

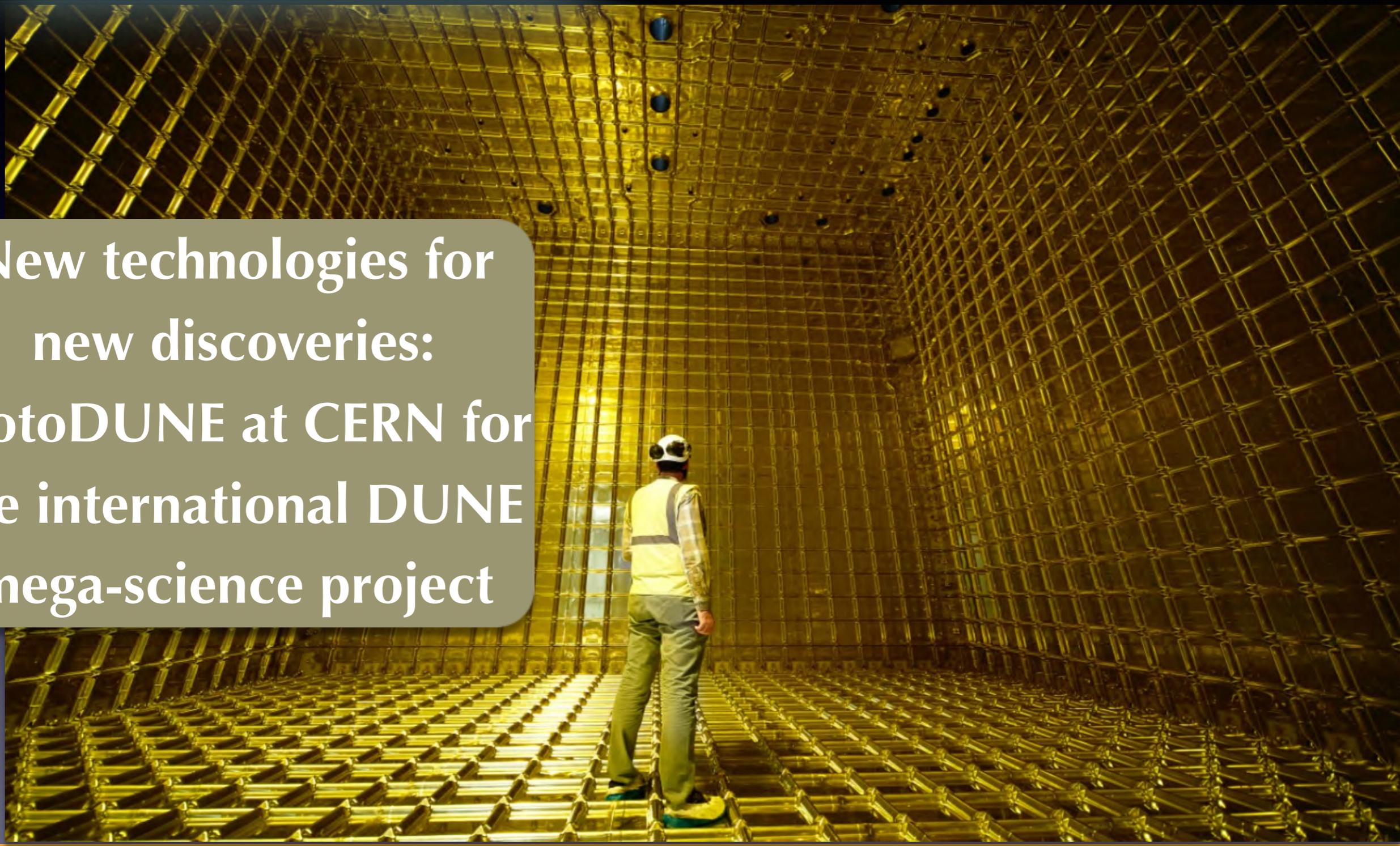


CERN Colloquium

500/1-001 - Main Auditorium



DEEP UNDERGROUND
NEUTRINO EXPERIMENT



New technologies for
new discoveries:
ProtoDUNE at CERN for
the international DUNE
mega-science project

Jan. 30, 2020

Flavio Cavanna |
on behalf of the DUNE Collaboration



Outline

The LArTPC technology: from the original concept to protoDUNE - the ultimate step of detector development.

Motivations to the LArTPC technology choice for DUNE: *new technologies for new discoveries*

LArTPC technology in two “flavors”

ProtoDUNE at the CERN Neutrino Platform:
500 days of continuing operation

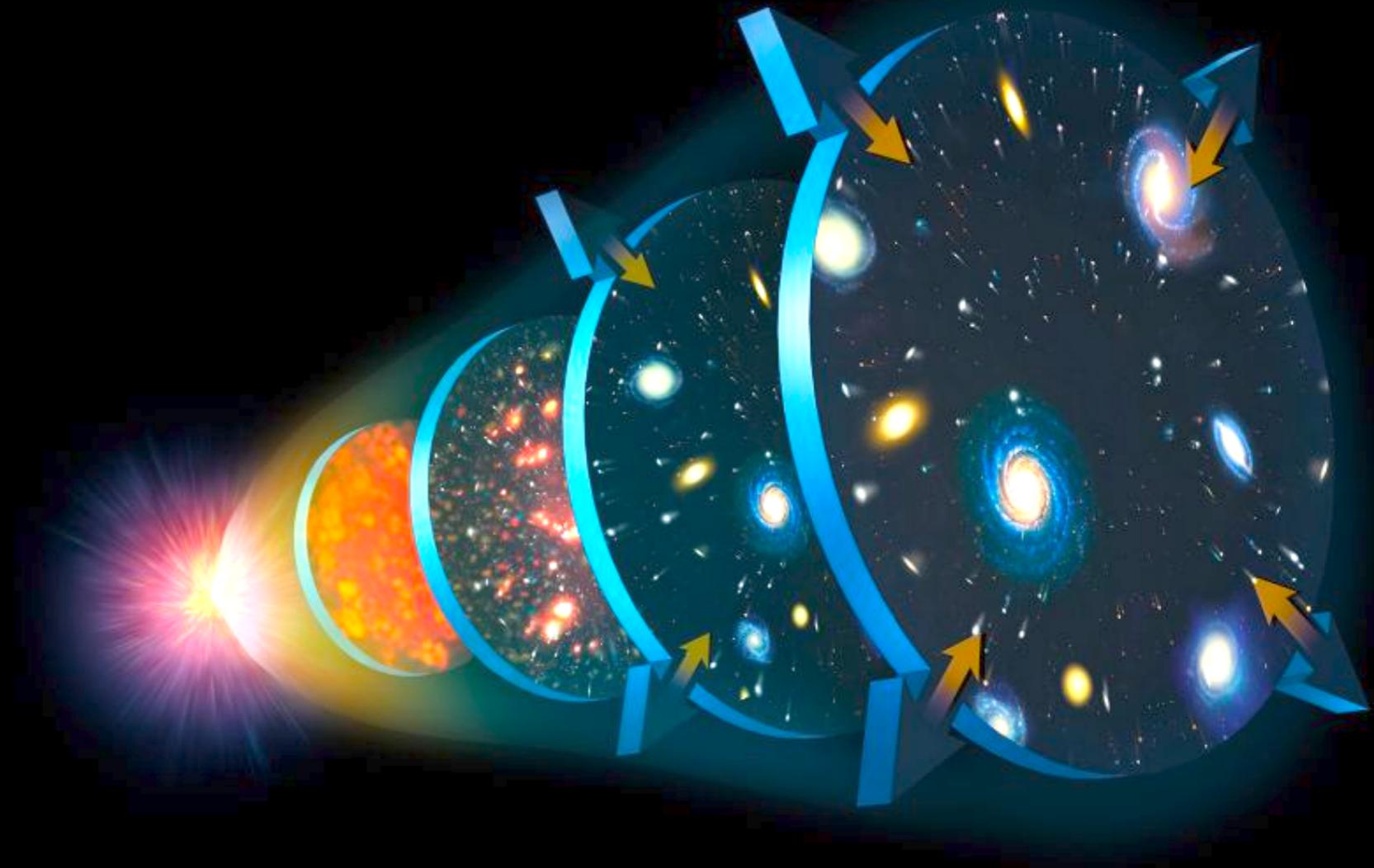
Preview of first results on LArTPC performance

Motivations to the LArTPC technology choice for DUNE

Prominent and long standing basic questions are still waiting for answer... for example:

© istock.com/Magnilion

According to current understanding of the Big Bang, matter and antimatter were formed in equal amounts when the universe began.



But if that were the case, all matter should have annihilated with antimatter by now, releasing lots of energy and filling the universe with light and radiation and no matter at all.

So, the question is “why is the world made of matter and not antimatter or nothing at all”?



The answer may hide in
the way we distinguish
between matter and
antimatter:
the CP transformations

*In the Standard Model a tiny amount
of violation of the CP symmetry
exists in the baryon sector...*

*.. but this CP violation is not enough to account for the observed matter-antimatter
unbalance. Therefore, other CP violation sources must contribute*

CP violation in the **neutrino** sector **is the prime candidate**

**If this is true, we should find signs of CP violation
in the oscillation of today's neutrinos....**

DUNE/LBNF: the Long Baseline Neutrino program

SANFORD UNDERGROUND RESEARCH FACILITY
Lead, South Dakota

FERMILAB
Batavia, Illinois

DUNE DEEP UNDERGROUND
NEUTRINO EXPERIMENT

1300 km

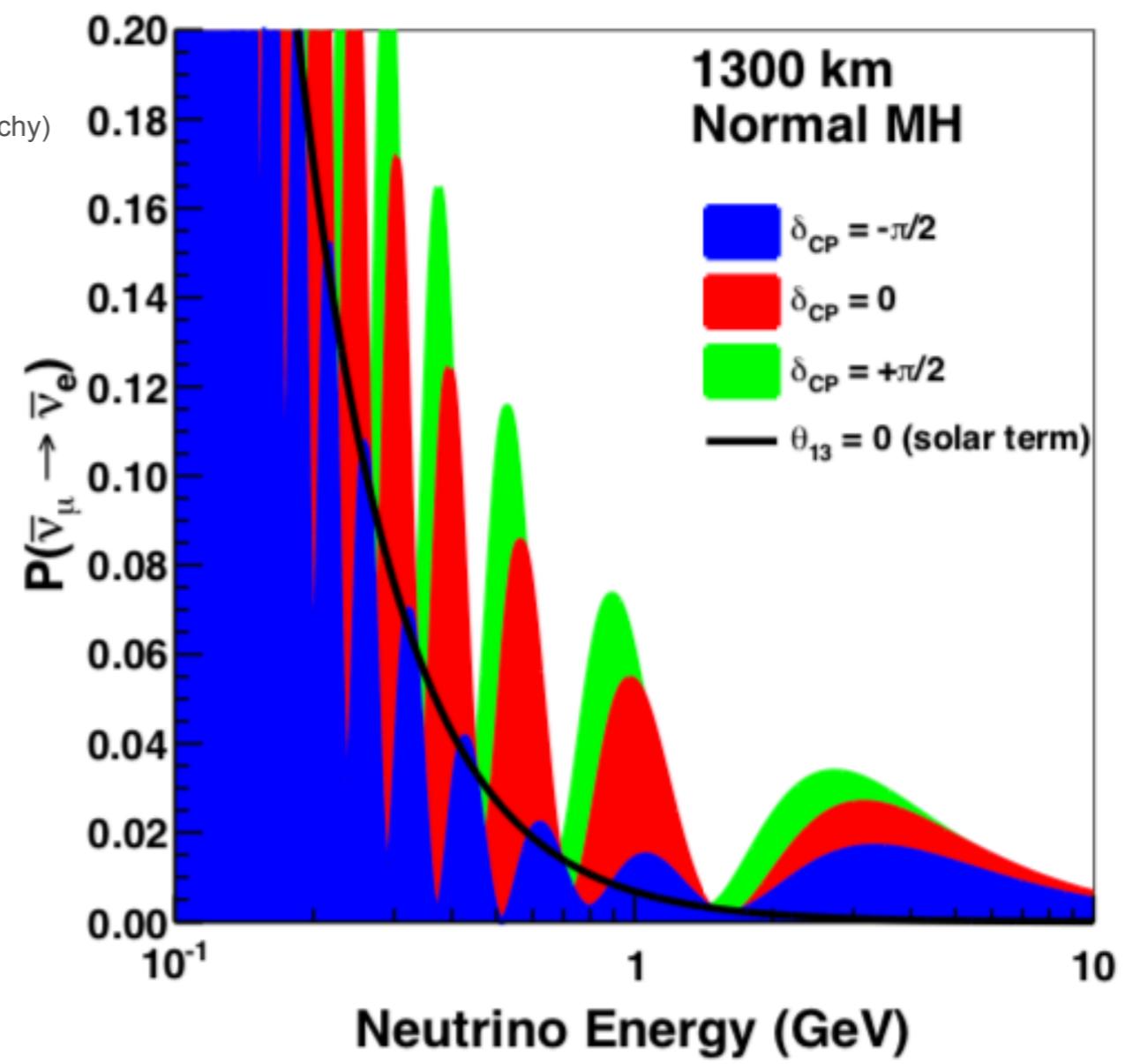
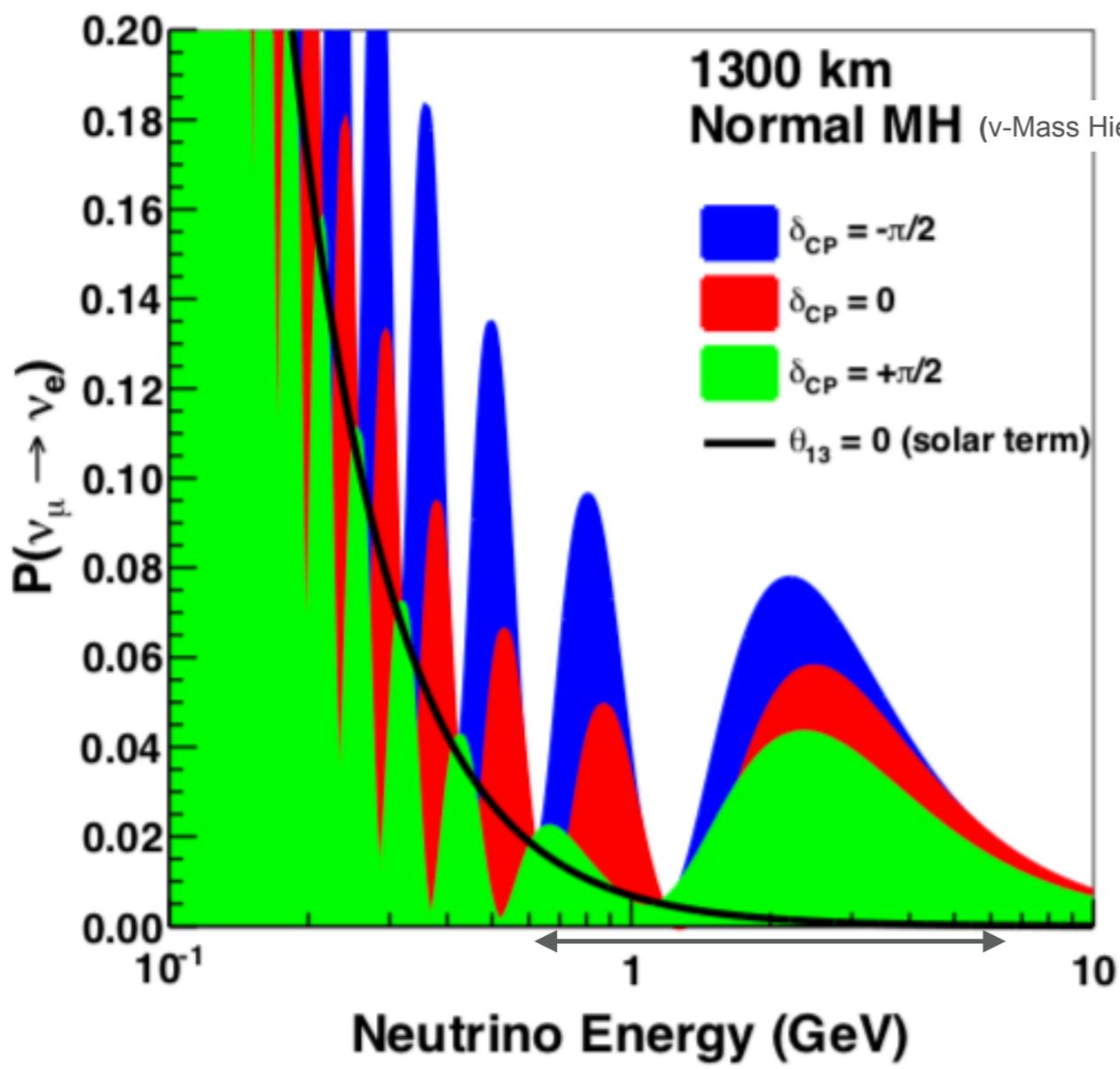
Far Detector

Near Detector



The **DUNE/LBNF** project in the US is the first **neutrino** international mega-science **project** [based on the ATLAS-CMS/LHC model at CERN in Europe and similar in size to LIGO]

the oscillation patterns of ν_μ and $\bar{\nu}_\mu$ beams over a 1300 km long baseline



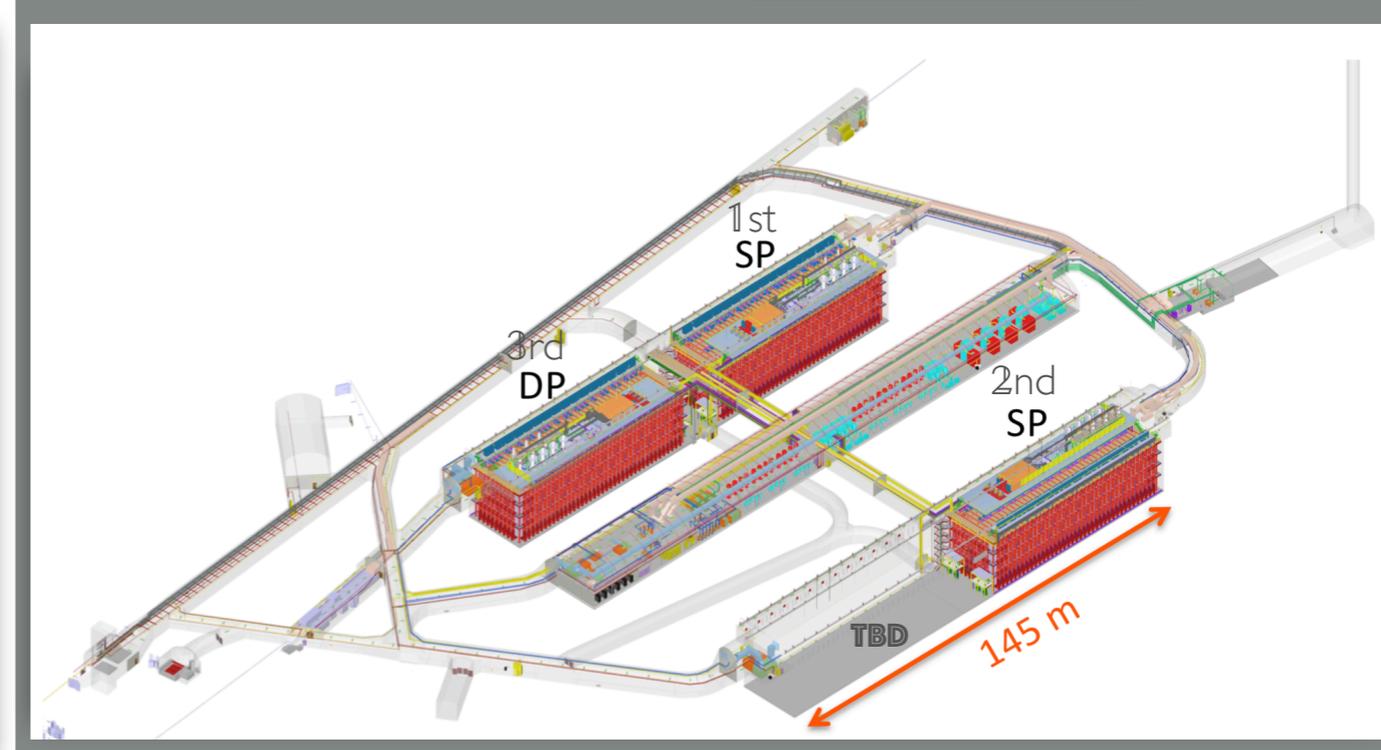
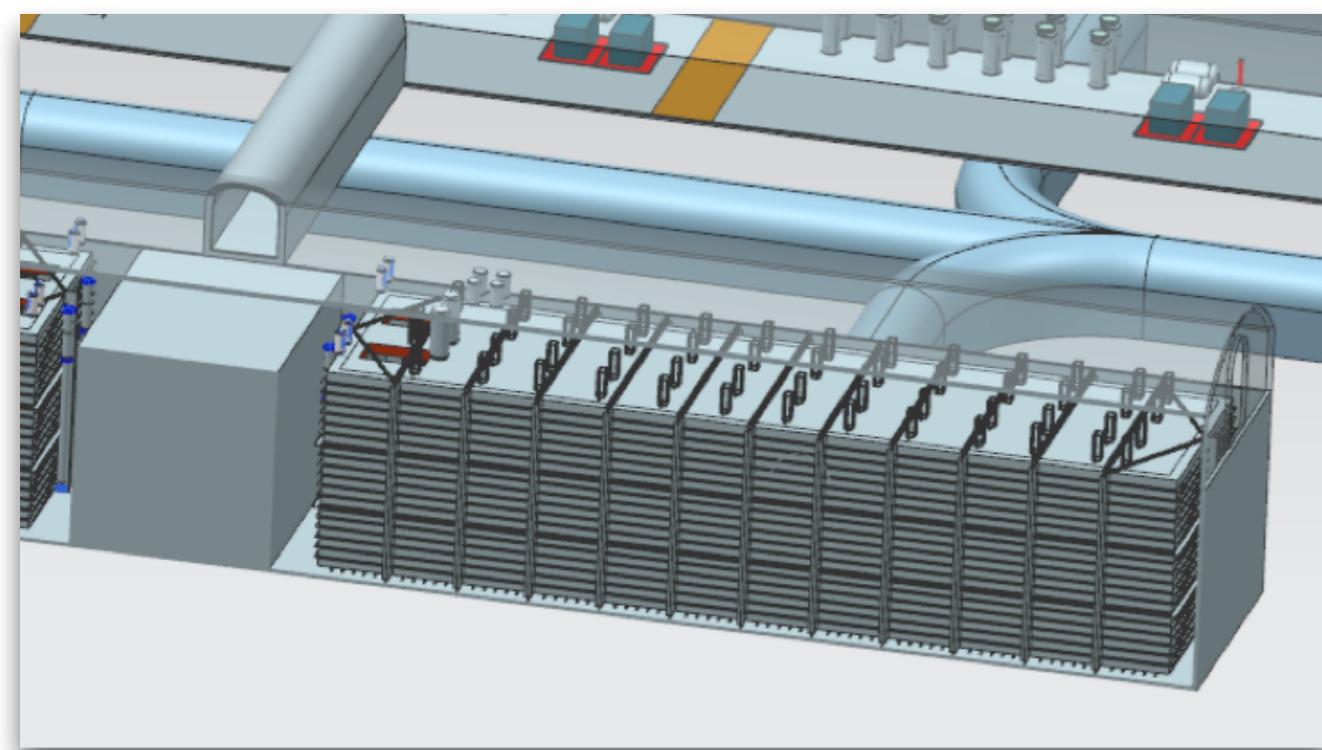
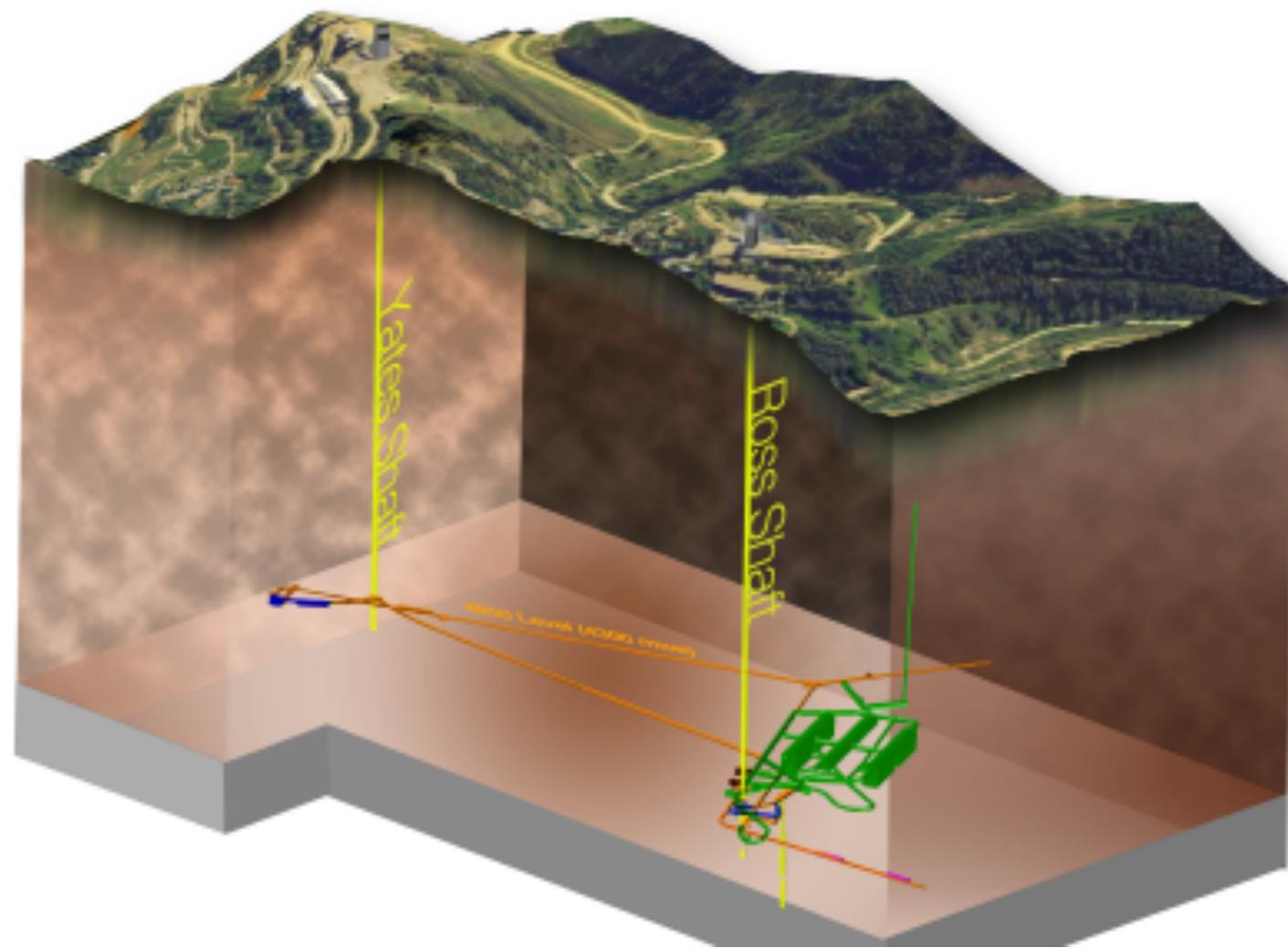
The CP Asymmetry

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

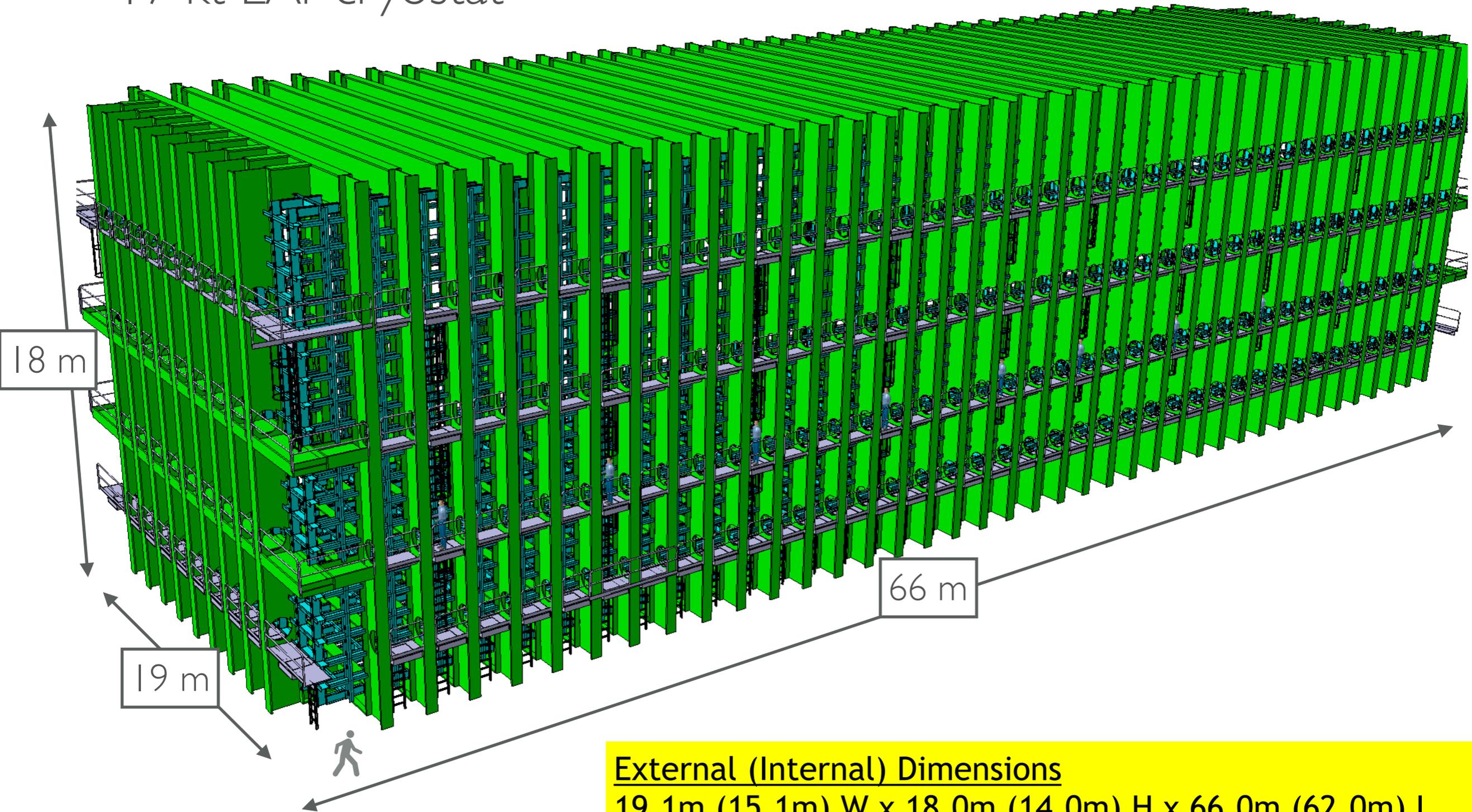
The signal for ν_e ($\bar{\nu}_e$) appearance is an excess of charged current (CC) ν_e and $\bar{\nu}_e$ events over the expected background (in the $\sim[0.5-5]$ GeV Energy range)

“Far Site”: SURF 4850 Level

- Major underground excavation removing ~800,000 tons of rock
- Two large caverns housing **four** cryostats and a central utility space
- $4 \times 17,000$ tons of LAr to fill the cryostats: *the target for neutrino interactions*

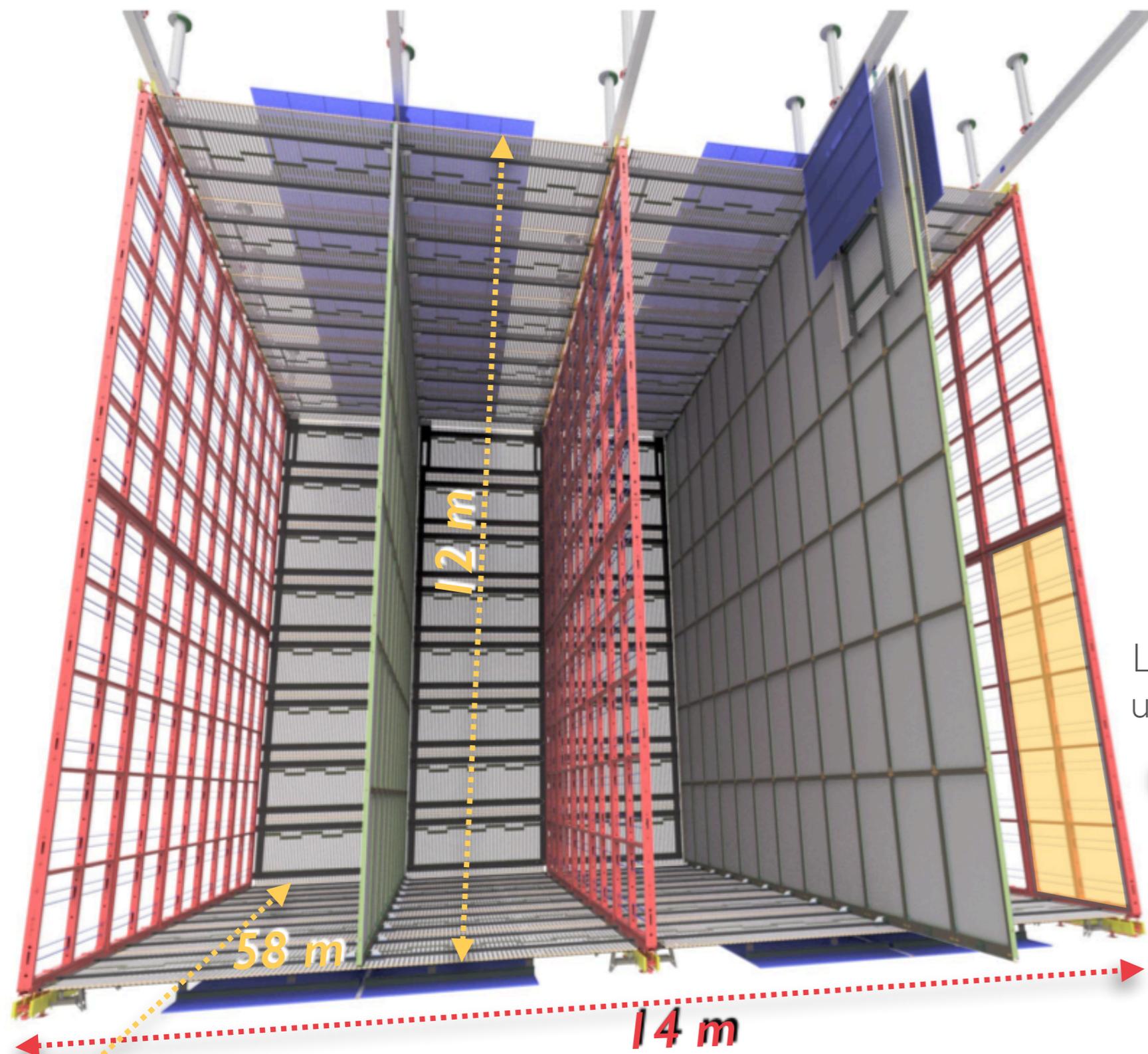


The first FD Module: 17 kt LAr cryostat



External (Internal) Dimensions
19.1m (15.1m) W x 18.0m (14.0m) H x 66.0m (62.0m) L

and the **LArTPC** instrumented inside the cryostat



LArTPC modular unit (APA) in real



New technologies for
new discoveries



Liquid Argon Time Projection Chamber - LAr TPC is the **Technology Choice** for the International Neutrino Program in the US

Q:

Why **Liquid Argon Time Projection Chamber**?

A:

LAr TPC is a modern technology with Automated 3D Imaging, Particle ID (e.g. e/γ separation) with added full Calorimetry and Self-Triggering Capability

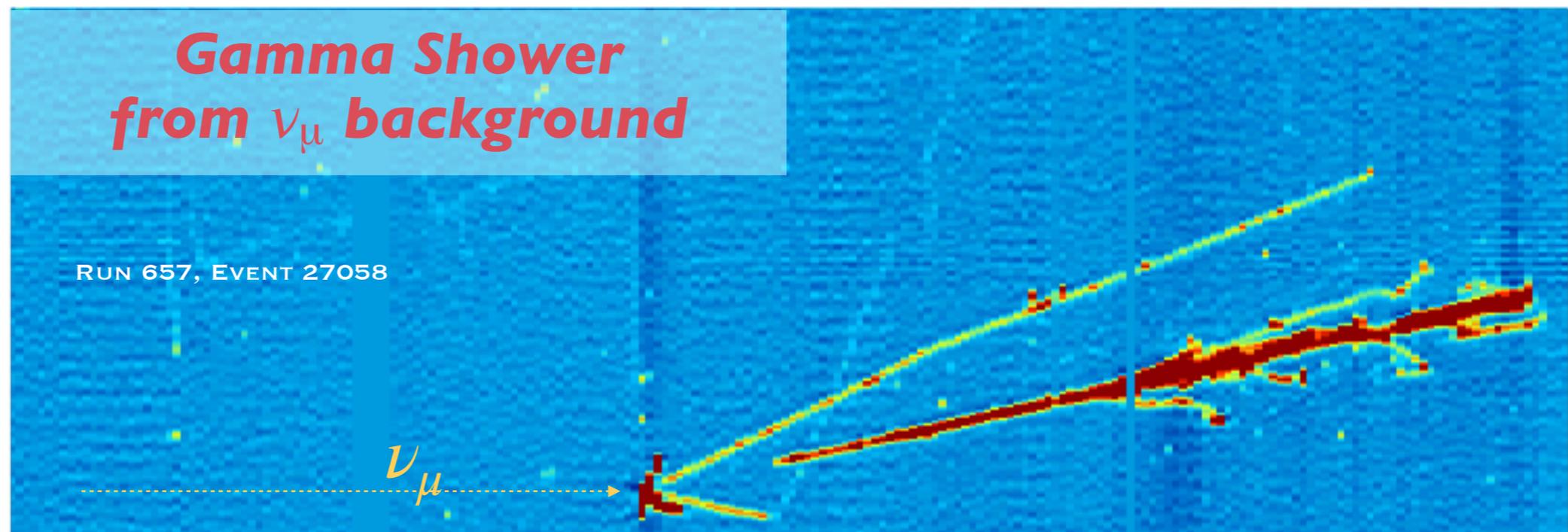
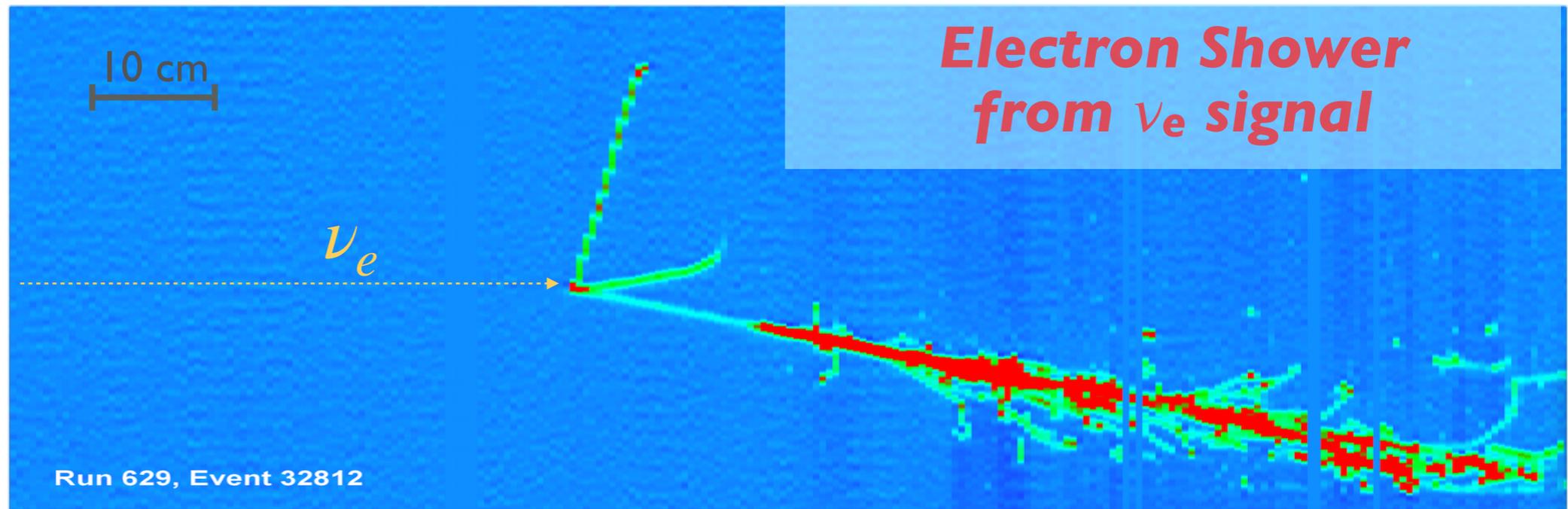
Combine Target and Detector in one

Scalable to very large mass

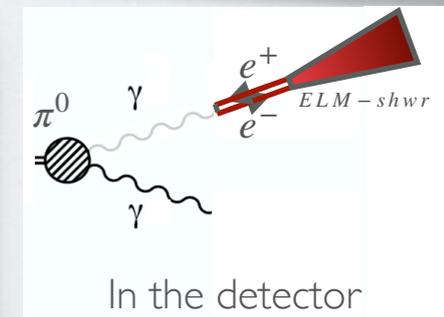
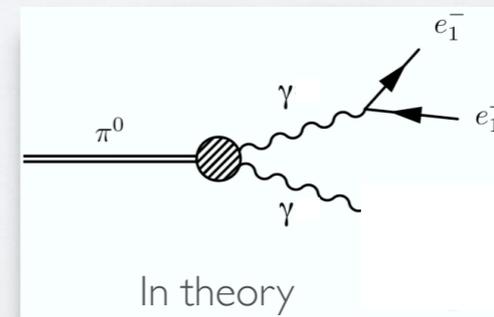
e/γ separation



ArgoNeuT
FNAL
2009-10



ν_e appearance and background rejection
($\nu_e \rightarrow$) electron / γ ($\leftarrow \pi^0$) discrimination



1977 - the LArTPC Concept

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

G E N E V A

1977

Quoting this document, "*the original idea of Nygren (1974)*" for a so-called "*Time Projection Chamber (TPC)*" with a noble gas as **ionization** medium "*is extended to a liquefied noble gas - more specifically, liquid Argon - leading to what is*" thereafter "*called a Liquid-Argon TPC (LAr-TPC)*". Briefly, the idea consists of drifting the whole electron image of an event occurring in the noble liquid towards a collecting multi-electrode array which is capable of reconstructing the three-dimensional image (x,y,z) of the event from the (x,y) information and the drift time (t) ".

- **Features of different experimental technologies are combined in a single device**
- **The liquid Argon is at the same time the active medium of the detector and the target of the experiment**

(ideal for detection and full reconstruction of rare events like neutrino interactions and nucleon decays).

The main limitation of the proposed technique was also clearly defined: "*the purity of the Argon is the main technological problem. ... electron lifetimes corresponding to residual Oxygen impurity content of about 4×10^{-2} ppm*" are reachable. However, this limits "*the electron mean free path to about 30 cm. Clearly, Oxygen-free Argon is the central problem for the LAr TPC*".

Only after several years an effective, fast purification method became available.

1977 - the LArTPC Concept

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THE LIQUID-ARGON TIME PROJECTION CHAMBER:

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C. Rubbia

NUCLEAR INSTRUMENTS AND METHODS 150 (1978) 585-588, © NORTH-HOLLAND PUBLISHING CO

OBSERVATION OF IONIZATION ELECTRONS DRIFTING LARGE DISTANCES IN LIQUID ARGON*

HERBERT H CHEN and JOHN F LATHROP†

Department of Physics, University of California, Irvine, California 92717, U S A

Received 26 September 1977 and in revised form 1 November 1977

Measurements using a ^{137}Cs internal conversion source demonstrate that ionization electrons will drift at least 35 cm in liquid argon in electric fields of a few kV/cm

G E N E V A

1977

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main limitation of the proposed technique was also clearly defined: "*the purity of the Argon is the main technological problem. ... electron lifetimes corresponding to equal Oxygen impurity content of about 4×10^{-2} ppm*" are not acceptable. However, this limits "*the electron mean free path to about 30 cm*". Clearly, Oxygen-free Argon is the central problem for the LAr TPC".

Only after several years an effective, fast purification method became available.

1986 - proposal for a massive LArTPC ICARUS

“Principle of Operation (from ICARUS Proposal):

The imaging of the ionising events inside the cryogenic volume of the detector is made possible because of

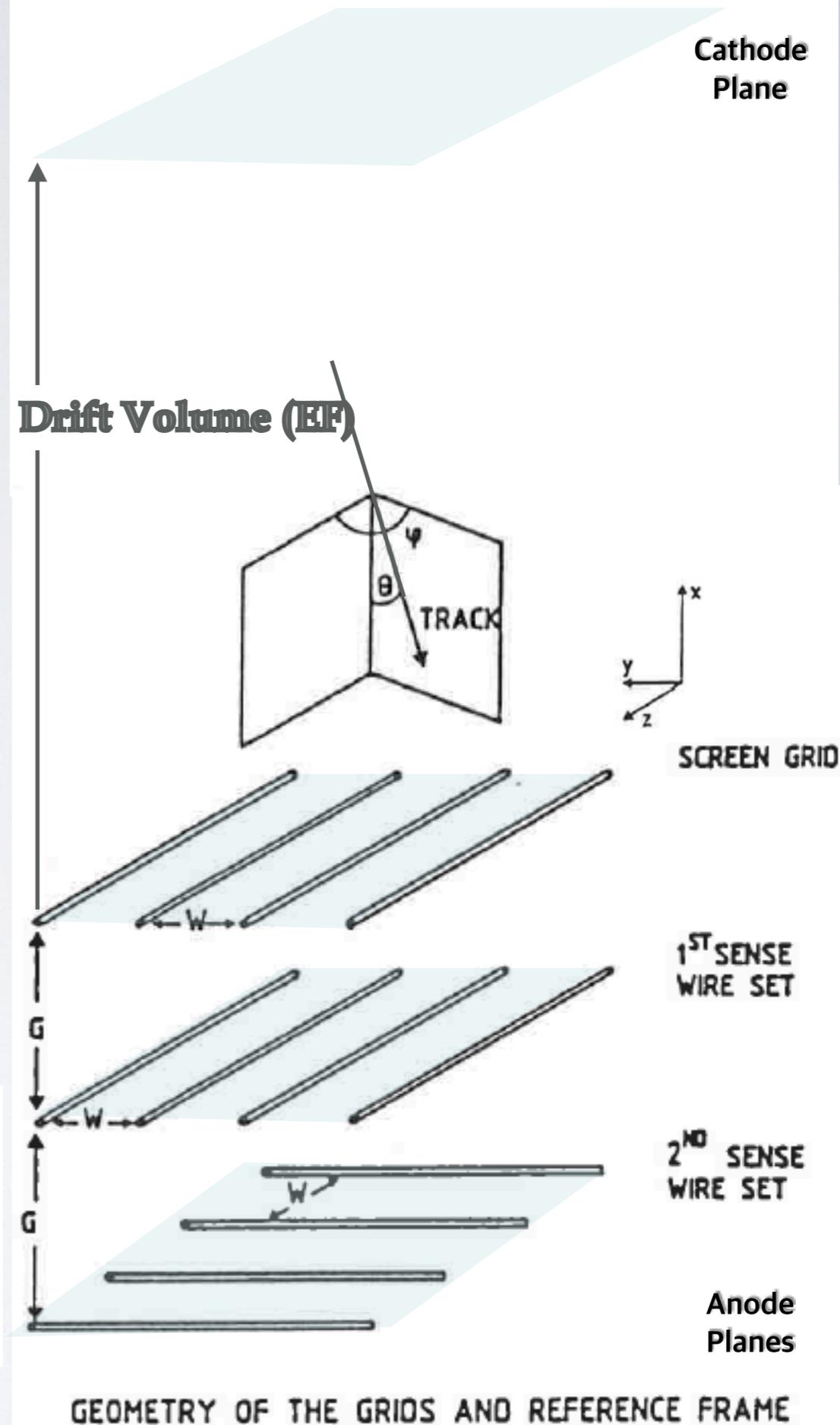
- (1) the long lifetime of the drifting electrons in excess of one millisecond (i.e. very high LAr purity) and*
- (2) the sensitivity of modern (low noise) charge sensitive amplifiers that are capable of sensing an electron signal produced by a few millimetres of minimum ionising tracks”.*

... “main features” ...

Non-destructive read-out with determination of the $t=0$ signal ... (for the measurement of) the drift time and hence of the drift distance

~~then the current through the grid is proportional to the solid angle $d\Omega$. We~~
remark that the signal is due to the images of the charges of the electrons and is not produced (as sometimes incorrectly assumed) by a simple electron collection.

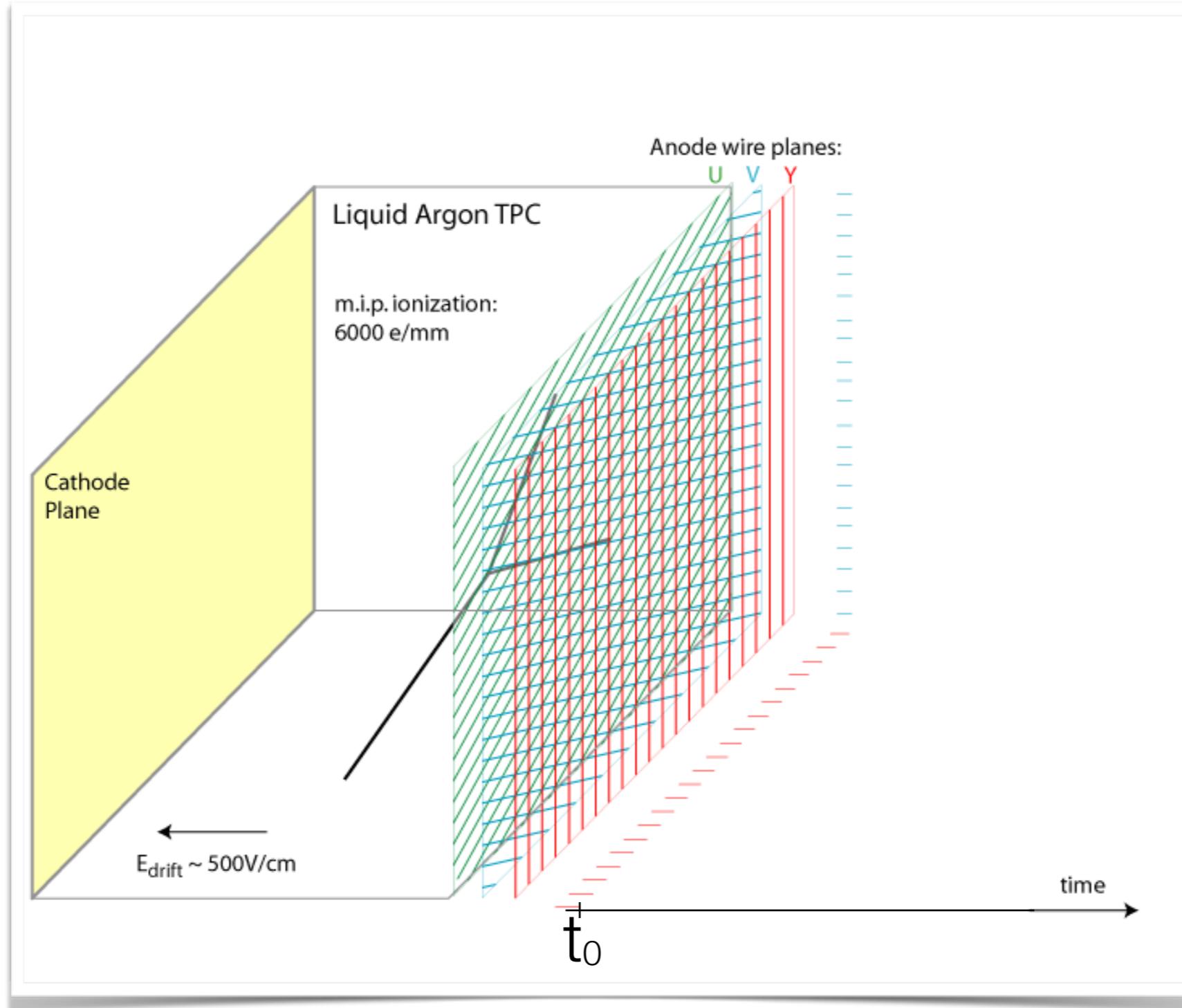
If we replace solid electrodes with wire planes or grids, we can preserve the electrons and we can realize a non - destructive read-out. ~~The use of a grid~~



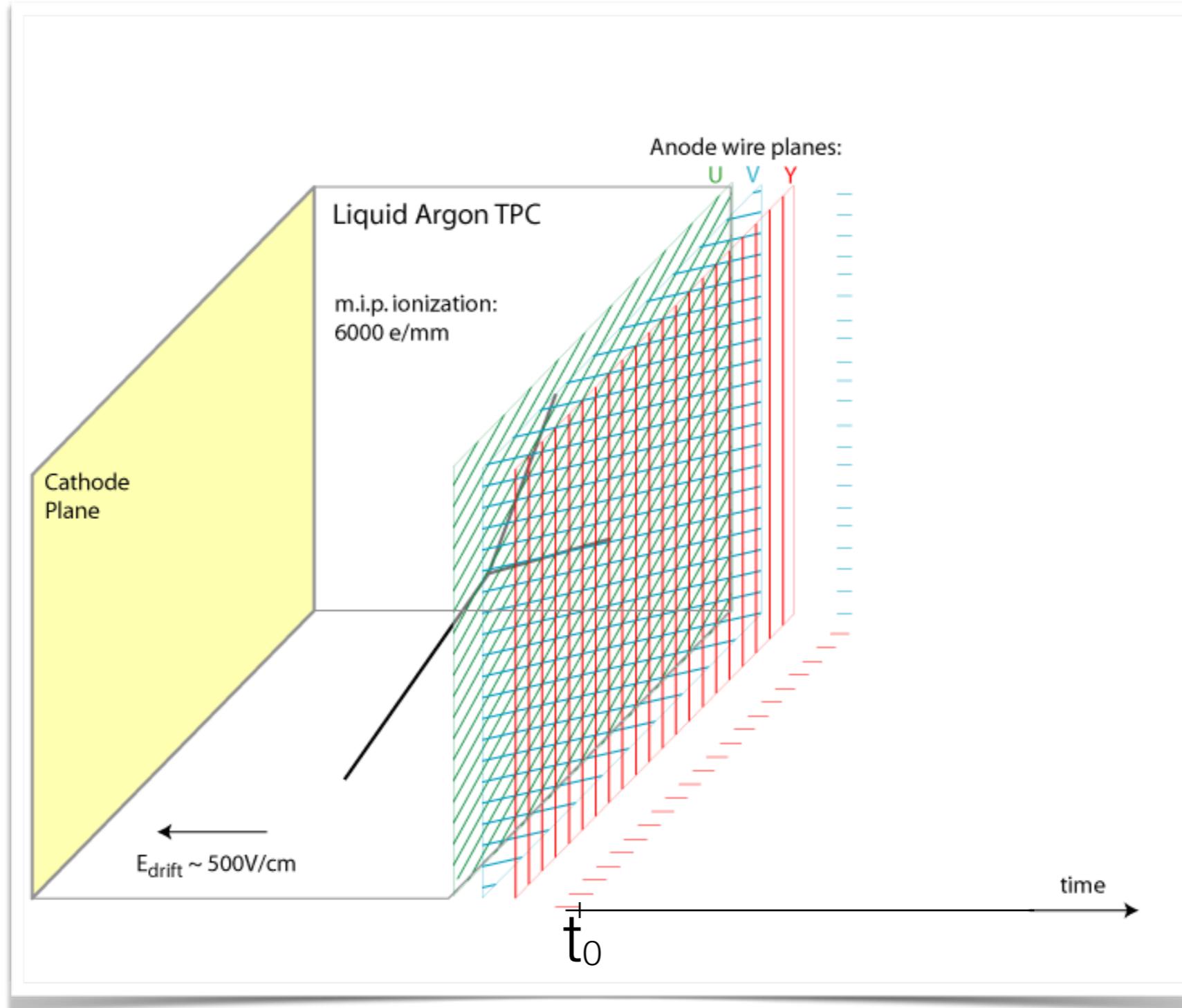
GEOMETRY OF THE GRIDS AND REFERENCE FRAME

Figure 40. Geometry of the grids and reference frame

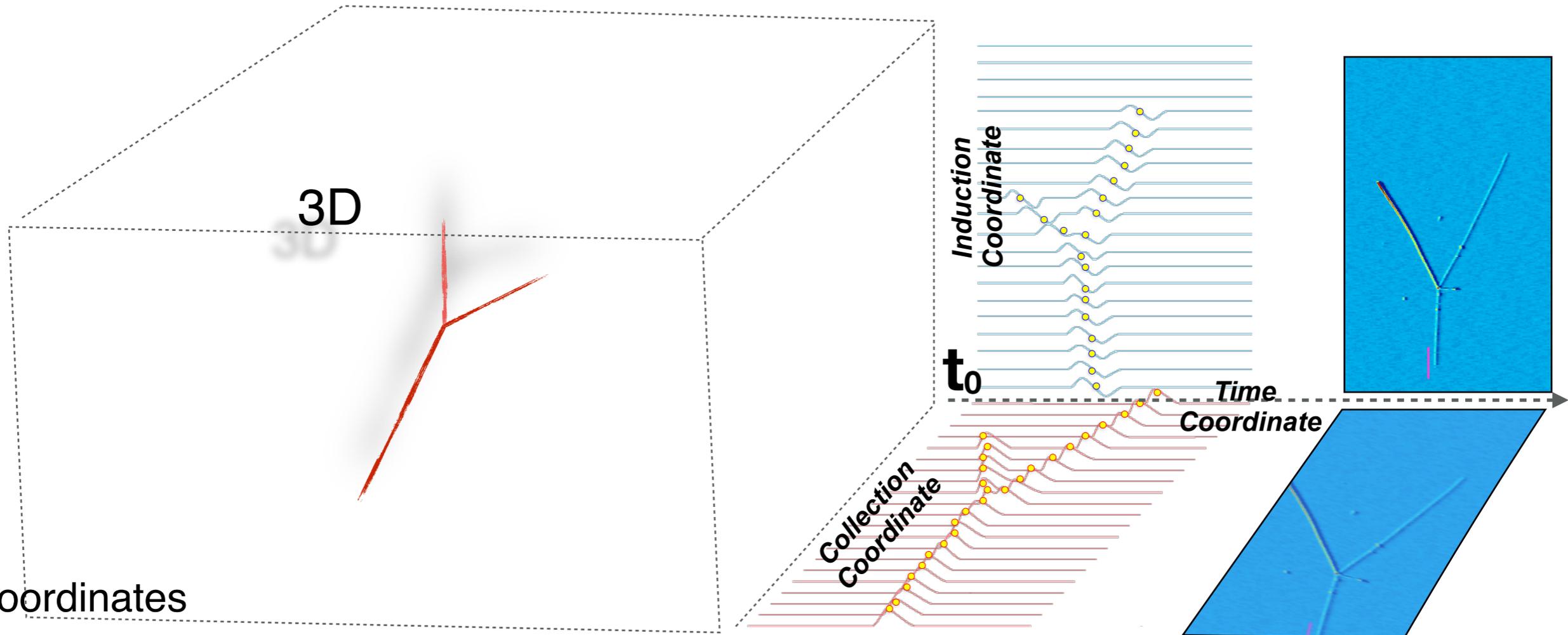
LArTPC at work: Imaging and Energy Reconstruction



LArTPC at work: Imaging and Energy Reconstruction



LArTPC at work: Imaging and Energy Reconstruction



1. Hit coordinates

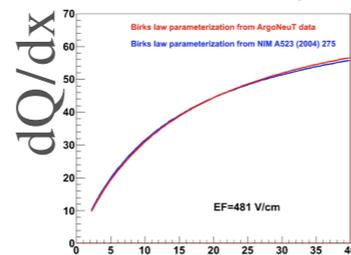
(wire# and $t_{hit} \Rightarrow 2 \times 2D \Rightarrow 3D$ image

2D Image(s)
(graphic rendering)

2. Hit Amplitude $\Rightarrow dQ$ Ionization Charge Deposited

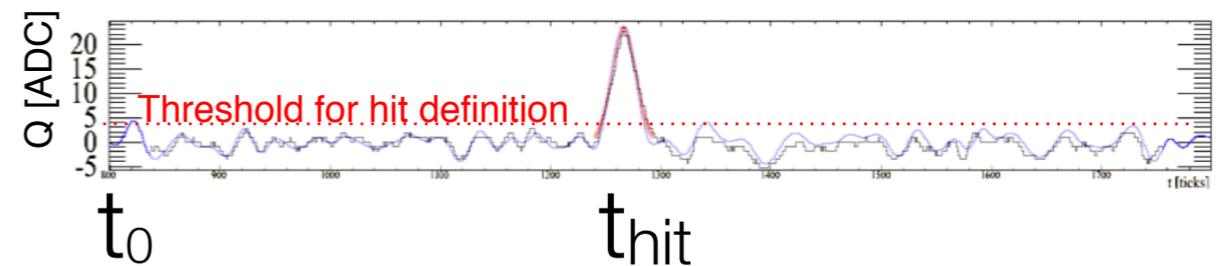
3. Distance in space between hits $\Rightarrow dx$ (track pitch)

4. $dQ/dx \Rightarrow dE/dx \Rightarrow$ Ptlcl Id



5. $\int_l \frac{dE}{dx} dx = E_{Tot} \Rightarrow$ Calorimetry

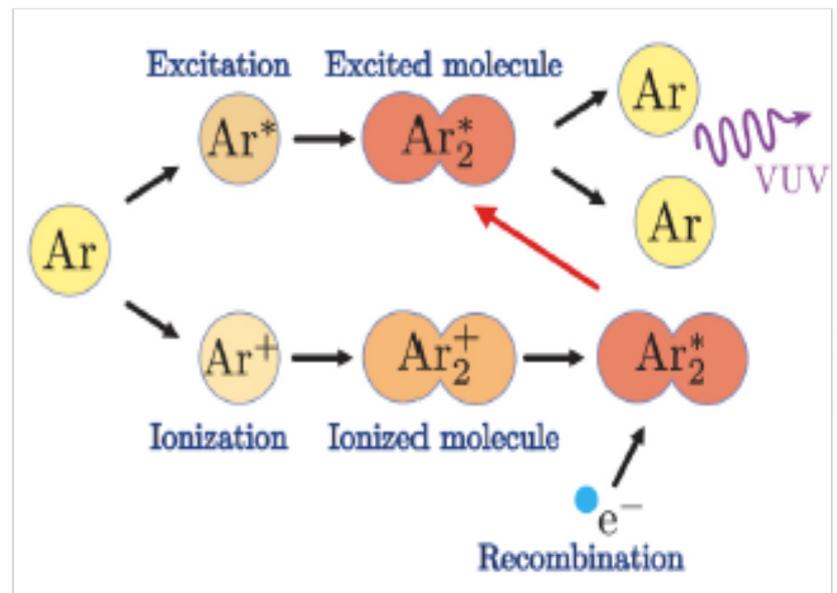
TPC wire Signal: find Hit



(real) TPC wire Signal

t0 time

*Need a fast signal
to identify the time of the interaction (t0)*



Prompt scintillation light produced in LAr as part of the ionization process ideal for t0 (and a lot more):

*Need a **Photo-Detector** embedded in the TPC structure*

Ar Scintillation light is very abundant (40 k photons/MeV) but photon wavelength is in the VUV (128 nm)

Need wavelength-shifter (easiest solution)

in the modern LArTPC technology - Light Detector (PDS) is becoming an important complement to the Charge Detector (TPC)

LArTPC at work: LAr purity - the issue, the solution

Ionization electrons must drift over distance of $\mathcal{O}(m)$, ie drift times $\mathcal{O}(ms)$, without substantial capture by electronegative impurities \Rightarrow limit on level of contamination $[O_2\text{-equiv}] \leq 100$ ppt (part per trillion)

"The starting material is Argon gas which has a (typical) impurity concentration of ≈ 0.1 ppm of Oxygen. The gas is passed through the (filter) cartridge to remove the Oxygen present ... at a typical rate of 0.35 l of gas per second. The gas is then liquefied ..."

[J. Bahcall, M. Baldo-Ceolin, D.B. Cline and C.Rubbia, **Phys.Lett B178**, (1986)]

The issue:

At this rate it would take ~ 1000 yr to purify&fill one DUNE Module

The solution:

"Argon purification in the liquid phase" [NIM A333 (1993), 567]

"we have shown that ultrapure liquid Argon can be obtained by direct purification of the liquid. The final purity corresponds to an electro-negative impurity concentrations below 0.1 ppb O_2 equivalent, equal to that obtained with similar procedures (OXY reactant + molecular sieves) purifying the gas phase. ... The flows are almost three orders of magnitude (the ratio of the densities) higher. As a consequence, the problem of filling a large scale detector is much simplified (... few weeks for a kiloton sized detector)".

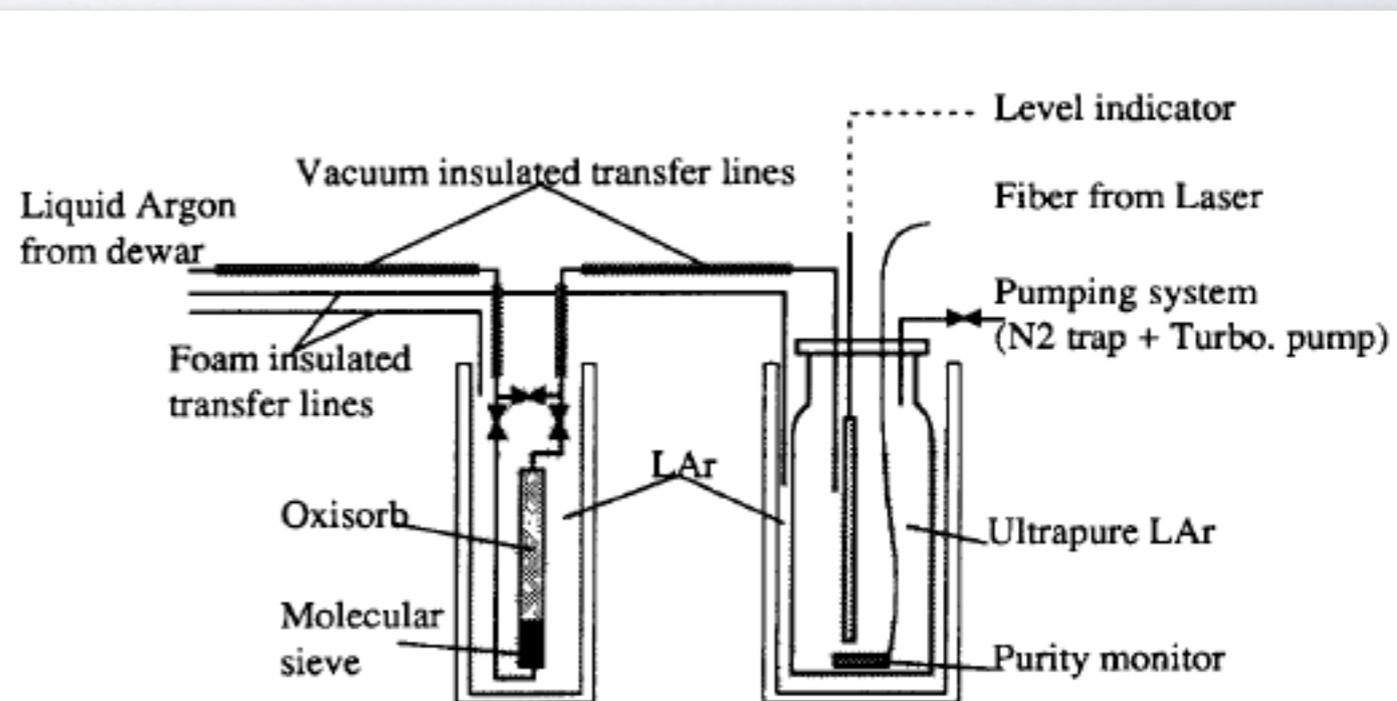


Fig. 1. Schematic view of the liquid phase argon purification system.

LArTPC technology in two “flavors”

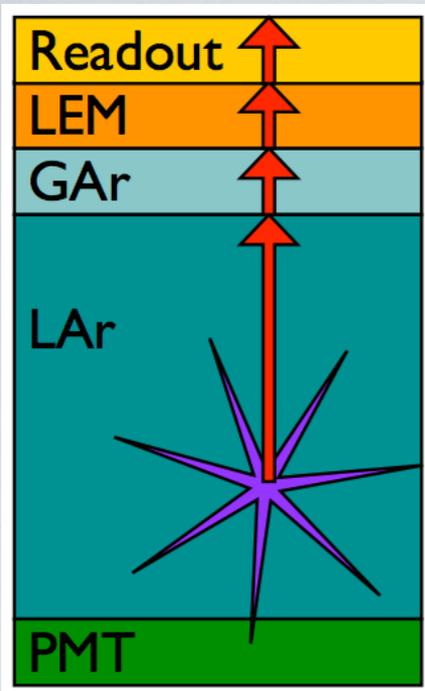
While the first LArTPC detectors for Neutrino Physics were built/operated..

a new concept in the technology was proposed and developed:

Dual Phase LAr+GAr TPC

where the read/out system is in the gas
(above the liquid)

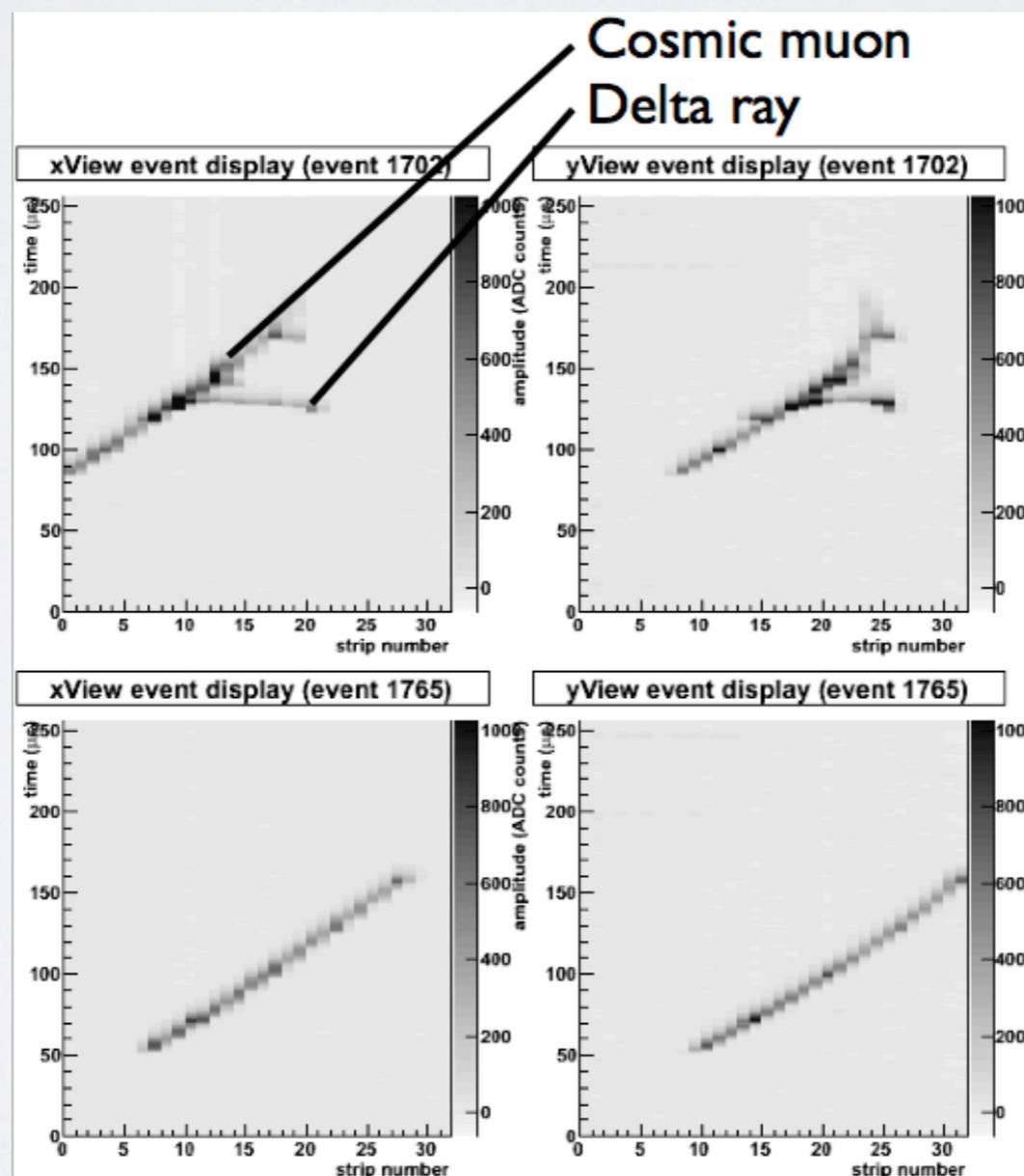
Dual Phase Ar TPC Concept (~2005)



a 3D-imaging and calorimetric device capable of adjustable charge amplification based on LEM - Large Electron Multiplier



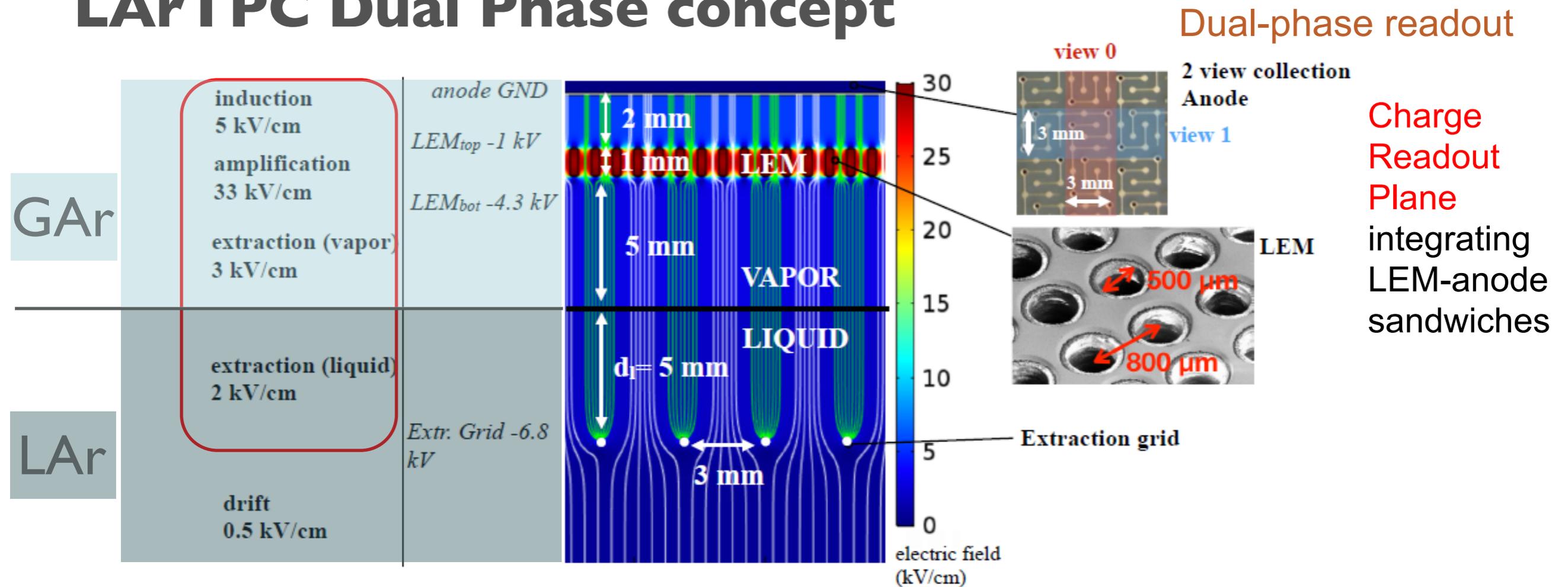
Electron avalanche in LEM hole



Proof of Principle

LAr LEM-TPC
@ CERN (by **ETH**)

LArTPC Dual Phase concept



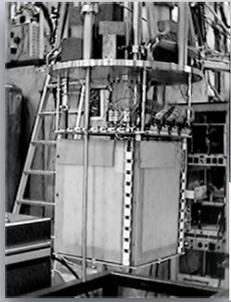
Features of dual-phase design:

- **Gain** in the gas phase \rightarrow robust and tunable S/N, lower detection threshold, compensation for charge attenuation due to long drift paths
- **Finer readout pitch** (3.125 mm), implemented in two identical collection views (X,Y) on 3m long strips
- **Long drift projective geometry**: reduced number of readout channels, absence of dead materials in the drift volume
- **Fewer construction modules, costs, installation**
- **Full accessibility and replaceability** of cryogenic front-end (FE) electronics during detector operation

LARTPC (SINGLE PHASE)

READY FOR PHYSICS ON NEUTRINO BEAMS

Icarus 50 t - CERN WANF (1997)

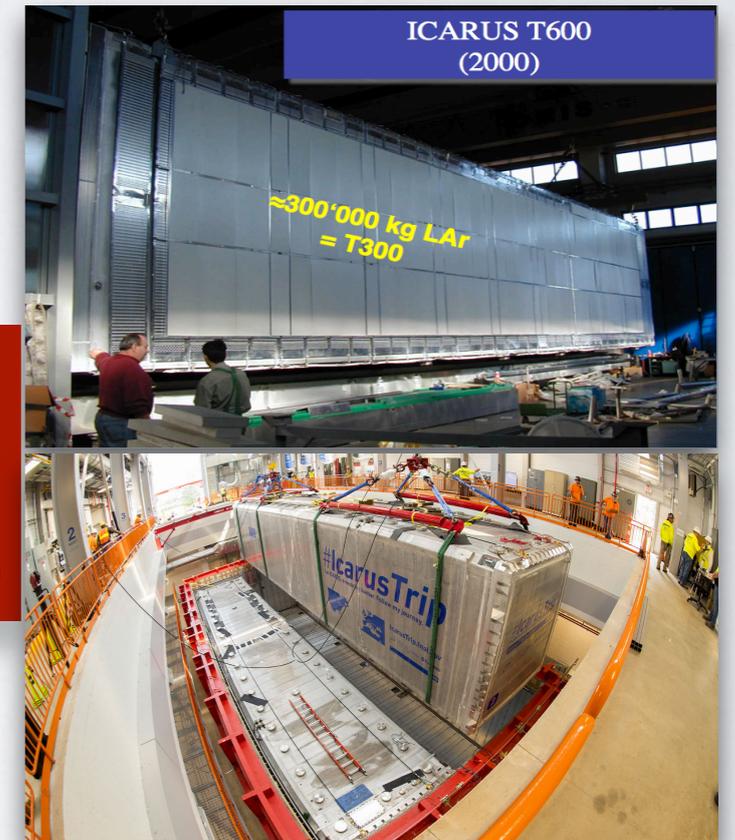


ArgoNeuT 0.5 t - FNAL NuMI (2008-9)

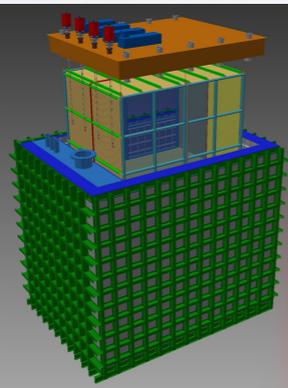
MicroBooNE 100 t -
FNAL Booster (2015-present)



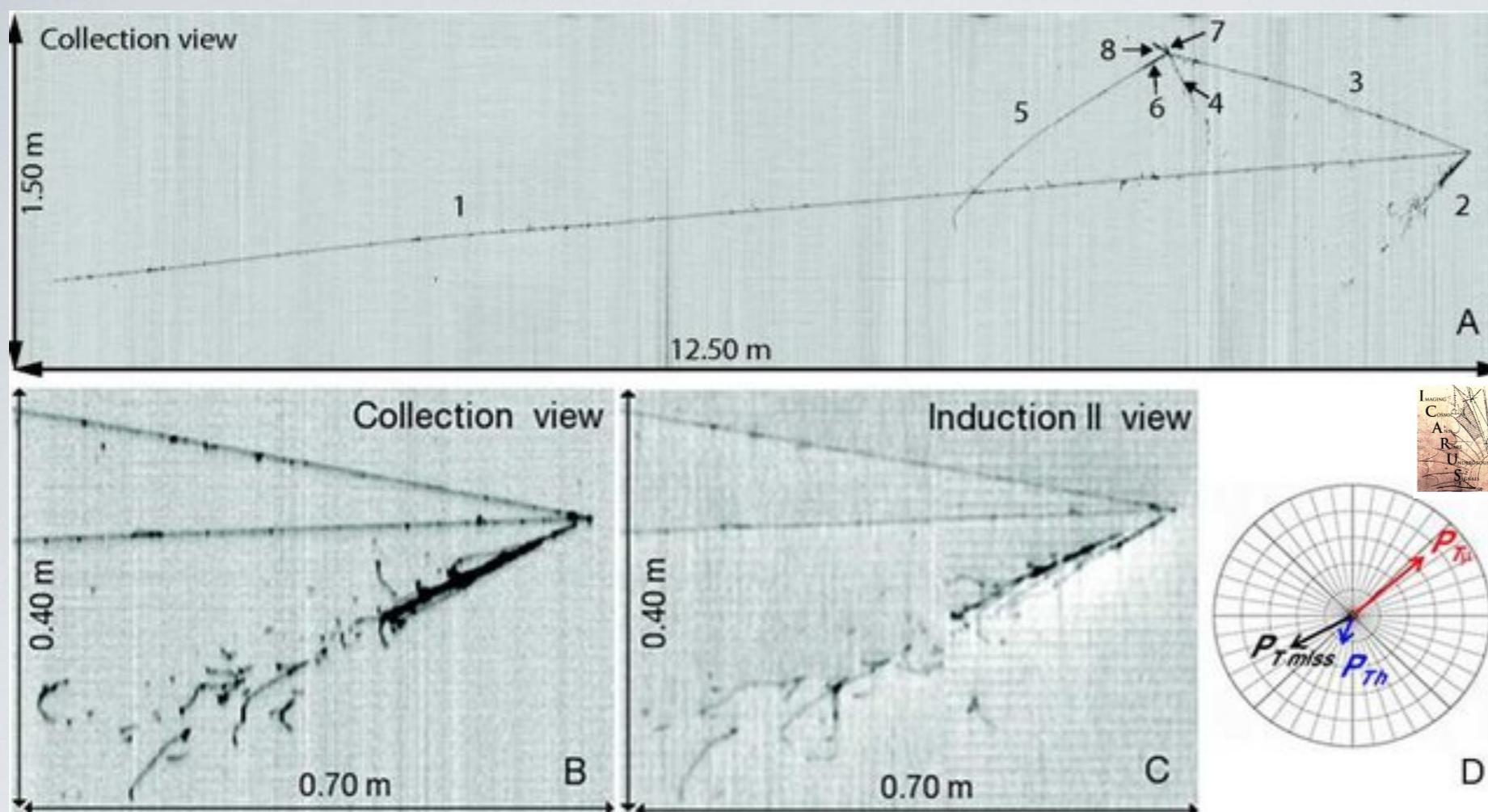
ICARUS 300 t x 2
- CERN CNGS (2010-13)
- FNAL Booster (ready for cooling)



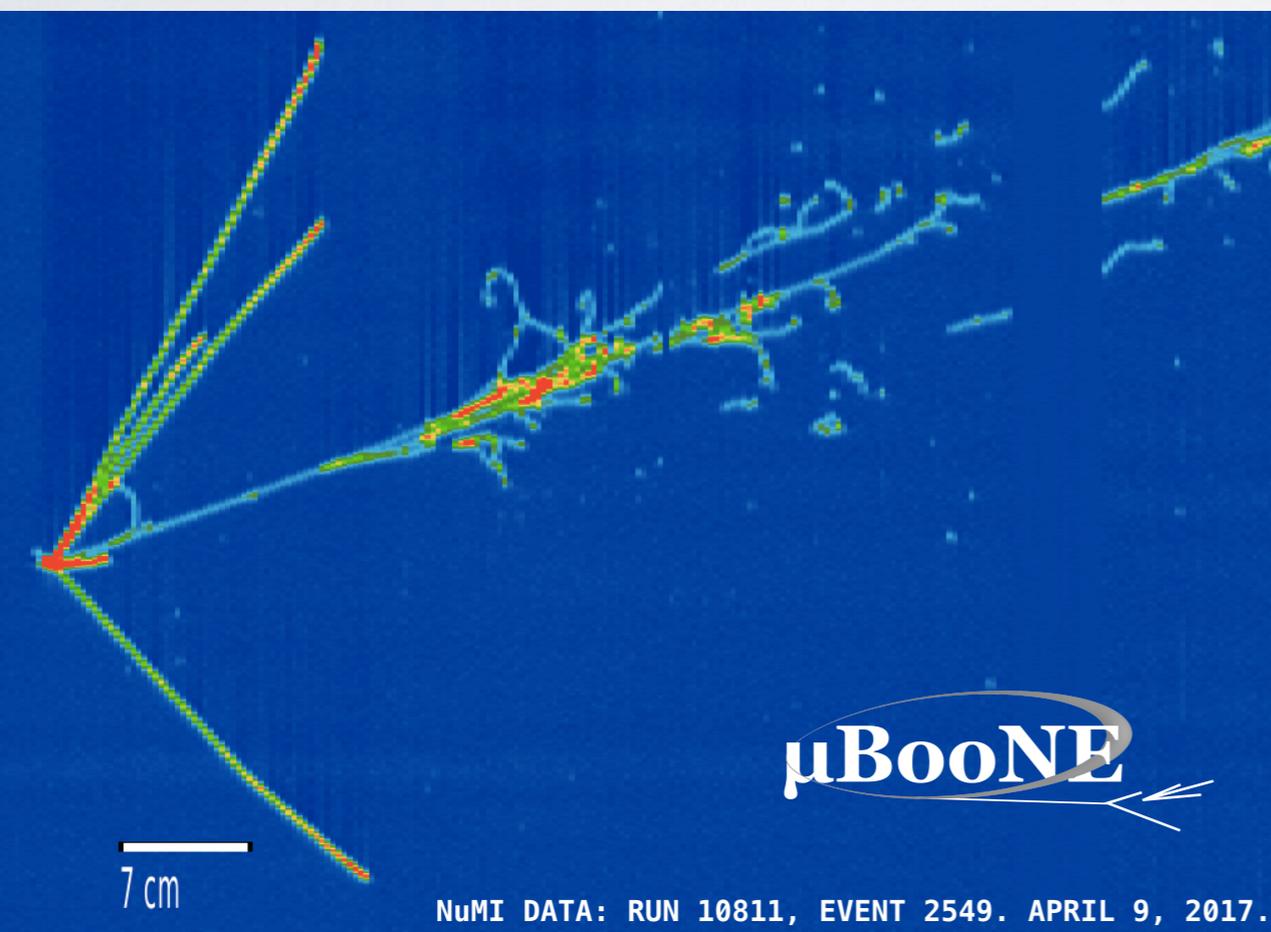
SBND 200 t -
FNAL Booster (under construction)



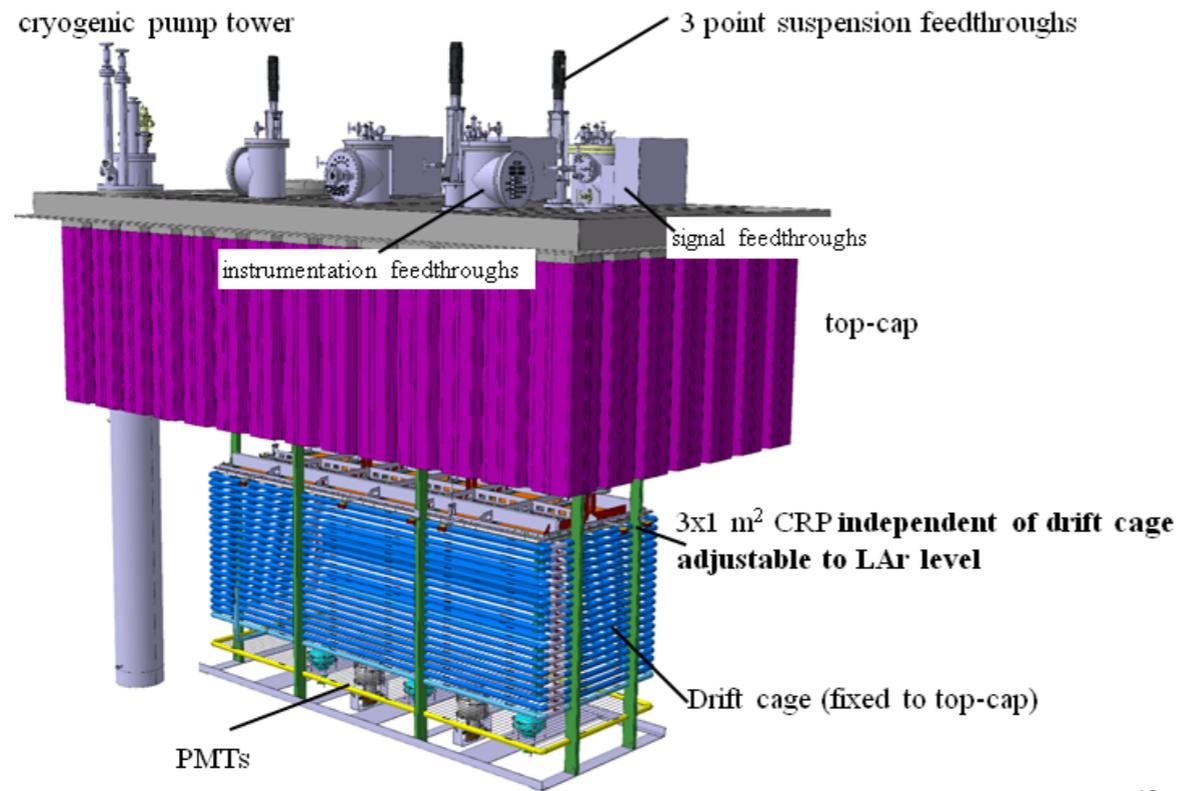
ICARUS at
 GranSasso Lab
 operated on the
 CNGS beam
 from 2010 to
 2013
 producing
 physics results



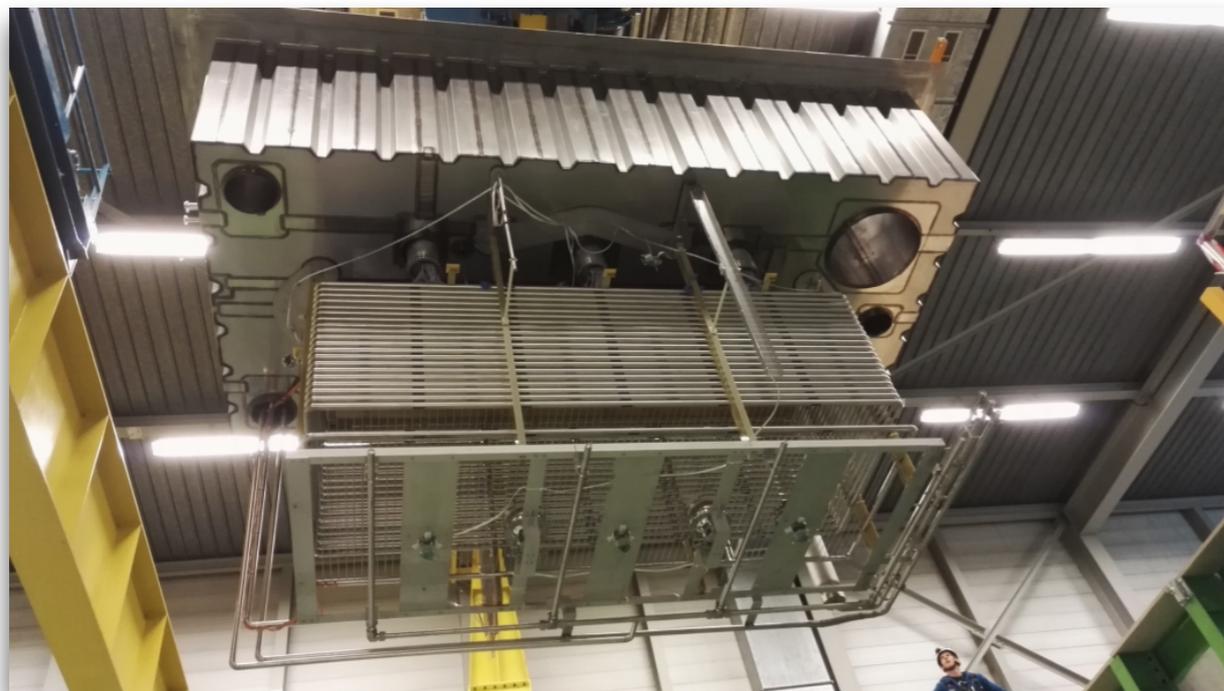
MicroBooNE at
 FNAL
 takes neutrino
 data since 2015
 and is producing
 physics results
 (a main one
 expected in summer)



Pilot Dual Phase Detector: $3 \times 1 \times 1 \text{ m}^3$ at CERN



Detector installation
completed in fall 2016



DUNE First Module

17,000 t LArTPC Single Phase

one giant leap for the technology



ICARUS



26



MICROBOONE

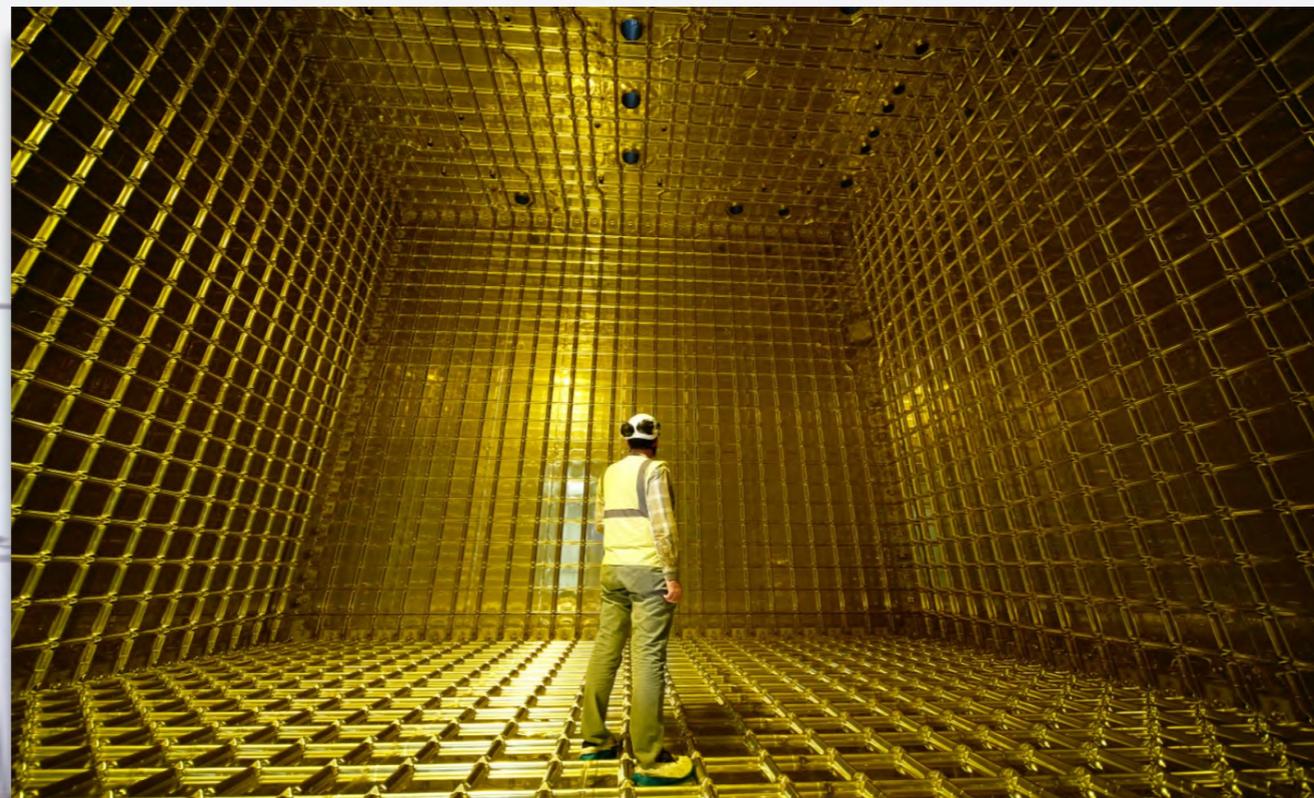


SBND

DUNE First Module

17,000 t LArTPC Single Phase

one giant leap for the technology



protoDUNE-SP
1kt LAr



ICARUS



MICROBOONE



SBND

DUNE 2nd or 3rd Module

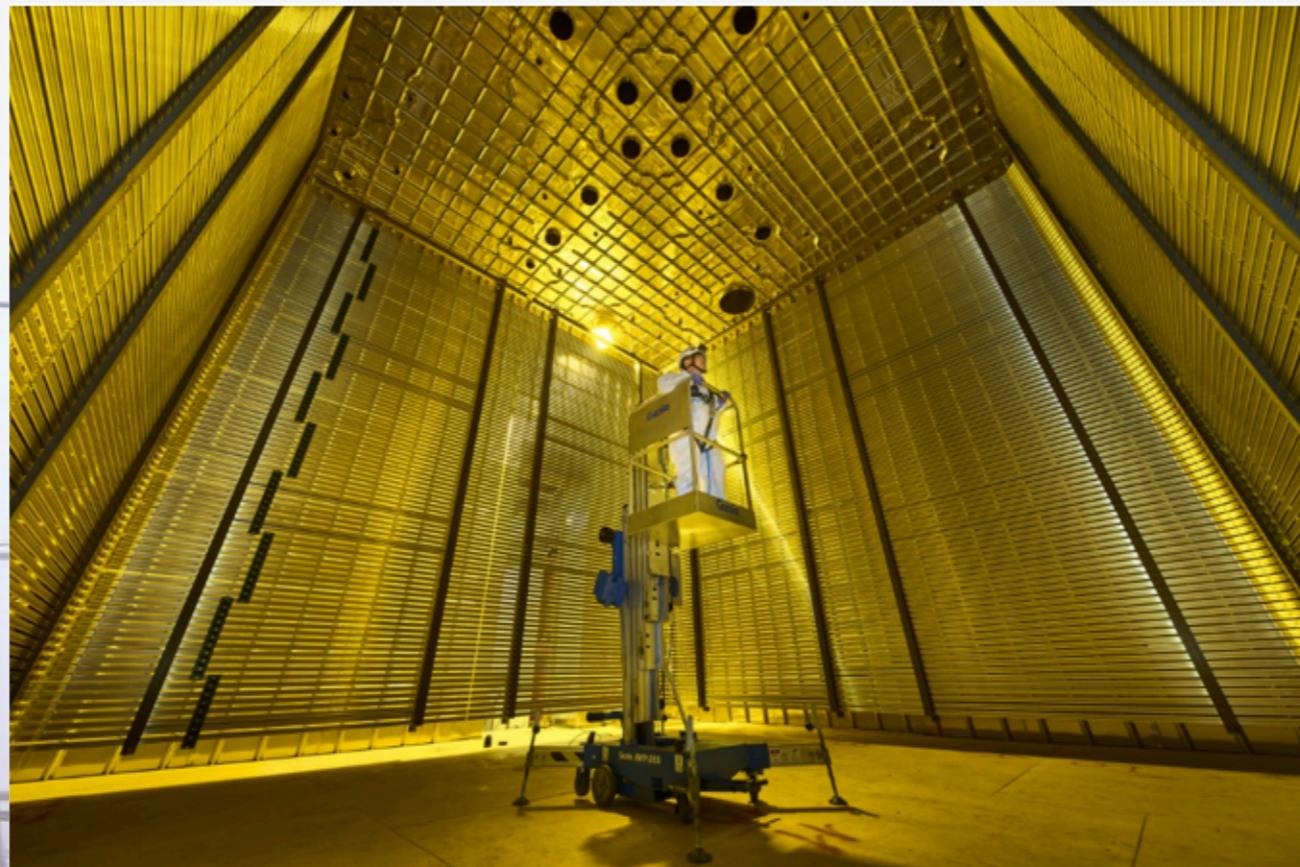
17,000 t LArTPC Dual Phase



$3 \times 1 \times 1 \text{ m}^3$

DUNE 2nd or 3rd Module

17,000 t LArTPC Dual Phase

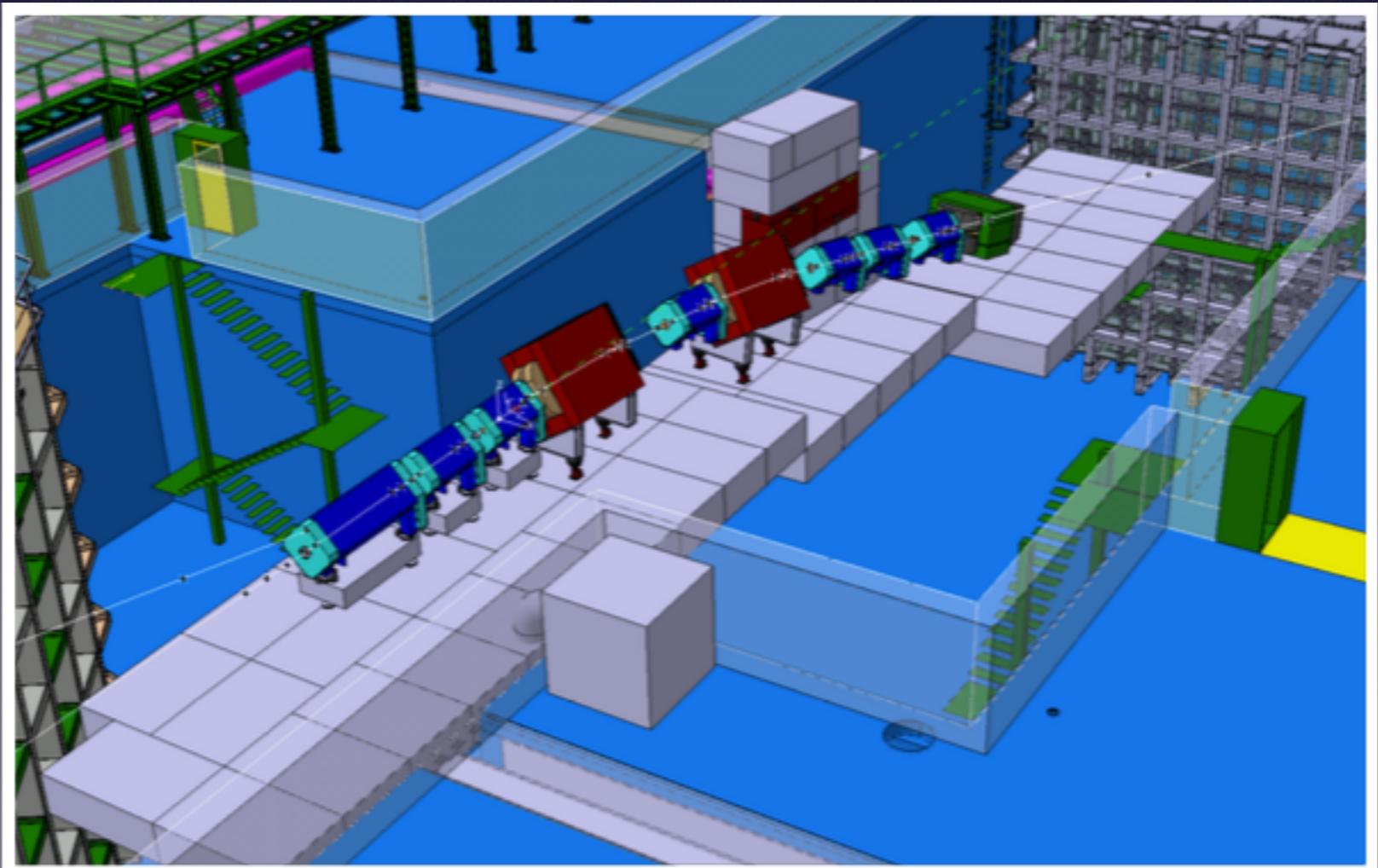


protoDUNE-DP
1kt LAr

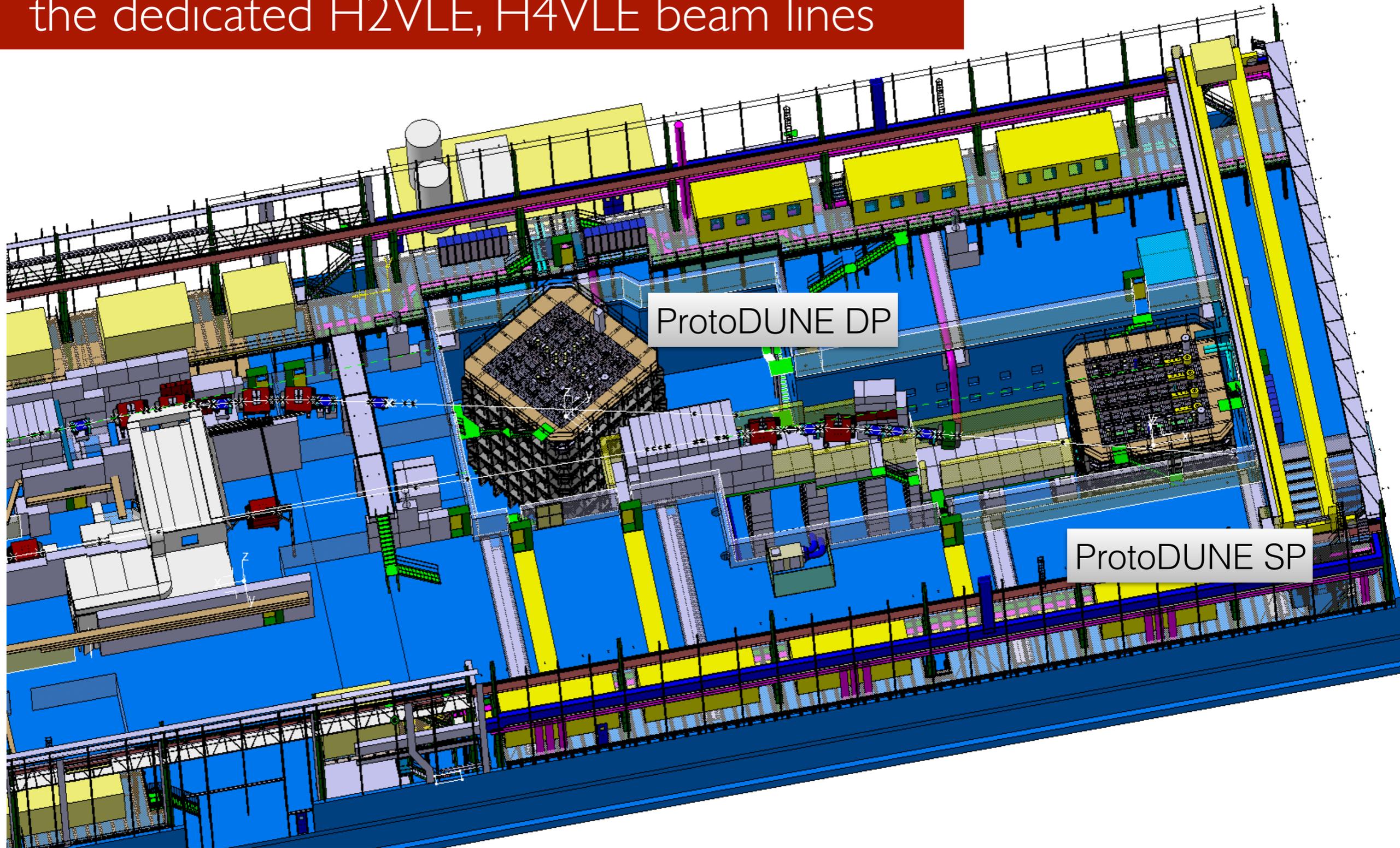


$3 \times 1 \times 1 \text{ m}^3$

ProtoDUNE at CERN



The Neutrino Platform and the dedicated H2VLE, H4VLE beam lines



extension of the EHN1 experimental area at CERN's Prévéssin site

the CERN Neutrino Platform: a new dedicated experimental facility for



• Dec. 12, 2015

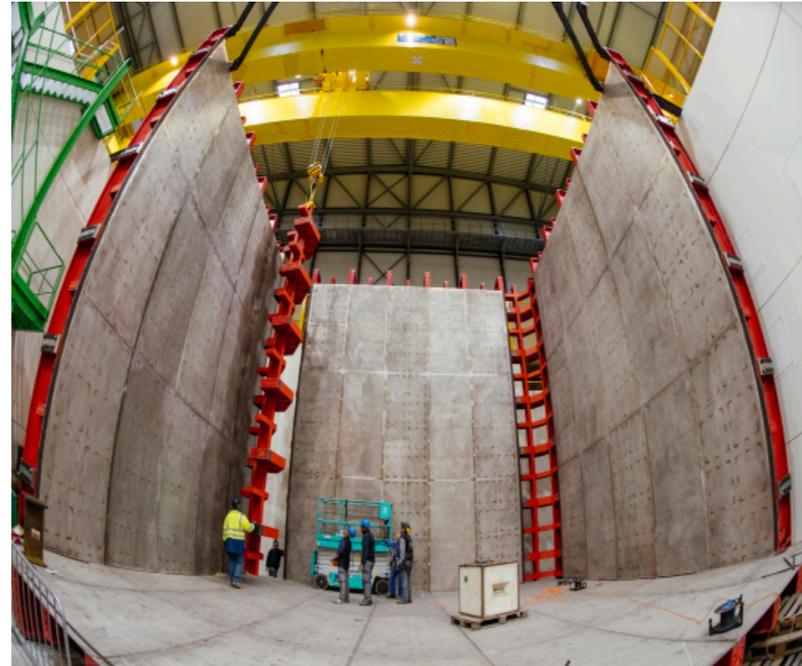
Sept. 21, 2018



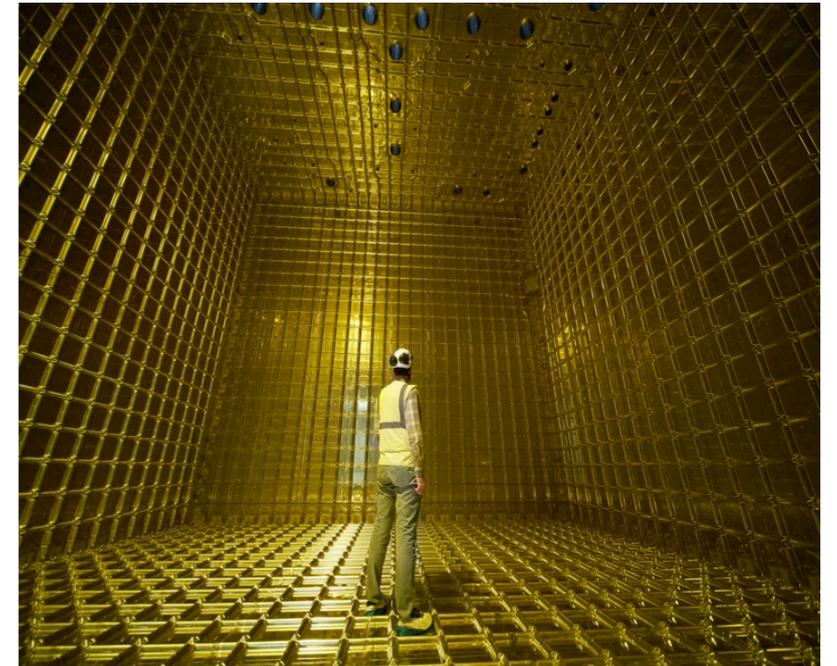


CERN EHN1 extension

March 2016, construction of EHN1 extension



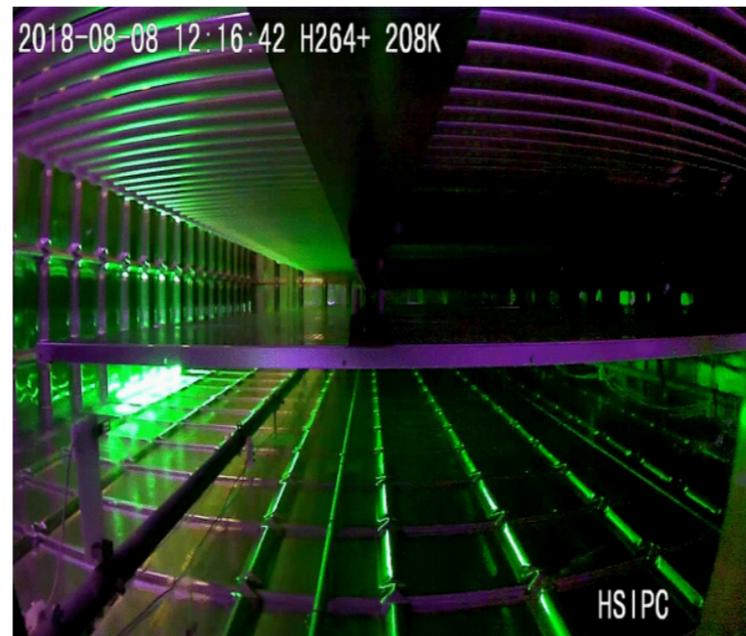
November 2016, cryostat structure assembly



September 2017, cryostat completion



February 2018, detector assembly



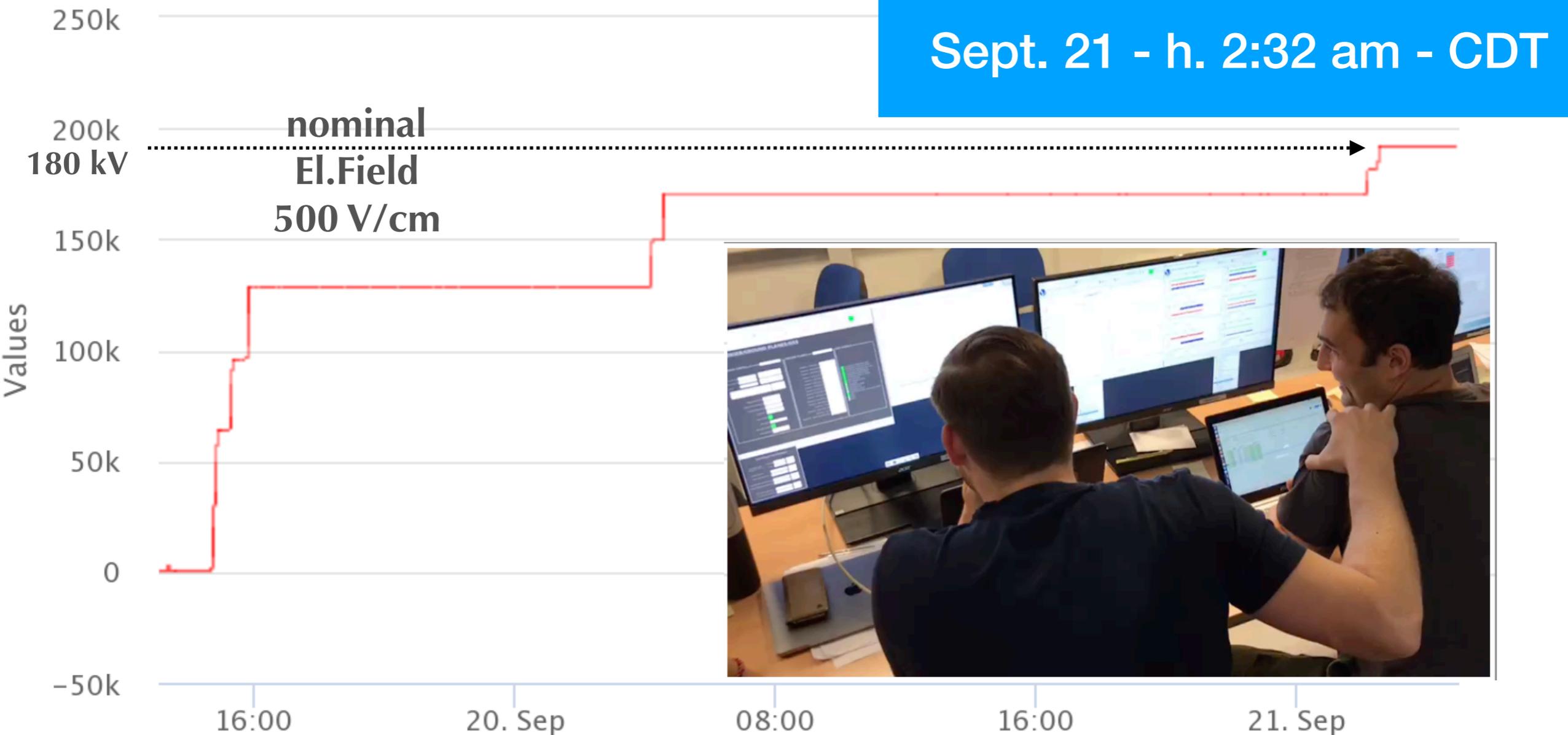
August 2018, LAr filling



September 19, 2018 - ready for beam!

NP04_DCS_01_Heinz_V_Raw

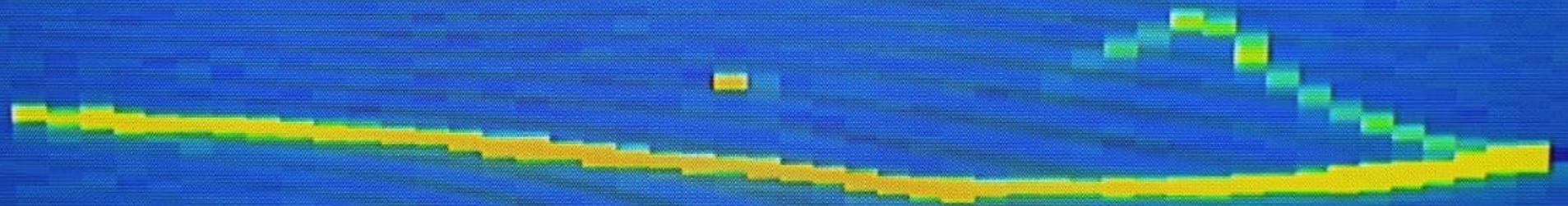
Using the Boost module



HV Ramp from 0 to 180 kV (Nominal)



few seconds after, from the On-Line Monitor



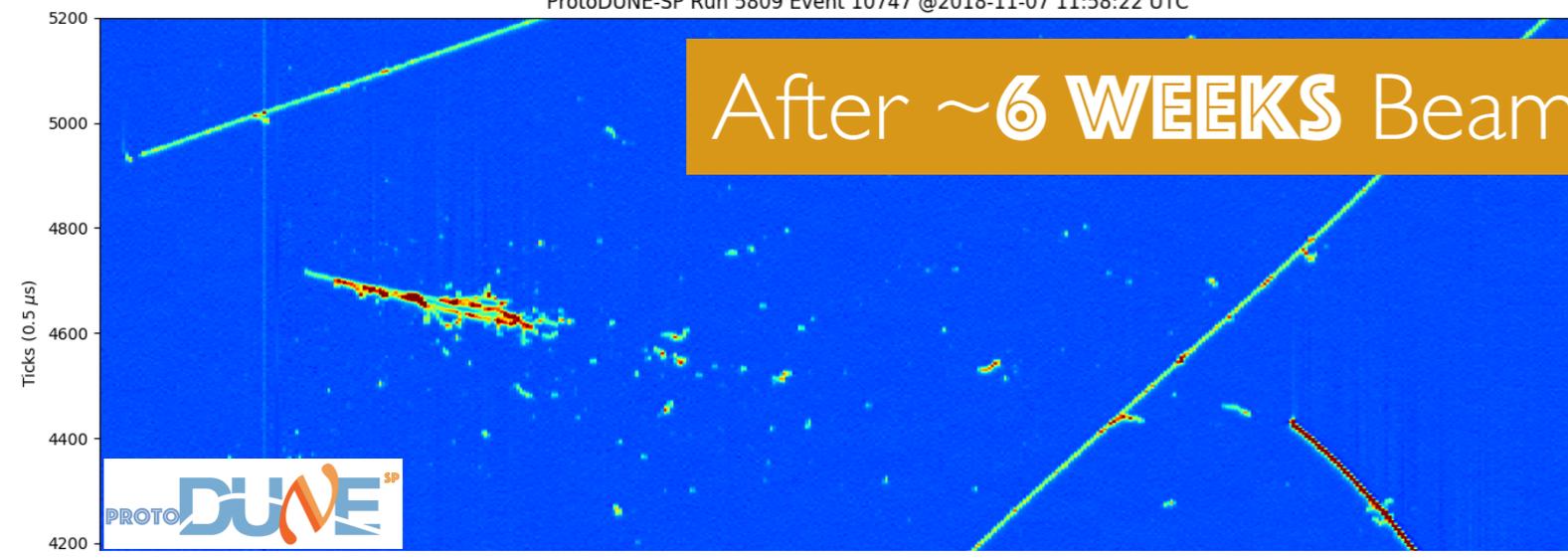
First track recorded at Nominal El.Field

11950

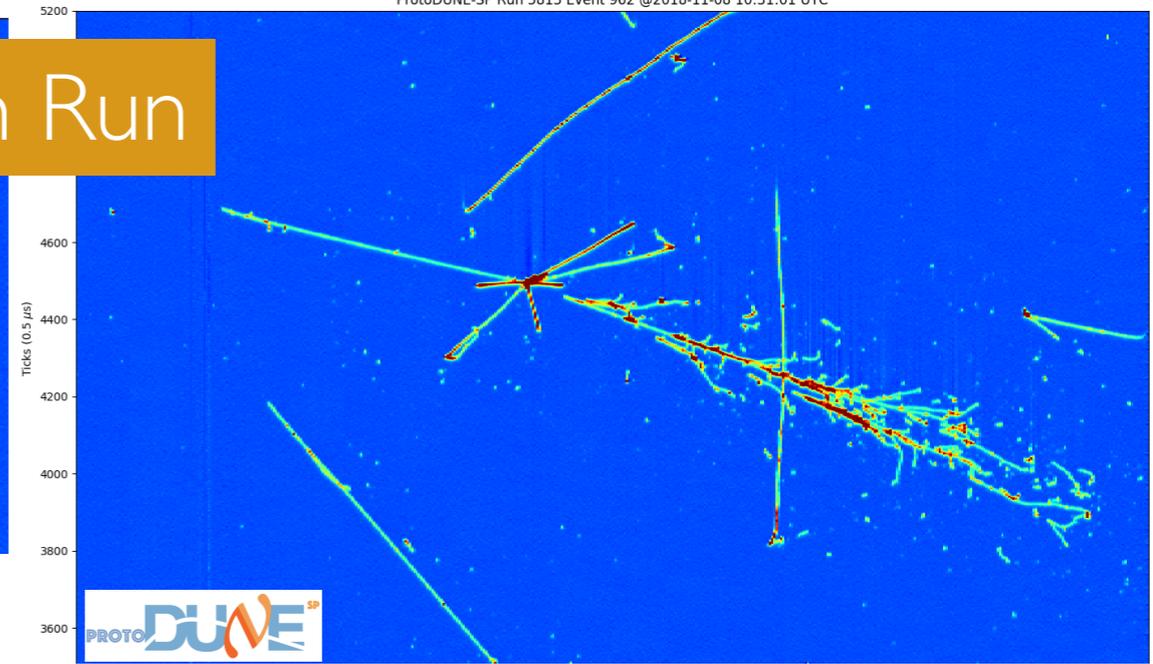


ProtoDUNE-SP Run 5809 Event 10747 @2018-11-07 11:58:22 UTC

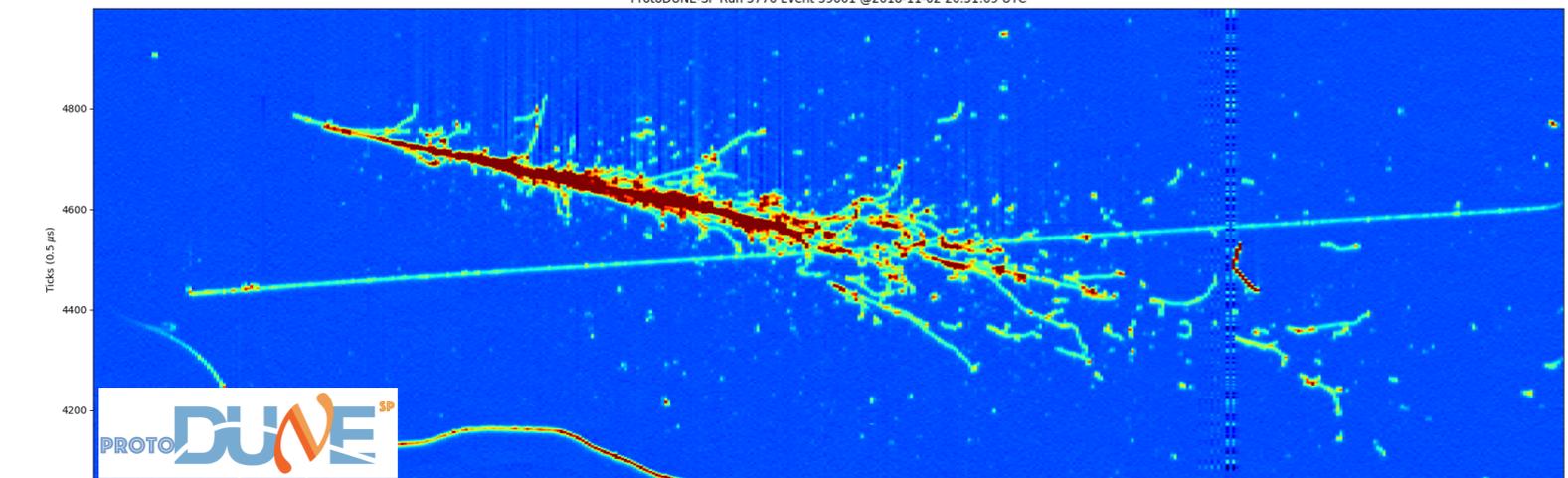
After ~6 WEEKS Beam Run



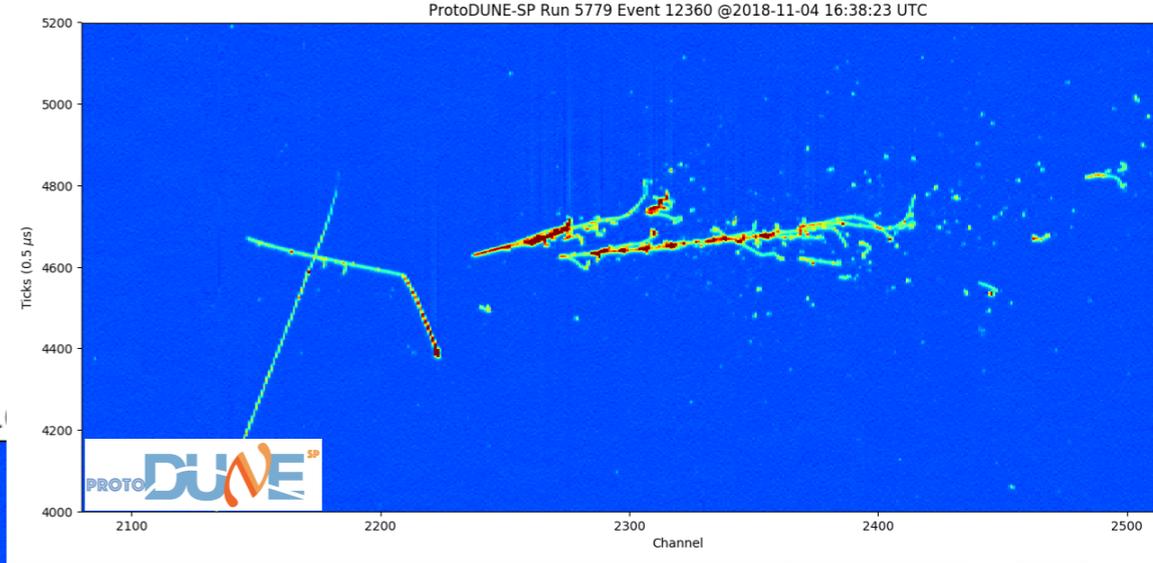
ProtoDUNE-SP Run 5815 Event 962 @2018-11-08 10:31:01 UTC



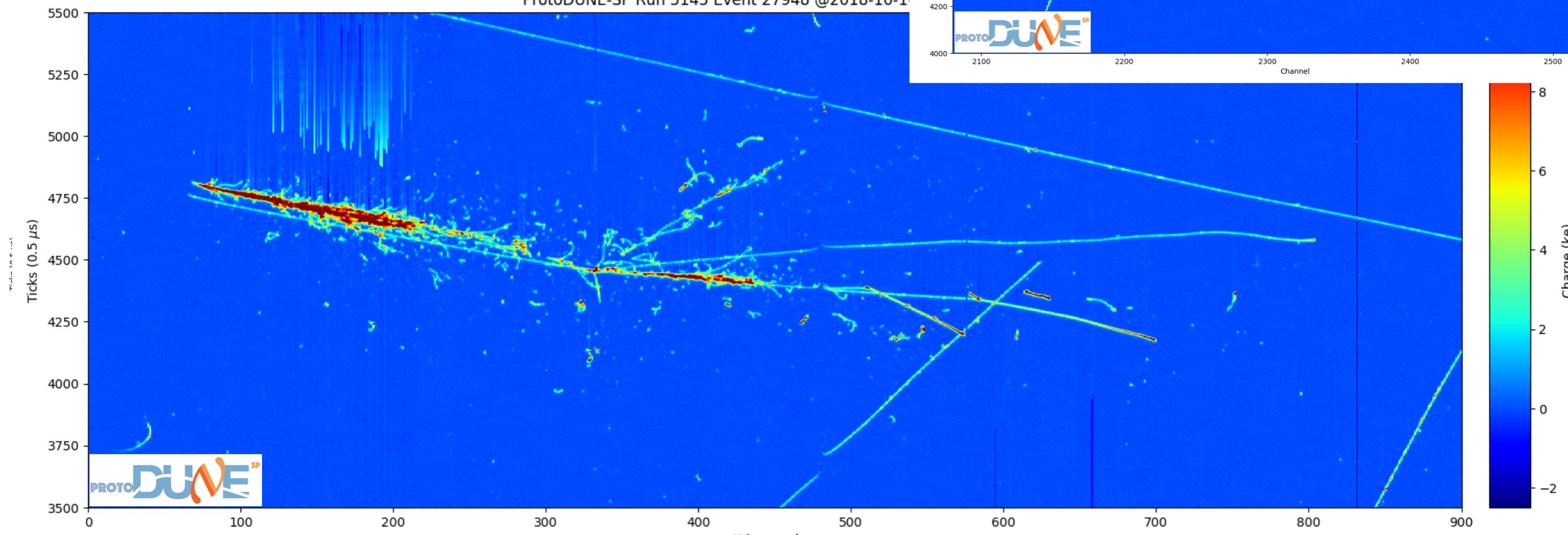
ProtoDUNE-SP Run 5770 Event 59001 @2018-11-02 20:51:09 UTC



ProtoDUNE-SP Run 5779 Event 12360 @2018-11-04 16:38:23 UTC



ProtoDUNE-SP Run 5145 Event 27948 @2018-10-11 10:00:00 UTC



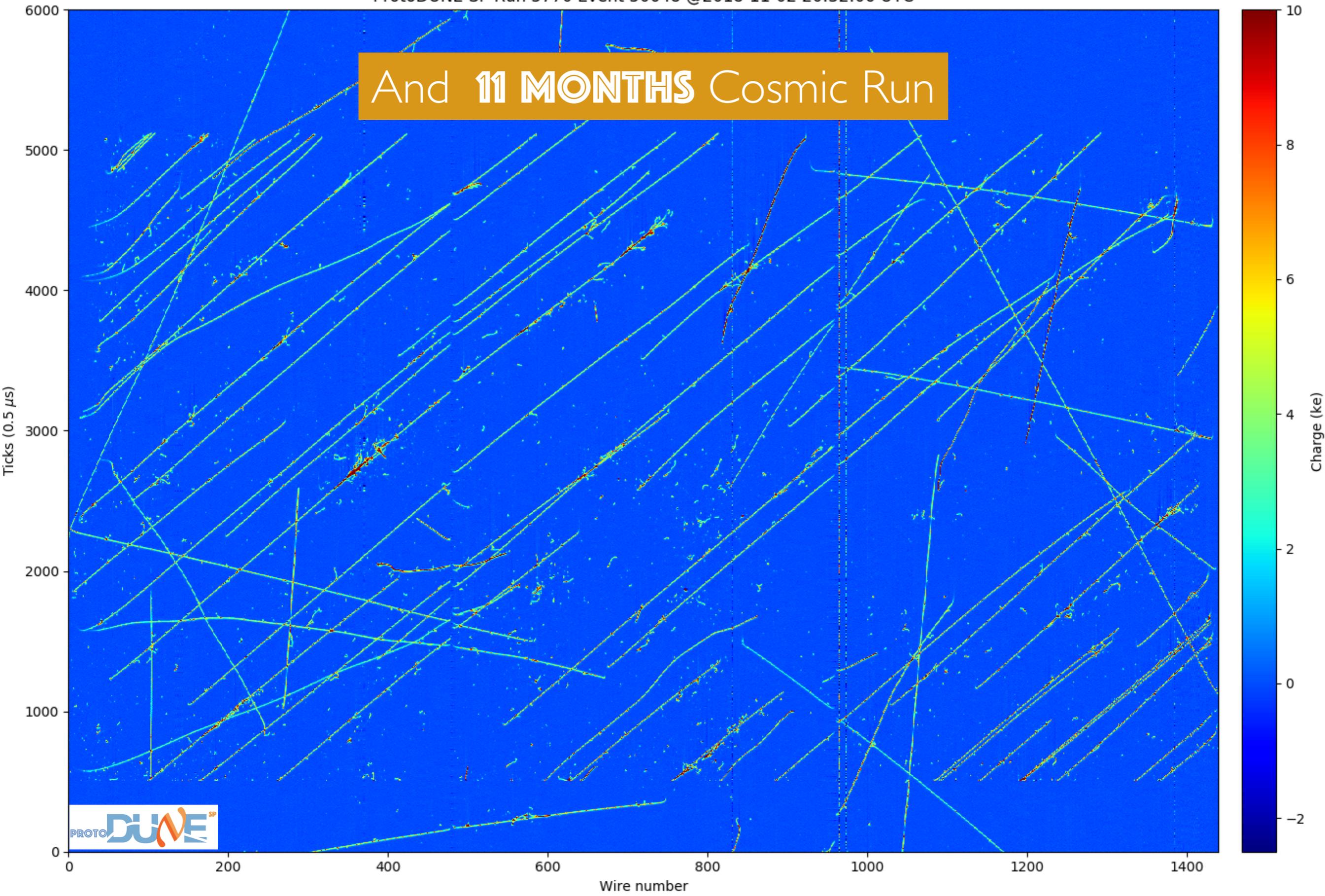
real beam event in 3D

click here for a
[gallery of ProtoDUNE events](#)

real beam event in 3D

click here for a
[gallery of ProtoDUNE events](#)

And **11 MONTHS** Cosmic Run



1ST PAPER COMPLETED ON DEC. 15, 2019

Currently under DUNE internal review - expect to submit for publication in February

2 PREPARED FOR SUBMISSION TO JINST

3 **First results on ProtoDUNE-SP LArTPC performance from** 4 **a test beam run at the CERN Neutrino Platform**

5 **ABSTRACT:** The ProtoDUNE-SP detector is a single-phase liquid argon time projection chamber
6 (TPC) with an active volume of $7.0 \times 6.0 \times 3.6 \text{ m}^3$. It is installed in a specially-constructed
7 calibration beam that provides samples of incident particles with well-measured momenta and
8 high-purity particle identification. The ProtoDUNE-SP detector is a prototype for the first far
9 detector module of the Deep Underground Neutrino Experiment, and it incorporates full-size
10 components as designed for that module. ProtoDUNE-SP's successful operation during 2018 and
11 2019 and its production of large samples of high-quality data demonstrate the effectiveness of the
12 single-phase far detector design. This paper describes the beam line, the TPC, the photon detectors,
13 the signal processing and particle reconstruction. It presents the first results on ProtoDUNE-SP's
14 performance. These results include TPC noise and gain measurements, dE/dx calibration for
15 muons, protons, pions and electrons, drift electron lifetime measurements, and photon detector
16 noise, signal sensitivity and time resolution measurements.

DETECTOR RESPONSE (BEAM DATA)

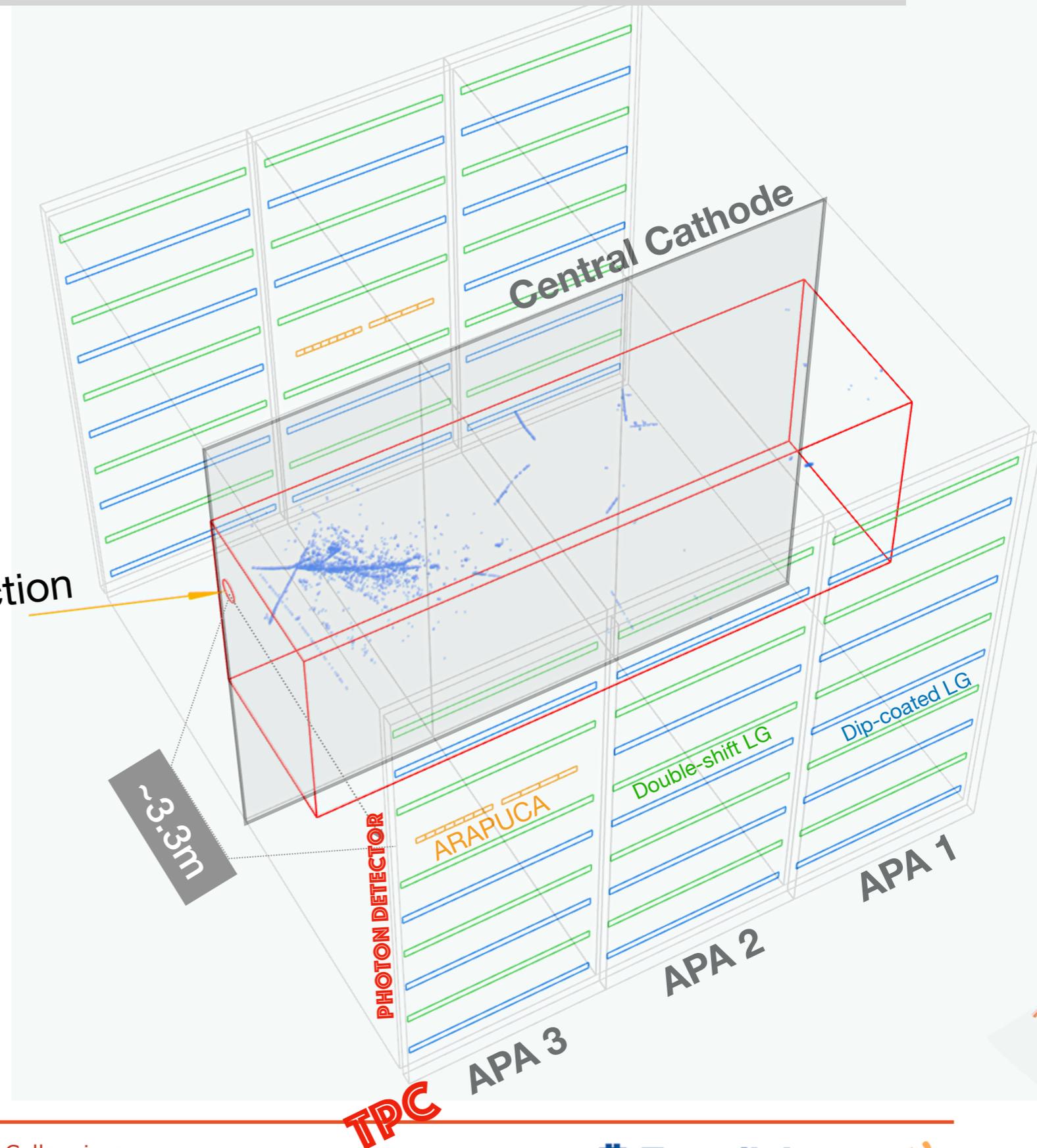
TPC

- Signal-to-Noise & Imaging
- dE/dx - Calorimetry
- Particle ID

PHOTON DETECTOR

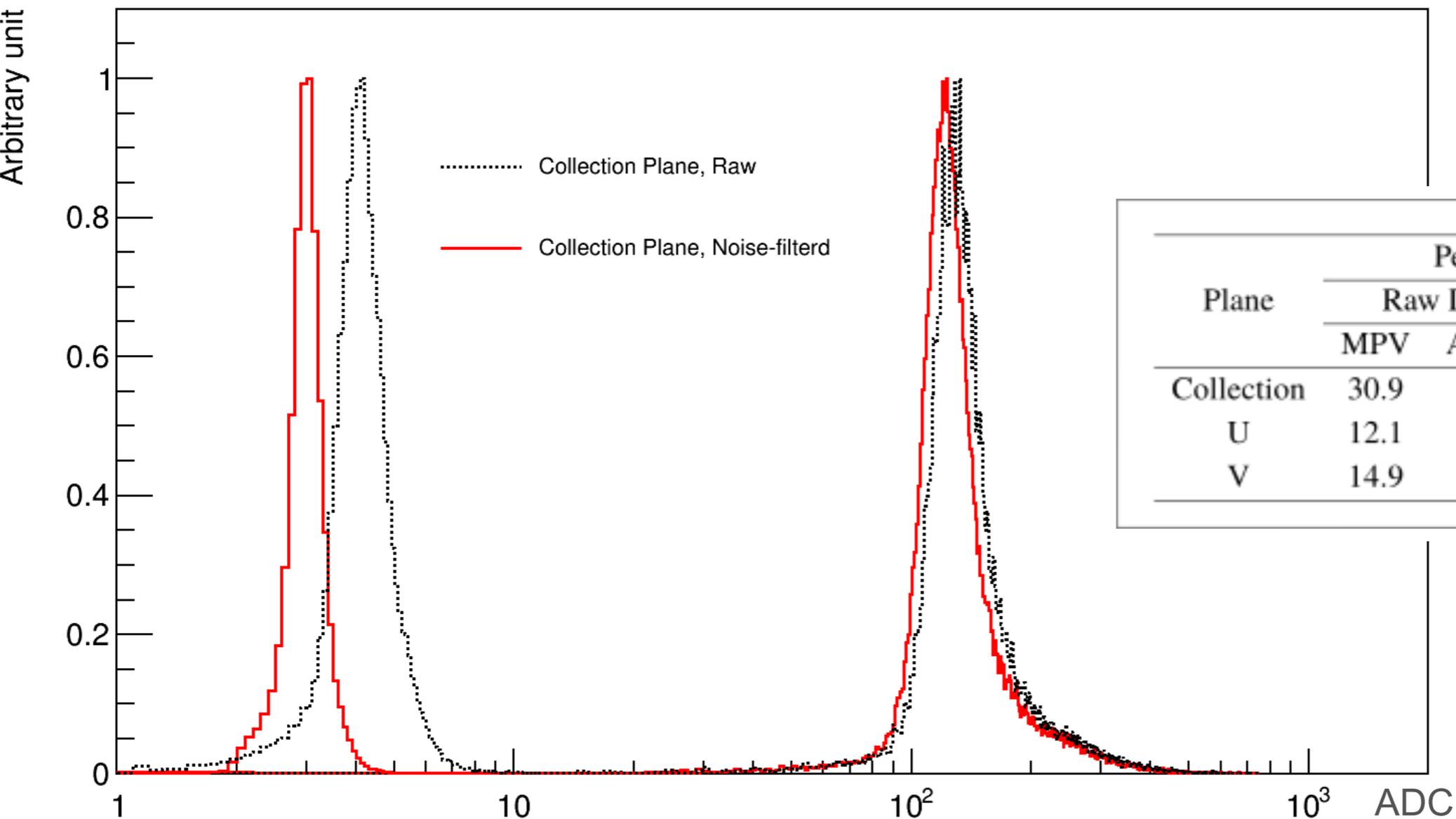
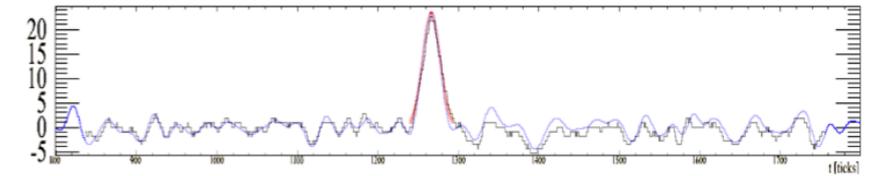
- Efficiency
- Light Yield
- Calorimetric Energy from Light

Beam Entry Point and Direction



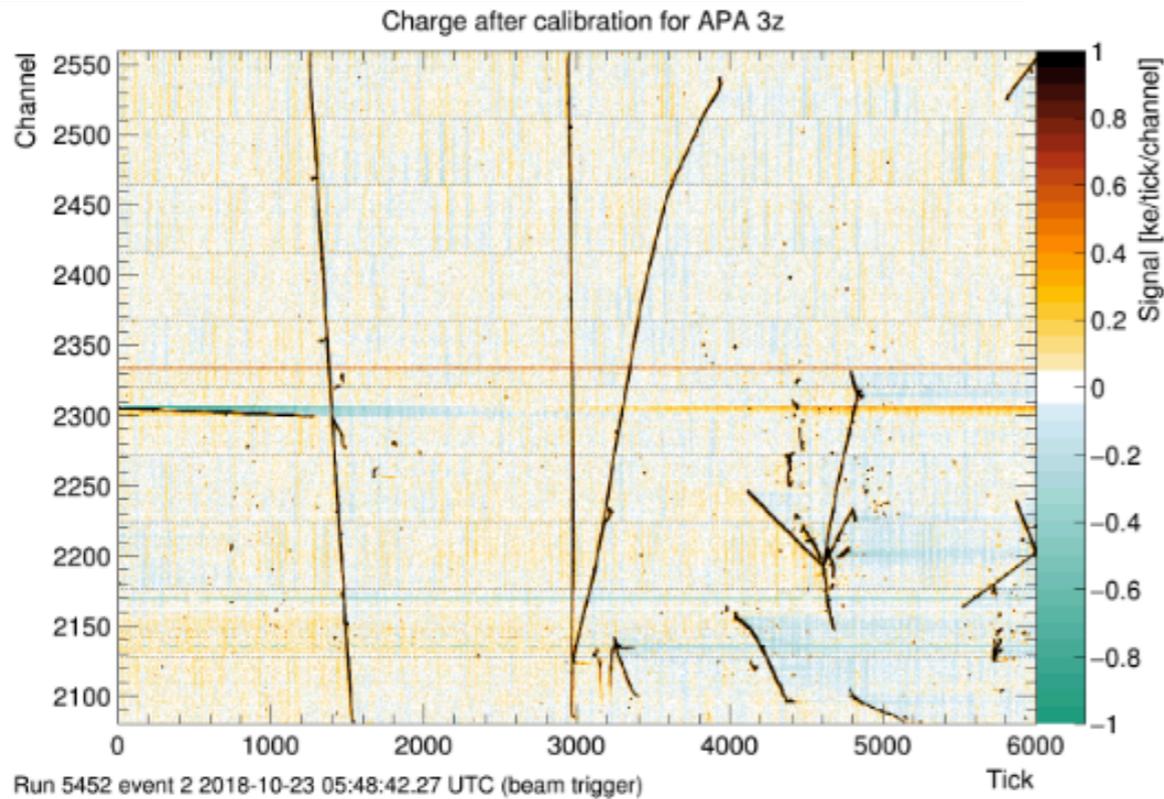
Signal: detected Charge (*hit Peak-amplitude*) in individual channel waveform from mip tracks (the minimal detectable signal)

Noise: σ of baseline fluctuation in corresponding channel waveform

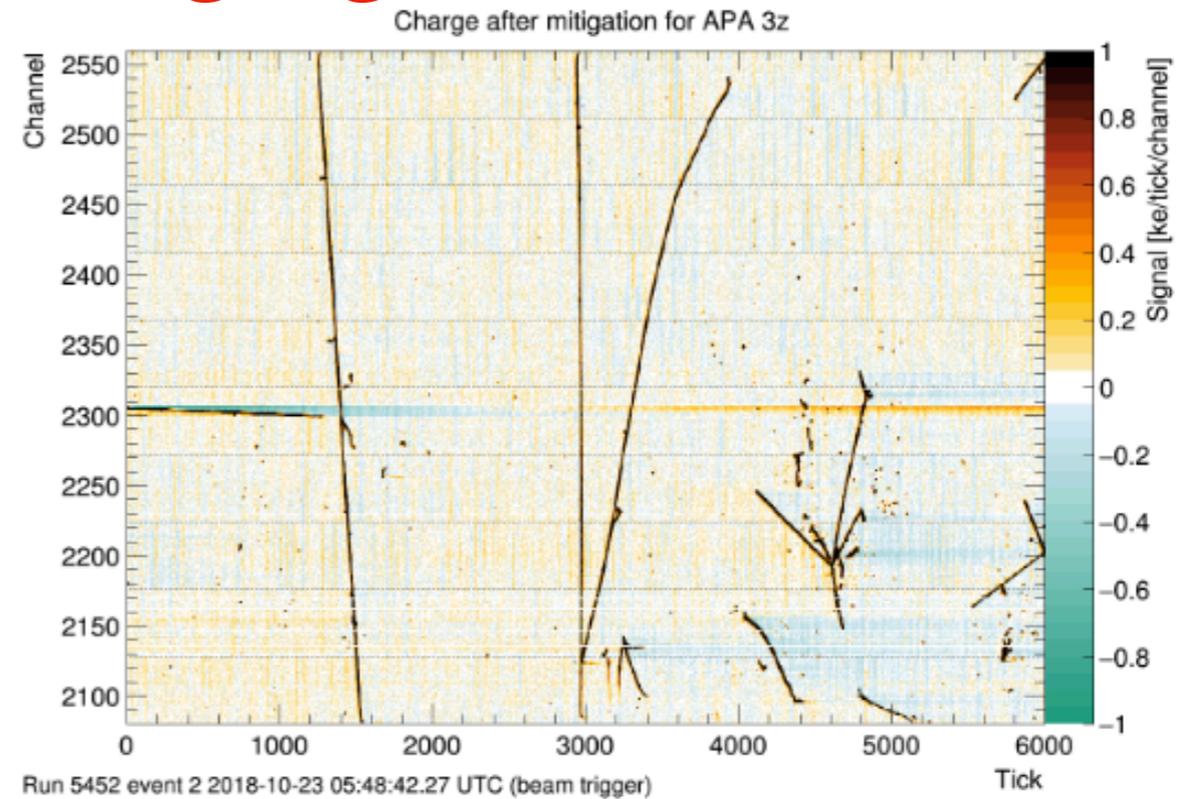


Plane	Peak signal-to-noise ratio			
	Raw Data		After Noise Filtering	
	MPV	Average	MPV	Average
Collection	30.9	38.3	40.3	48.7
U	12.1	15.6	15.1	18.2
V	14.9	18.7	18.6	21.2

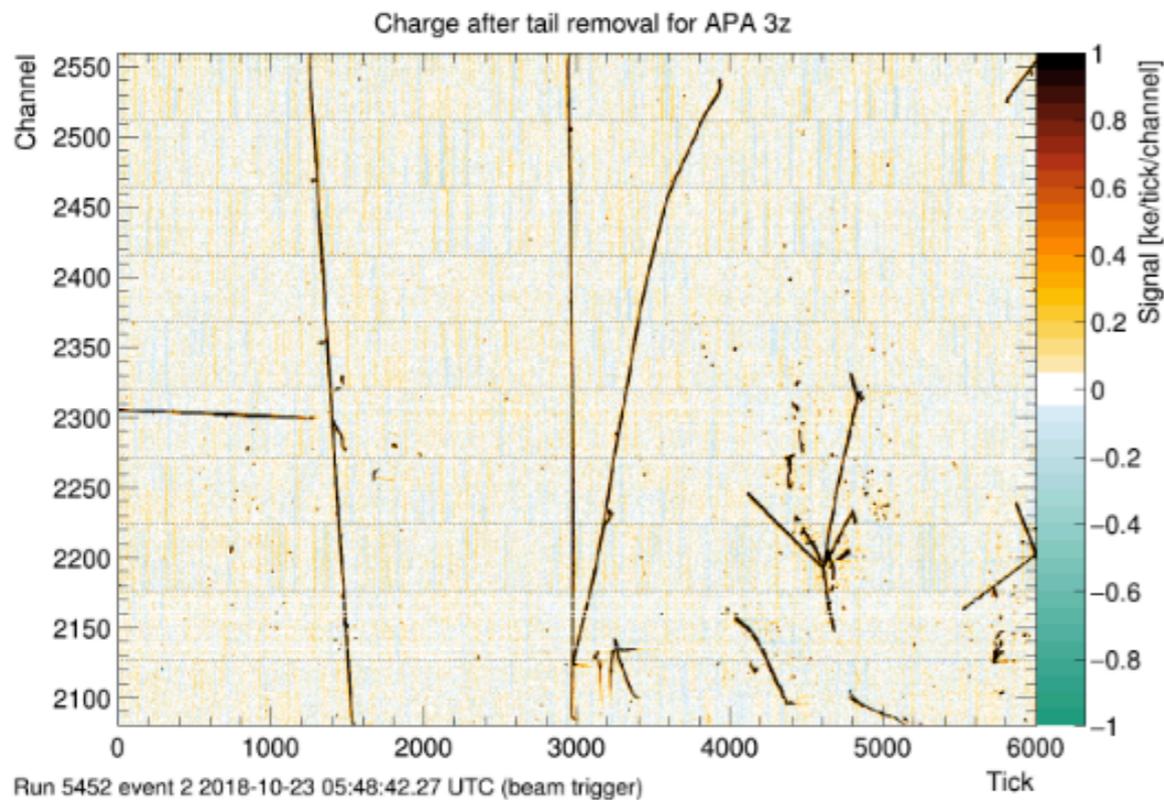
138 e/ADC



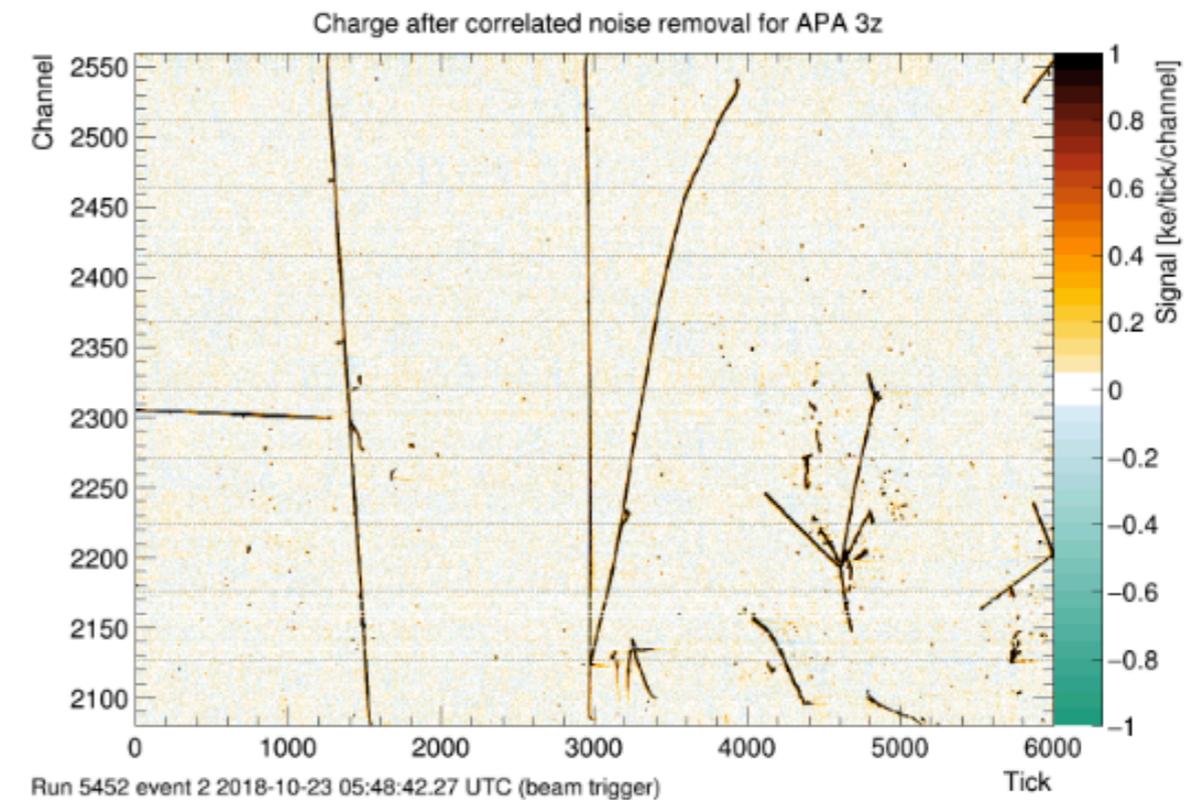
(a) After pedestal subtraction and calibration.



(b) After mitigation (Sticky code)



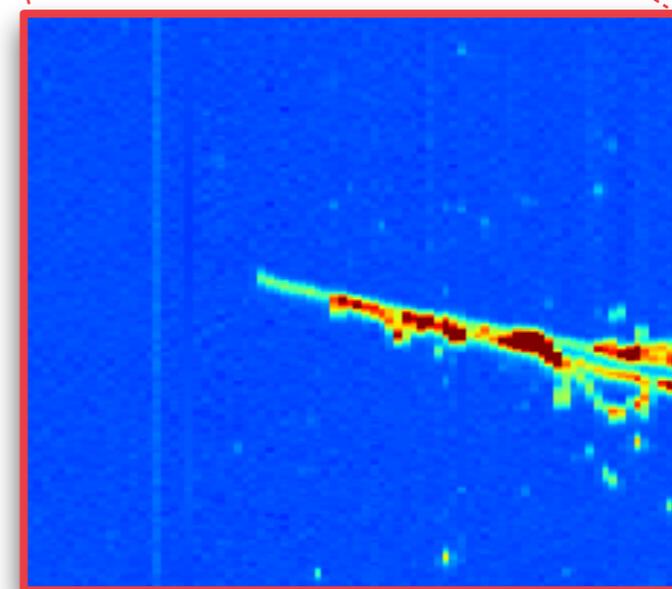
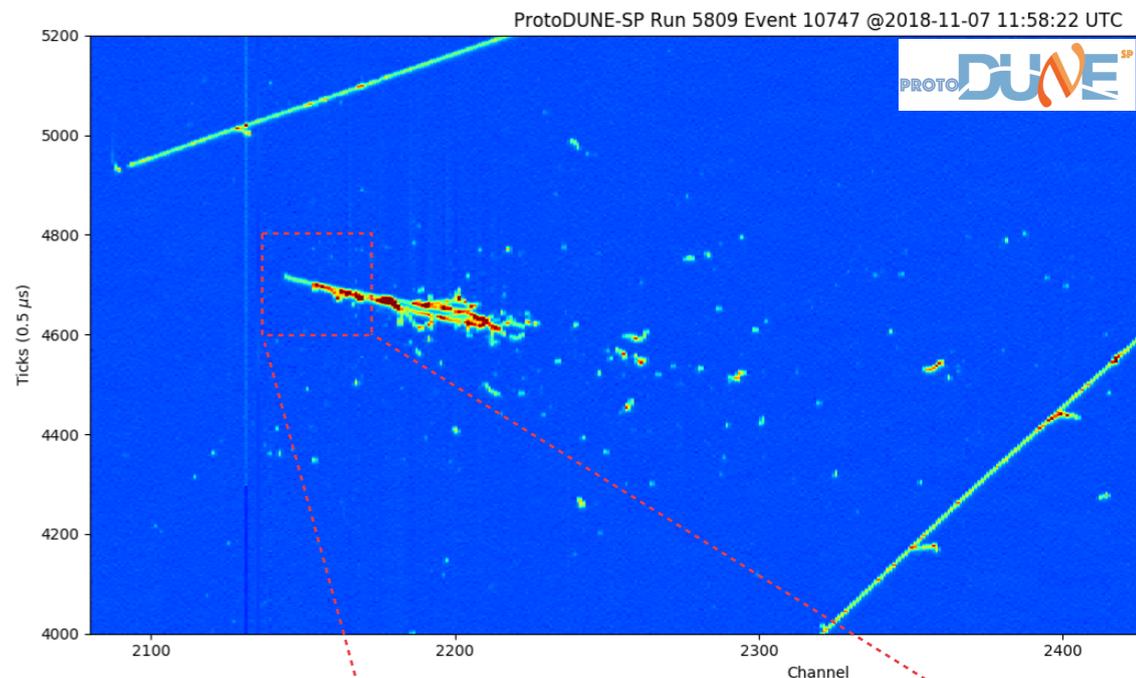
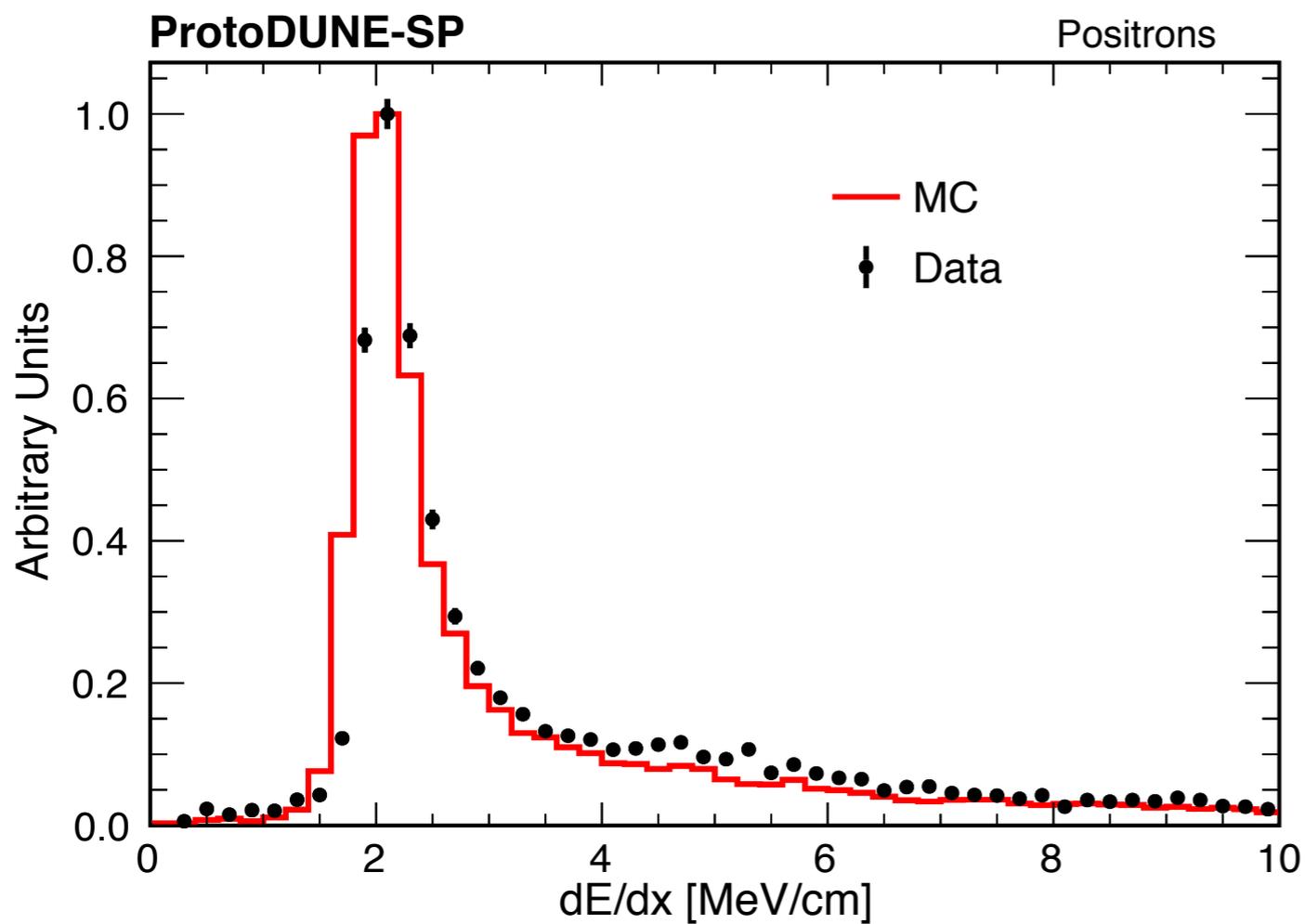
(c) After tail removal.



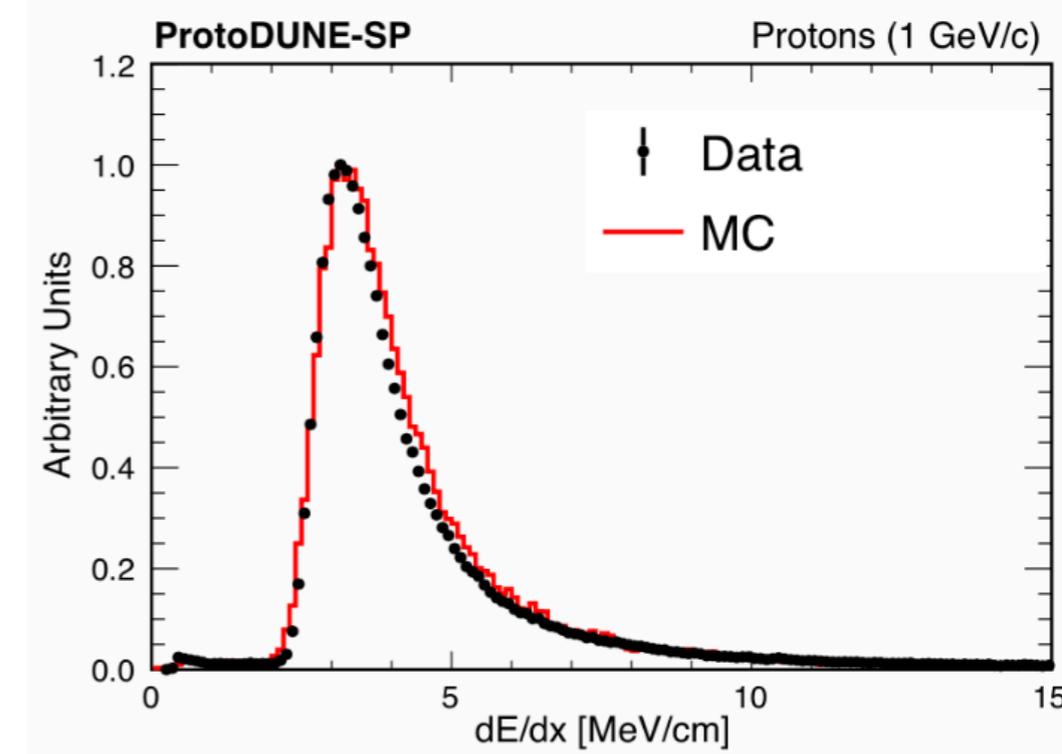
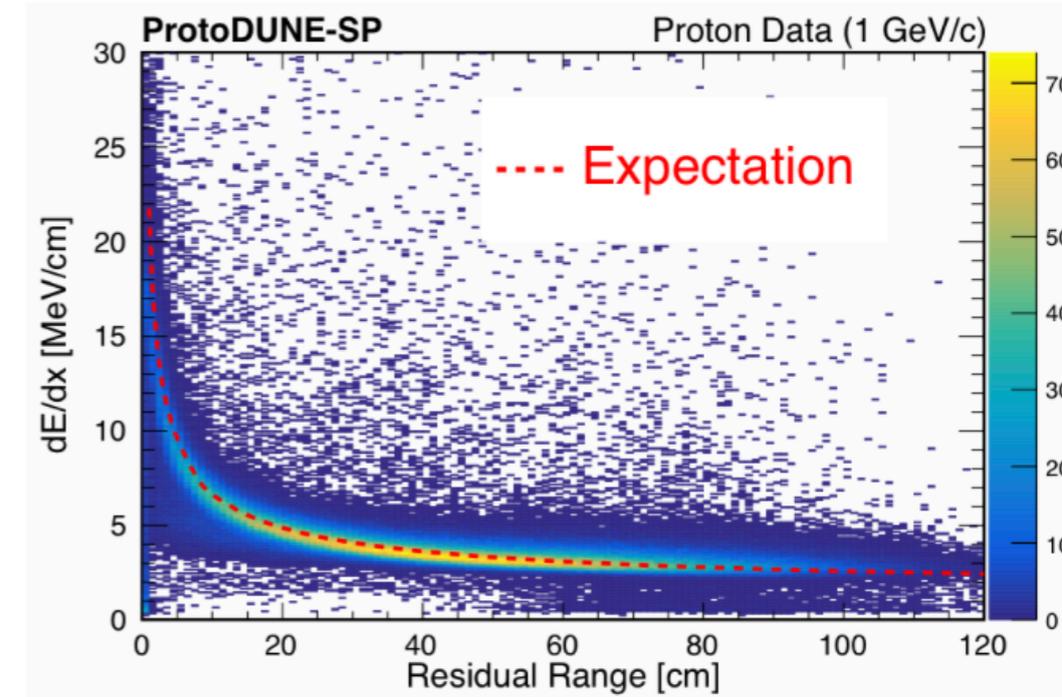
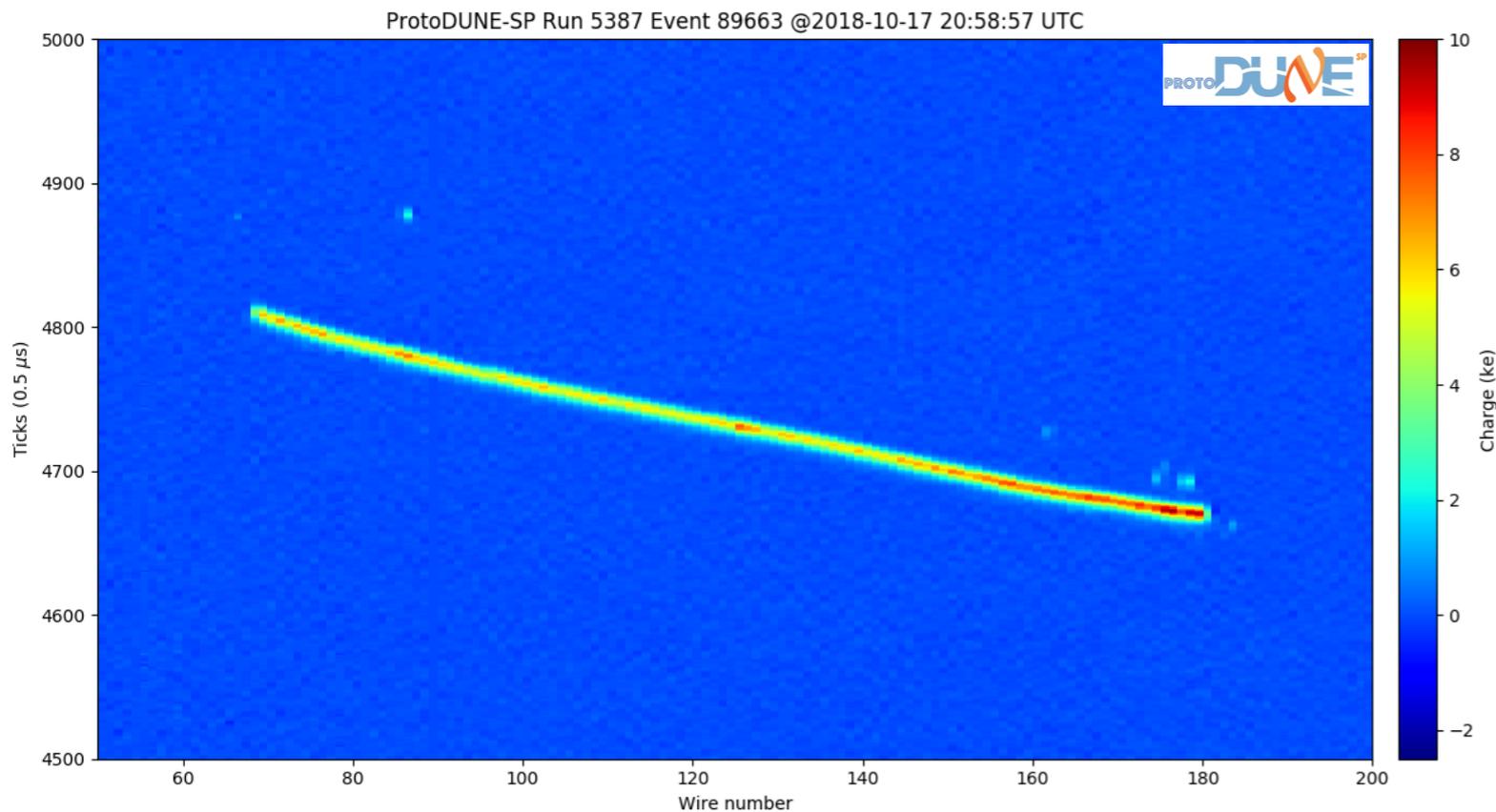
(d) After correlated noise removal.

(after Space Charge Calibration)

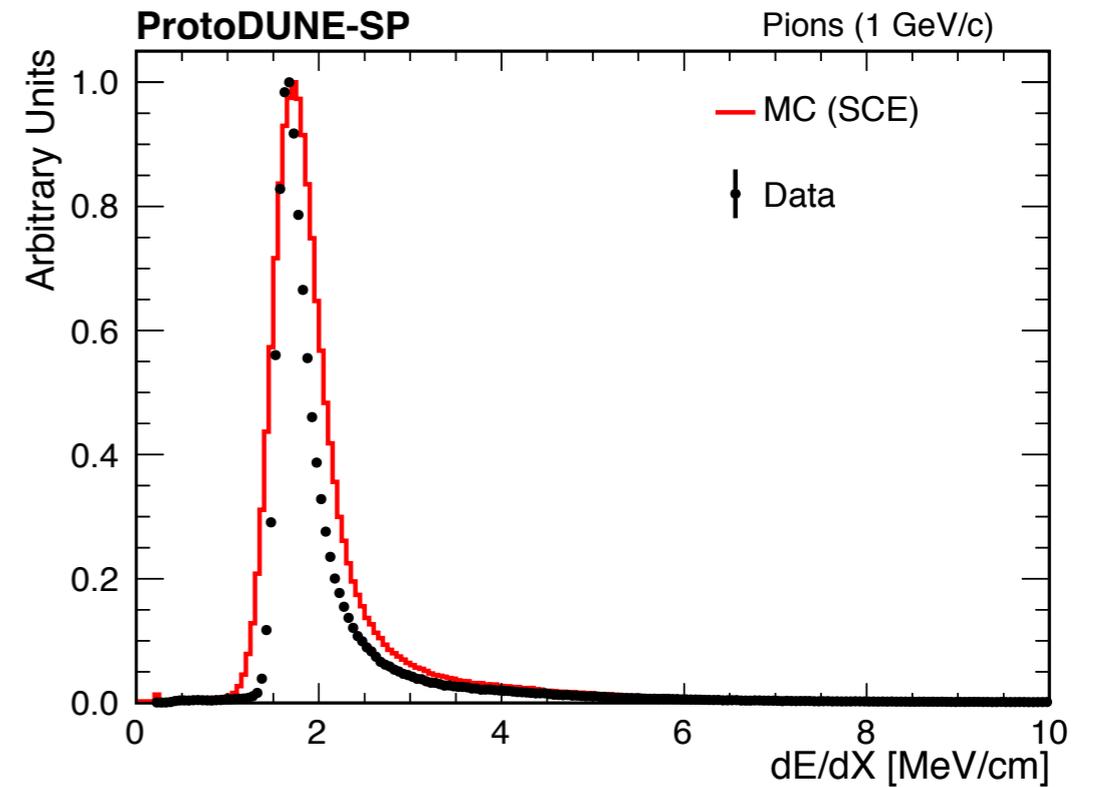
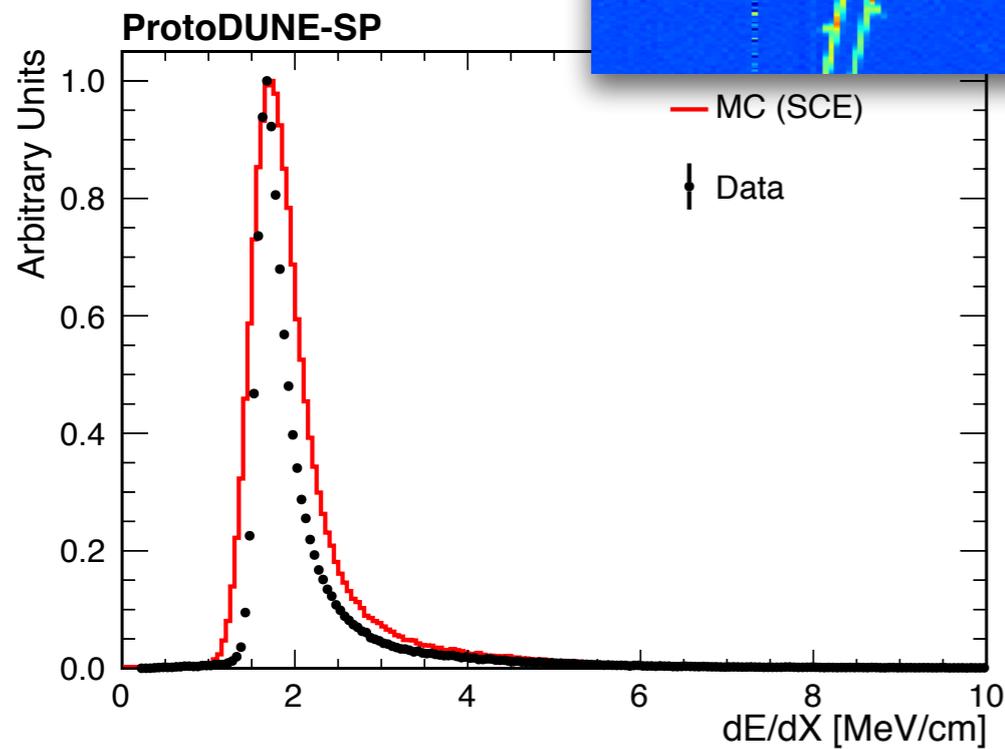
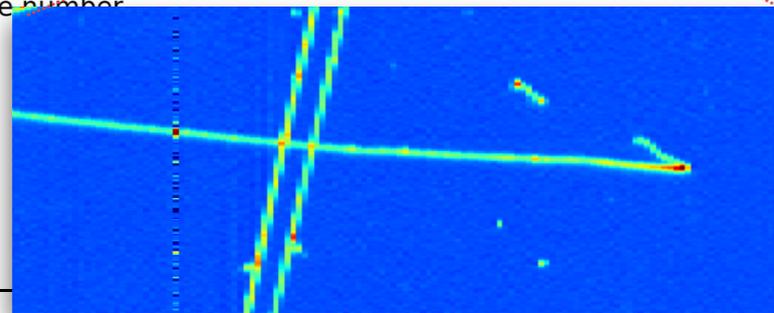
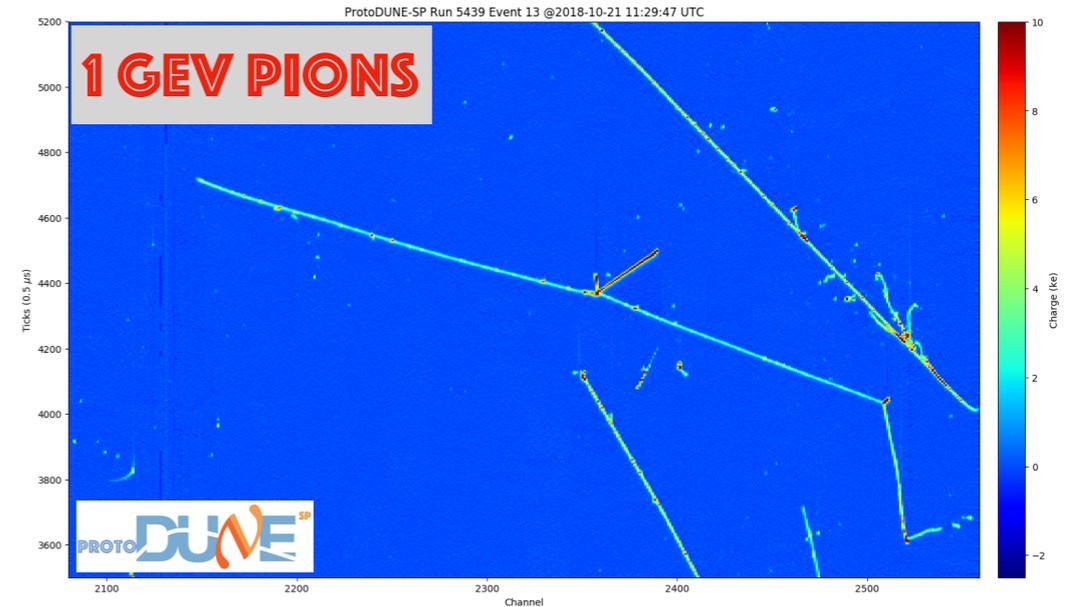
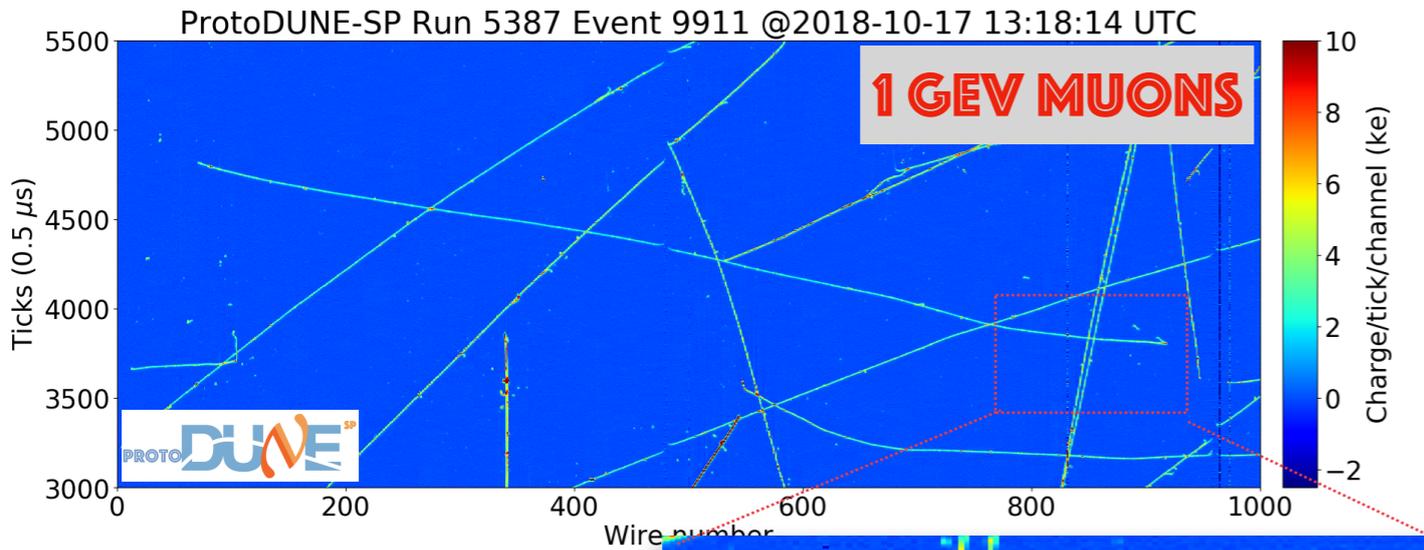
1 GEV ELECTRONS



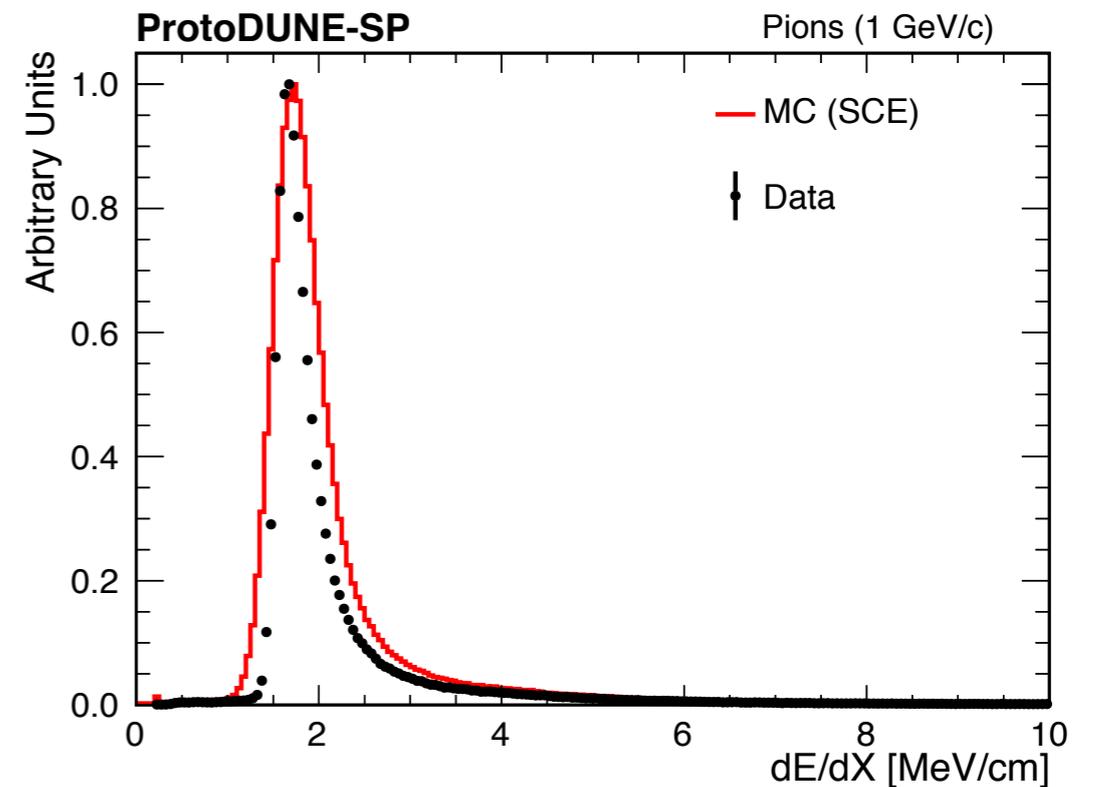
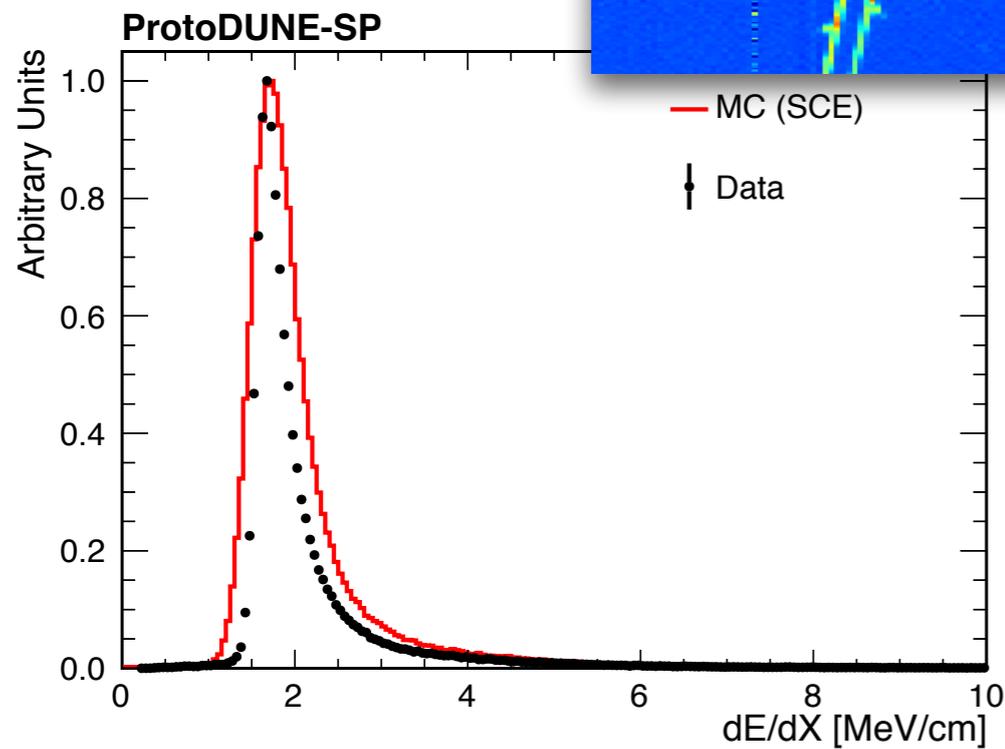
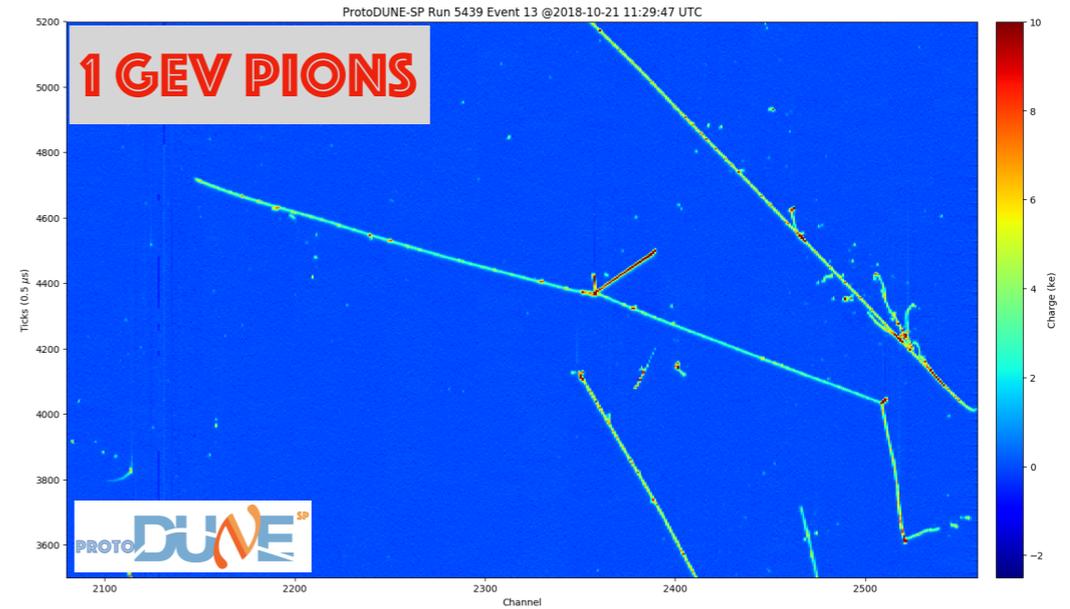
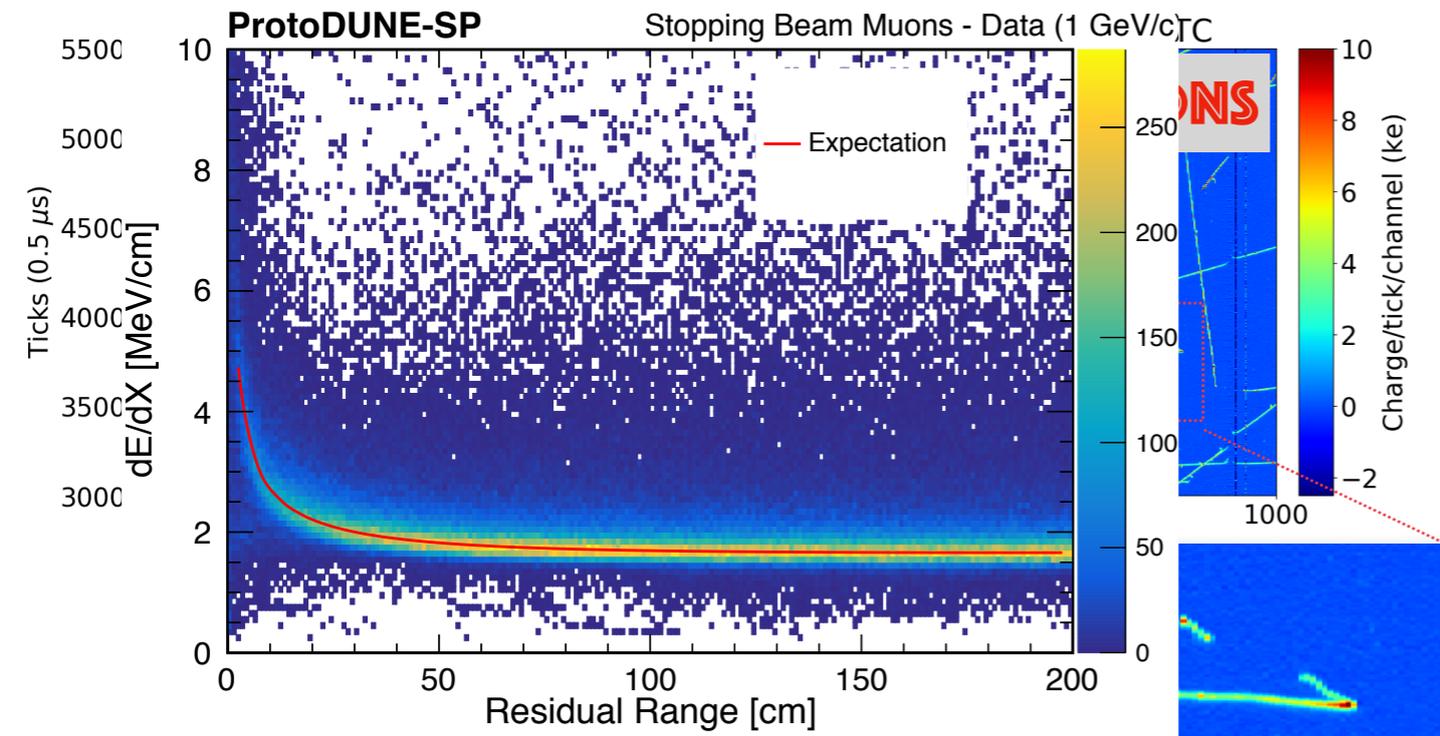
1 GEV PROTONS



Resolution appears better in DATA than in MonteCarlo !



Resolution appears better in DATA than in MonteCarlo !
 dE/dx width is found to depend on diffusion constants



Resolution appears better in DATA than in MonteCarlo !
 dE/dx width is found to depend on diffusion constants

Stopping muon dE/dx distributions for the ProtoDUNE-SP cosmic data and MC.

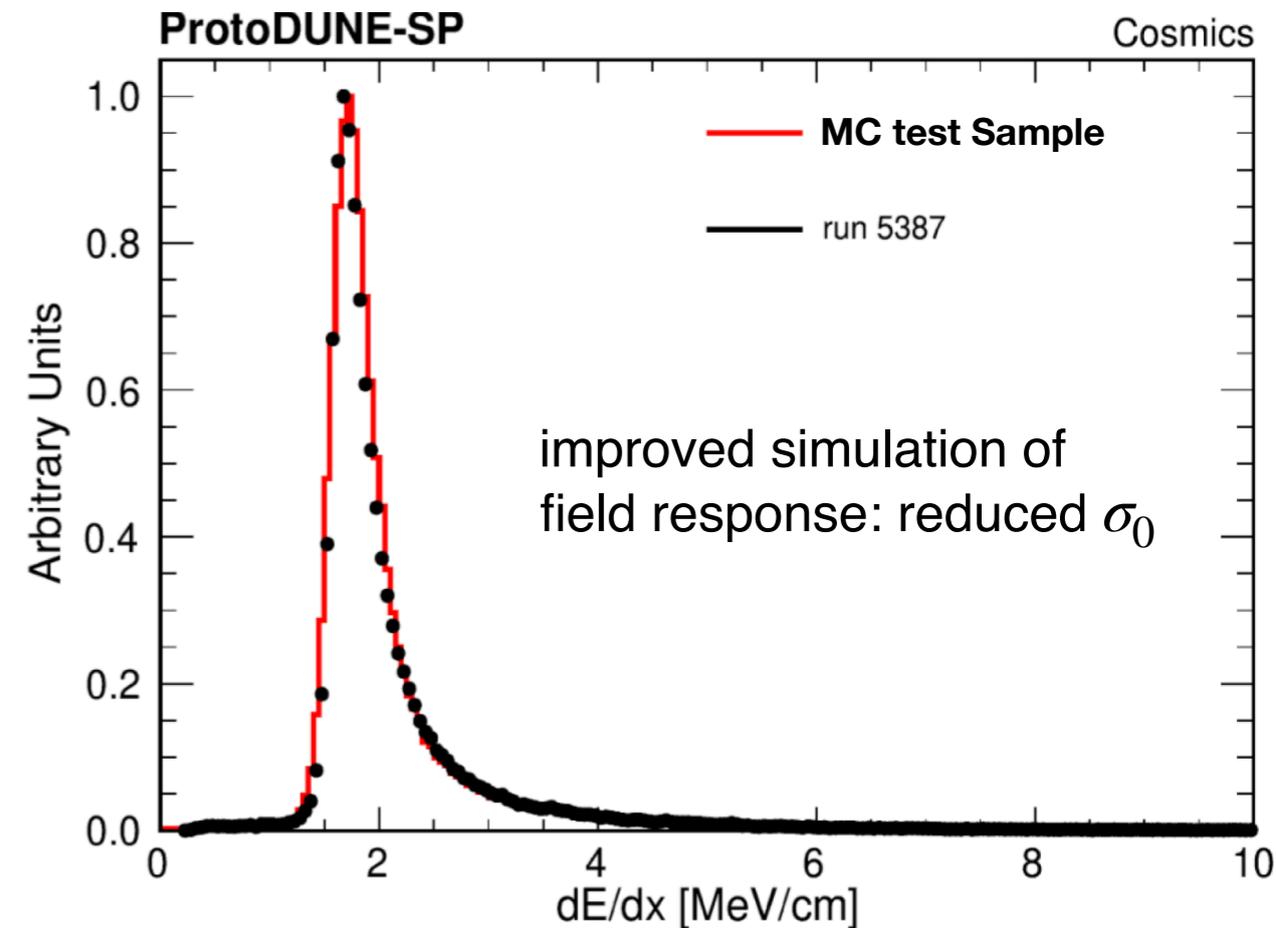
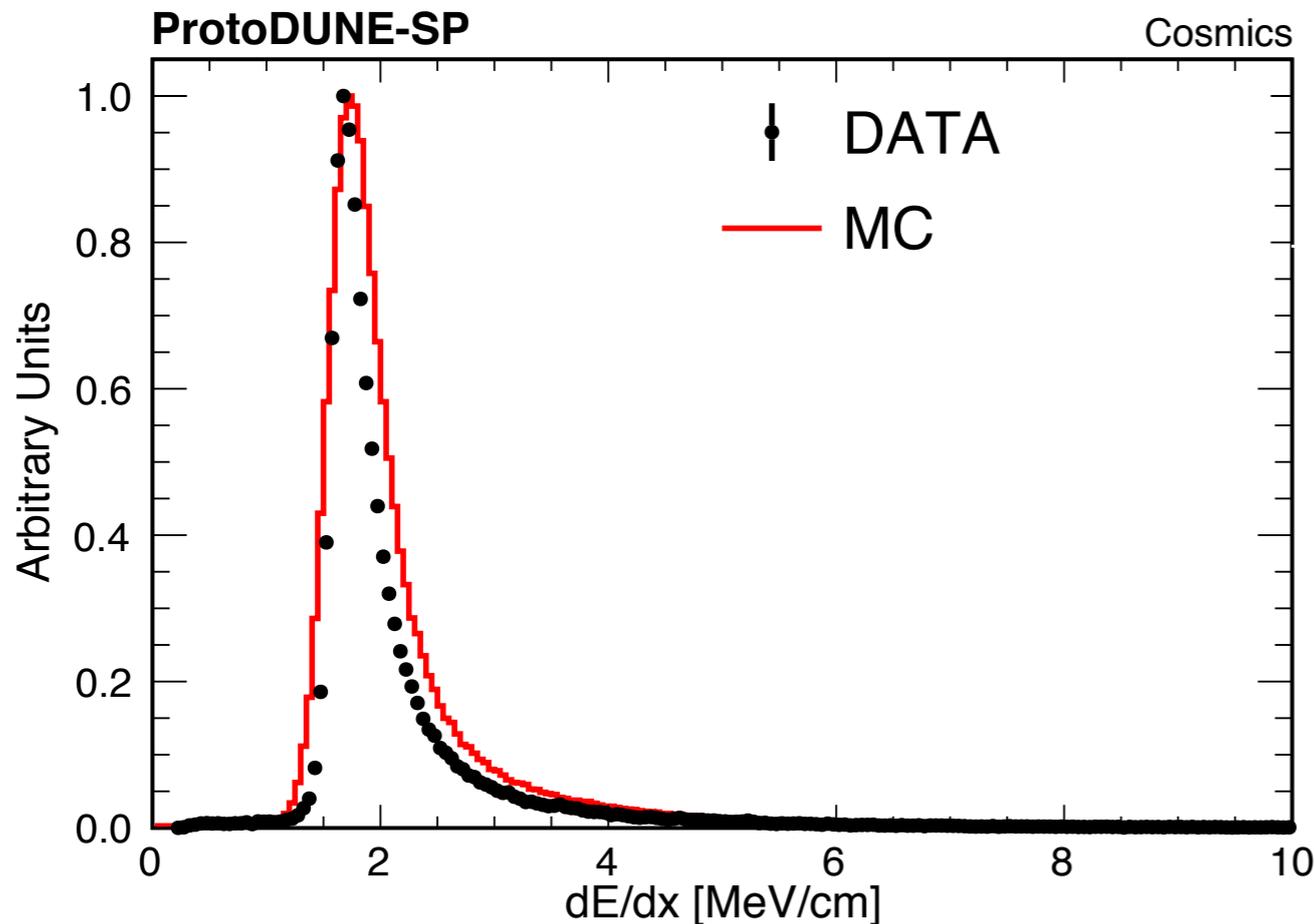
Diffusion in data appears to be less than in simulation

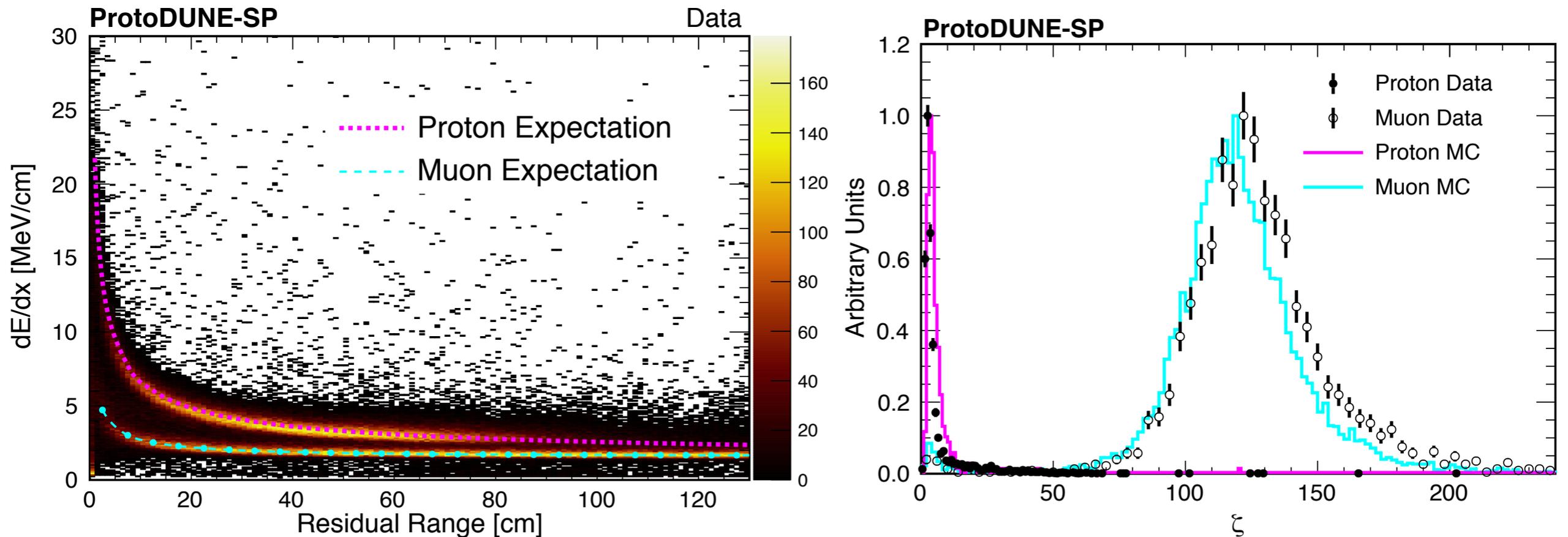
$$\sigma_t^2 = \left(\frac{2DL}{v_d^3} \right) x + \sigma_0^2$$

Labels in diagram:
 - Diffusion coefficient (points to D)
 - Drift distance (points to L)
 - Drift velocity (points to v_d)
 - Total time width of pulse (points to σ_t^2)
 - Inherent pulse width (points to σ_0^2)

Width of dE/dx for Data and MC doesn't agree

MC Tuning of longitudinal diffusion in progress

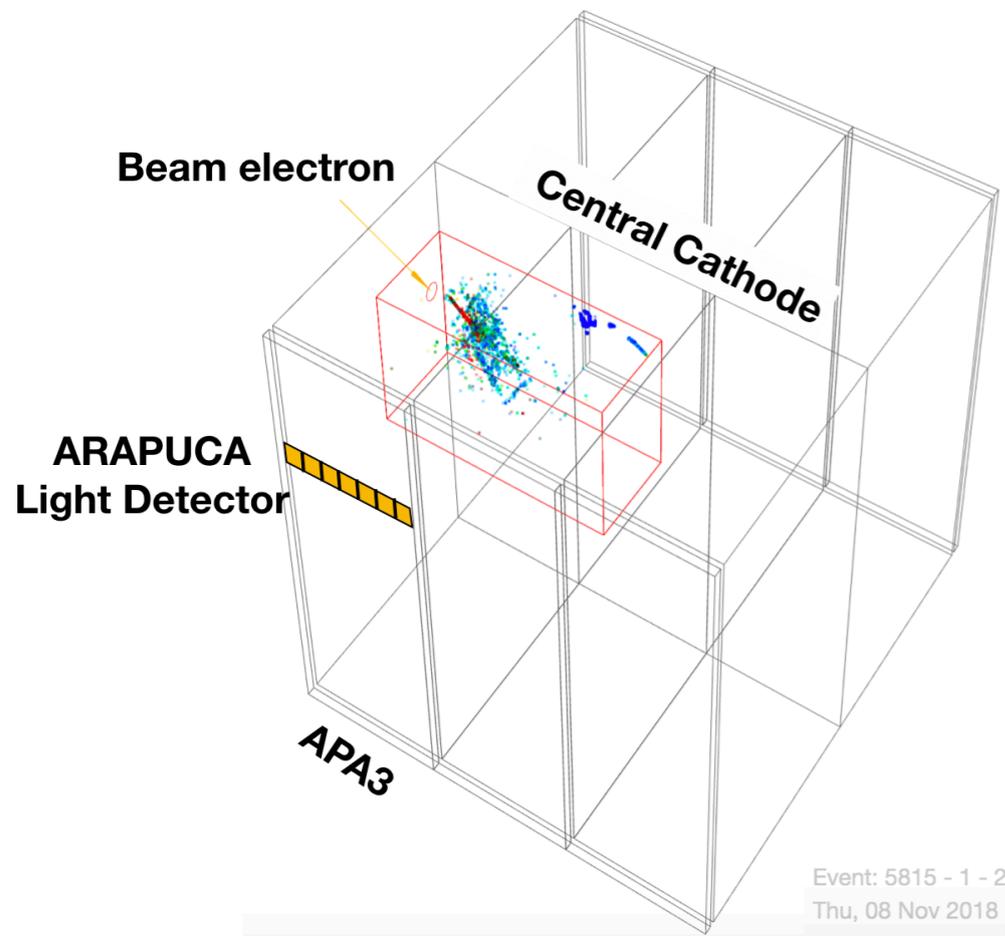




- Very well understood detector response to particles of different species.
- Excellent separation of muons and protons using calorimetric information.

PHOTO-DETECTOR PERFORMANCE :

calorimetric response to EM showers from *LIGHT Signal*



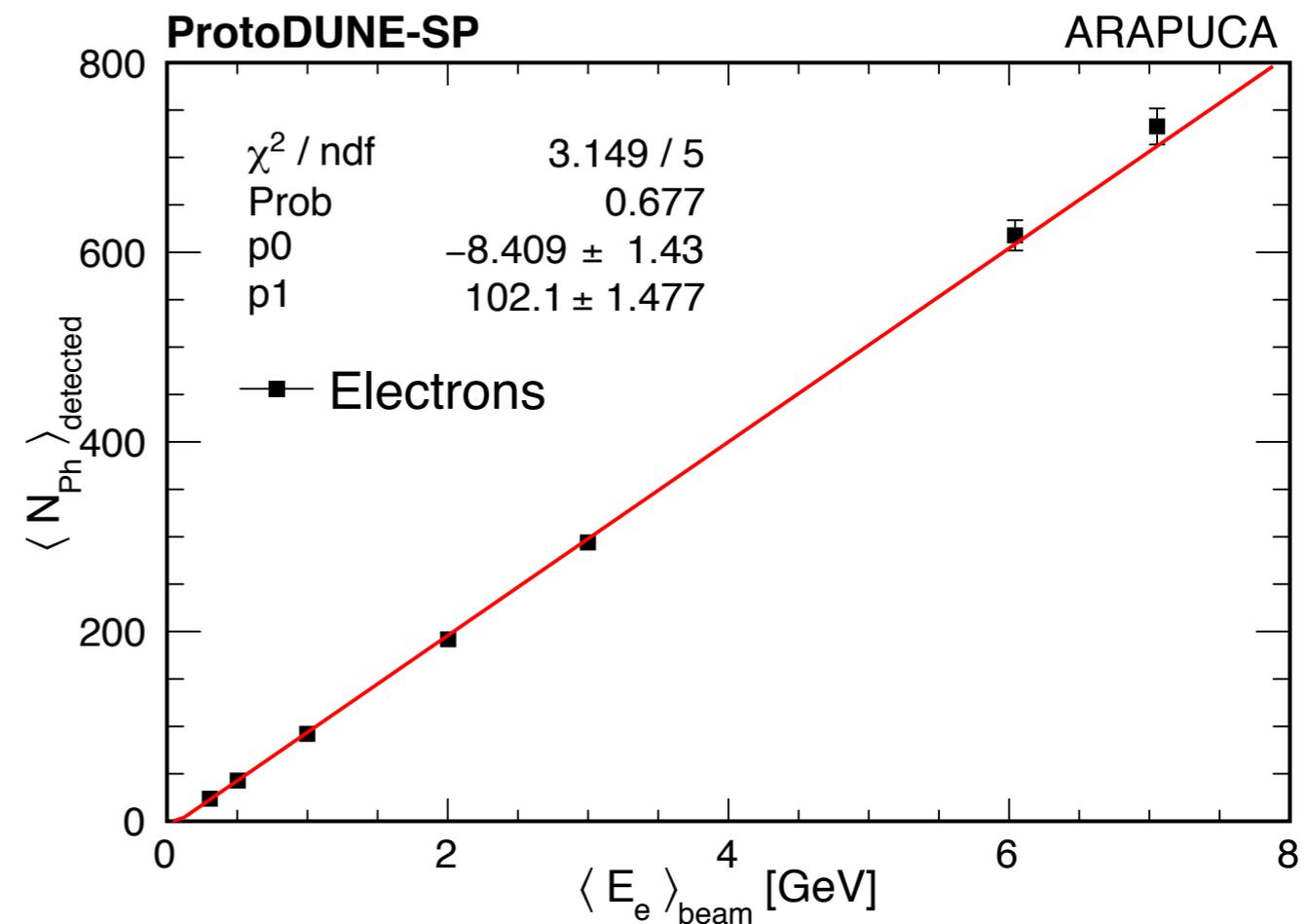
LINEARITY

Observed (first approx) linear response over the entire range of energies.

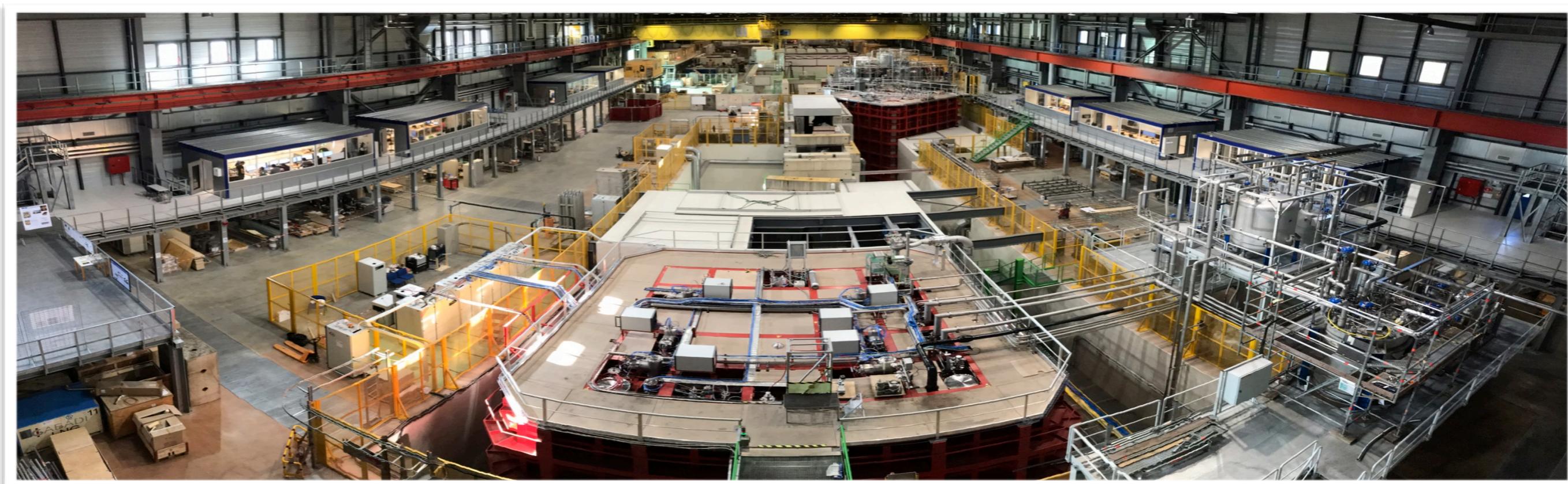
The slope gives the light yield

$$LY = 102 \text{ Ph/GeV}$$

from (only) one ARAPUCA PhDet module,
relative to a diffused light source (EM shower)
at a distance of about 3 m



single ARAPUCA module
(~0.5‰ photo-sensitive area coverage)



PROTO **DUNE**^{SP} (Phase 1) **MISSION**

- ✓ Prototyping production and installation procedures for DUNE Far Detector Design
- ✓ Validating design from perspective of basic detector performance → inform TDR
- ✓ Accumulating test-beam data to understand/calibrate response of detector to different particle species **~ 3M BEAM TRIGGERS ACCUMULATED AND ANALYZED**
- ✓ Demonstrating long term operational stability of the detector **500 DAYS OF OPERATION**

protoDUNE DUAL Phase

History of Dual-Phase ProtoDUNE / WA105

LBNO-DEMO (WA105)

Project started in 2013 (CERN RB approval) following the submission of LBNO Expression of Interest

Collaborators from 10 countries and 22 institutes

• University of Glasgow
 • University College London
 • University of Jyväskylä
 • University of Oulu
 • Rockplan Ltd
 • Horia Hulubei National Institute (IFIN-HH)
 • University of Bucharest
 • University of Geneva, Section de Physique
 • ETH Zürich
 • INFN-Sezione di Pisa
 • CERN
 • Institut de Física d'Altes Energies (IFAE), Bellaterra (Barcelona)
 • CHEMAT
 • Faculty of Physics, S.K. Simionov University of Sofia
 • Institute for Nuclear Research of the Russian Academy of Sciences, Moscow
 • High Energy Accelerator Research Organization (KEK)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

March 31st, 2014
CERN-SPSC-2014-013
SPSC-TDR-004

Technical Design Report
for large-scale neutrino detectors prototyping
and phased performance assessment
in view of a long-baseline oscillation experiment

Collaboration

TDR:
submitted on 31st March 2014
CERN-SPSC-2014-013
SPSC-TDR-004(2014)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SR-XXX
March 31, 2015

Progress report on LBNO-DEMO/WA105 (2015)

The WA105 Collaboration

G. Balik, L. Brunetti, I. De Bonis, P. Del Amo Sanchez, G. Deleglise, C. Drancourt, D. Duchesneau, N. Geffroy, Y. Karyotakis, and H. Pessard
LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France

B. Bourguille, S. Bordonì, T. Lux, and F. Sanchez
Institut de Física d'Altes Energies (IFAE), Bellaterra (Barcelona), Spain

A. Jipa, I. Lazanu, M. Calin, C.A. Ene, T. Esanu, O. Ristea, C. Ristea, S.A. Nae, and L. Nita
Faculty of Physics, University of Bucharest, Bucharest, Romania

P. Bourgeois, F. Duval, I. Efthymiopoulos, U. Kose, G. Maire, D. Mladenov, M. Nesi, and F. Noto
CERN, Geneva, Switzerland

G.A. Nuijten
Rockplan Ltd., Helsinki, Finland

K. Loo, J. Maalampi, M. Stupecki, and W.H. Trzaska
Department of Physics, University of Jyväskylä, Finland

CERN-SPSC-2015-001 / SPSC-SR18
31/03/2015

CERN-SR-XXX
April 6, 2016

Yearly progress report on WA105/ProtoDUNE dual phase (2016)

G. Balik, L. Brunetti, A. Chappuis, I. De Bonis, G. Deleglise, C. Drancourt, D. Duchesneau, N. Geffroy, Y. Karyotakis, H. Pessard, and L. Zambelli
LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France

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K. Loo, J. Maalampi, W.H. Trzaska,
Department of Physics, University of Jyväskylä, Finland

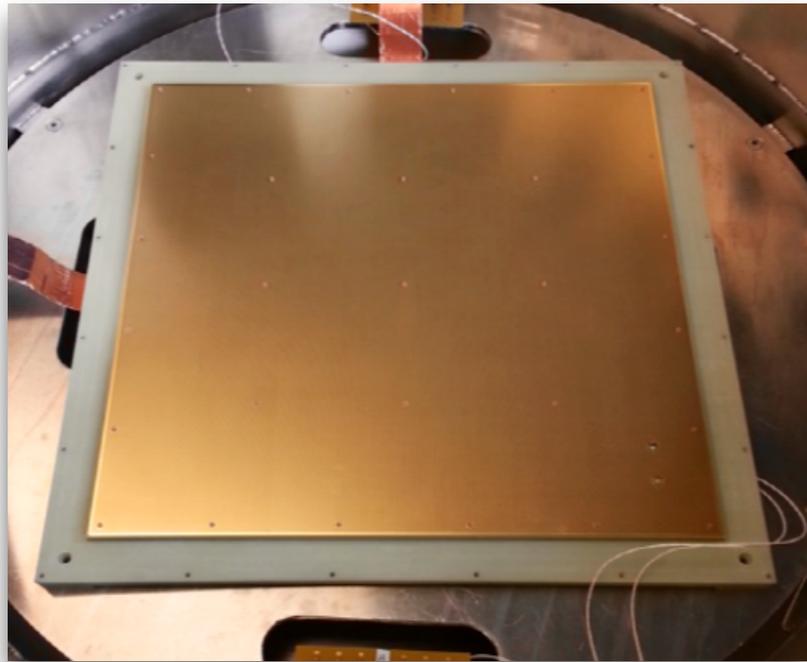
DUNE CDR, July 2015: WA105 and Dual-phase 10 kton design

WA105 project MOU signed December 2015

Integration in the DUNE project as ProtoDUNE-DP - December 2015

Technical Design Review April 2017

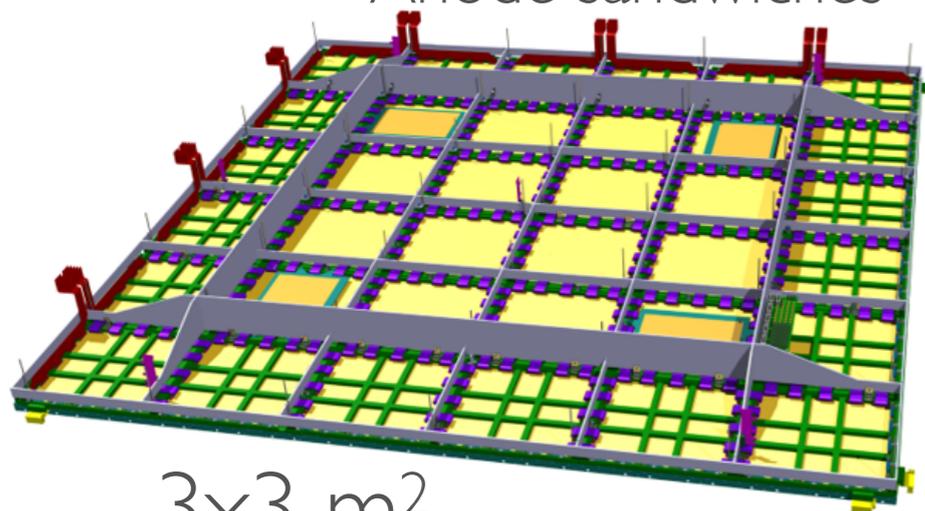
During detector installation
inside cryostat (spring 2019)



LEM-anode
sandwich
(50x50 cm²)



Charge Readout Plane (CRP)
integrating 36 LEM
Anode sandwiches

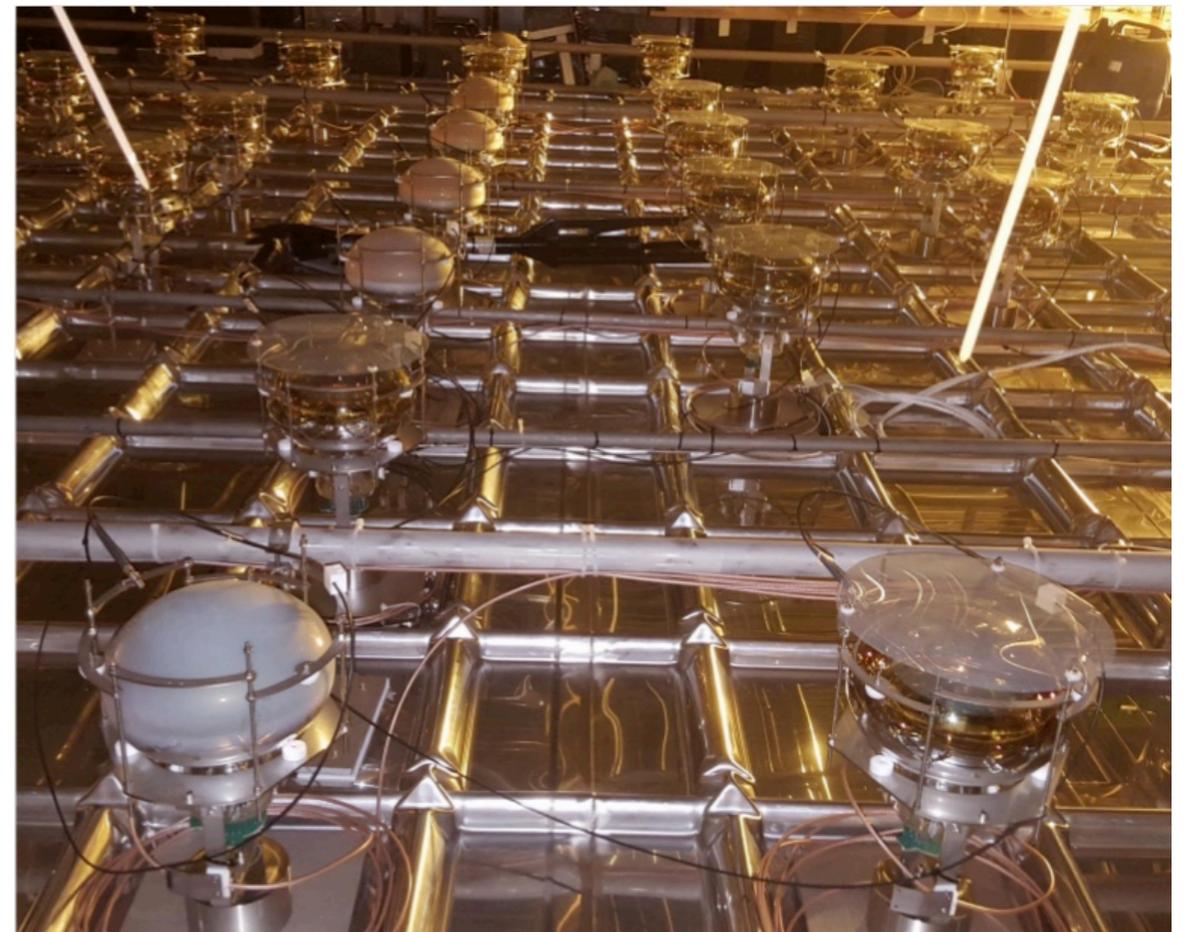


3x3 m²

< 50 μm accuracy in
positioning wrt to LAr surface level

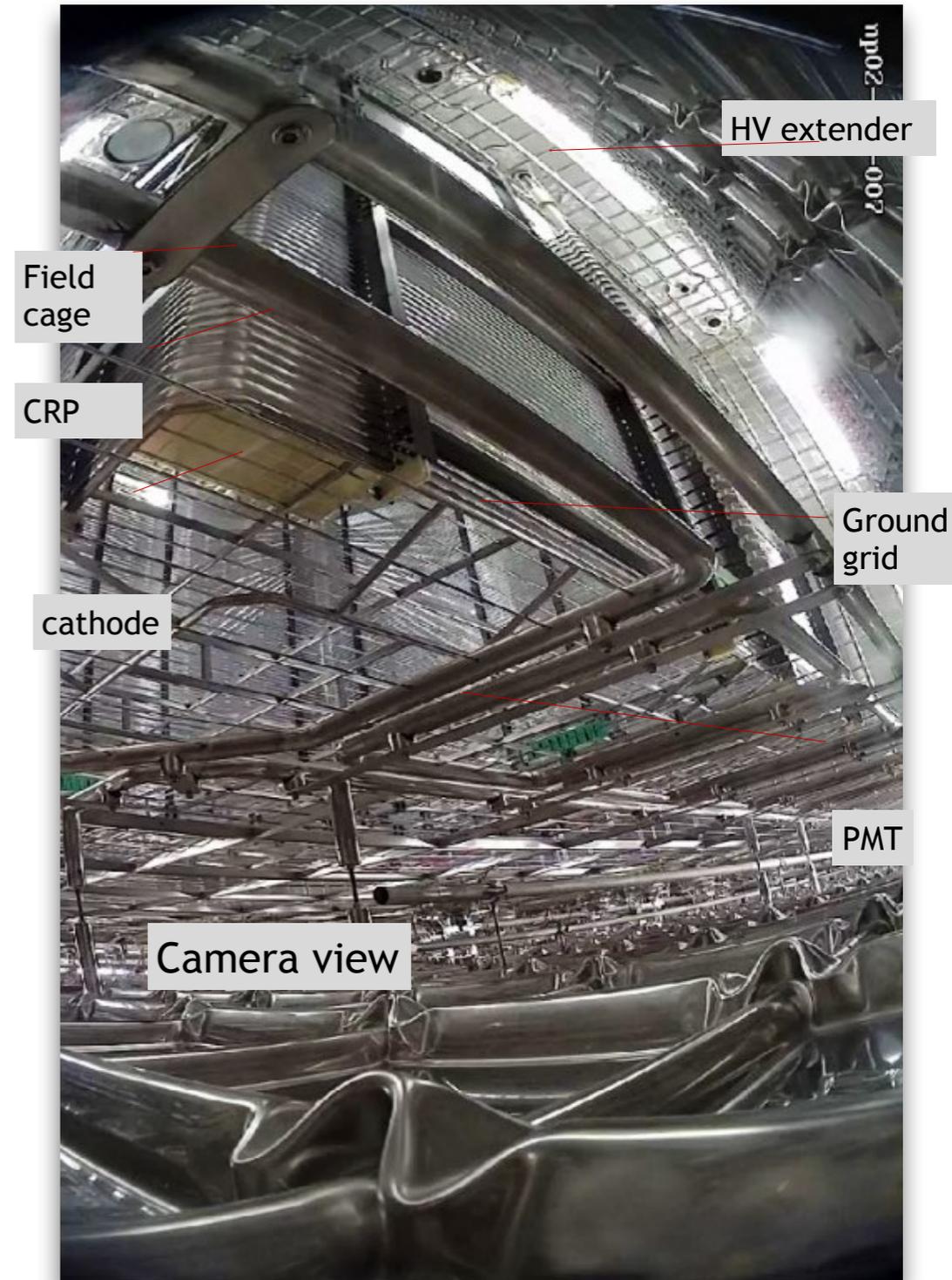
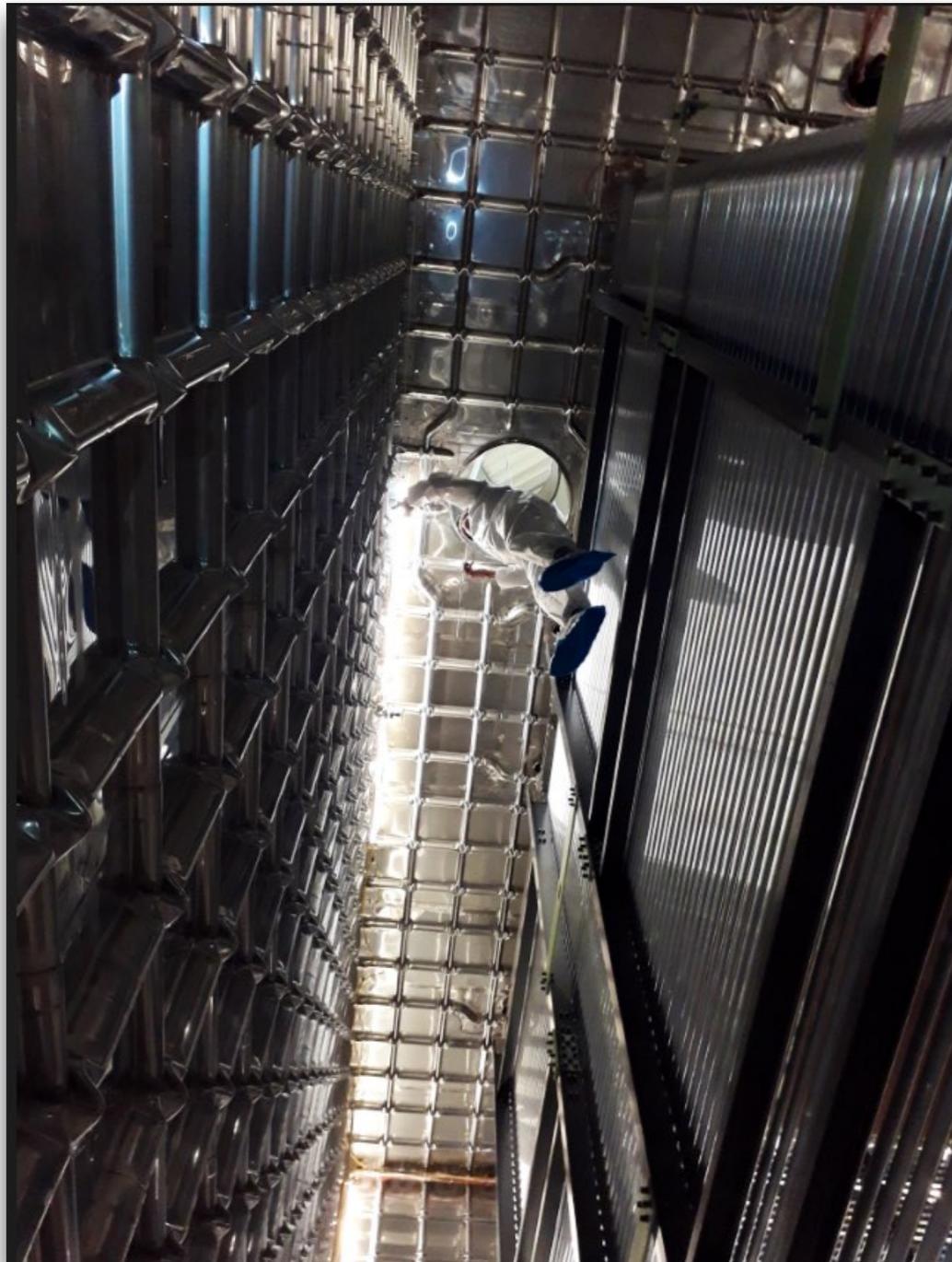
Photon Detector: PMT Array with wavelength-shifter

- 30 PMTs with PEN sheets and 6 PMTs with TPB coating



Last day with cryostat open

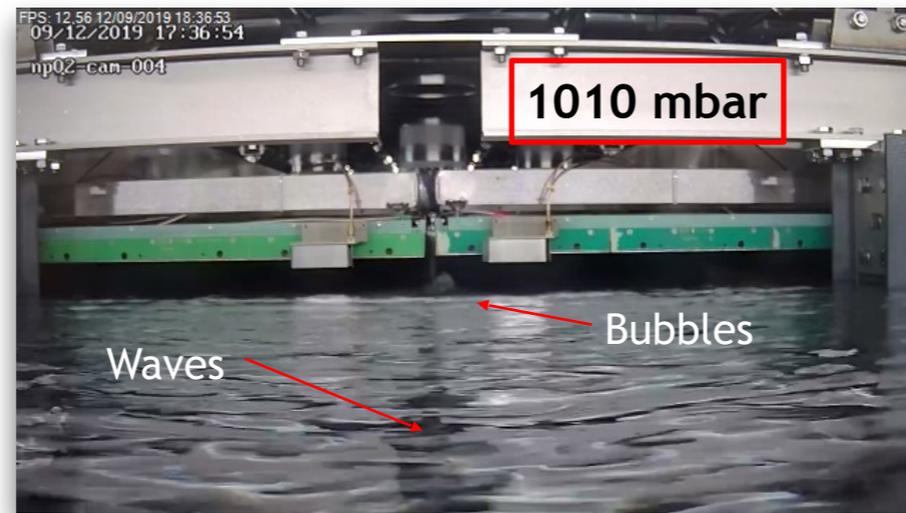
June 13th 2019



- June 2019: cryostat purge with Ar gas and cool-down procedure with a mist of LAr droplets to about 150k
- July 2019: filling with LAr
~40 tons/day
- August 2019 detector filled, start of operation



✓ Bubbles forming along internal surface of first field cage ring.
Phenomenon not yet completely characterized related to heath flow and cryogenics



✓ CRP operation at higher cryostat gas pressure (1045 mbar) to dump formation of bubbles and LAr surface perturbations.

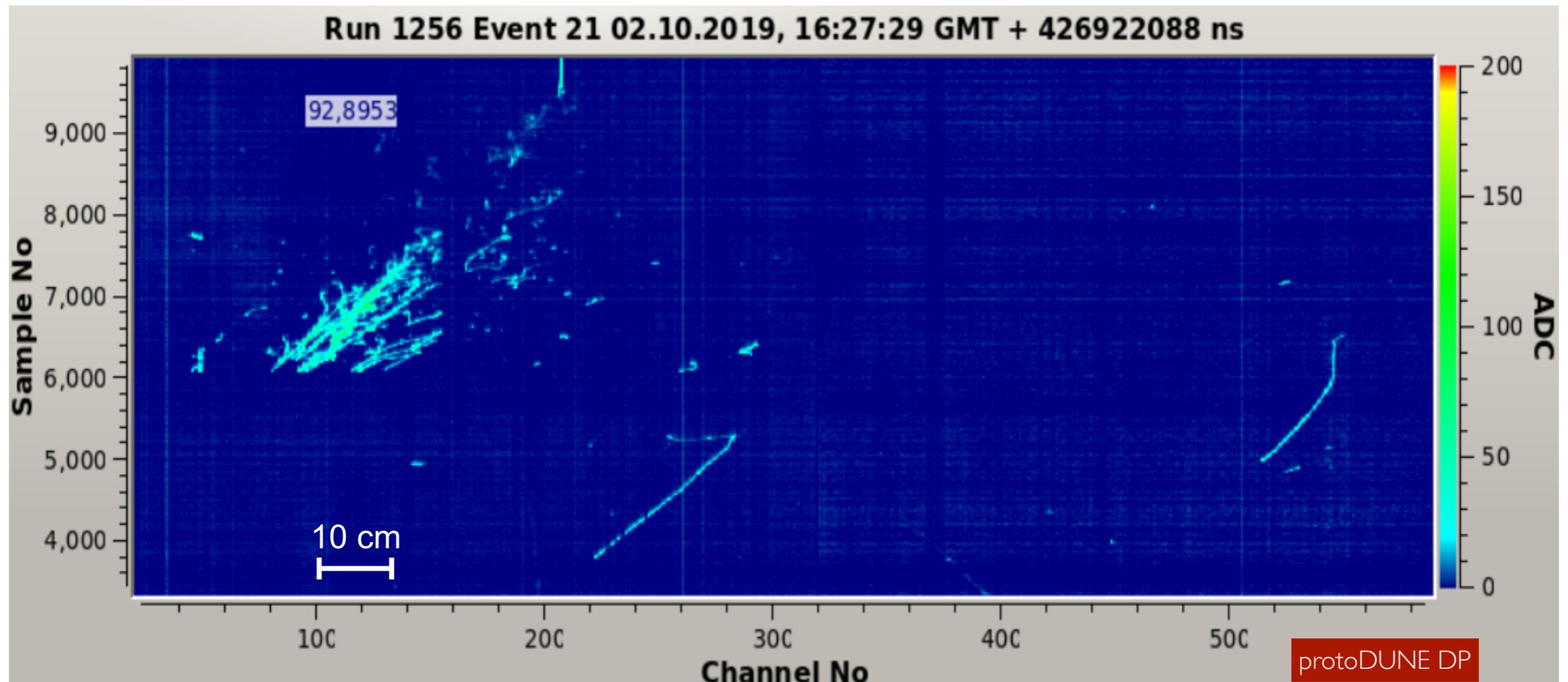
- Stability HV tests of grids + LEMs
- Grids of all 4 CRPs tested up to 7.5kV extraction voltage (exceeding goal)

CRP LAr level tracking (adjustments of 250 um every 15 minutes). LAr level increasing by ~1mm/hour

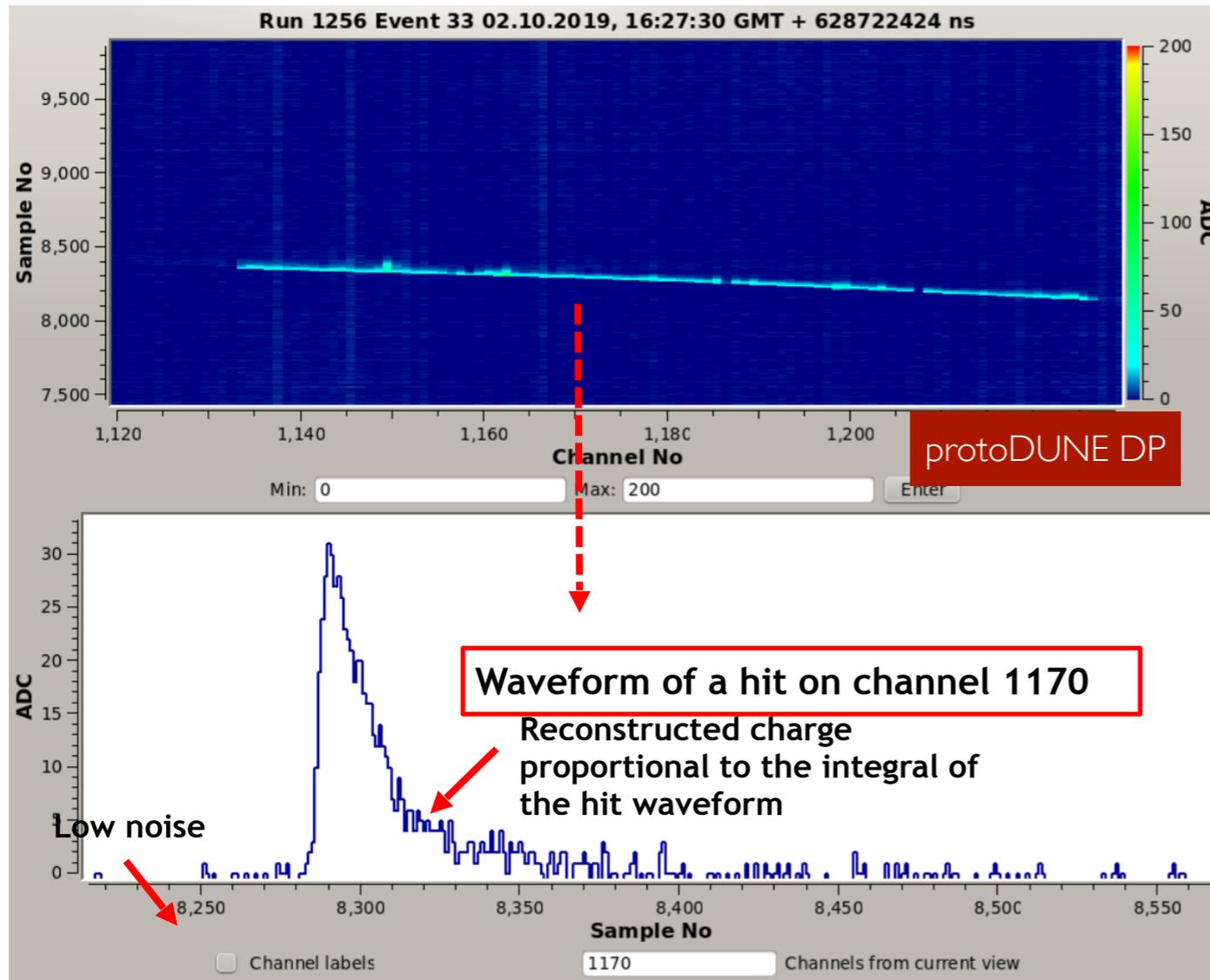
✓ Implemented automatic tracking of LAr level based on level meters reading



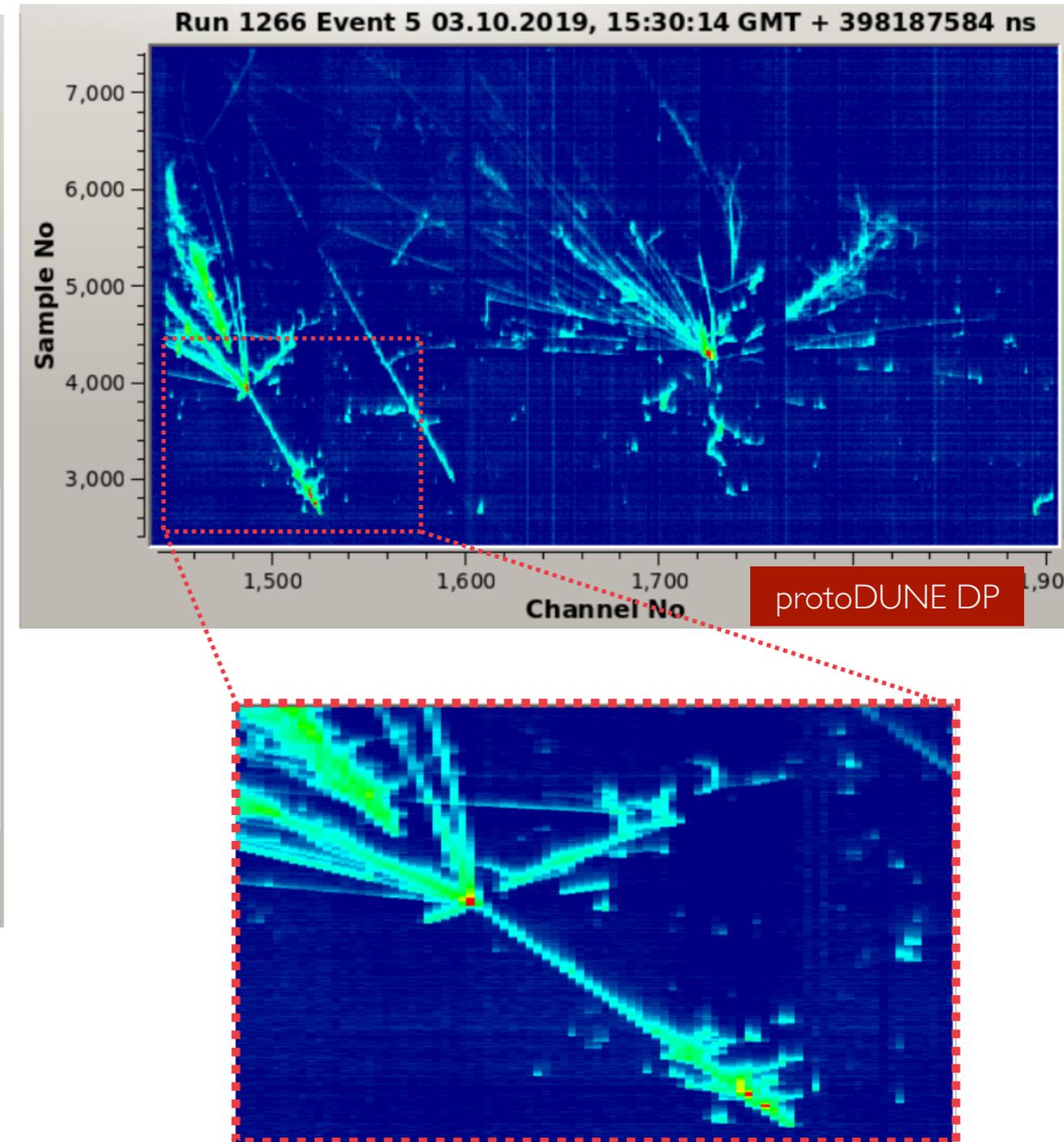
Event with electromagnetic showers and two muon decays
- LEM $\Delta V = 3.1$ kV



Horizontal muon track
- LEM $\Delta V = 3.1$ kV



Multiple hadronic interactions in a shower - LEM $\Delta V = 3.2$ kV



Compelling questions in Physics await being addressed

The liquid Ar TPC is the new experimental technology adopted for the worldwide Neutrino Program in the U.S.

The realization of the DUNE/LBNF will represent one of the most challenging and endeavoring effort in HEP.

The path toward DUNE is now open by the success of ProtoDUNE at CERN

BACKUP SLIDES

1986 - proposal for a massive LArTPC

ICARUS Logo from the Flying Machine with Beating Wings by Leonardo da Vinci

SEARCHING FOR NEW UNDERGROUND PHENOMENA WITH HIGH

RESOLUTION VISUAL TECHNIQUES AND MAGNETIC ANALYSIS

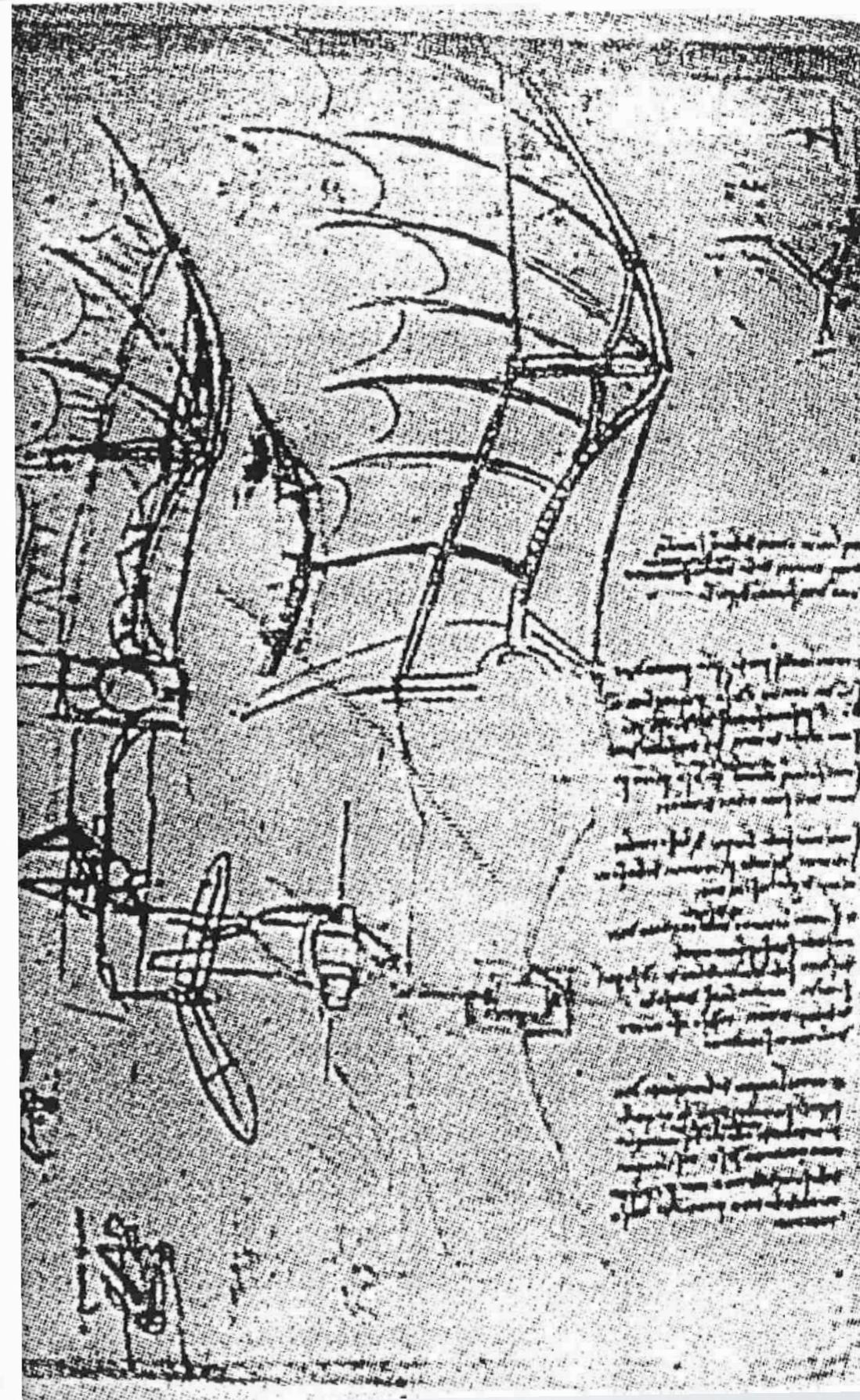
(ICARUS)

A PROPOSAL

Quoting the Abstract of the ICARUS Proposal, "We propose a very large volume ($>4500\text{ m}^3$) Liquid Argon, homogeneous detector fully and continuously sensitive ... (with) spatial separation of $\sim 1\text{mm}^3$ Ionization electrons are collected over a two meter long path and they are sensed by three planes of collecting wires. The detector is self-triggering, .. and with an accurate calorimetry and unambiguous p , K and π/μ separation of slow or stopping particles.

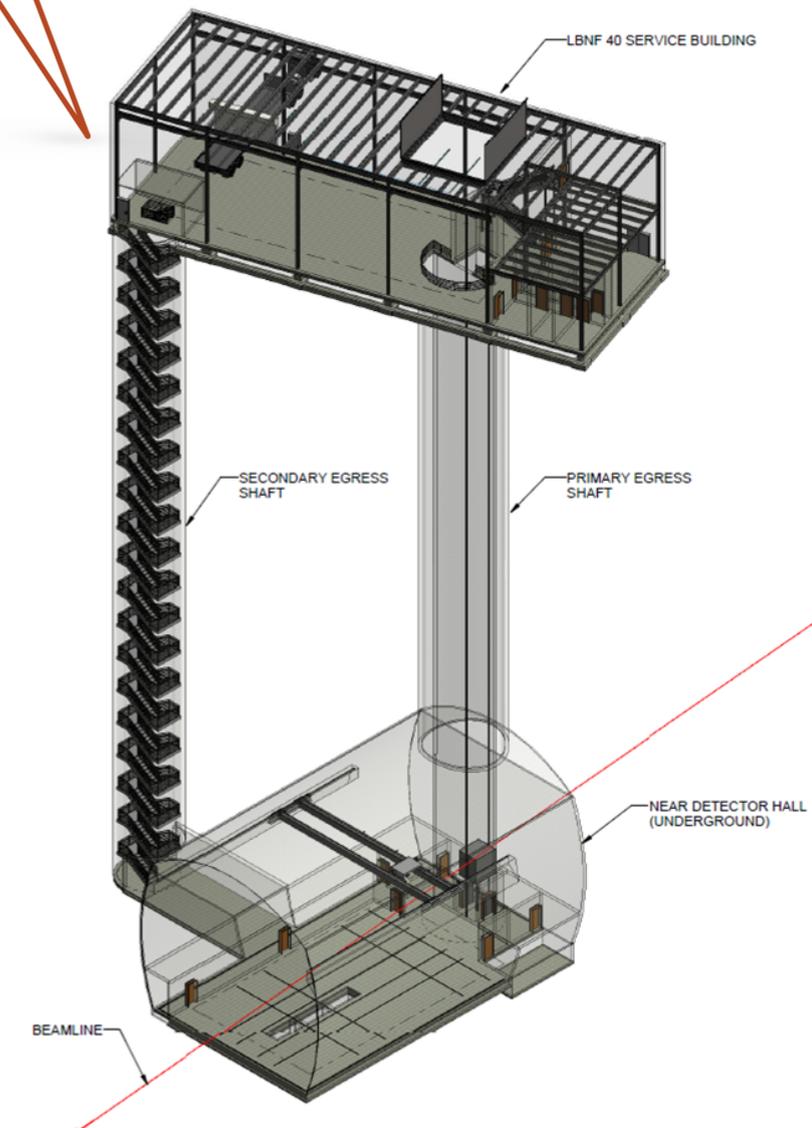
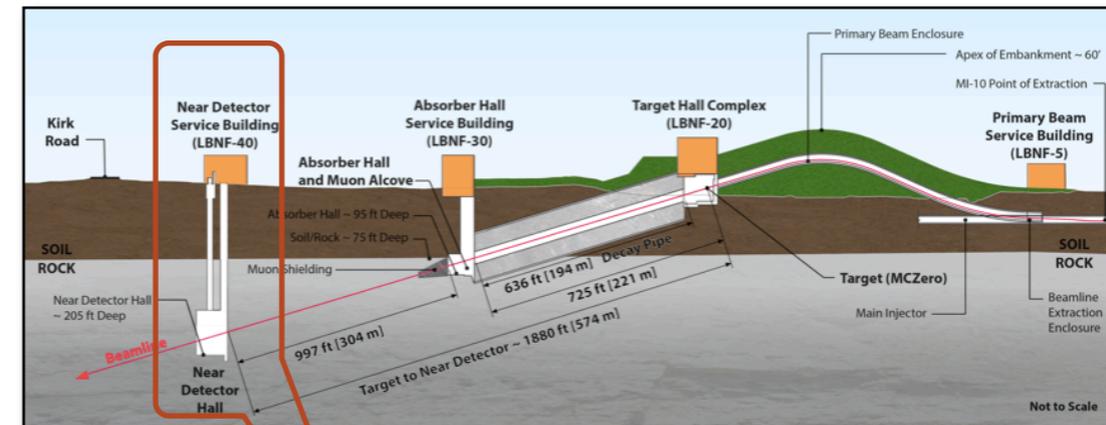
CERN - Harvard - Milano - Padova - Roma - Tokyo - Wisconsin

Collaboration



DUNE Near Detector

- DUNE ND design concept is an integrated system composed of multiple detectors:
 - HPGArTPC
 - Highly segmented LArTPC
 - Magnetized multi-purpose tracker
 - Electromagnetic calorimeter
 - Muon chambers
- Primary purpose is to **constrain systematic uncertainty** for long-baseline oscillation analysis
 - Constrain flux, cross-section, and detector uncertainties

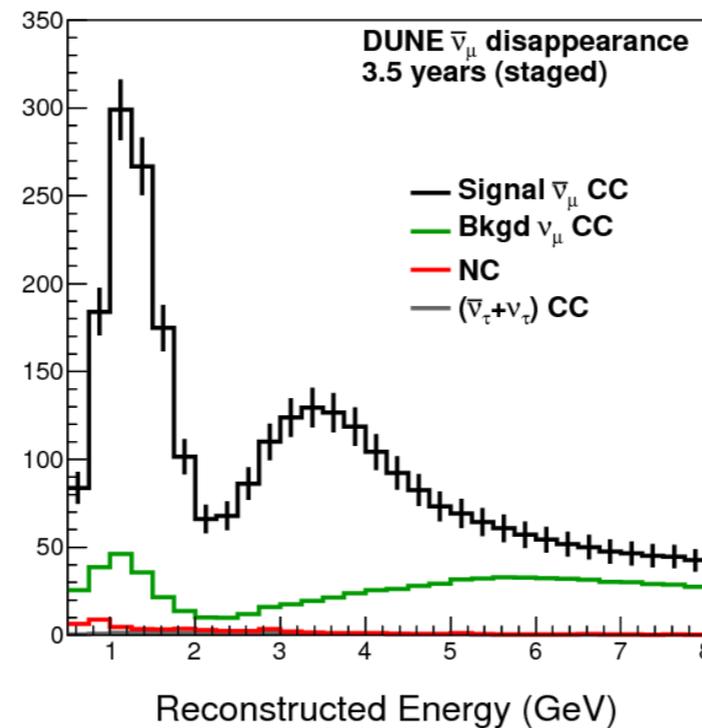
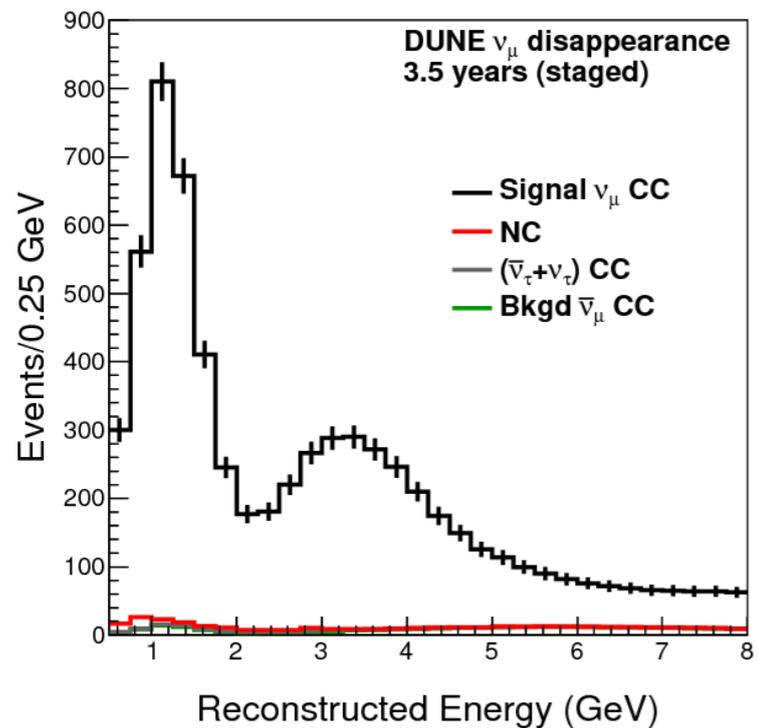
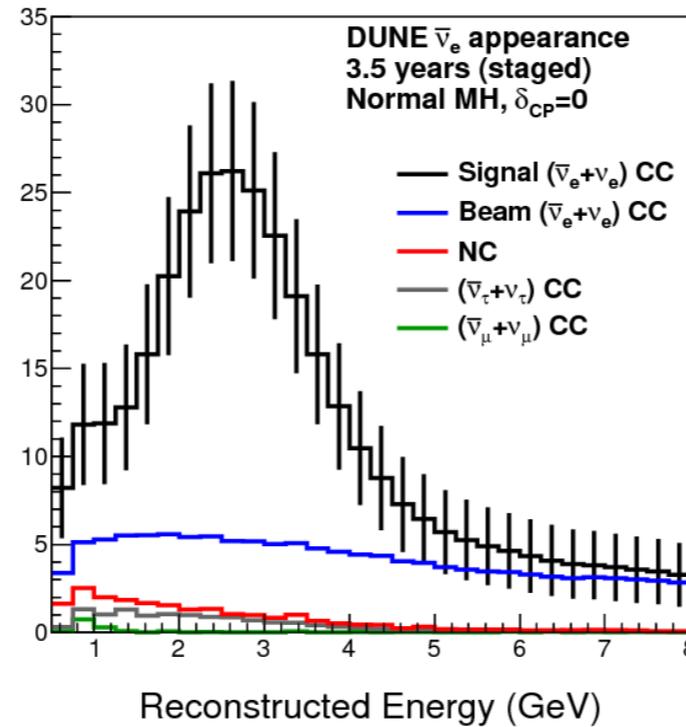
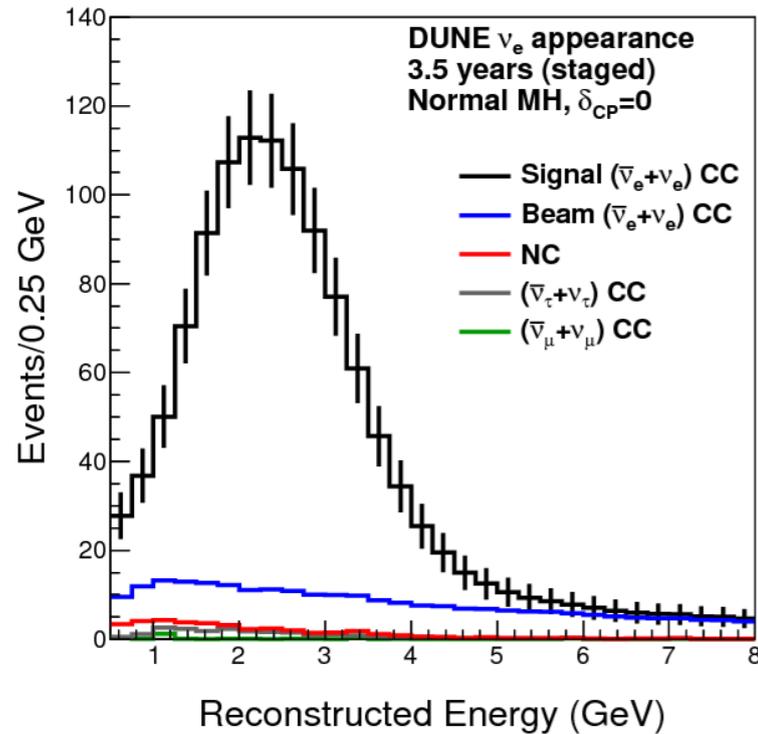


Oscillation Sensitivity Calculations

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148

Beam: ν -mode

Beam: $\bar{\nu}$ -mode

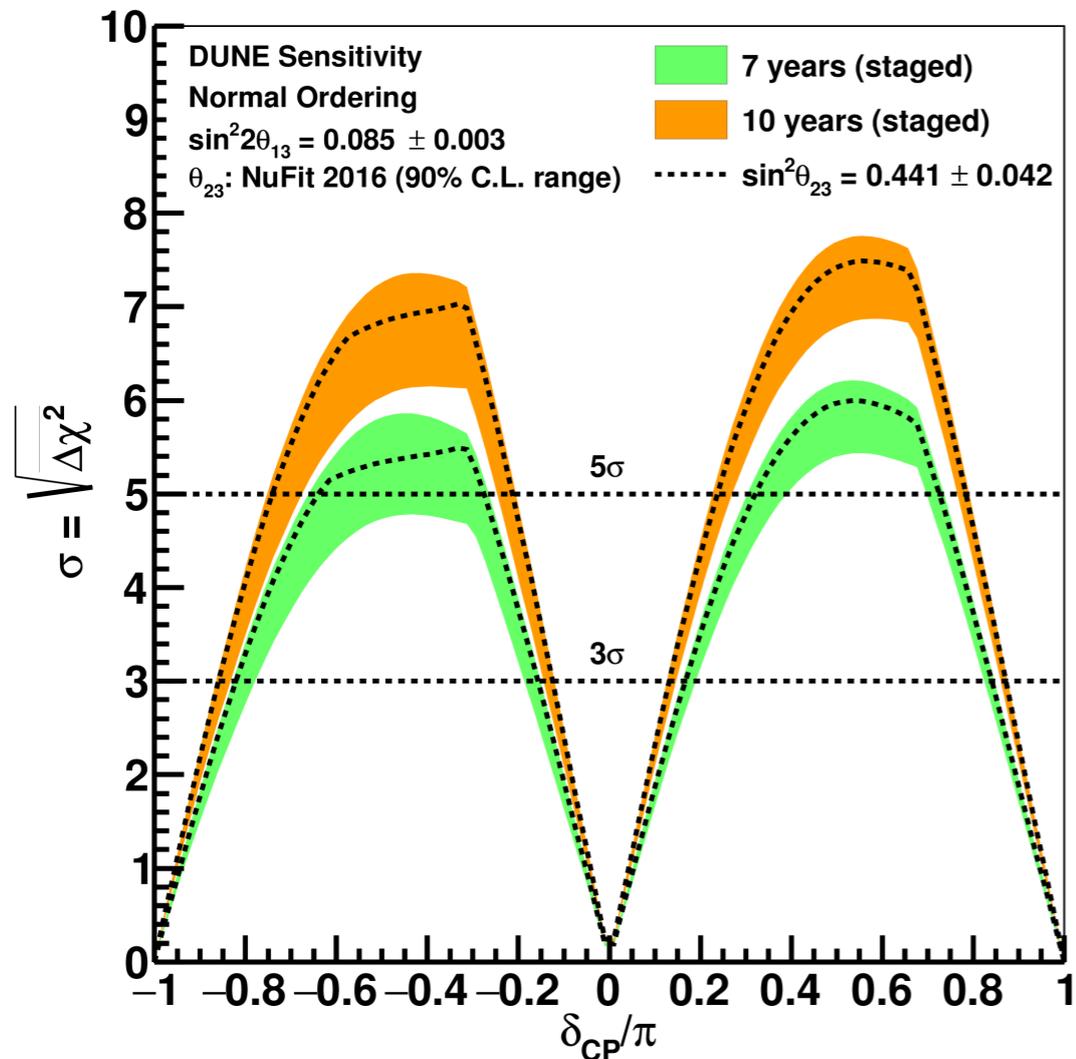


- Order 1000 ν_e appearance events in ~ 7 years of equal running in neutrino and antineutrino mode
- Simultaneous fit to four spectra to extract oscillation parameters
- Systematics approximated using normalization uncertainties
- Reconstructed spectra based on GEANT4 beam simulation, GENIE event generator, and Fast MC using detector response parameterized at the single particle level
 - Efficiency tuned using hand scan results
- GLoBES configurations arXiv: 1606.09550

CP Violation Sensitivity

CP Violation

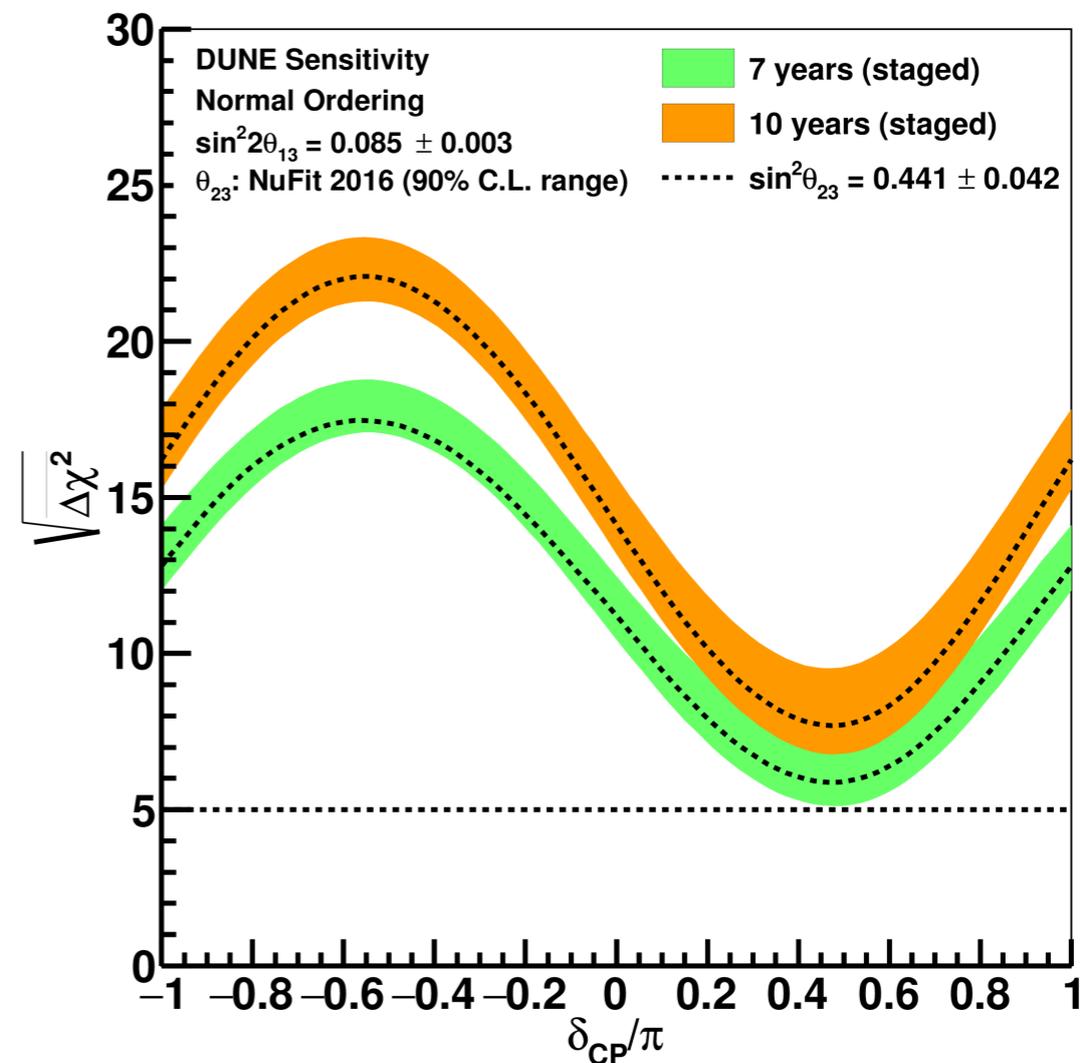
CP Violation Sensitivity



Width of band indicates variation in possible central values of θ_{23}

Mass Ordering

Mass Hierarchy Sensitivity



Width of band indicates variation in possible central values of θ_{23}

DUNE Far Detector Challenges

Scale up in size

- Cryostat for 10-kt fiducial: 15.1 (W) x 14.0 (H) x 62 (L) m³
a big step up from ICARUS & MicroBooNE [from $\mathcal{O}(100\text{ t})$ to $\mathcal{O}(10\text{ kt})$]

underground location&expected duration of the experiment

- Assembly in underground and no access (no maintenance/repair for ~ 20 yrs) - somehow similar constraints as for HEP experiments in space

Technical challenges

- Longer Drift and related more stringent requirement:
 - *on HV system*
 - *on LAr Purity*
- Detector Stability over time: Cold electronics/TPC, PhotoSensor/PDS
- Overall Mechanical engineering + QA/QC
- ...

Solution to proof FD design:

- **build a large-scale 1kt prototype**