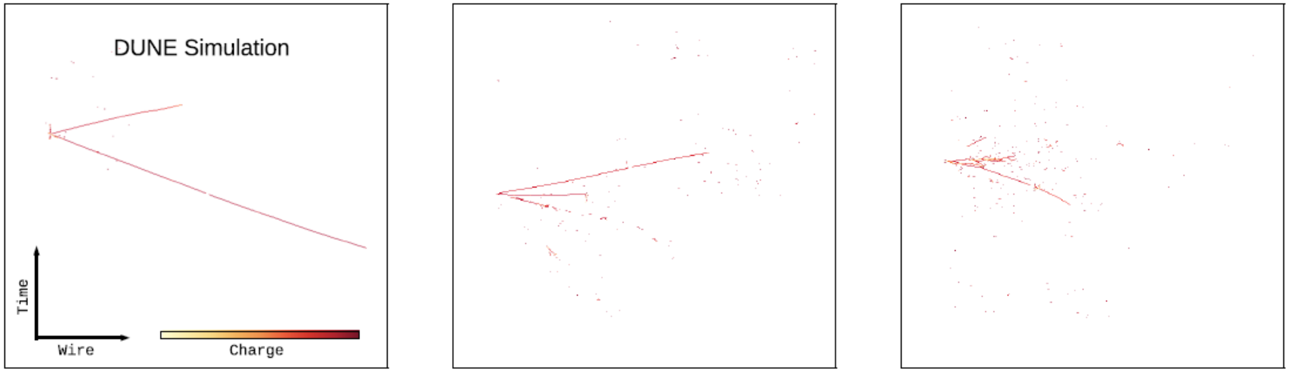
~90% efficiency for nue CC

~95% efficiency for numu CC

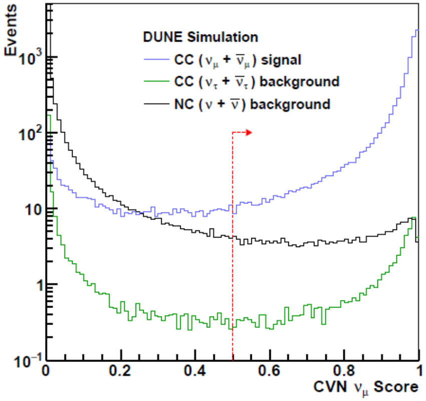
2.2 GeV nue CC

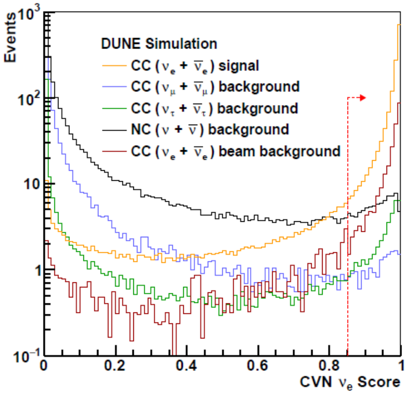


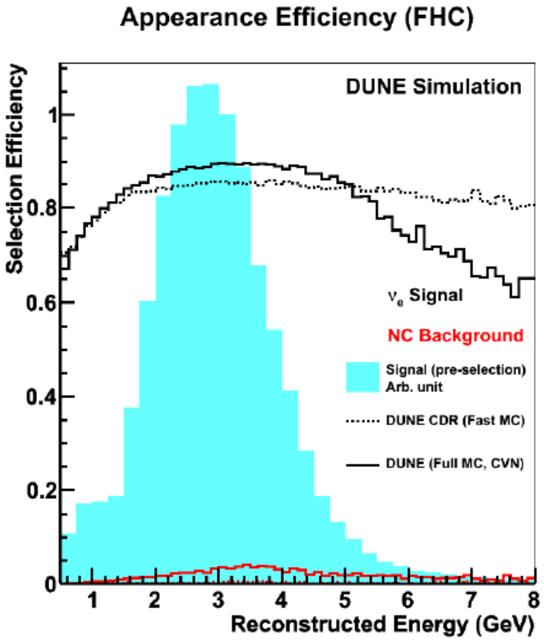
(a) View 0: Induction Plane. (b) View 1: Induction Plane. (c) View 2: Collection Plane.



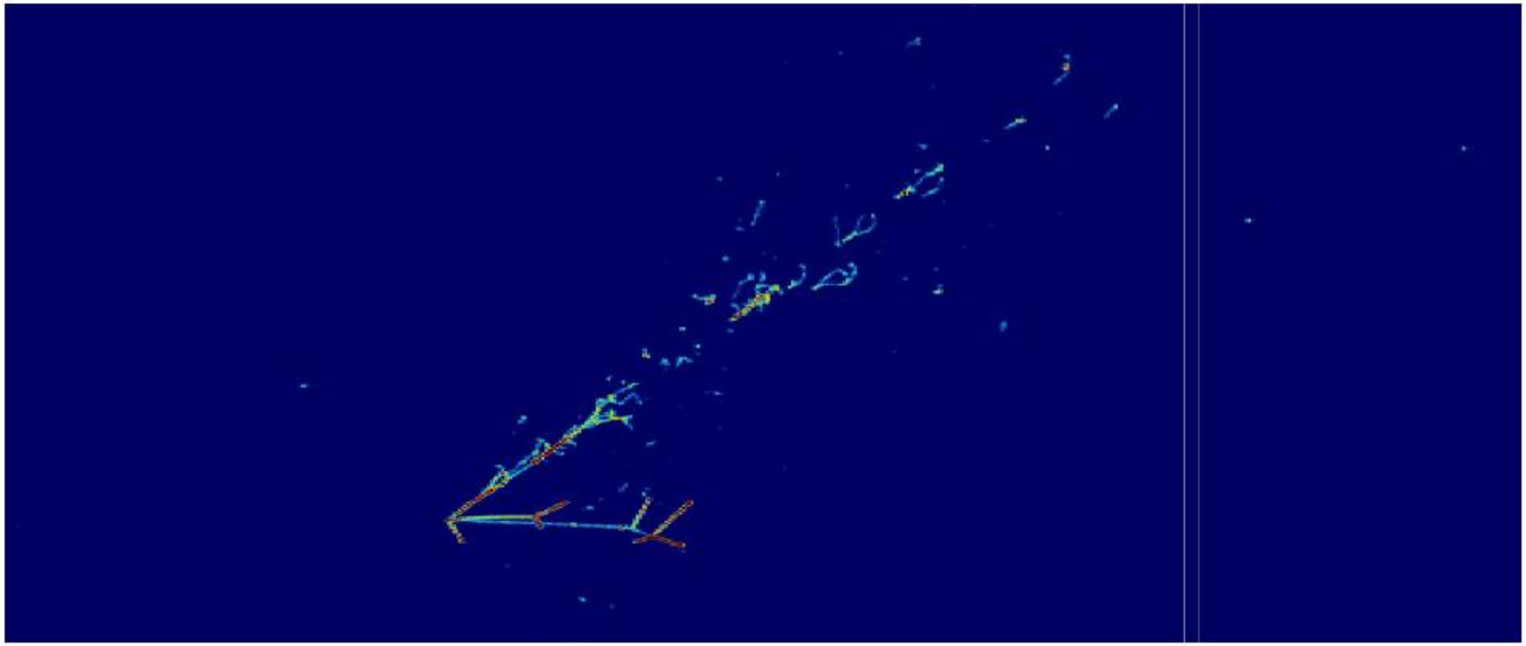
(a) 1.6 GeV CC ν_μ. (b) 2.2 GeV NC $1\pi^+$. (c) 2.4 GeV NC $1\pi^0$.







How DUNE sees neutrinos and measures oscillations



- Identify as ν_e CC from electromagnetic shower
- Measure E_ν by summing the energy of the electron and hadrons (one pion and two protons, in this case)

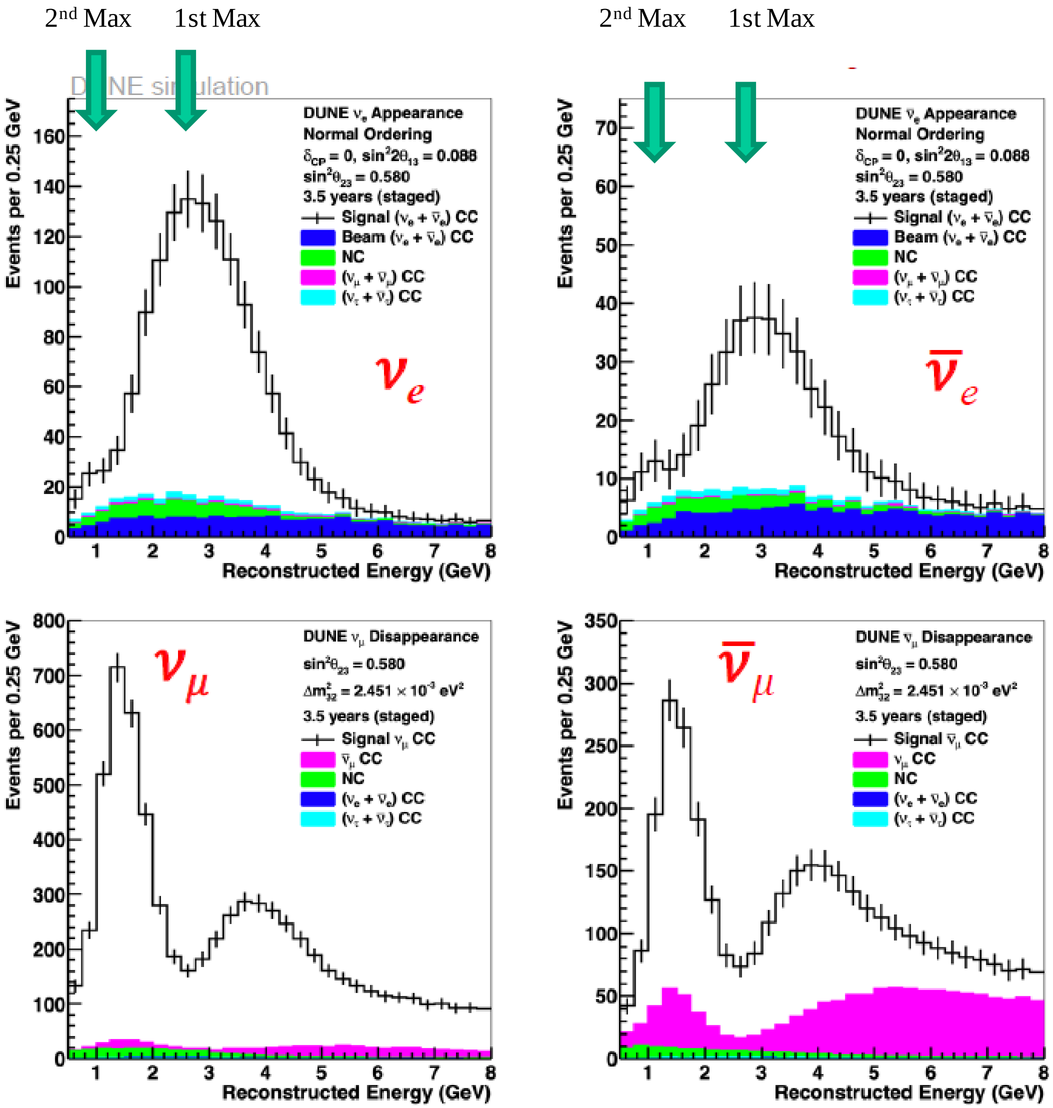
Very rich amount of information, ongoing studies on the events reconstruction, particles identification (LarSoft and Pandora software) and neutrino energy reconstruction in order to improve the sensitivity and fully exploit the detector capabilities

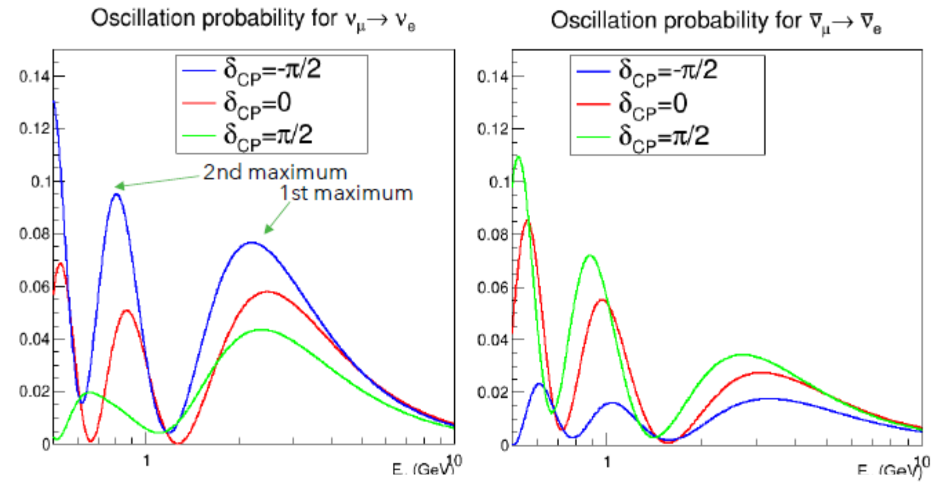
Neutrino oscillations measurement strategy

ν_e anti-ν_e appearance
~1000 events in 7 years

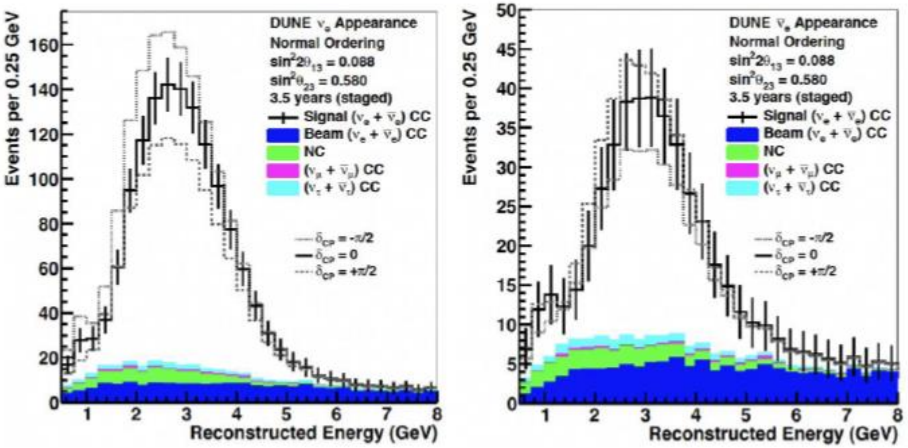
Fit 4 samples
→ Oscillation parameters

ν_μ anti-ν_μ disappearance
~10k events in 7 years



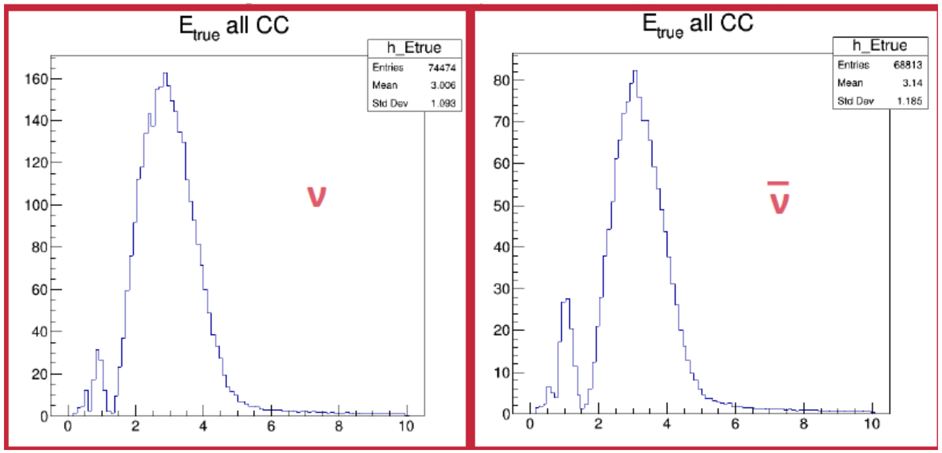


Ideally it would be nice to measure the oscillation probability for neutrinos and antineutrinos as a function of energy (first two maxima at 0.8 and 2 Gev)



The spectral information measured in the detector is a convolution of

- The incoming neutrino flux as a function of energy
- The oscillation probability
- The neutrino interaction cross-section
- The energy scale on the X axis is the reconstructed neutrino energy

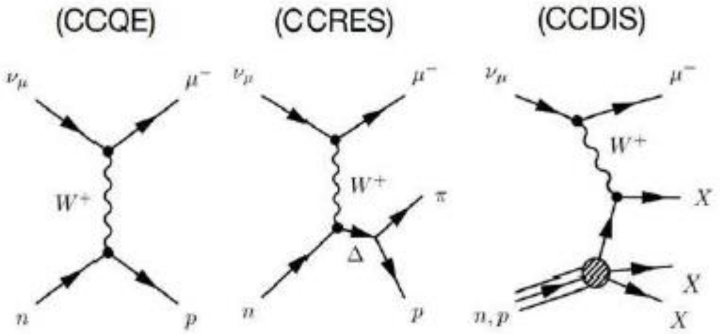


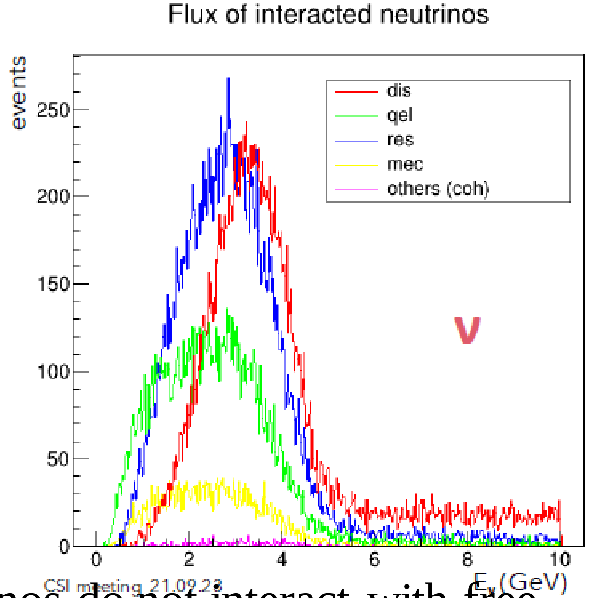
Same plot with the true neutrino energy

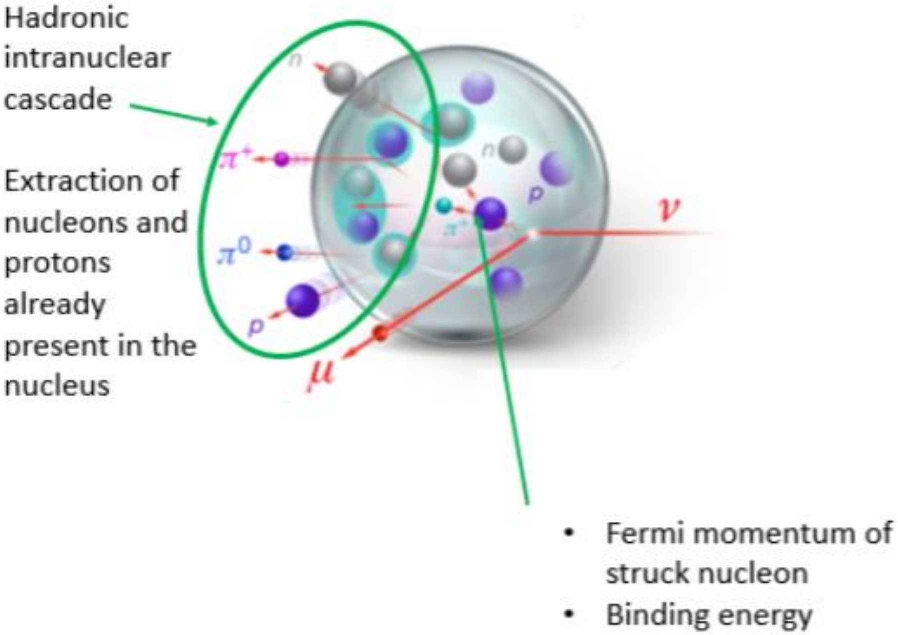
The physics of charged current neutrino interactions with nuclei is by itself an important experimental and theorerical topic

3 main interactions processes are involved in a proportion changing with the neutrino energy due their cross-section energy dependence:

Quasi-elastic scattering, Renonances production and Deep Inestatic scattering





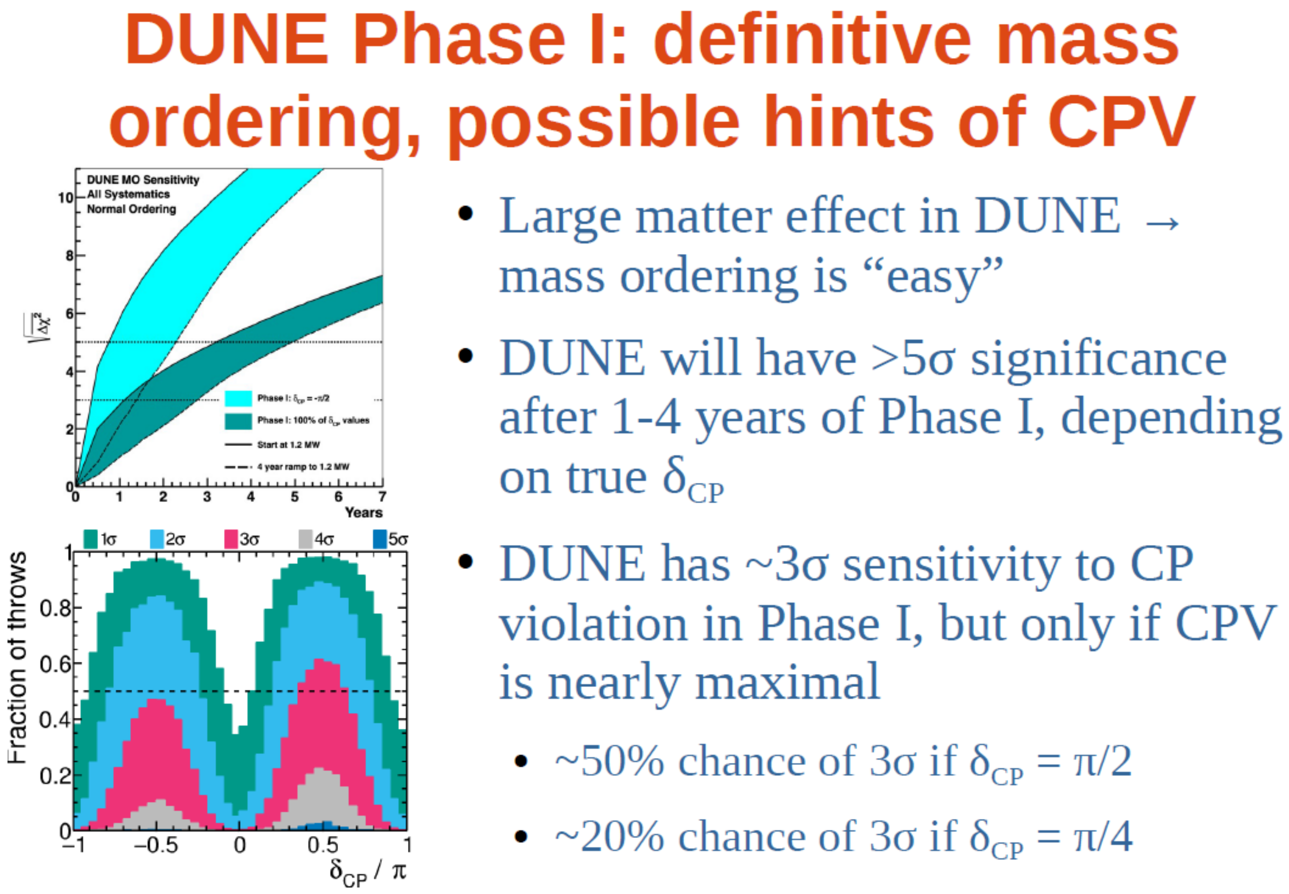


Neutrinos do not interact with free nucleons but with bound nucleons moving inside the nucleus due to Fermi momentum

The hadrons produced by the neutrino my undergo nuclear rescatting and extract nucleons

DUNE Phase I:
- Full near + far site facility and infrastructure
- Upgradeable 1.2 MW beam
- Two LArTPC Far Detector Modules
- Movable LArTPC near detector with muon catcher
- On-axis near detector

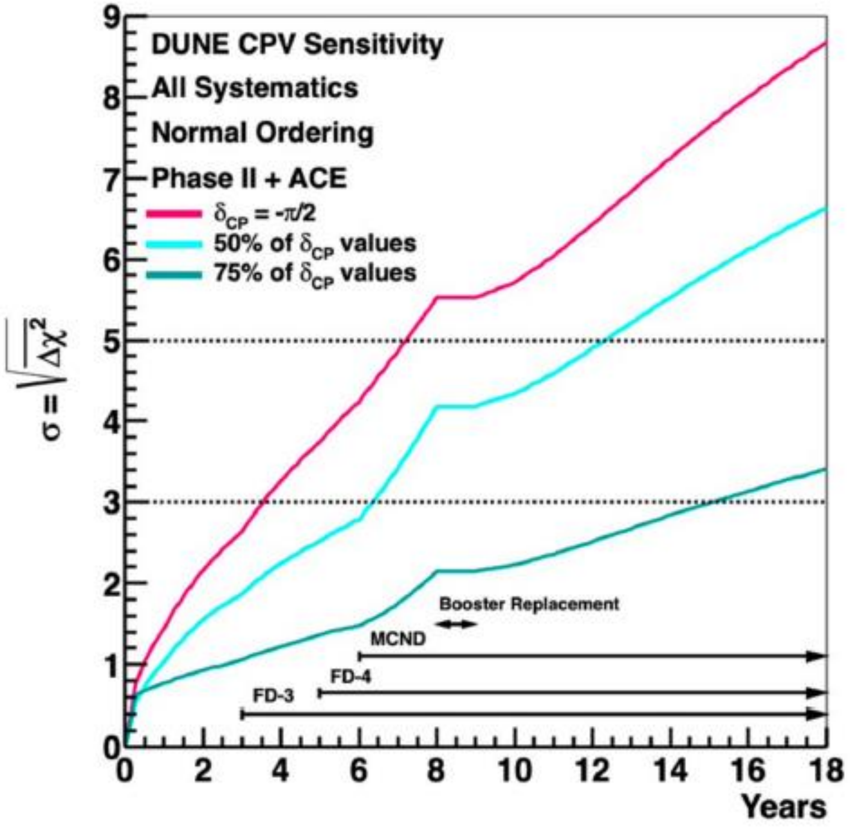
- DUNE Phase II:
- Two additional FD modules
- Beam upgrade to >2MW
- More capable Near Detector

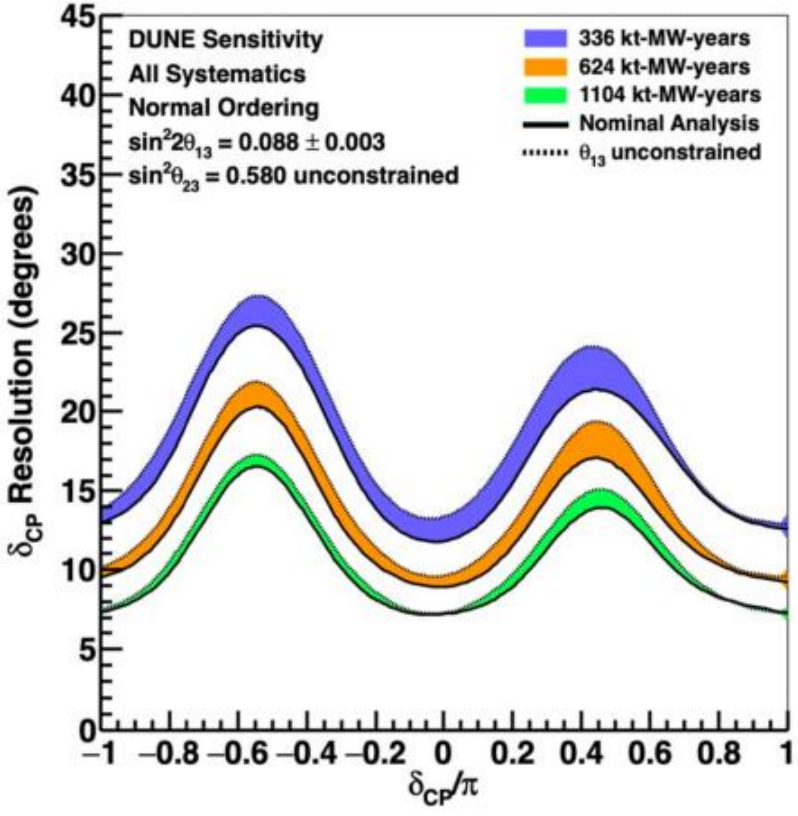


DUNE Phase I: definitive mass ordering, possible hints of CPV

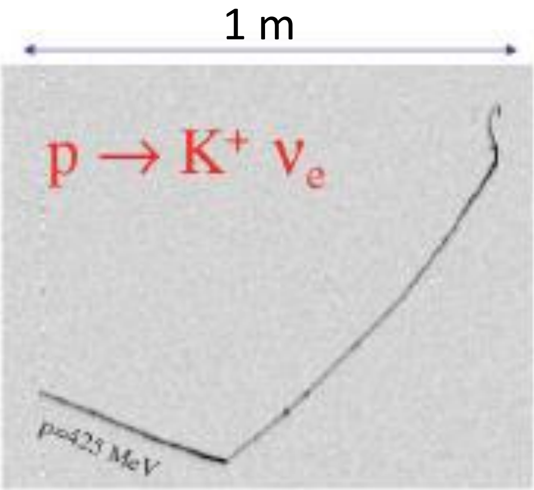
- Large matter effect in DUNE → mass ordering is “easy”
- DUNE will have >5σ significance after 1-4 years of Phase I, depending on true δ_{CP}
- DUNE has ~3σ sensitivity to CP violation in Phase I, but only if CPV is nearly maximal
  - ~50% chance of 3σ if $\delta_{CP} = \pi/2$
  - ~20% chance of 3σ if $\delta_{CP} = \pi/4$

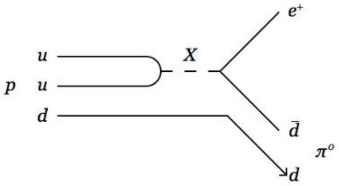
Observation of CP Violation, measurement of θ_{CP}

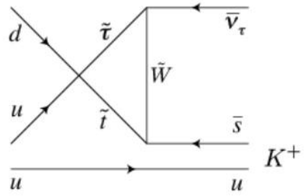


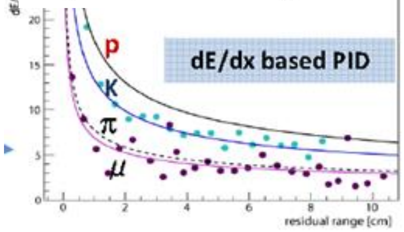


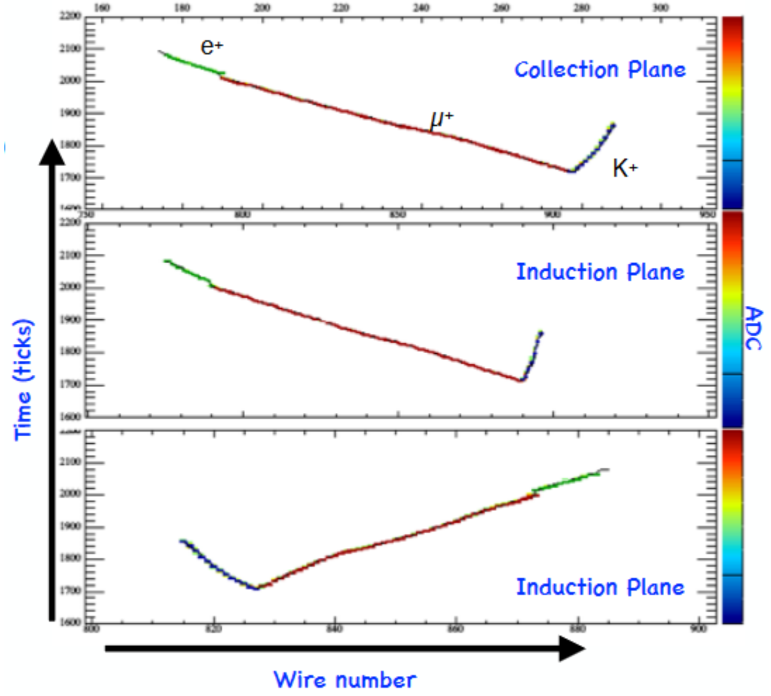
Proton Decay







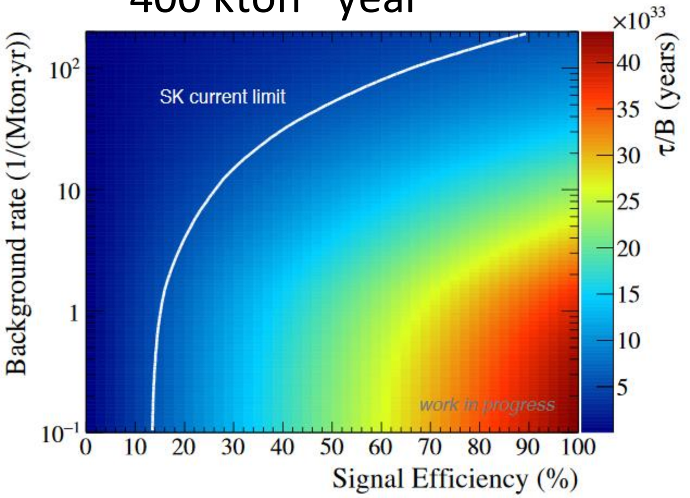




JHEP 0704 (2007) 041 200 kton*year, linear sensitivity imrovement with exposure

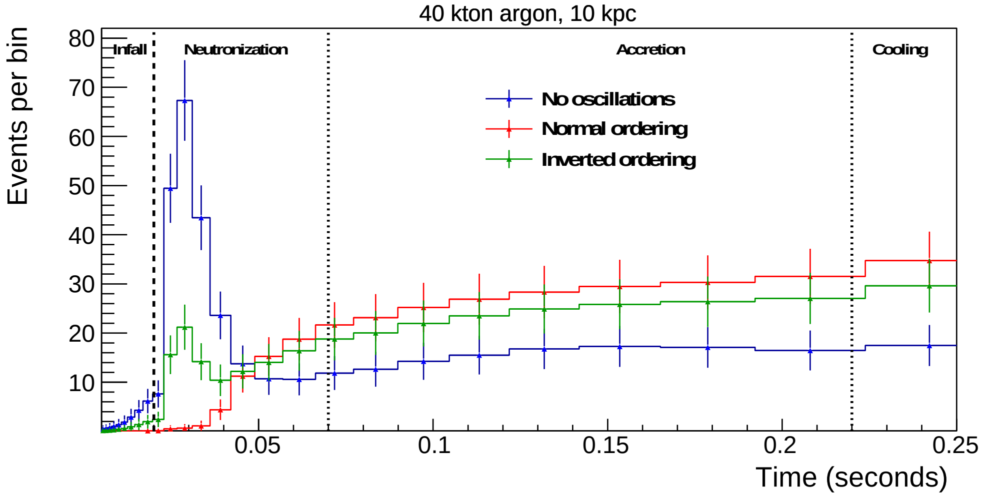
Mode	Lifetime (90%C.L.)
$p \to \nu K^+$	$>3\times10^{34}$ yrs
$p \to e^+\gamma$, $p \to \mu^+\gamma$	$>3\times10^{34}$ yrs
$p \to \mu^-\pi^+K^+$	$>3\times10^{34}$ yrs
$n \to e^-K^+$	$>3\times10^{34}$ yrs
$p \to \mu^+K^0$, $p \to e^+K^0$	$>1\times10^{34}$ yrs
$p \to e^+\pi^0$	$>1\times10^{34}$ yrs
$p \to \mu^+\pi^0$	$>0.8\times10^{34}$ yrs
$n \to e^+\pi^-$	$>0.8\times10^{34}$ yrs

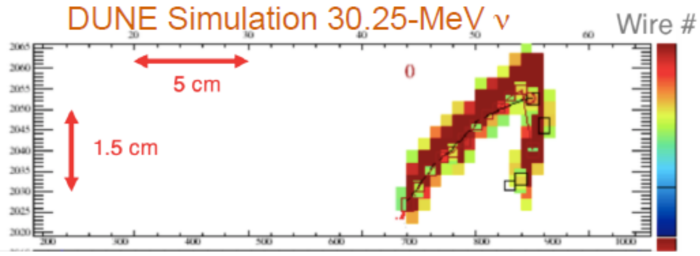
400 kton* year



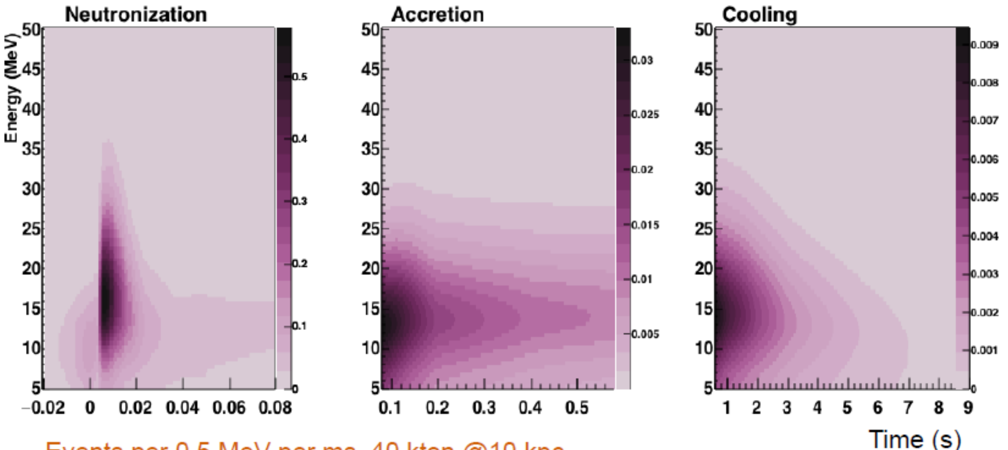
Supernova Neutrino Bursts

- Vast information from flavor-energy-time profile of events
- Unique sensitivity to ν_e's:
  - Elastic scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ ($x = e, \mu, \tau$)
  - Absorption: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ (E>1.5 MeV), $\overline{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ (E>7.5 MeV)
  - NC : $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$ ($x = e, \mu, \tau$)





Reaction	Livermore model [9]	GKVM model [10]
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$	2720	3350
$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770



Events per 0.5 MeV per ms, 40 kton @10 kpc

10 kpc 40 kton
NC ~ absorption

The Liquid Argon approach:

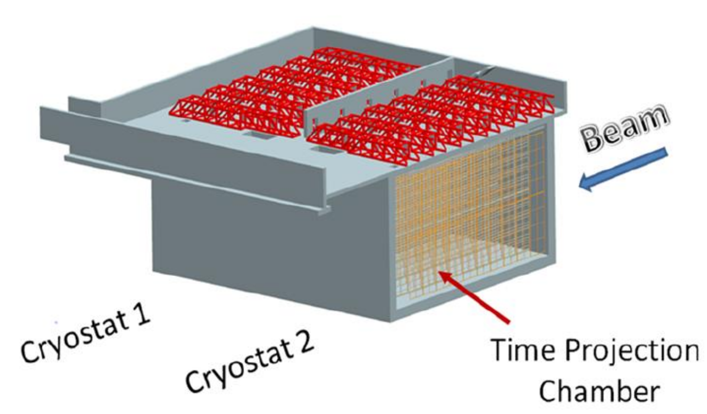
- LAGUNA-LBNO:

✓ Liquid argon TPC 20+50 kton

✓ High energy (>1 GeV) beam, all final states accessible

→ L/E pattern and second oscillation maximum

✓ Long baseline (>1000 km) → mass hierarchy measurement (2300km for LBNO)



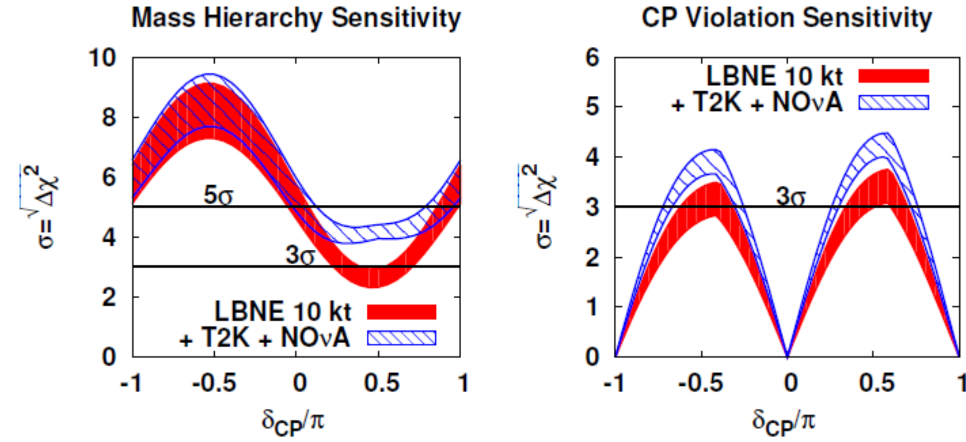
- LBNE project in USA (before 2014)

→ First phase 2022 (~900 M$):
700 kW beam from FNAL to Homestake,
1300 km → matter effects
10 kton LAr far detector on surface
no near detector

(→ marginal outcome of Phase I)

- Sensitivity from only first oscillation max.
- Needs very small syst. errors.

Further stages: underground far detector
35 kton, 2.3 MW beam (Project X)



Can resolve MH with $\geq 5/4\sigma$ for 50%/all δ_{cp} combined

Can resolve CPV with $\geq 3\sigma$ for 45% δ_{cp} combined

LAGUNA-LBNO Design Study:

2 EU programs: 2008-2011/2011-2014

~17 Meur investment

Completed August 2014

Prototyping activity for dual-phase since 2003

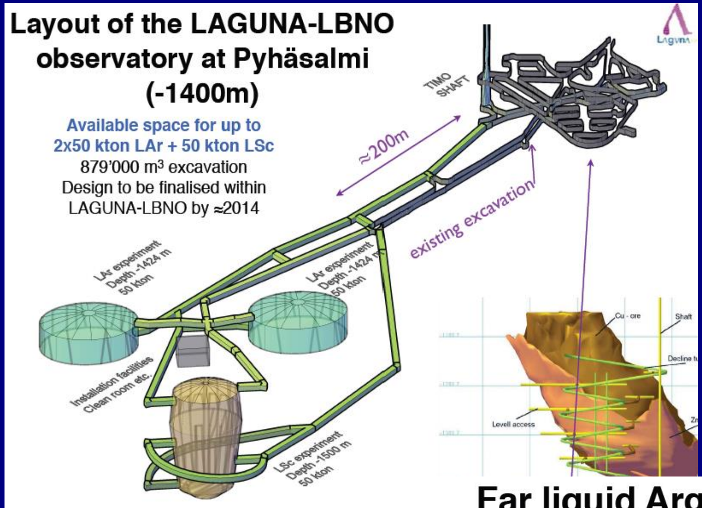
- LBNO EOI June 2012 (CERN to Pyhasalmi)

http://cdsweb.cern.ch/record/1457543

Physics program:

- Determination of neutrino mass hierarchy
- Search for CP violation
- Proton decay
- Atmospheric and supernovae neutrinos

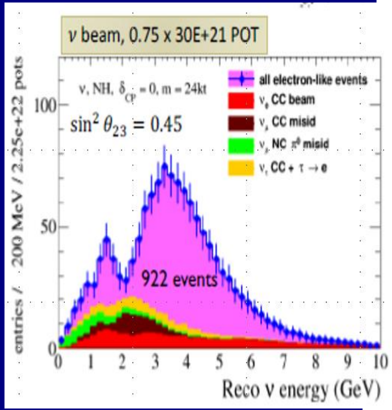
→ Use of a wide band beam to exploit the spectral information, relevance of the 2nd oscillation maximum for CP sensitivity


Layout of the LAGUNA-LBNO observatory at Pyhäsalmi (-1400m)

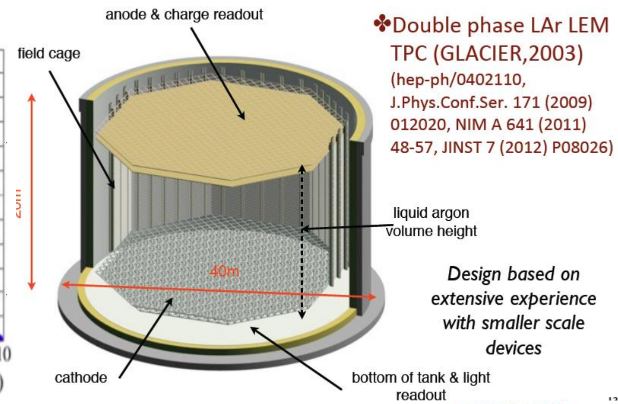
Available space for up to 2x50 kton LAr + 50 kton LSc

879'000 m³ excavation

Design to be finalised within LAGUNA-LBNO by ≈2014



Far liquid Argon detector



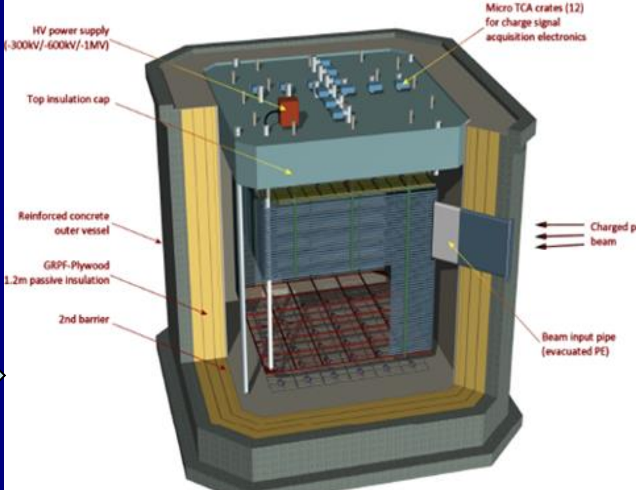
✤Double phase LAr LEM TPC (GLACIER,2003)
(hep-ph/0402110, J.Phys.Conf.Ser. 171 (2009) 012020, NIM A 641 (2011) 48-57, JINST 7 (2012) P08026)

Design based on extensive experience with smaller scale devices

2100 km from RAL, 1500 km from DESY, and 1160 km from Protvino.

Development of technical aspects for building an affordable underground detector. LBNO Phase I: 20 kton dual-phase LAr TPC

WA105/LBNO-DEMO (6x6x6 m³) approved at CERN in 2013 (now ProtoDUNE dual-phase)



LBNO physics strategy

- Select a very long baseline (2300km and optimized site for installation) to explore the L/E pattern predicted by the 3 flavor mixing mechanism over the 1st and 2nd max.
- Staged experiment adjusting the beam and detector mass on the bases of the findings of the first phase, most efficient use of resources:

- **Phase I (LBNO20)**
  24 kton DLAR + SPS beam (700 kW, 400 GeV/c), 15E20 pot, 25% antinu
  Guaranteed 5σ MH determination + 46% CP coverage at 3σ + proton decay + astroparticle physics

- **Phase II (LBNO70)**
  70 kton DLAR + HPPS beam (2 MW, 50 GeV/c) 30E21 pot, 25% antinu or Protvino beam, 80% (65%) CP coverage at 3σ (5σ) + proton decay + astroparticle physics

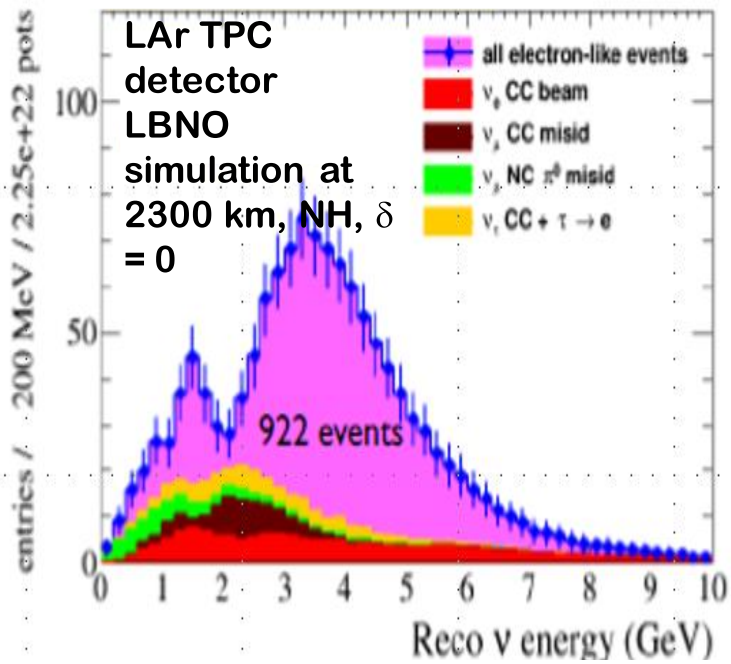
- Complementarity to HyperK (numu vs anti-numu at first max, 300 km) → L/E dependence at 2300 km, 25% antinumu. matter effects

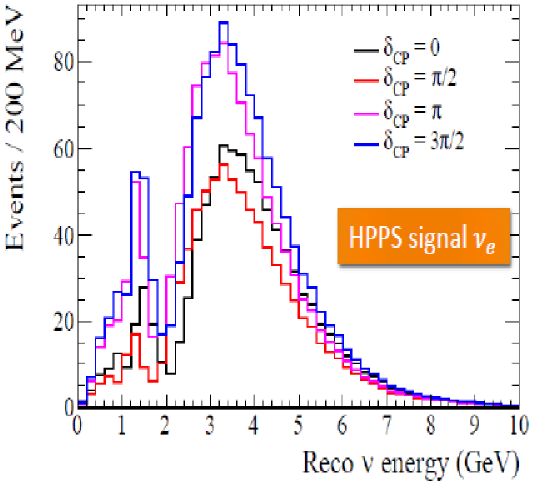
- L/E pattern measurement releases requirements on systematic errors related to the rate normalization at the first maximum

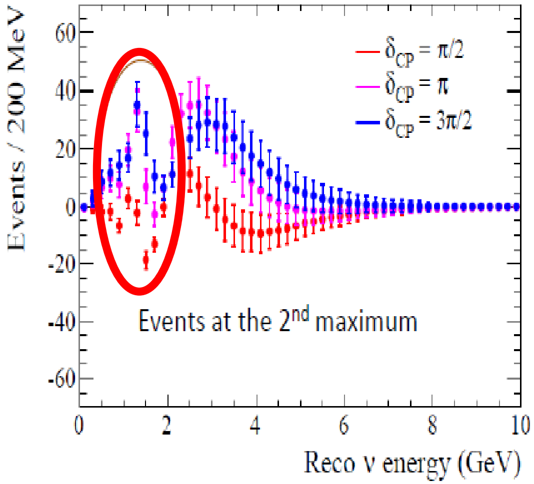
→ Guarantee MH at 5σ and incremental CP coverage satisfying the P5 requirements

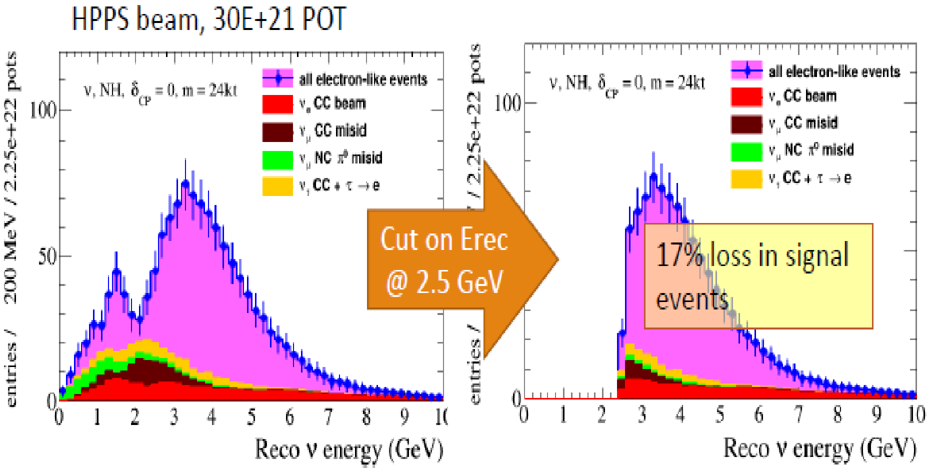
What is observed in the detector: relevance of spectral informations

ν_e CC spectrum for neutrino run


LAr TPC detector LBNO simulation at 2300 km, NH, $\delta = 0$

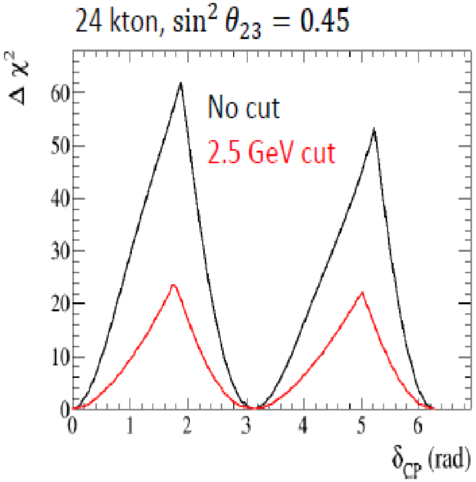

HPPS signal ν_e


Events at the 2nd maximum


HPPS beam, 30E+21 POT

Cut on Erec @ 2.5 GeV

17% loss in signal events


24 kton, $\sin^2\theta_{23} = 0.45$

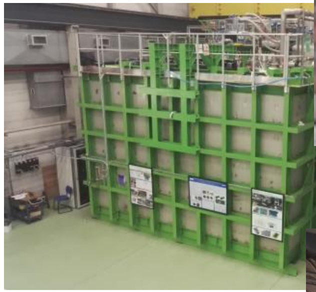
No cut

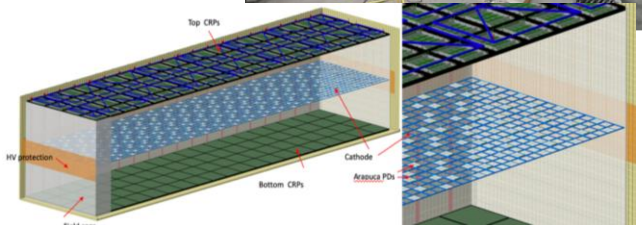
2.5 GeV cut

Studying CP at only the first oscillation maximum results in a strong loss of sensitivity!

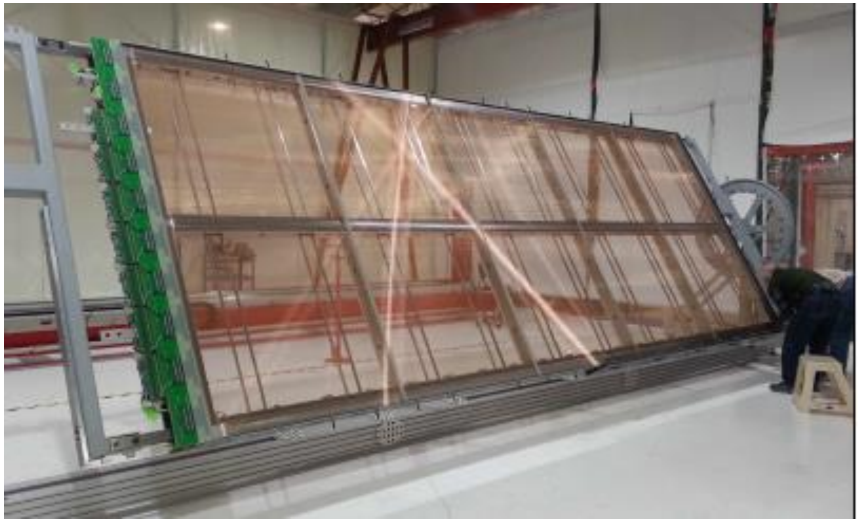
A little bit of history of the project in France:

- LAr **R&D started in 2006 at IPNL/IP2I for the charge readout electronics**, also **supported by the LABEX LIO since 2012**
- INPL with other IN2P3/CEA groups contributed to the **LAGUNA-LBNO program (2008-2014) and R&D** where the **dual-phase detector** technology was developed
- **Project for the dual-phase R&D program at CERN** launched **at CS IN2P3 of June 2013 for LBNO-Demo**, then becoming **NP02/protoDUNE dual-phase in 2015**
- **D.A.** contributed in **2014** to the **fusion of the EU and US efforts** and to the birth of DUNE (**IIEB, LBNF/ELBNF EOI**)
- Since **2015** → **DUNE/protoDUNE IN2P3 project**
- **2016-2017: construction and operation of the 3x1x1** detector. Provided: Charge Readout Electronics (IP2I), suspension system of Charge Readout Plane (LAPP)
- **2017-2019: construction of NP02/protoDUNE dual-phase**. Provided: Charge Readout Electronics (IP2I), Charge Readout Planes (LAPP/CERN) +LEMs (CEA), DAQ system (IP2I)
- 2017 start of discussions for **DUNE IR project**, **2018 DUNE in TGIR roadmap**
- **2018 IN2P3 CS, start of discussions for TGIR project**, based on DP module: submitted summer 2019, on the way of approval in fall 2020
- **August 2019-September 2020: operation of protoDUNE dual-phase**
- **October 2020- December 2020: definition of Vertical Drift FD module #2**
- **2021-2022 Vertical Drift tests large scale campaign at CERN**
- **2023-2024 Vertical Drift Module-0**
- **2023 IN2P3 KDP3 Review and DUNE MOU**
- **2024 Start of production**
- **2027 FD module #2 Installation**

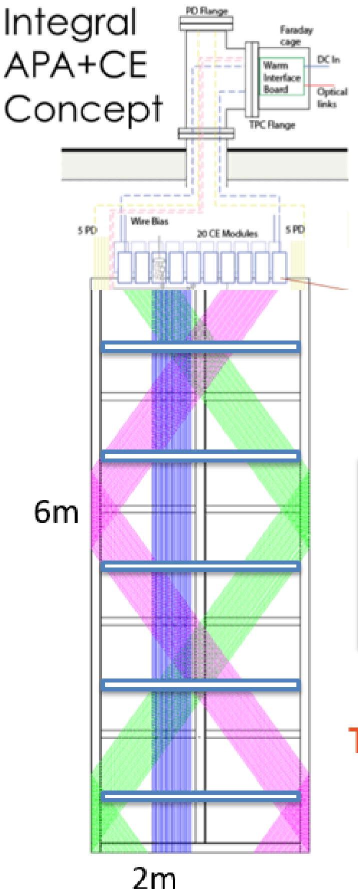




Single-phase/horizonal drift active elements design: Anode Planes Assemblies (APA)



6x2 m^2 Modules of 3 wire planes immersed in LAr: Anode Plane Assembly



Core detector element: Anode Plane Assemblies (APA) with integrated Cold Electronics Boards and Ph.Detector modules

Each APA : 960 X, 800 V, 800 U, 960 G (un-instrumented) wires

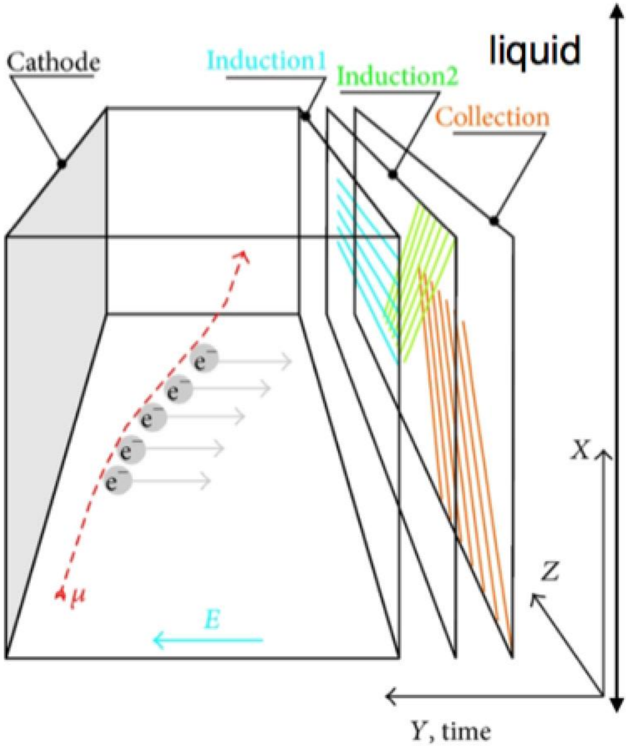
10 Photon Detectors are installed into each APA frame

20 ColdElectronics Boxes mounted onto the APA frame and connected to the wires - 2560 Channels-Wire

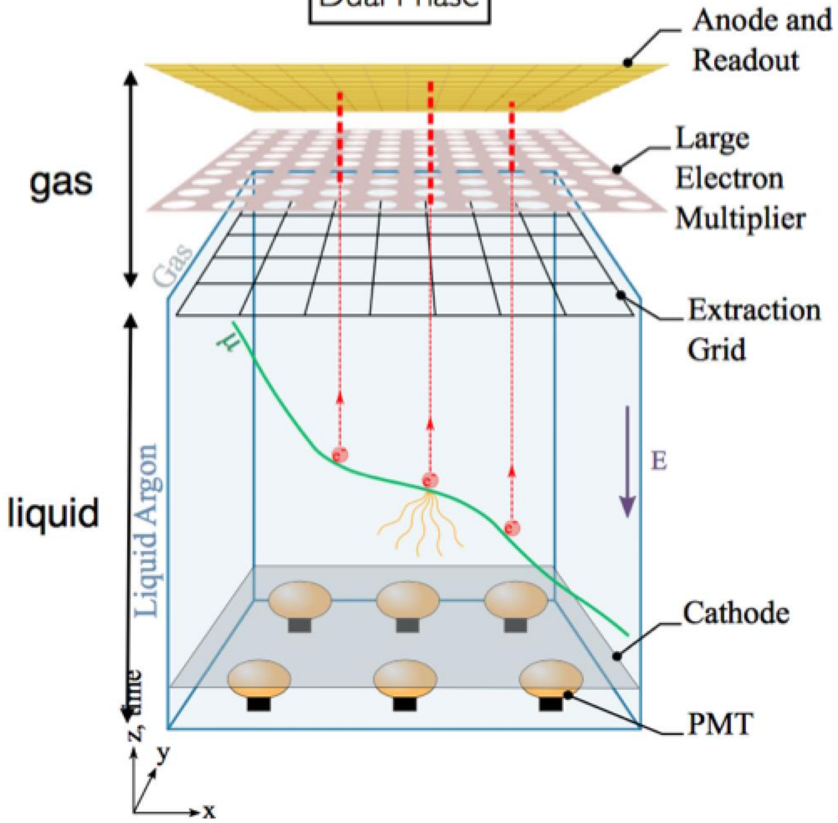
The modular approach to detector construction enables the construction of detector elements to take place in parallel and at multiple sites.

This will be an essential approach for the DUNE Far Detector

Single Phase



Dual Phase



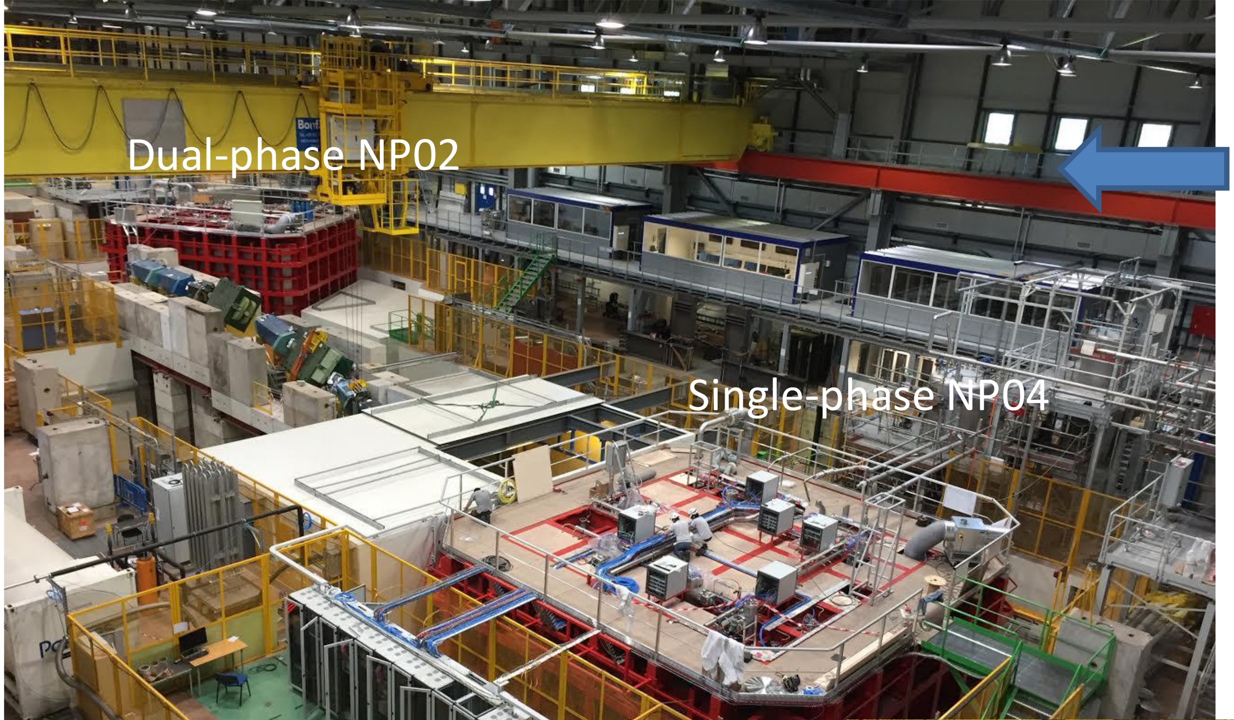
Single-phase Design:

- Ionization charges drift horizontally and are read out with wires
- Drift up to 3.6 m
- No signal amplification in liquid
- Read out by APAs (wire planes)

DUNE originally committed in deploying both technologies in 10 kton modules. Planning: Module #1 SP, Module #2 DP

Dual-phase Design: long drift (up to 12 m), high S/N:

- Vertical drift → extraction of electrons from the liquid and multiplication in avalanches in micro-pattern detectors LEM (Large Electron Multipliers) operating in pure argon gas.
- Tunable LEM gain ~20 , two symmetric collection views, coupling to cold electronics accessible through chimneys on top
- Light readout performed with an array of cryogenic photomultipliers below the cathode



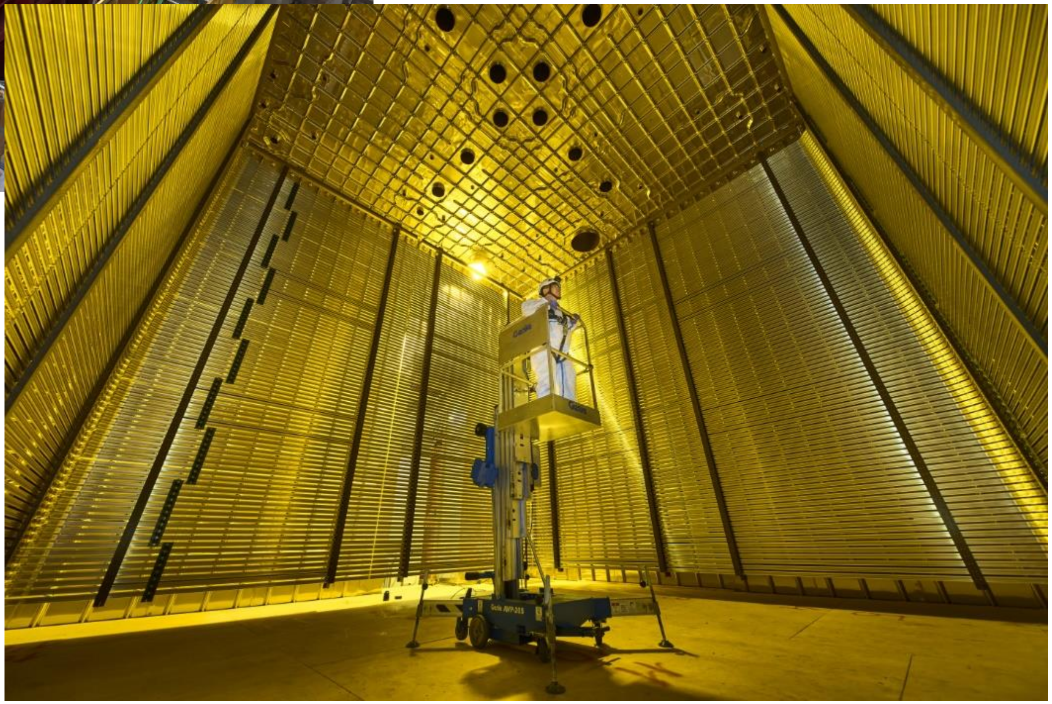
ProtoDUNE detectors at
CERN EHN1 Neutrino Platform

Dedicated charged particles test-beam lines 1-10 GeV/c + beamline instrumentation for particles identification: tagging of e, muons, pions, kaons, protons

Membrane cryostats with LNG tanks technology and external steel structure

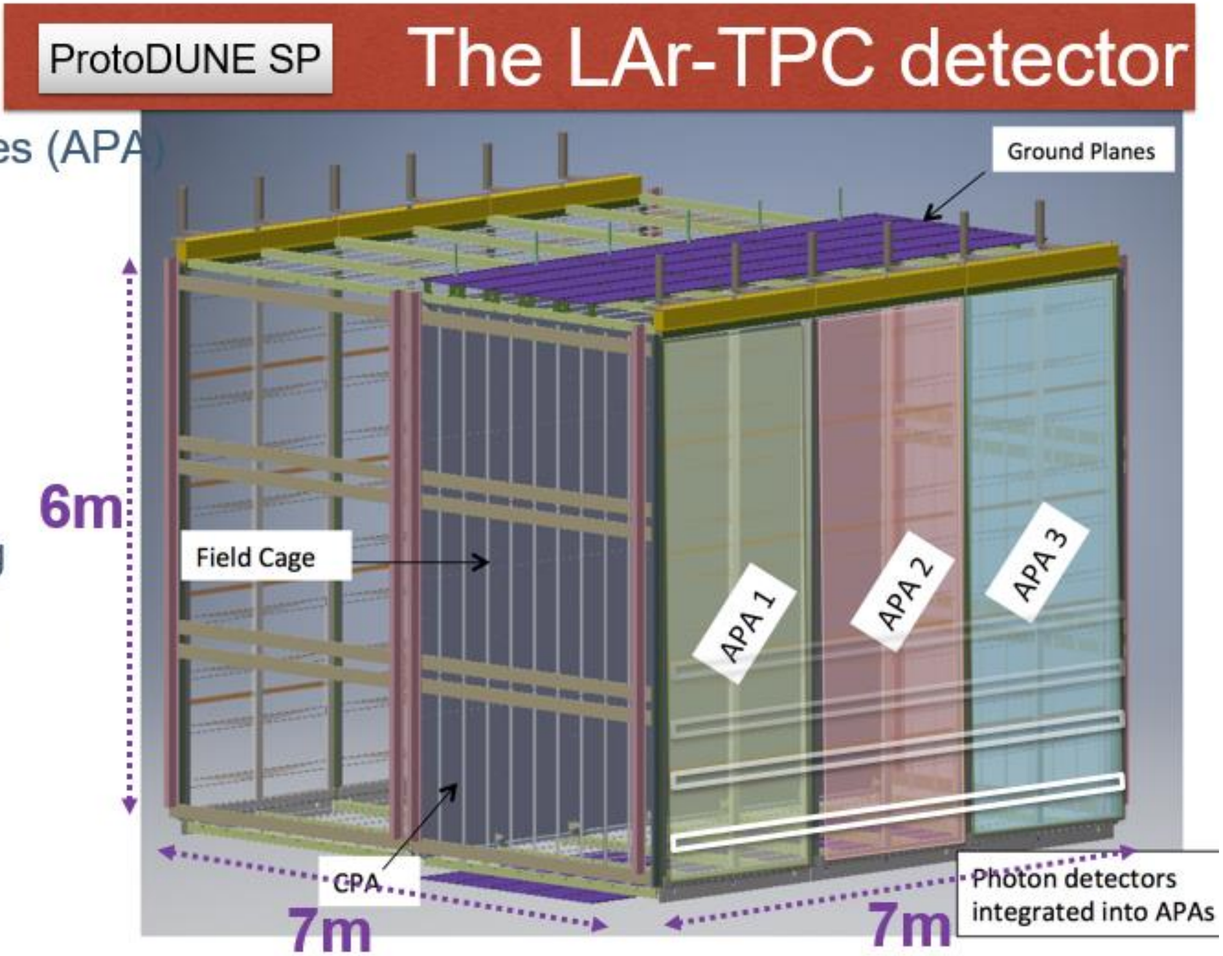
11m x 11m x 11 m external size

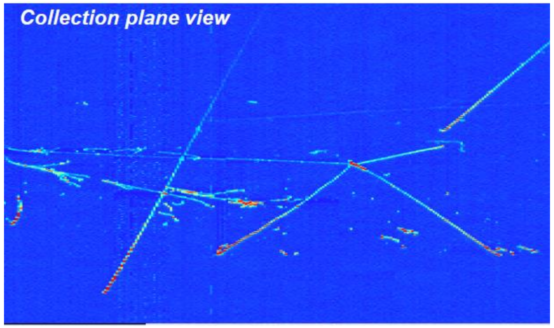
ProtoDUNE dual-phase
(view inside the field cage
Spring 2018)



The ProtoDUNE SP Detector

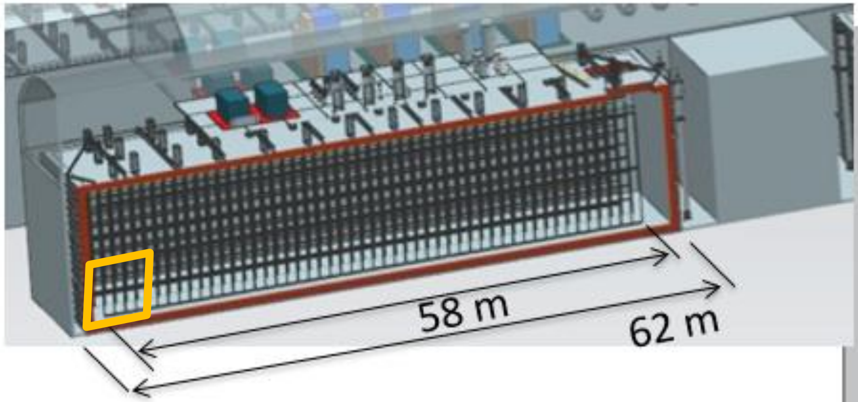
- Six Anode Plane Assemblies (APA)
  - 3 APAs on each side
- Central cathode plane
  - -180 kV nominal
- Field Cage for field shaping
  - shaped profiles / G-10 I-Beam
  - Constructed in panels
- Ground Planes



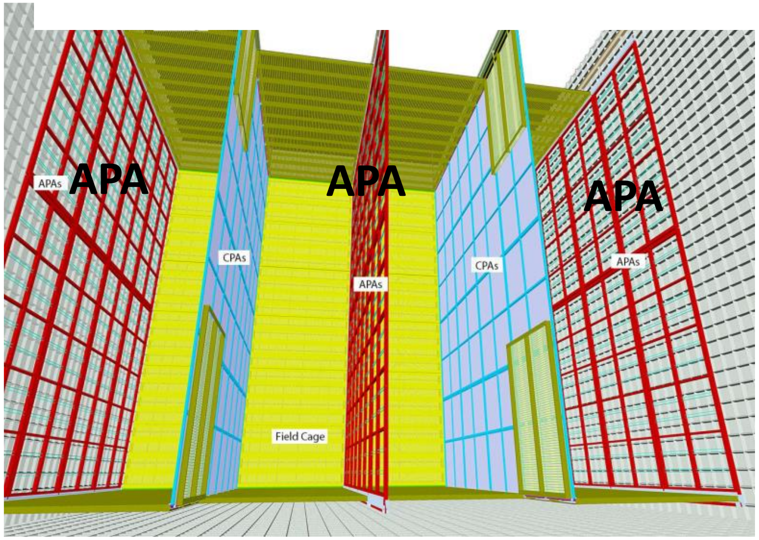


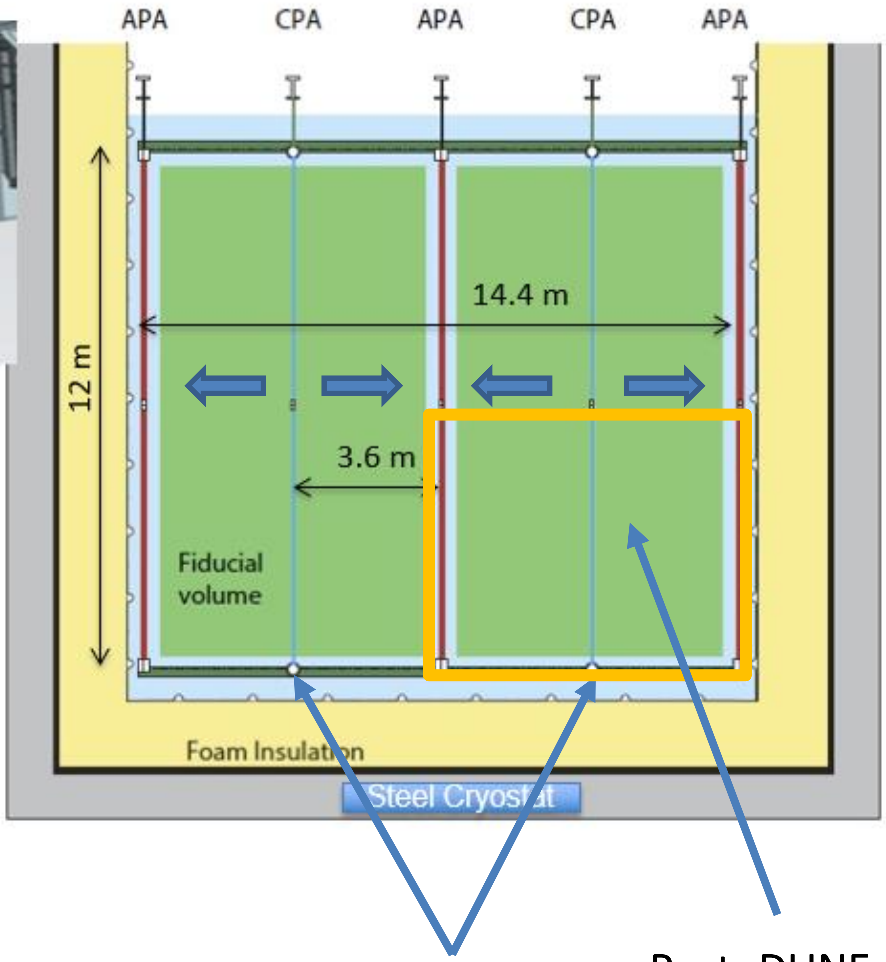
Phase-I operation: September 2018 – July 2020
Detector then emptied for upgrades

Drift space in between anode and cathode planes in NP04



- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - Cold electronics 384,000 channels
- Cathode planes (CPA) at 180 kV
  - 3.6 m max drift length





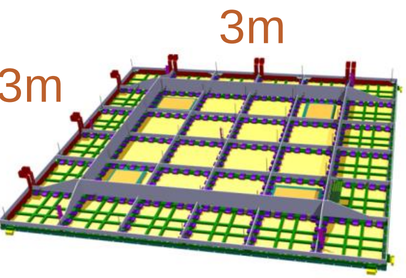
Cathode planes

ProtoDUNE-SP section

DUNE 10 kton Single-phase module

x40 ProtoDUNE-SP

Dual-phase readout



Charge Readout Plane integrating LEM-anode sandwiches

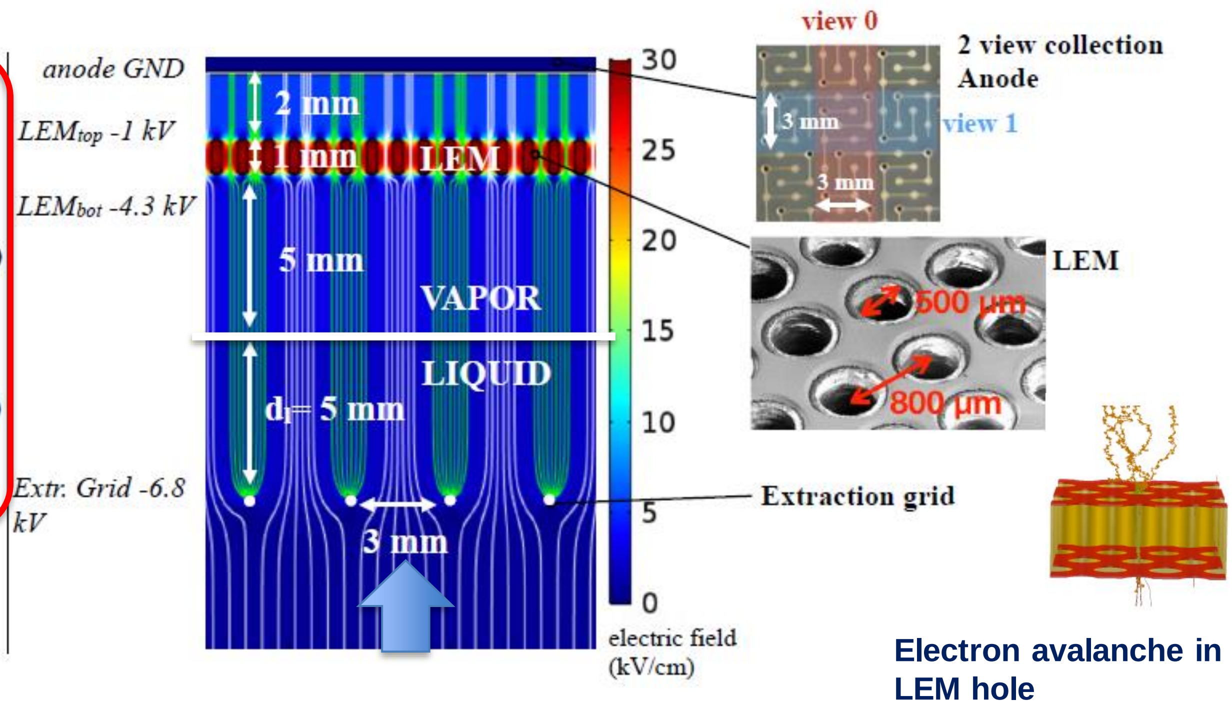
induction
5 kV/cm

amplification
33 kV/cm

extraction (vapor)
3 kV/cm

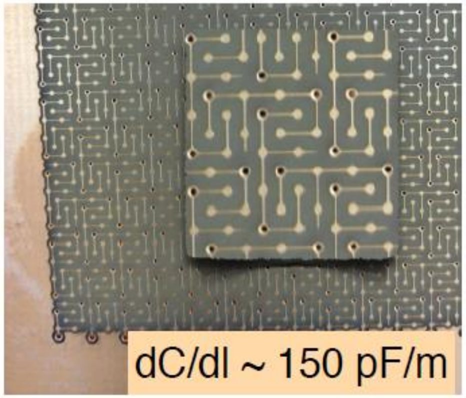
extraction (liquid)
2 kV/cm

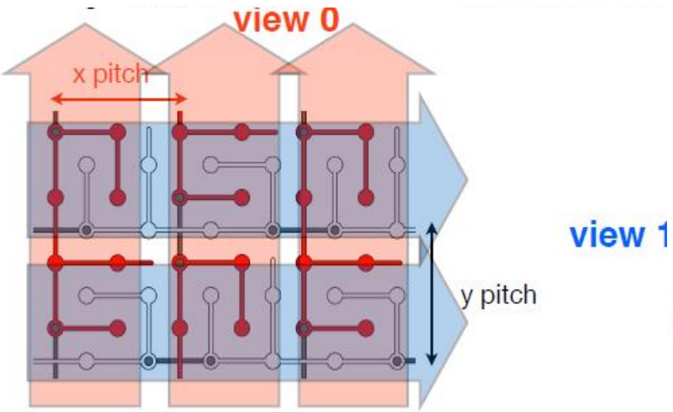
drift
0.5 kV/cm



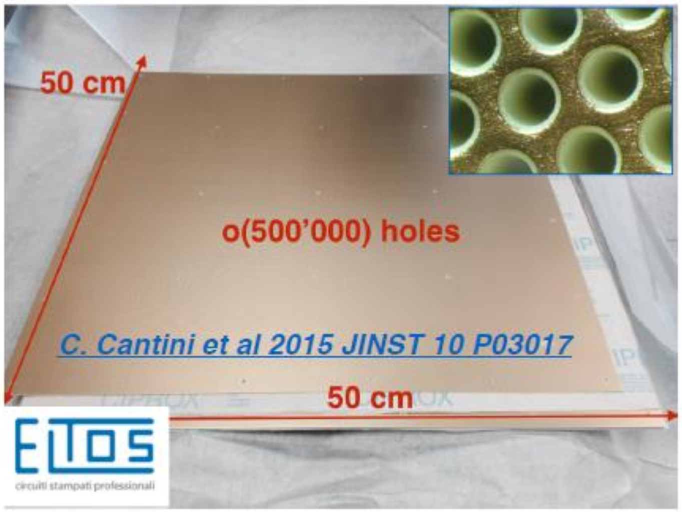
Electron avalanche in LEM hole

50x50 cm² anodes with 2 collection views

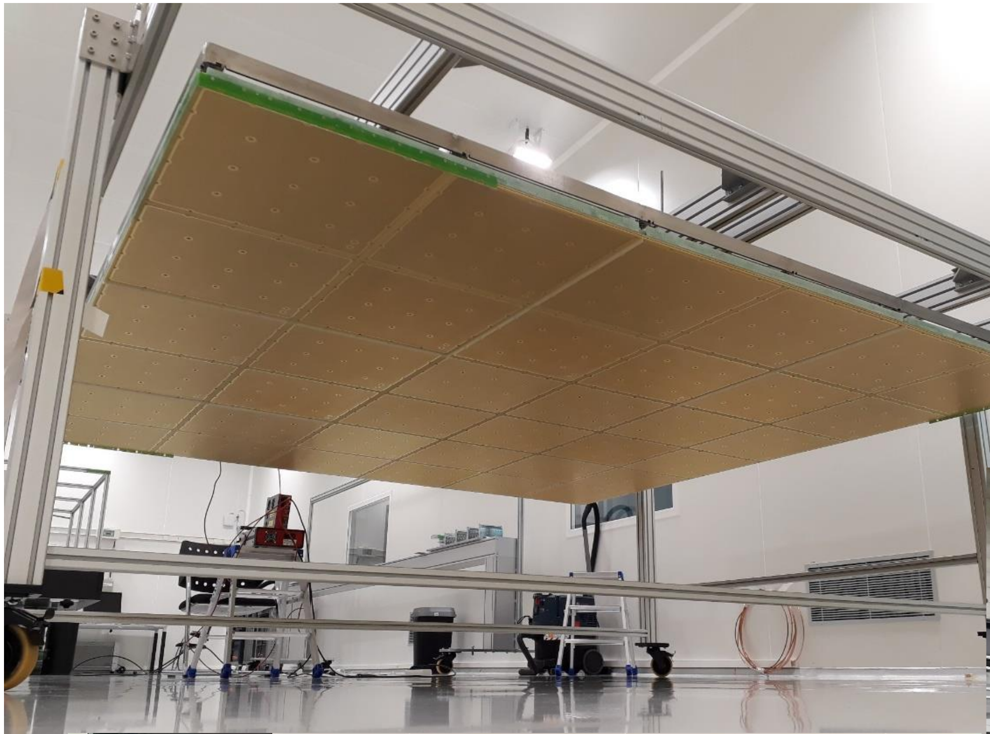




50x50 cm² LEM

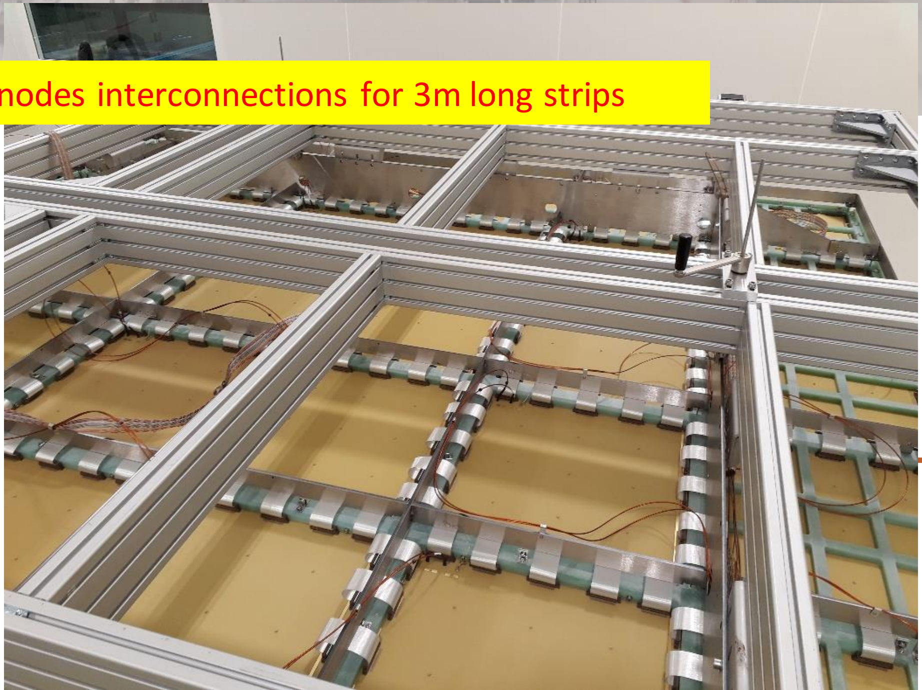


C. Cantini et al 2015 JINST 10 P03017



Charge Readout Plane (CRP) with LEM/anodes mounted

CRP cold--box test



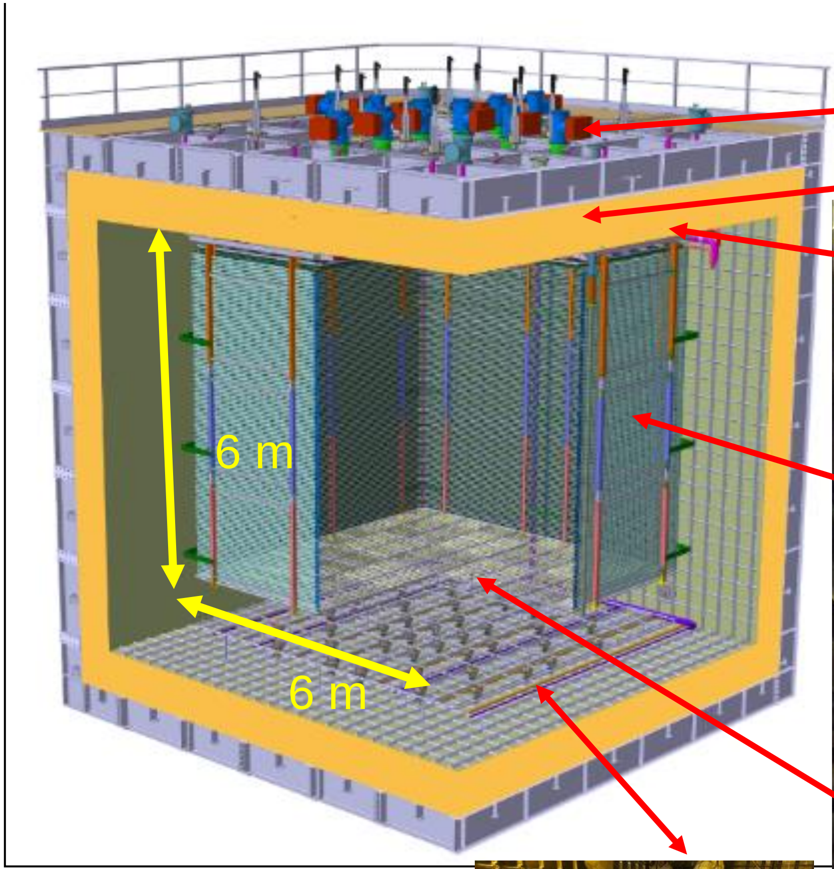
Anodes interconnections for 3m long strips

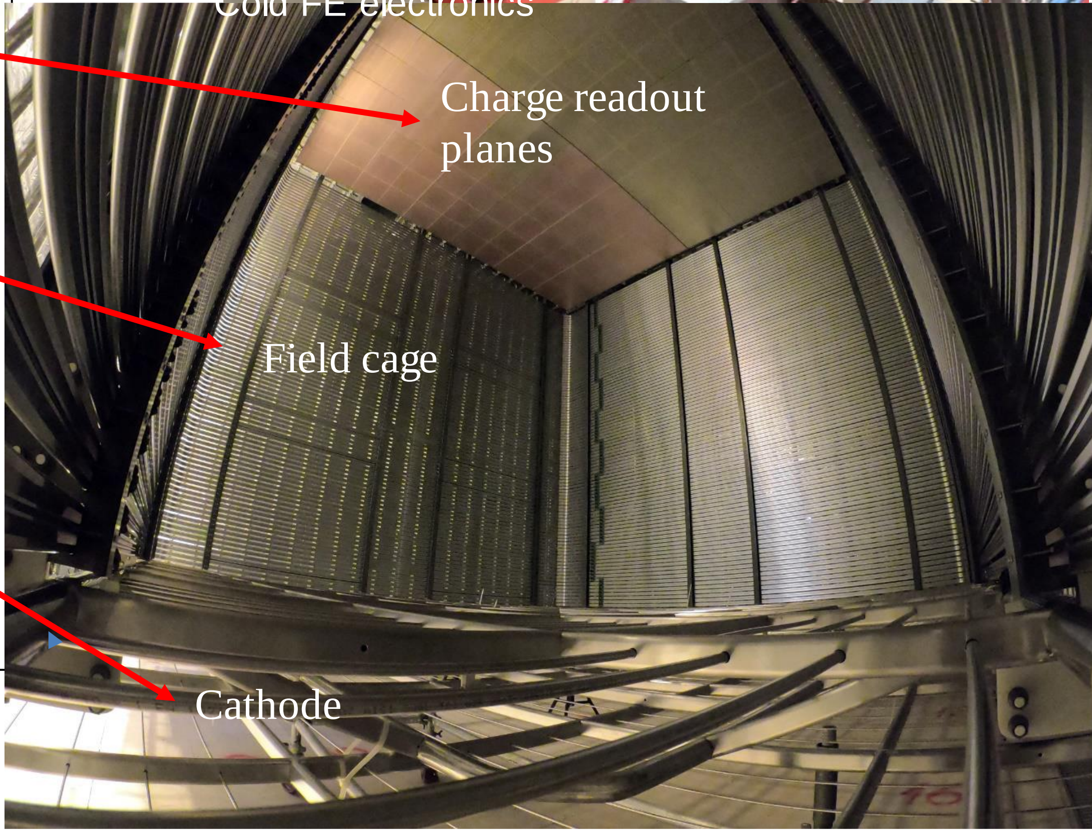
NP02/protoDUNE dual-phase

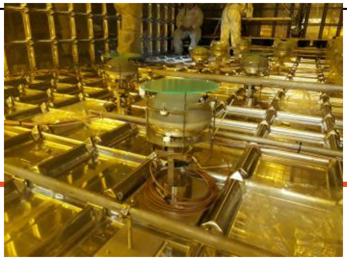
dual-phase FD design based on NP02:

- 1/20 of active area of DP 10 kton
- NP02/protoDUNE DP 4 CRPs → DUNE 80 CRPs

Construction 2018-19 Operation 2019-20

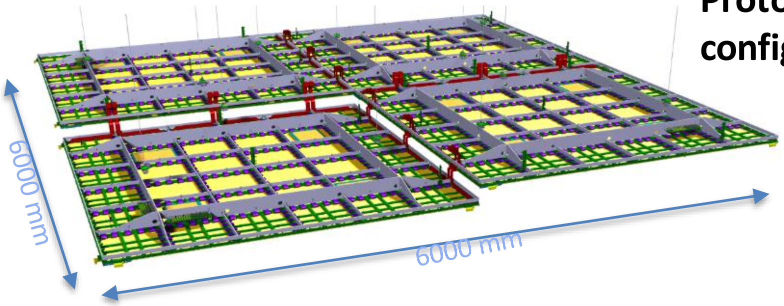






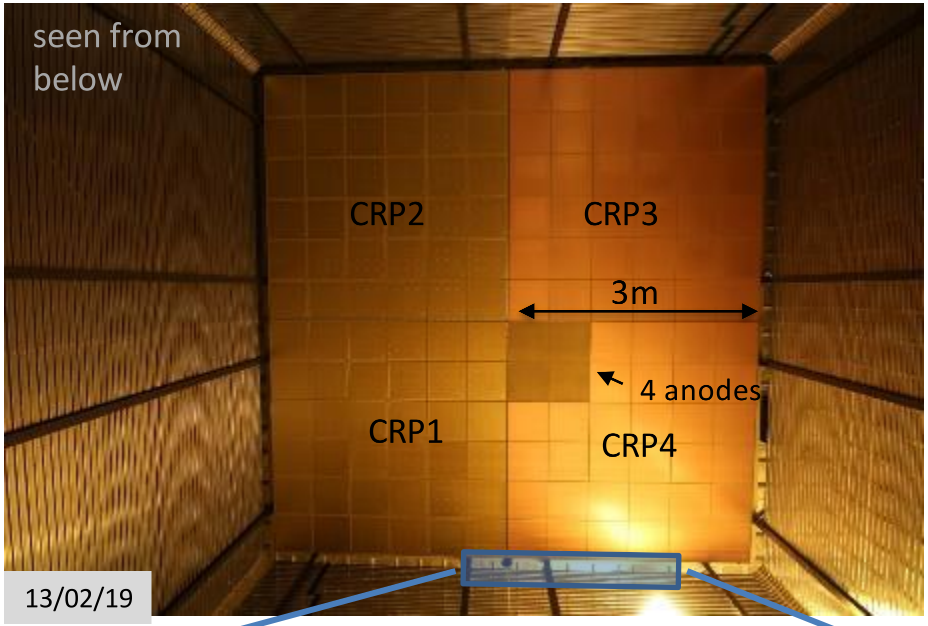
36 cryogenic photomultipliers
Hamamatsu R5912-02mod
with TPB coating

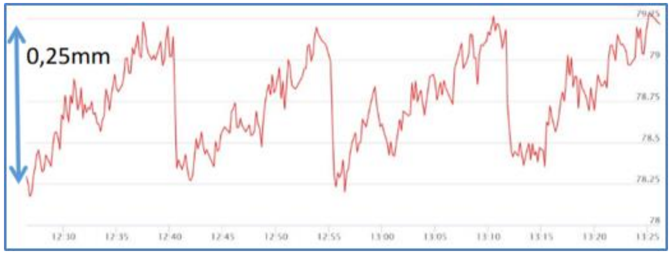
Charge Readout Planes

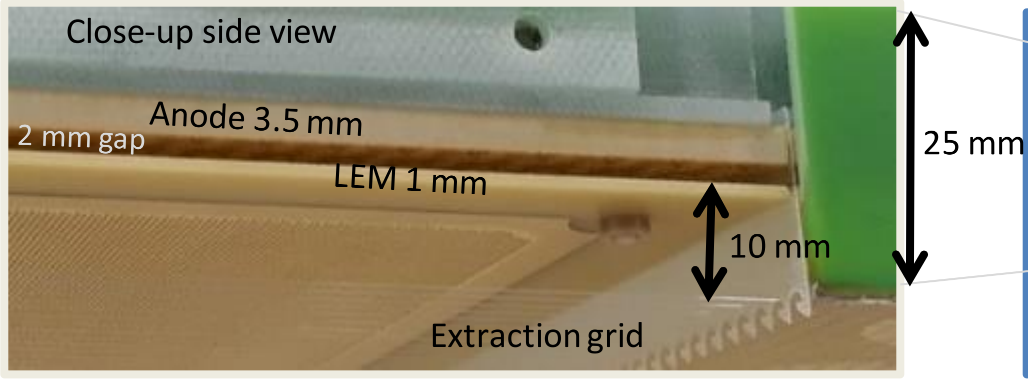


ProtoDUNE-DP configuration

4 CRPs

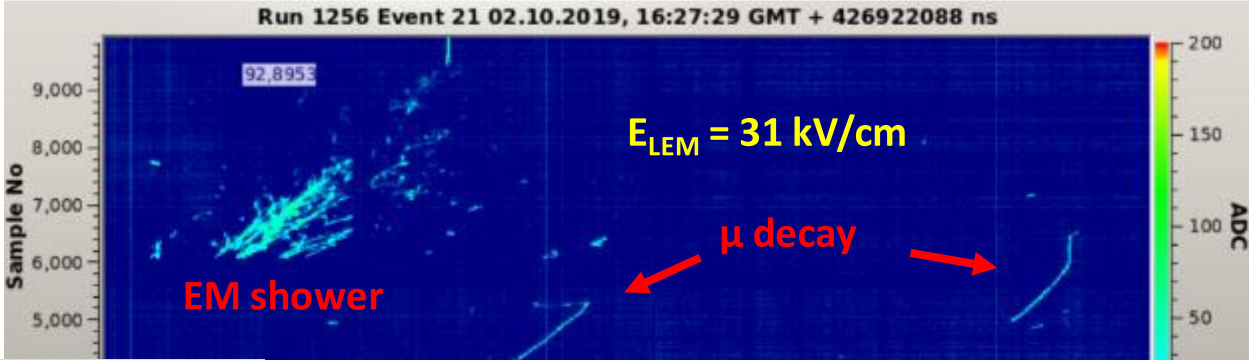




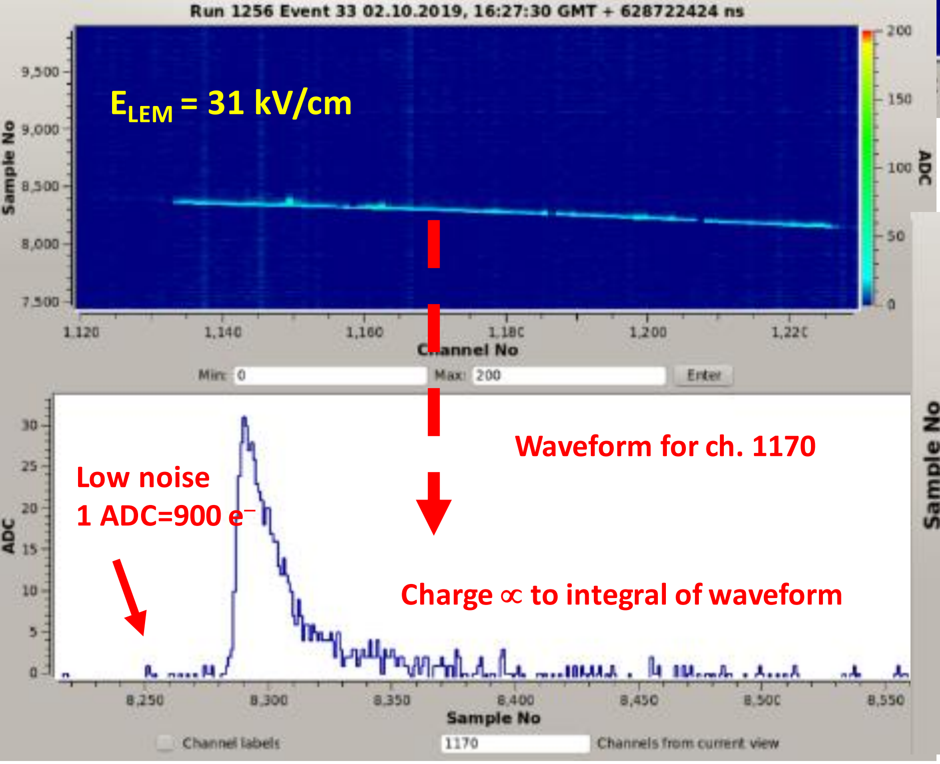


Examples of cosmic ray events

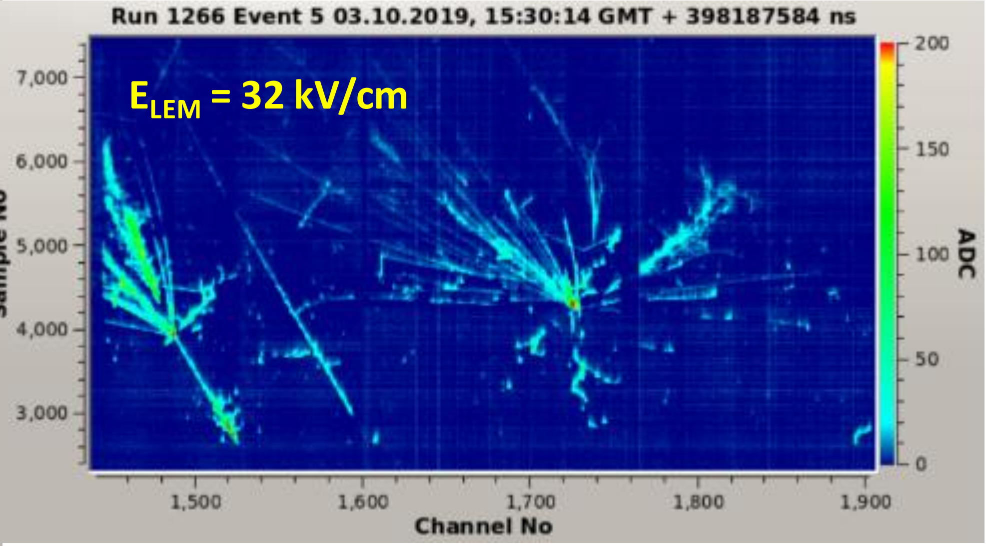
Electromagnetic shower + two muon decays



Horizontal muon track

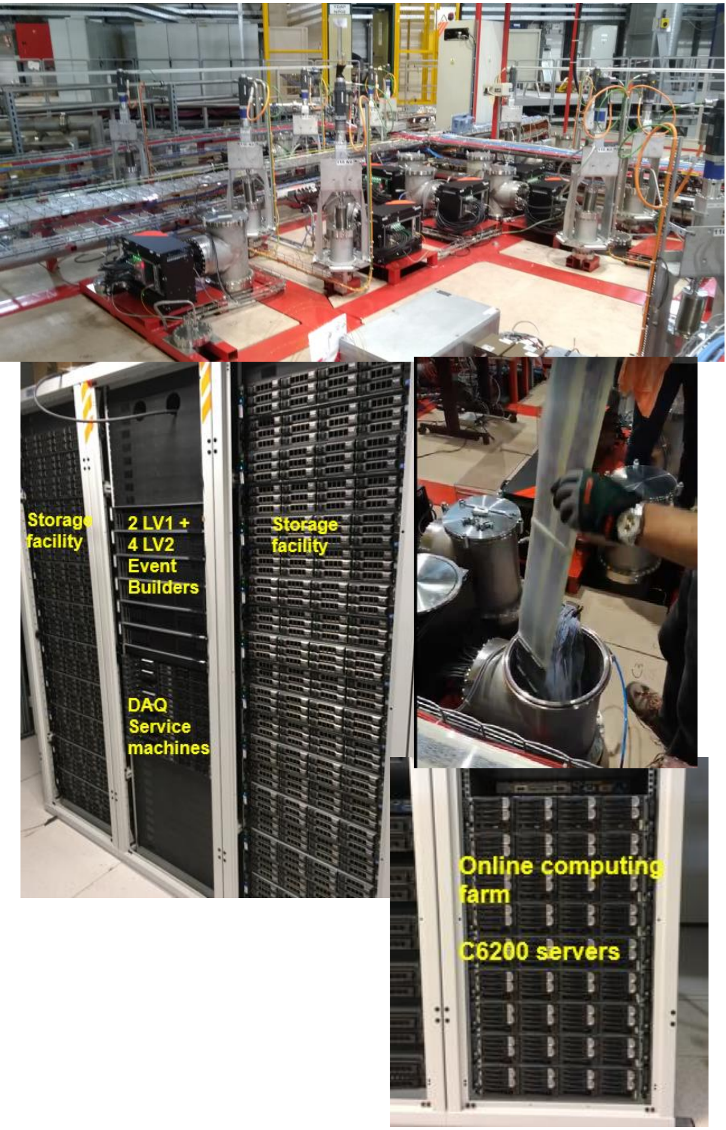


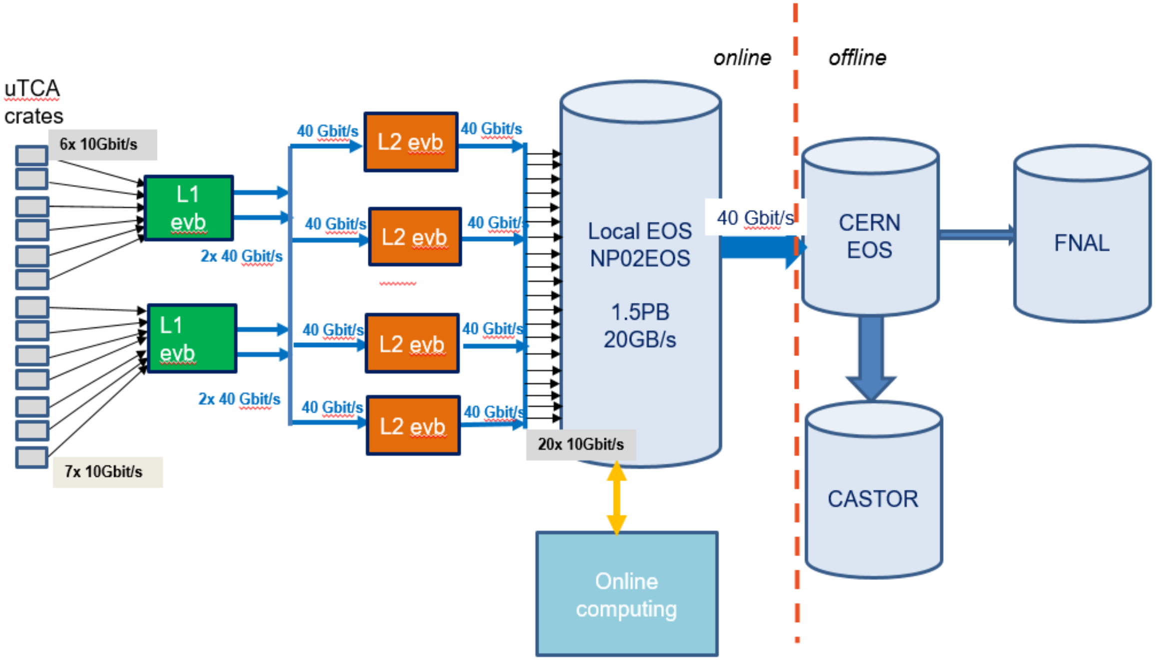
Multiple hadronic interactions in a shower



Charge readout electronics & DAQ

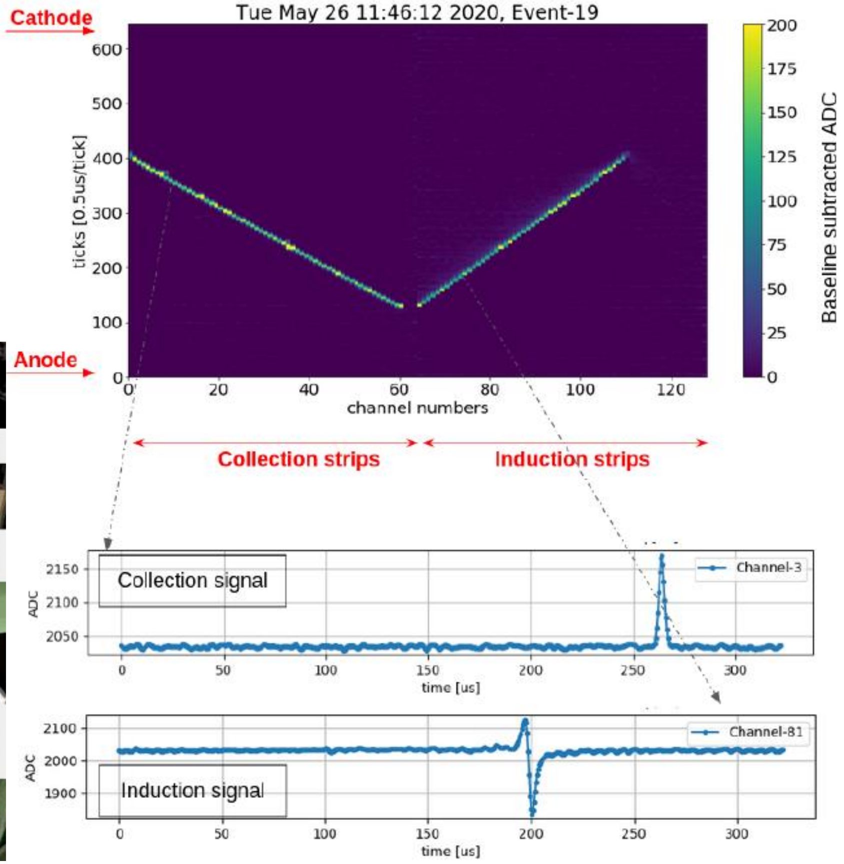
NP02 DAQ/network infrastructure

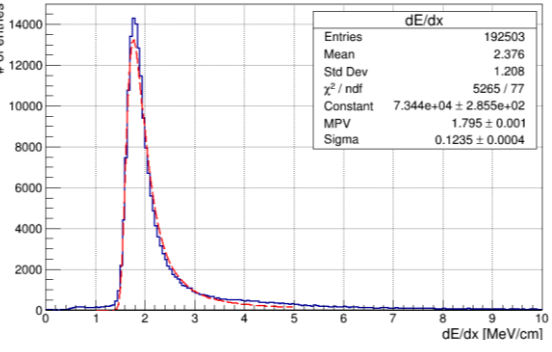


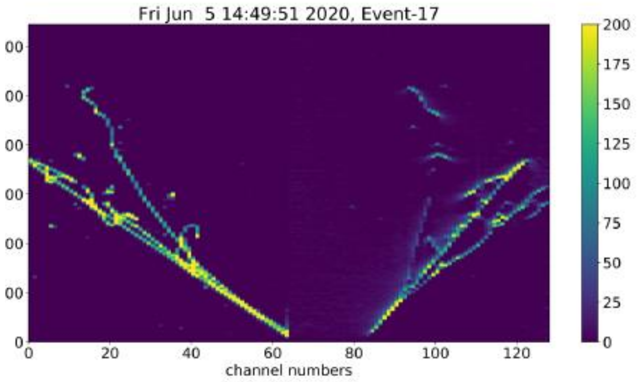


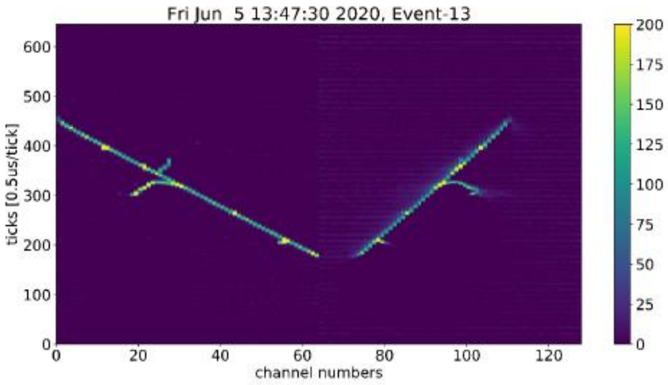
- ✓ Excellent performance of front-end analog cryogenic electronics, digital uTCA front-end electronics and DAQ back-end system (20 GB/s data storage bandwidth)
- ✓ Low noise ~1.5 ADC RMS dominated by residual issues on slow control grounding. FE electronics accessibility demonstrated
- ✓ Fast reconstruction (15s/event) performed on real time on the online computing farm (450 cores)

Perforated anodes tests at CERN Neutrino Platform with the 50l TPC test stand (Summer 2020)









The evolution of dual-phase: can we think of a simplified version of the detector without LEMs which could be immediately built for DUNE, quickly and at affordable costs ?

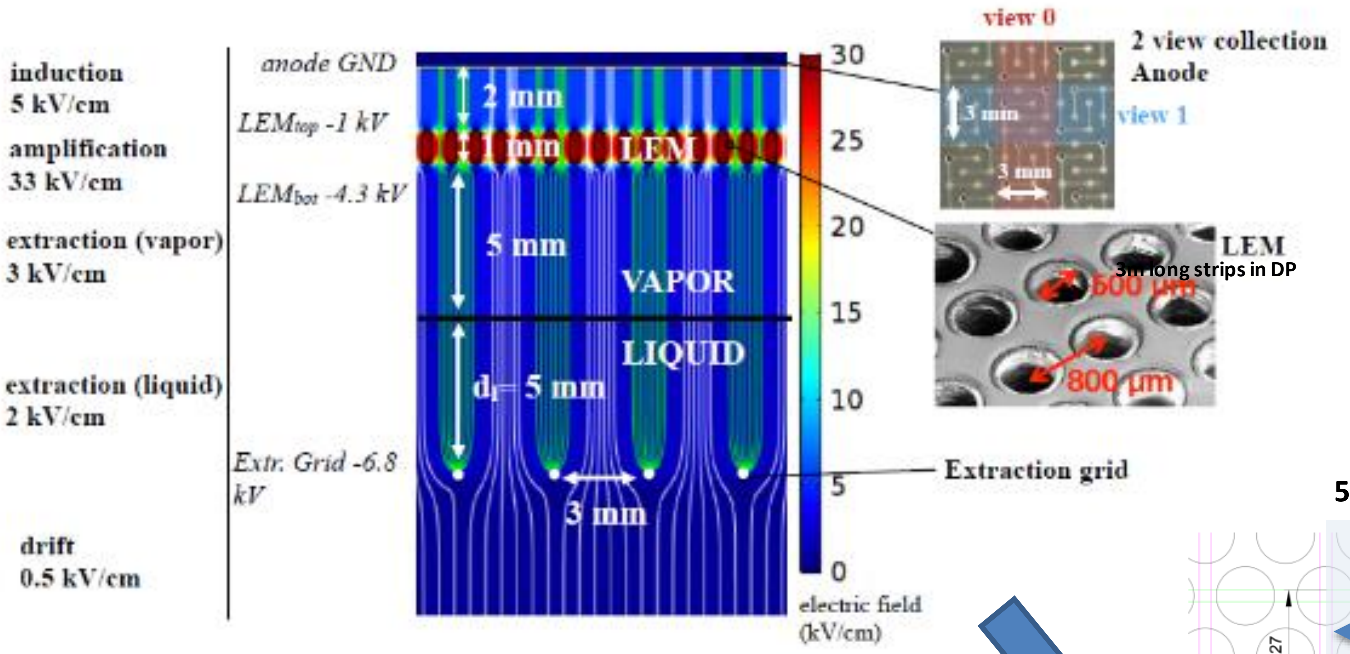
→Yes, the so called « **Vertical Drift** » which immediately became the baseline for the second (and future) DUNE Far Detector Modules

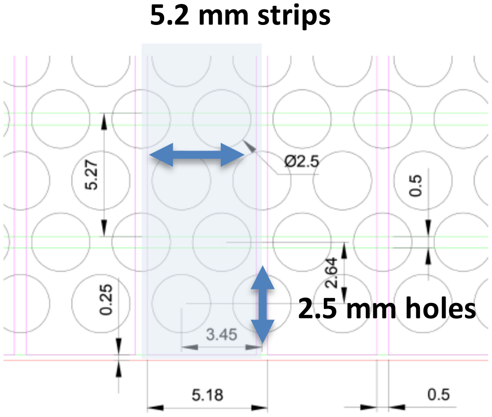
- **No LEMs → CRP evolution to perforated anodes**
- **No further changes in the cryostat needed to ensure better stability of LAr surface, can work with current performance**
- **No 600 kV → ~300 kV operation**
- **All detector components developed for dual-phase (CRPs, electronics, field cage, cathode, HV system) and associated investments maintained**
- **Geometry optimized to increase the sensitive volume, very much needed for physics → 15 kton**
- **Large cost and time reductions from the point of view of installation costs in South Dakota with the vertical geometry and simpler modularity of components**

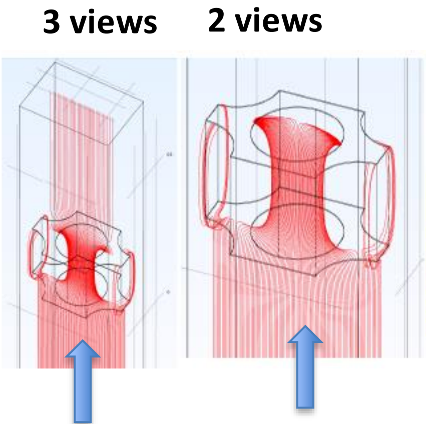
- **Tests at CERN on Vertical-Drift perforated anodes, since beginning of summer 2020 and then achieved in more complicated configurations (3 views)**

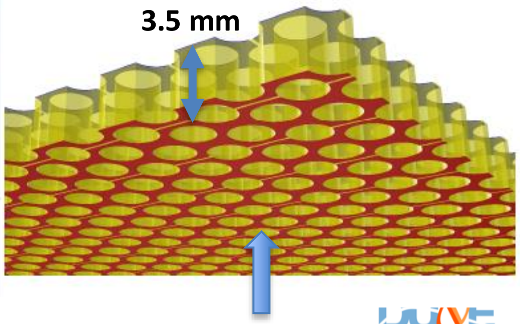
→ Fully launched at the end of 2020 the evolution from the dual-phase to the Vertical Drift

Evolution of CRP charge readout stack: Dual-Phase → Vertical Drift







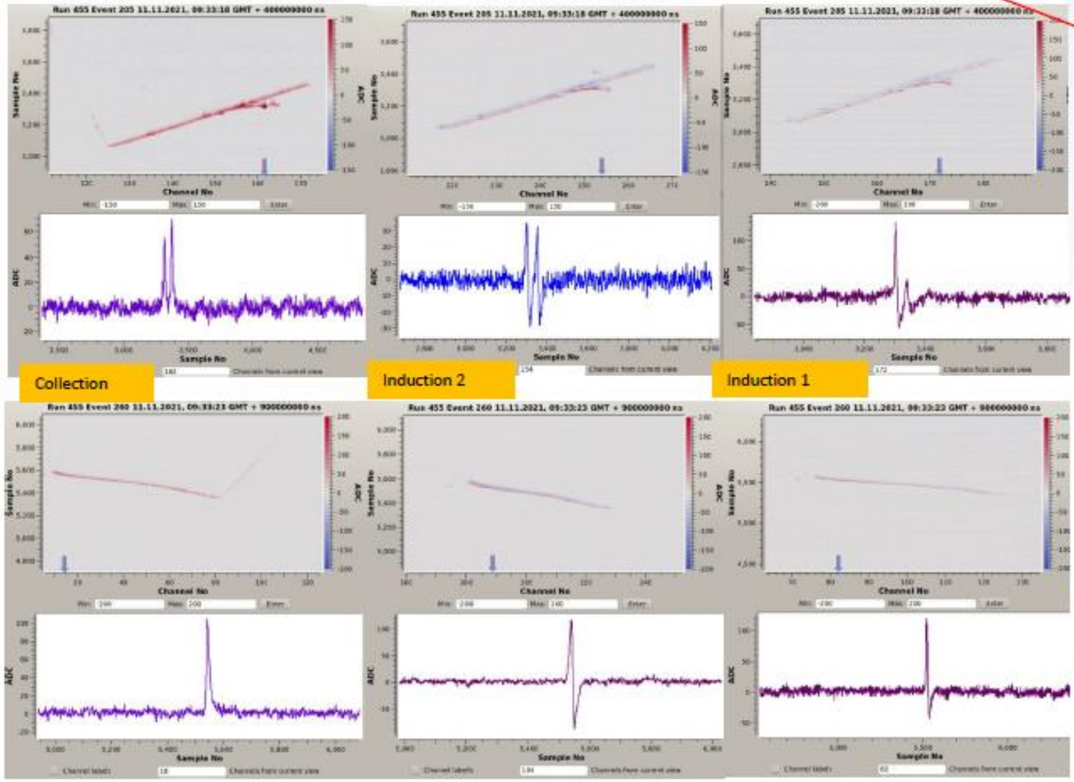


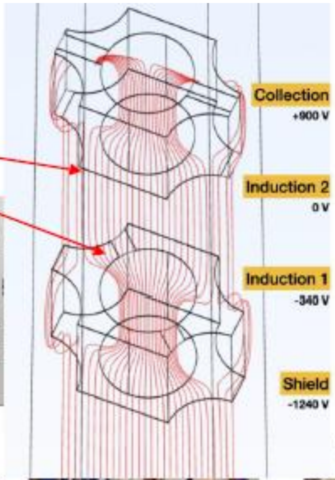
Vertical drift:

- Anode PCB (3.2 mm thick) directly immersed in LAr, 2.5 mm holes
- Perpendicular strips on the top and bottom faces of the PCB: 5.2 mm pitch, 1.5 or 1.68 m long
- Bottom strips induction signals, top strips collection, 1kV across for full transparency

Images and channel waveforms for the 3 views

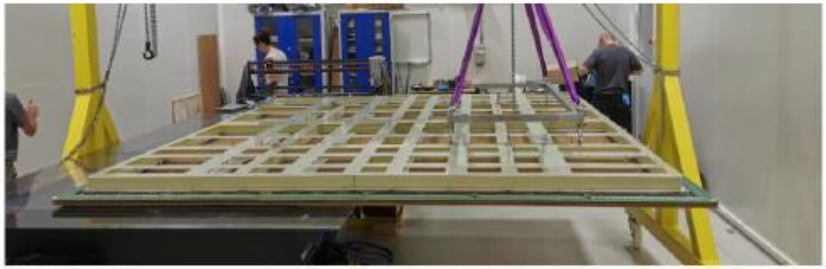
- → induction views have, as expected, bipolar signals due to the approaching and departure of the electrons
- → Last view (collection) has unipolar signals





Composite structure supporting the stack of two perforated PCB with the 3 views

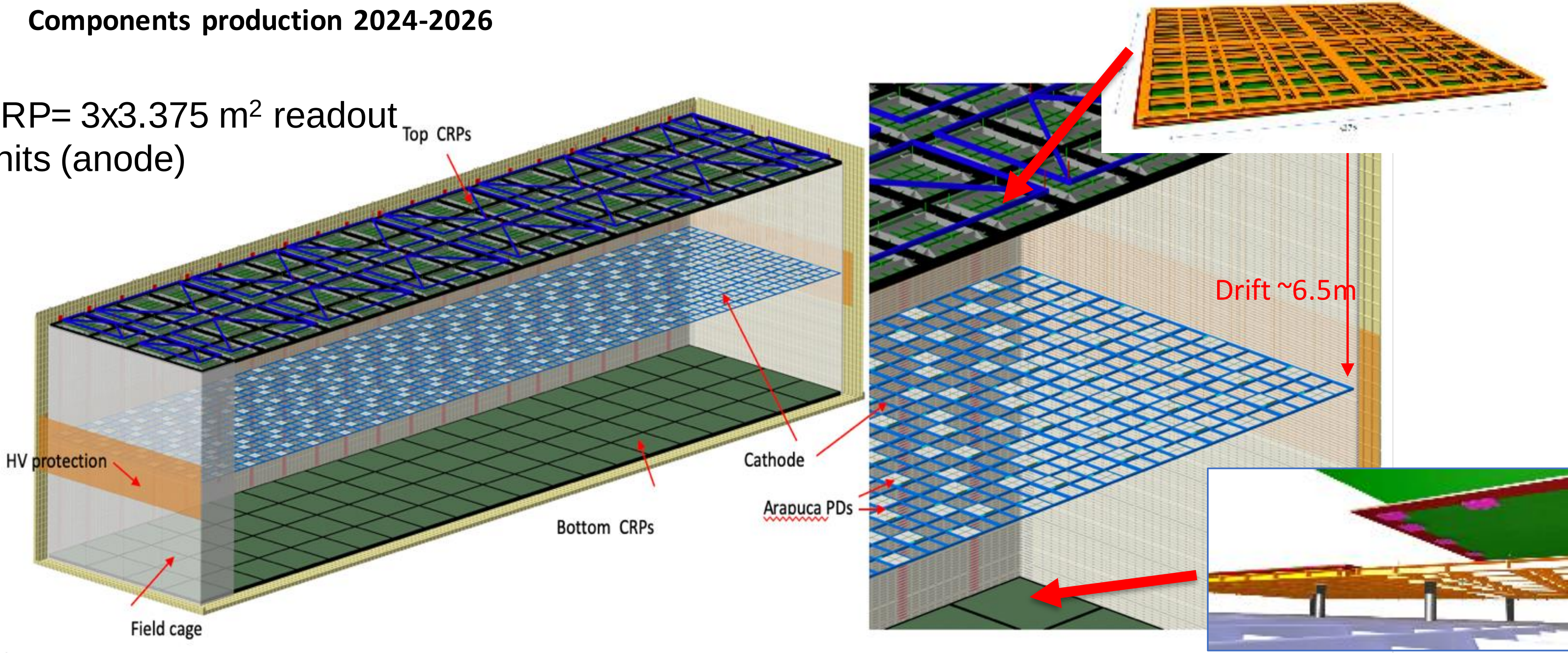


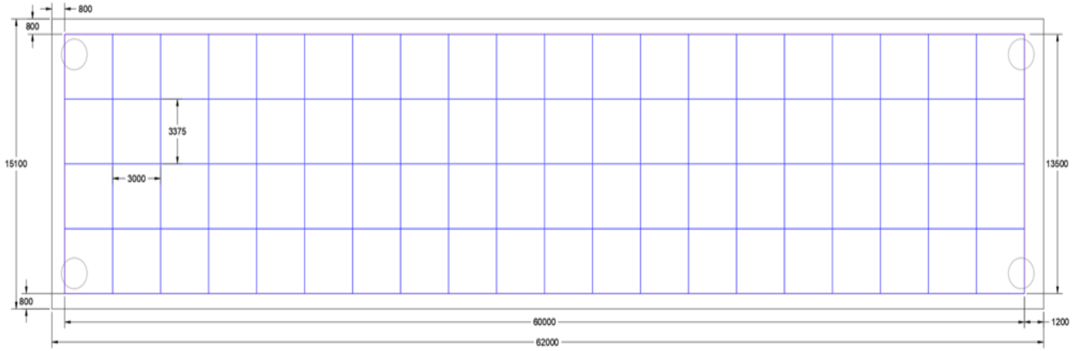



Vertical Drift far detector module (FD2)

- **Involved IN2P3 groups: APC, IJCLAB, IP2I, LAPP, LP2I, LPSC**
- **Vertical Drift reuses many dual-phase developments for the CRPs, top-drift electronics, field cage/cathode**
- **Components production 2024-2026**

CRP= 3x3.375 m^2 readout units (anode)





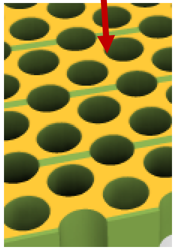
✓ 160 CRP units (80+80 on top/bottom, readout with DP/SP electronics)

✓ Drift active volumes 2*5’265 m^3 = LAr 14.74 kton

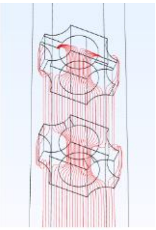
2nd DUNE Far Detector Module (**FD2-VD**) : 15 kton of active LAr (strong contribution of IN2P3/CNRS via IR* program) *Vertical Drift:* novel and optimized LAr TPC technology, anodes based on segmented perforated PCB

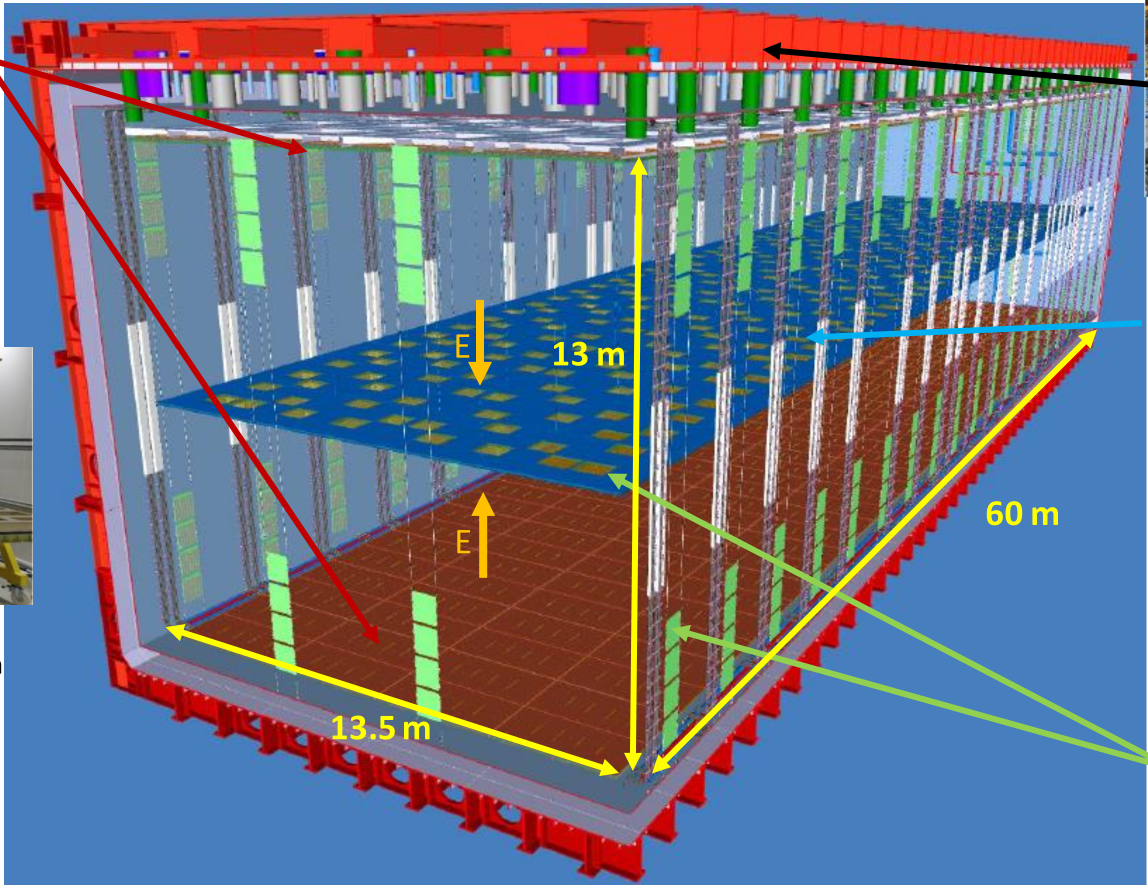
Top and bottom anode charge readout surfaces:

Made of 80+80 Charge Readout Plane units 3x3.375 m^2
Each unit: 2 stacked layers of segmented perforated PCBs



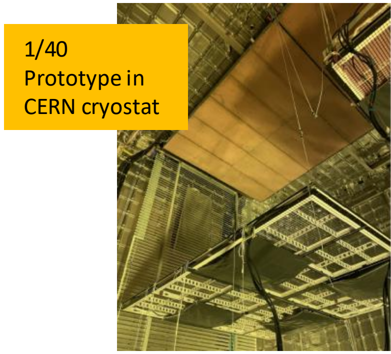
Strips 5 mm
Holes 2.4 mm





μTCA charge readout

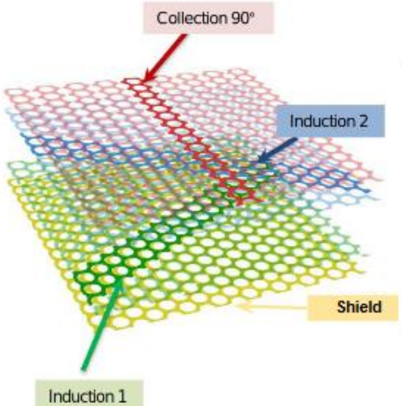
Cathode surface at -300 kV
→ E~500V/cm

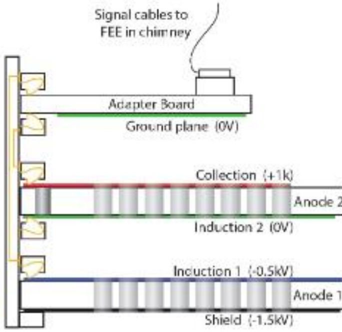


1/40 Prototype in CERN cryostat

UV photon detectors on cathode and cryostat walls

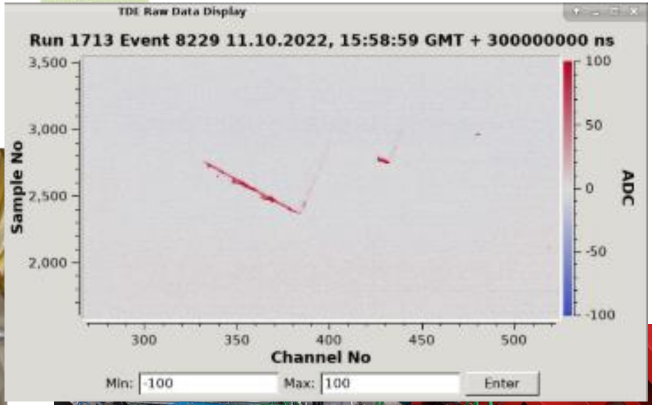
2021-2022 tests of FD2-VD Charge Readout Planes and associated electronics in dedicated cold-box TPC cryostat at CERN tailored to the CRP size





Top-drift CRPs with final channels layout (2 PCB layers, two induction views and one collection view with strips at +-30° and 90°) successfully tested in 2022 (3072 readout channels per CRP, 2 CRPs, 5+5 μTCA crates, 96 AMC)

40 Gbit/s connectivity, 10 AMCs/crate matching chimneys modularity (final FD2 chimneys allow exploiting 12 AMC/crate)

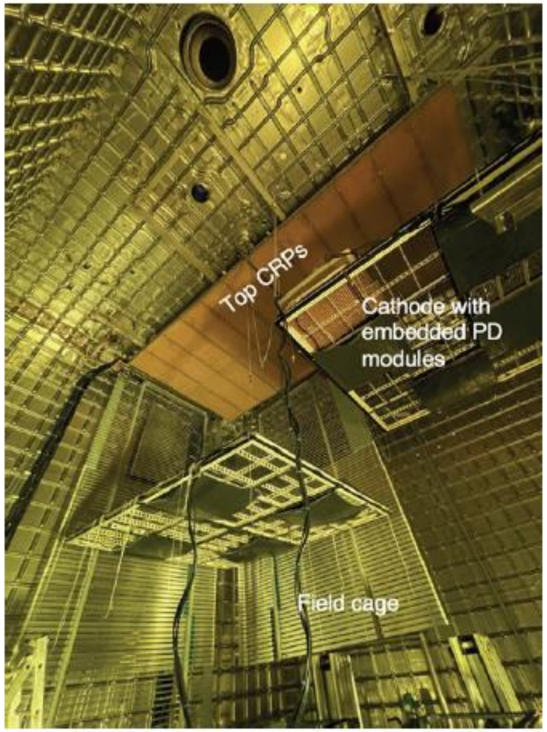

TDE Raw Data Display

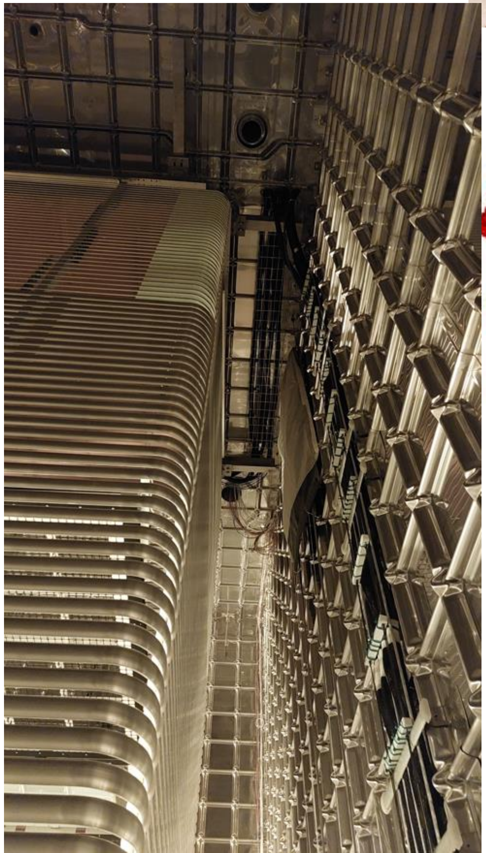
Run 1713 Event 8229 11.10.2022, 15:58:59 GMT + 300000000 ns

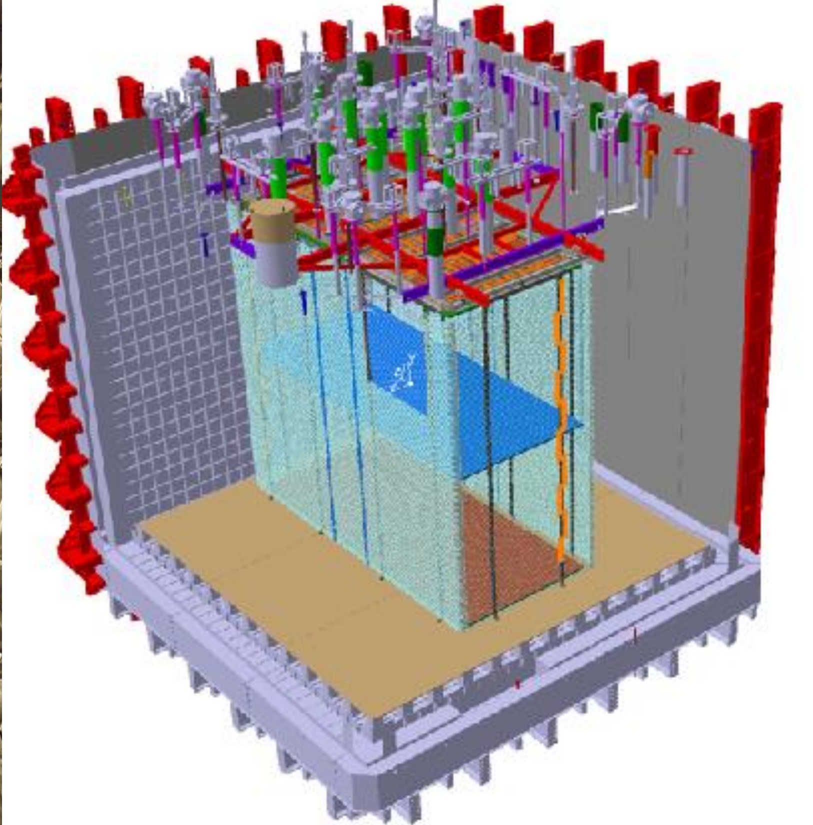
Min: -100 Max: 100 Enter

Far Detector 1 and2 Module-0 integration tests in NP02 and NP04 cryostats 2023-2024

Vertical Drift in NP02: 4 Charge Readout planes, top CRP readout 6144 readout channels, 400 Gbit/s

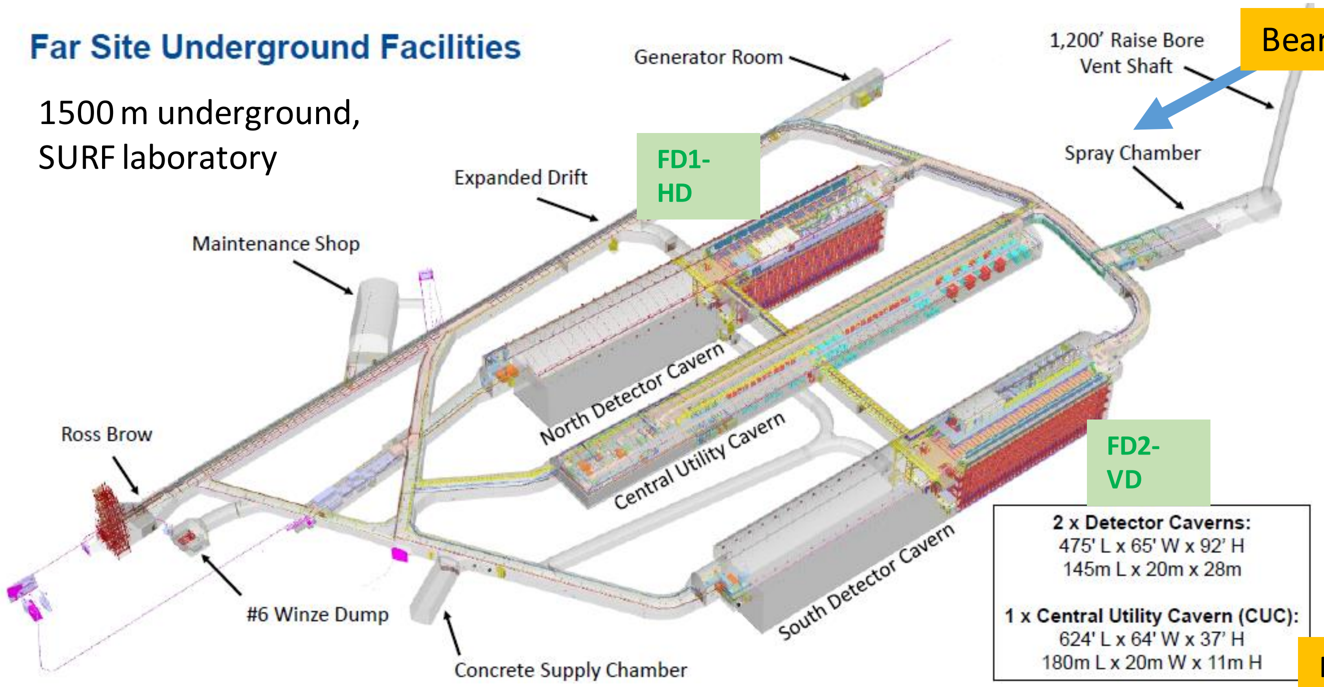






Far Site Underground Facilities

1500 m underground,
SURF laboratory



2 x Detector Caverns:
475' L x 65' W x 92' H
145m L x 20m x 28m

1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H

Surface infrastructure (Ross Shaft) of the mine in the Black Hills

DUNE Phase-I :

- Beam 1.2 MW
- ND initial configuration
- **Two FD LAr TPC modules: FD1-HD, FD2-VD**

Popular science DUNE videos on Youtube:
PIP-II/LBNF/DUNE
Science of DUNE
Far Detectors

North Detector Cavern – West End

October 2023:
>80% of underground infrastructure (0.6M m3 of rock) excavated

Drilling holes for blast charges for bench C (left) and removing muck (right) in North Detector Cavern (4850-33)

Cryostat steel structures being produced iby CERN, underground installation in 2024

Conclusions:

- The study of neutrinos provides fundamental information in particle physics, astrophysics and cosmology. They are a window on the physics beyond the SM. Unfortunately there are a lot of things I did not have time to mention in this seminar

- Experimental neutrino physics is a challenging field with a large variety of techniques requiring a lot of imagination at the level of the detectors and neutrino sources

- The history since the start of the Davis experiment in 1968 in the Homestake mine has shown many surprises. New ones may still be possible and there are still anomalies and aspects to be clarified

- The study of CP violation in the neutrino sector is now accessible and it is at the core of an unprecedented international effort among Europe and USA

- A last « anthropic-like » consideration ;-)

Although neutrino measurements are not easy Nature has been kind to us so far: somehow we have been lucky that the Δm^2 among the 3 mass states are such that the related solar and atmospheric oscillations are accessible with experimental means on earth ! We have been lucky that the large mixing angle solution is the one for solar neutrinos and again that θ_{13} is large and just below the CHOOZ limit.
Maybe this will happen again with CP violation ….