DUNE

CS IN2P3, 28/6/2018
Dario Autiero, IPNL Lyon

APC: Jaime Dawson, Thomas Patzak, Cayetano Santos, Andrea Scarpelli, Alessandra Tonazzo

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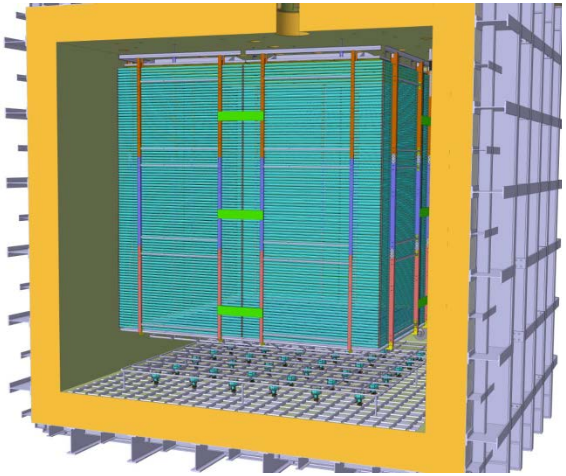
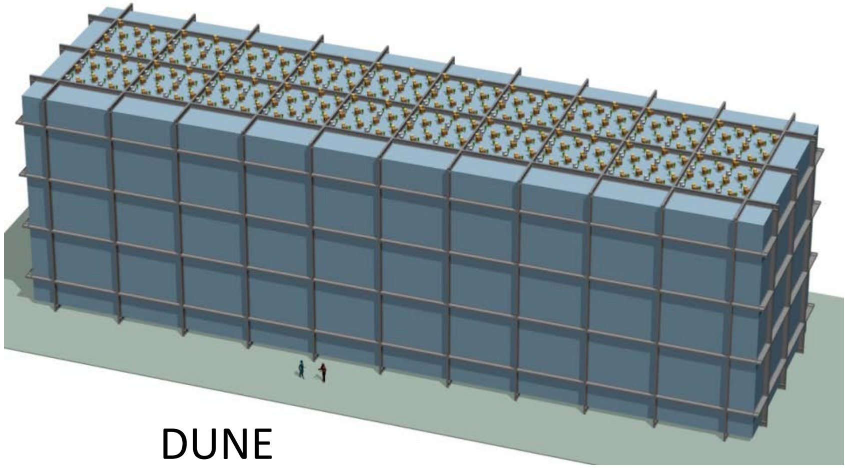
LAL: Mathieu Bongrand, Christian Bourgeois, Fabien Cavalier, Joao Coelho, Denis Douillet, Eric Guerard, Rodolphe Marie, Laurent Simard

LAPP: Benjamin Aimard, Gael Balik, Laurent Brunetti, Anne Chappuis, Isabelle Debonis, Cyril Drancourt, Dominique Duchesneau, Nicolas Geffroy, Yannis Karyotakis, Jean-Marc Nappa, Fabrice Peltier, Sebastien Vilalte, Laura Zambelli

OMEGA: Gisèle Martin-Chassard, Christophe de La Taille, Selma Conforti

WA105
Dual-Phase
ProtoDUNE





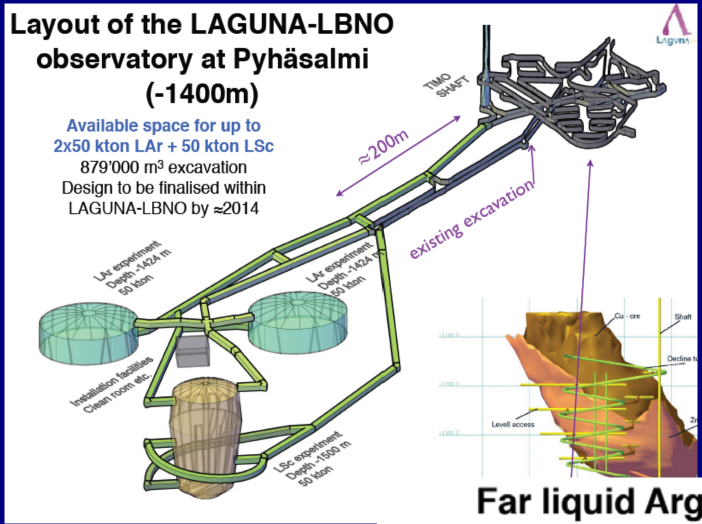
DUNE
10 kton module

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)

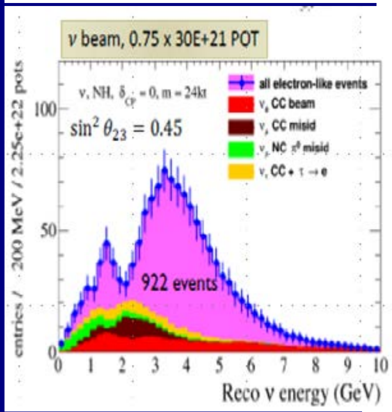
http://cdsweb.cern.ch/record/1457543

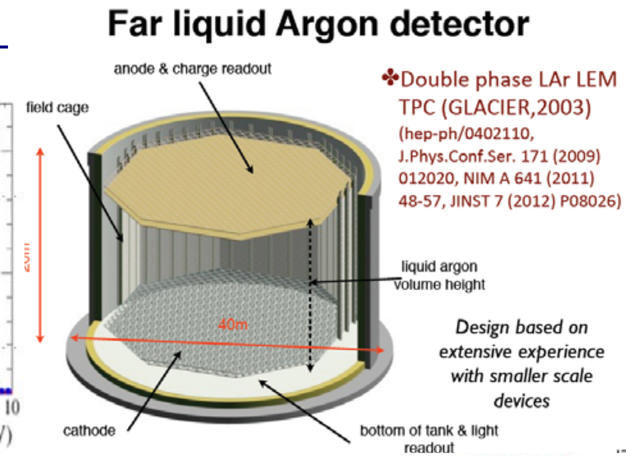


Physics program:

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

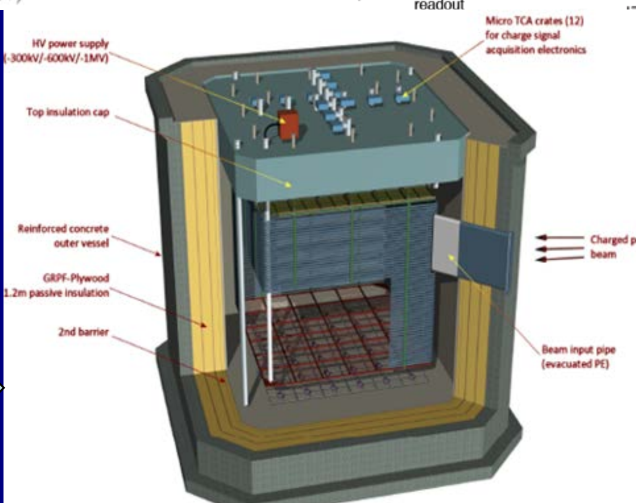
→ Use of a wide band beam to exploit the spectral information, relevance of the 2nd oscillation maximum for CP sensitivity





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)



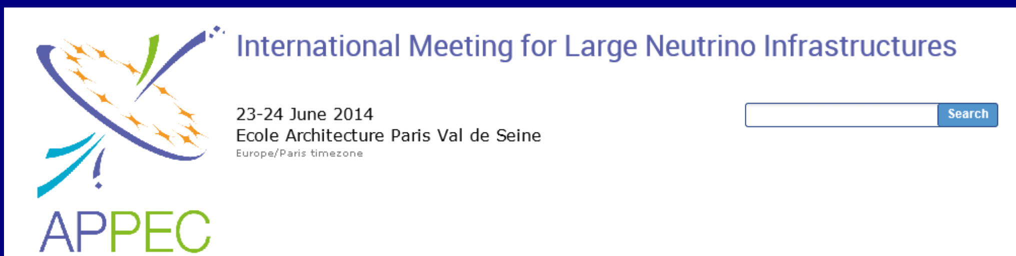
Joint USA-Europe initiative for a common long-baseline experiment (E)LBNF based on the liquid argon TPC technology

Very quick developments since July 2014:

- **Top priority of the USA P5 committee (HEP strategy in the USA) May 2014**

→ Reformulation of the program

- **APPEC Meeting on Neutrino Infrastructures Paris June 2014**



- **August 2014: creation of an Interim International Executive Board (IIEB) for LBNF chaired by the Fermilab Director N. Lockyer, active IN2P3 contribution**

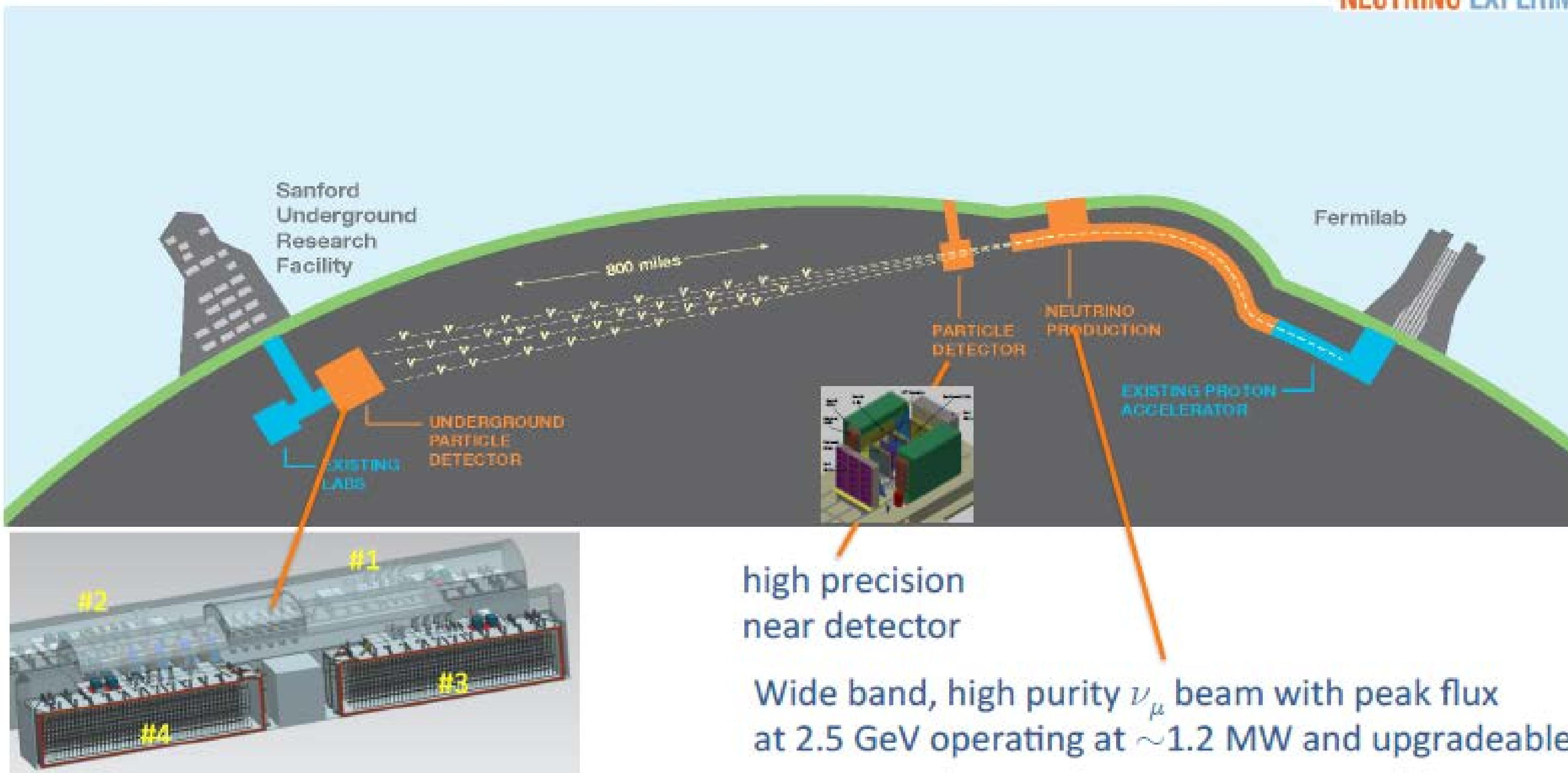
→ gathering the collaboration for the ELBNF LOI

- **January 2015: Presentation of the LOI to the FNAL PAC (LBNF (facility) + ELBNF (experiment): 40 kton at Homestake (1300 km from FNAL), 1.2 MW beam upgradable to 2.4 MW, excavation works start in 2017**

- **March 2015: Election of the two co-Spokesperson and choice of the final name for ELBNF: DUNE**

- **June 2015 DOE CD-1 Refresh approval and completion of the DUNE Conceptual Design Report**

Overall Experimental Layout



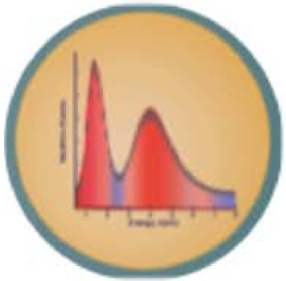
high precision
near detector

Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at $\sim$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

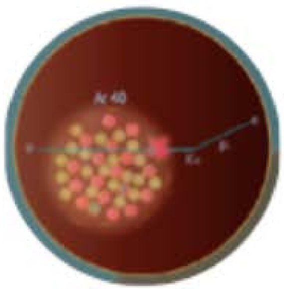
Beam 1.2 – 2.4 MW
40 kton Far Detector mass
Operation since 2026

The Primary DUNE Scientific Goals



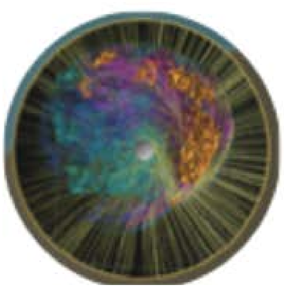
Neutrino oscillations

- 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

Additional physics goals (ancillary program):

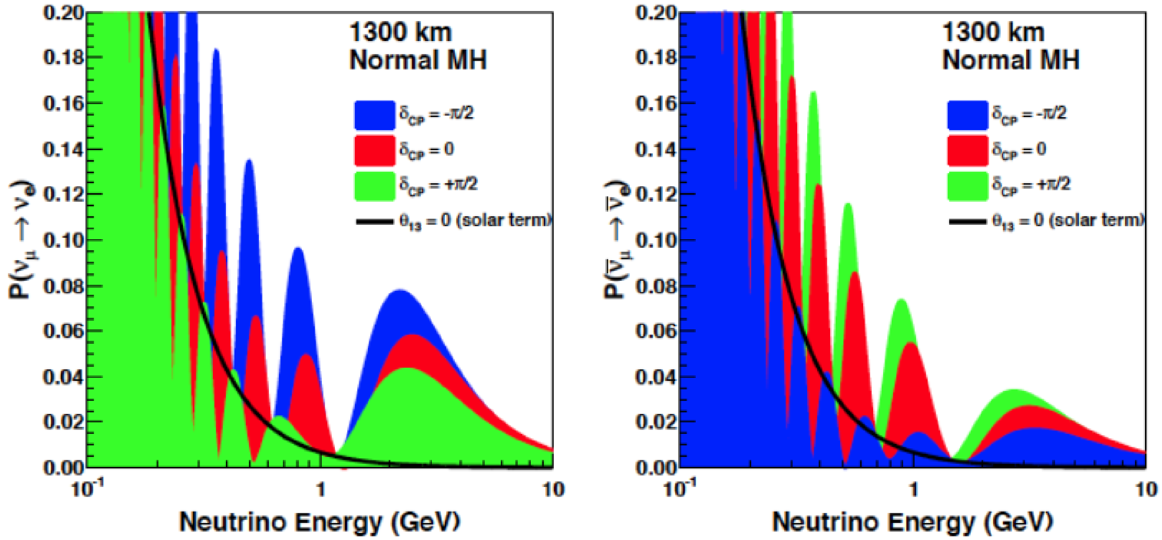
- ν_τ appearance
- Sterile neutrinos
- Search for Non Standard Interactions (NSI)
- Physics with atmospheric neutrinos: e.g. oscillations, mass hierarchy, BSM
- Searches for n–nbar oscillations
- Study of neutrino interactions in the near detector
- Searches for dark matter signatures

- 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

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) within the same set-up and with high significance for discovery. Checking of CP vs NSI with spectral info.
- It also provides a complete neutrino interactions final state reconstruction information

Neutrino oscillation measurement strategy

ν_e / $\bar{\nu}_e$ appearance:

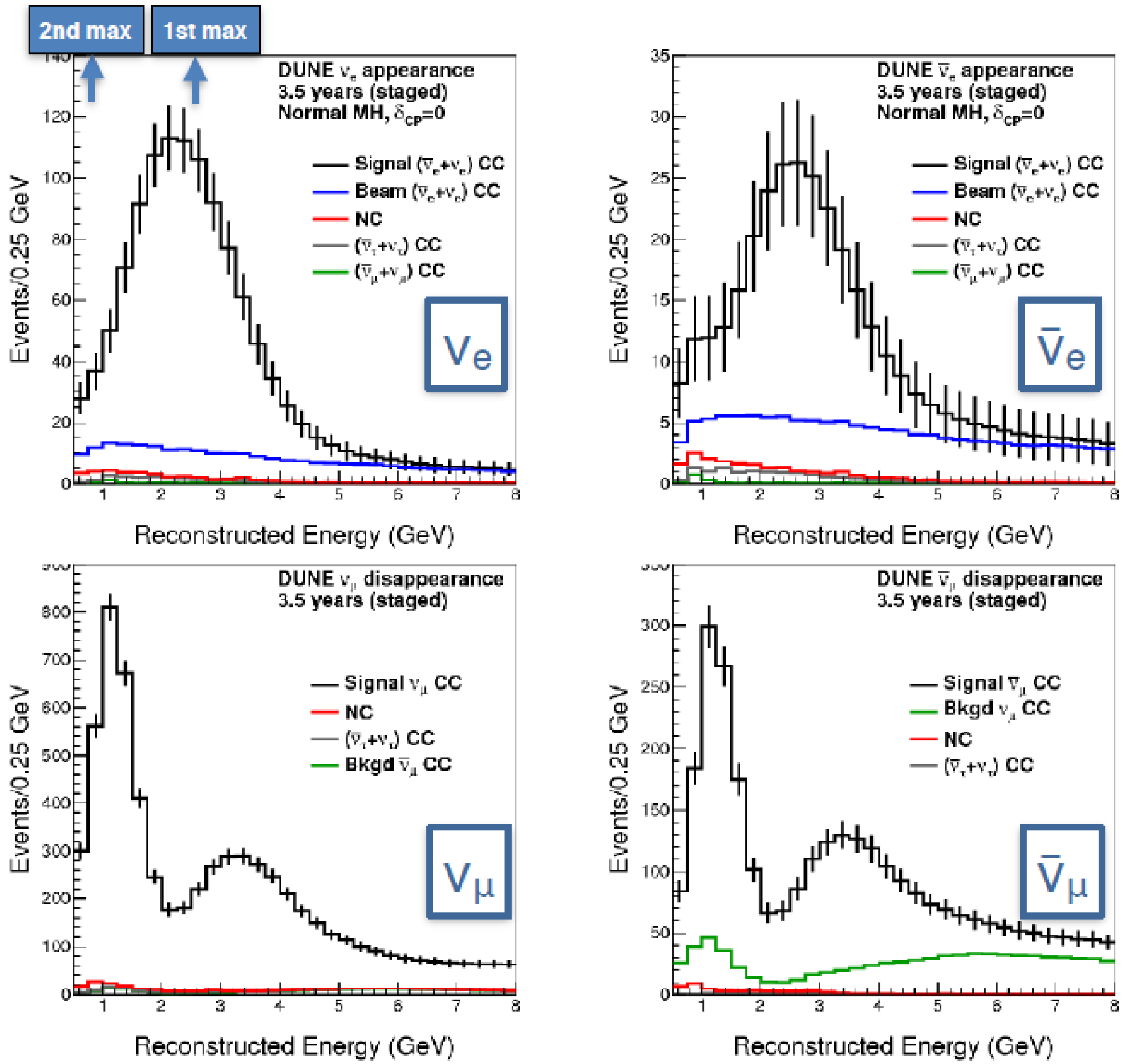
Fit to four samples

↓

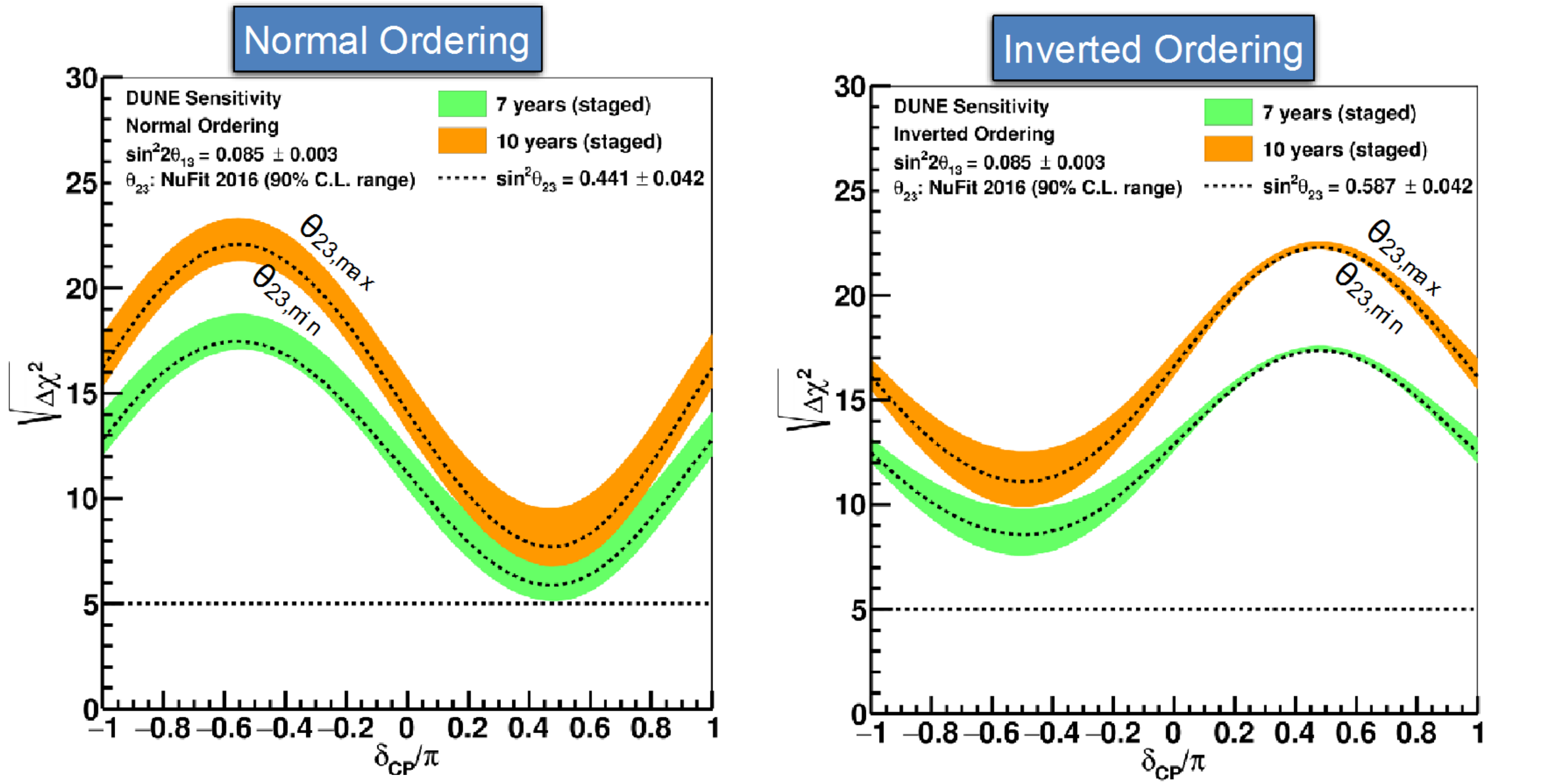
oscillation parameters

ν_μ / $\bar{\nu}_\mu$ disappearance:

Details about oscillation sensitivity calculations in arXiv:1606.09550



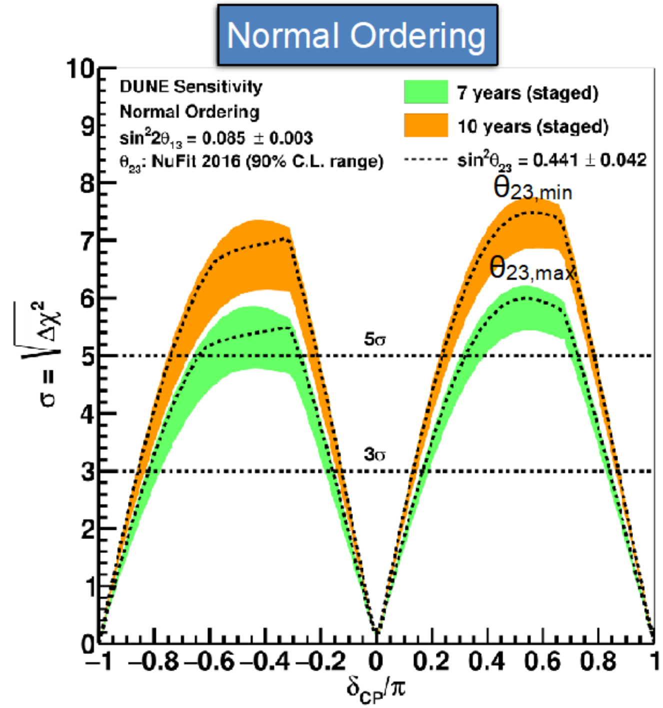
Sensitivity to the mass hierarchy determination

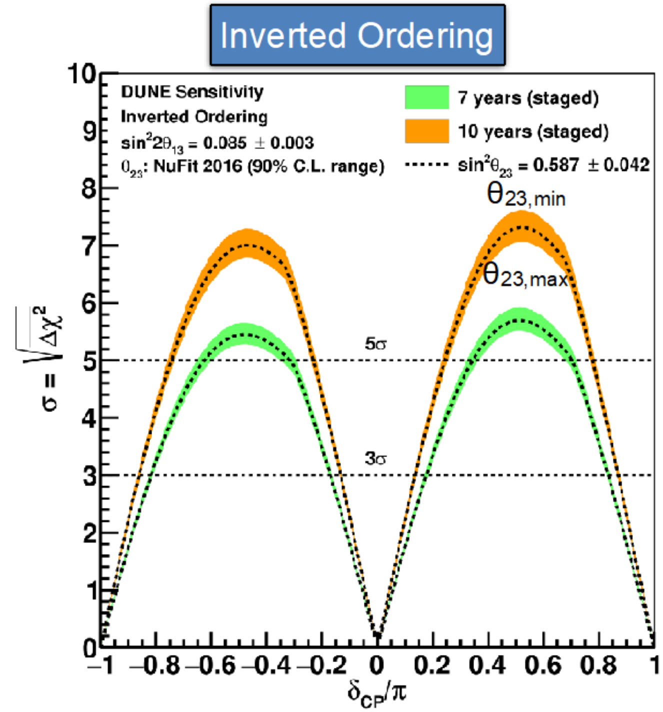


+-40% effect→ larger than any possible δ_{CP} effect , unambiguous determination of MH and CP within the same experiment with high confidence

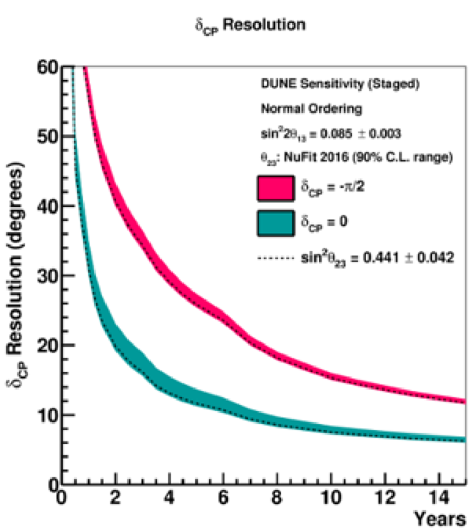
> 5σ significance on MH for any value of δ_{CP}

Sensitivity to CP violation





5σ sensitivity after 300 kton x MW x year exposure (7 yr)

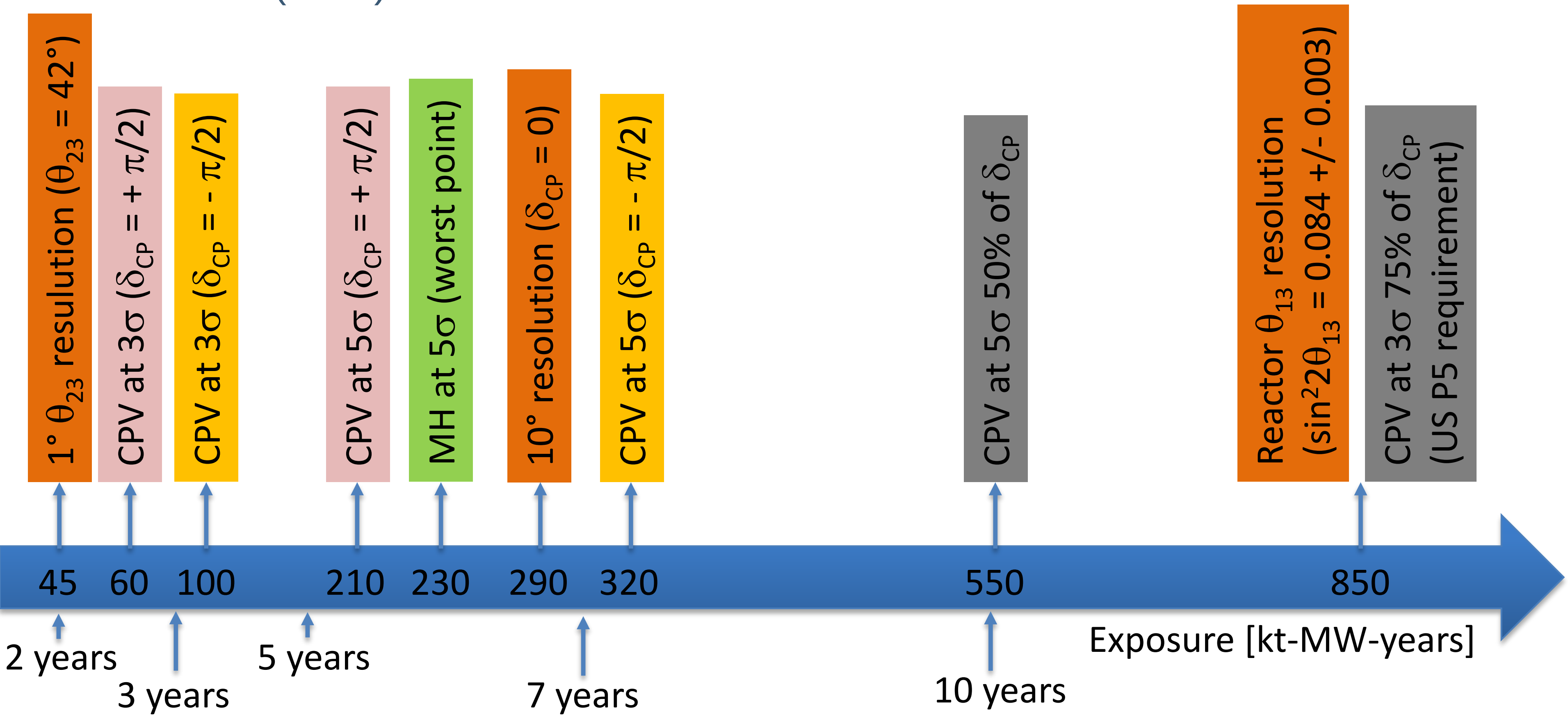


- Measurement of δ_{CP} with 7 – 14 % resolution

Physics milestones vs Exposure kt-MW-years

Staging scenario with equal running in neutrino and antineutrino modes:

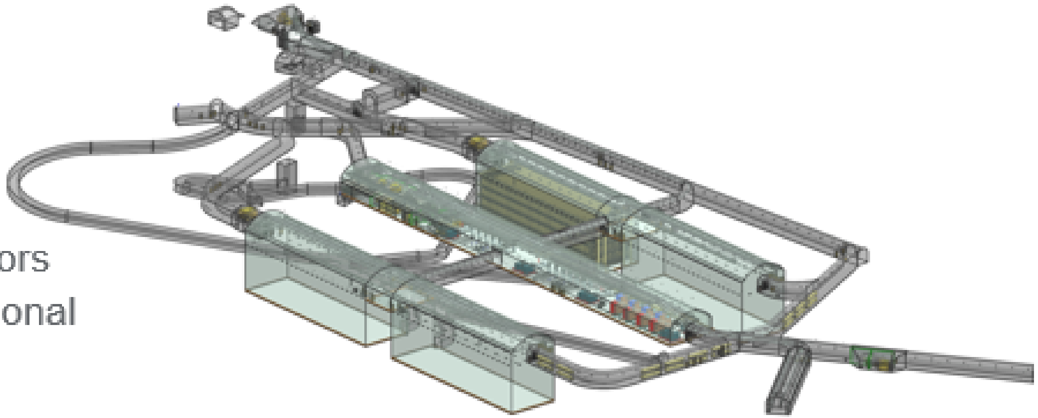
- **Year1**(2026): 20-kt FD,1.2 MW beam
- **Year2**(2027): 30-kt FD
- **Year4**(2029): 40-kt FD
- **Year7**(2032): 2.4 MW beam



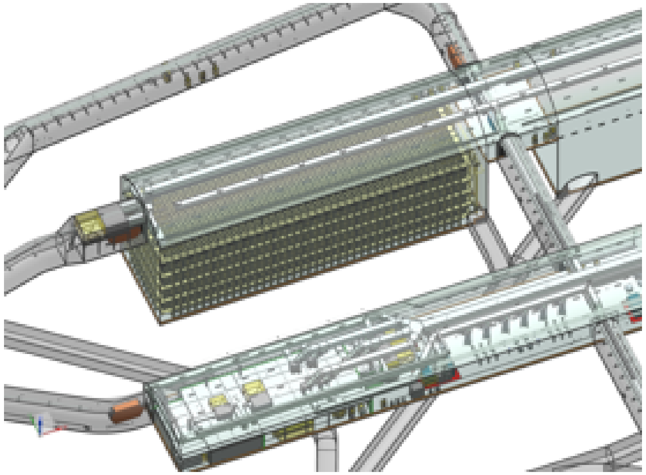
Overview – "Far Site" – LBNF at Sanford Lab, Lead, SD

- **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

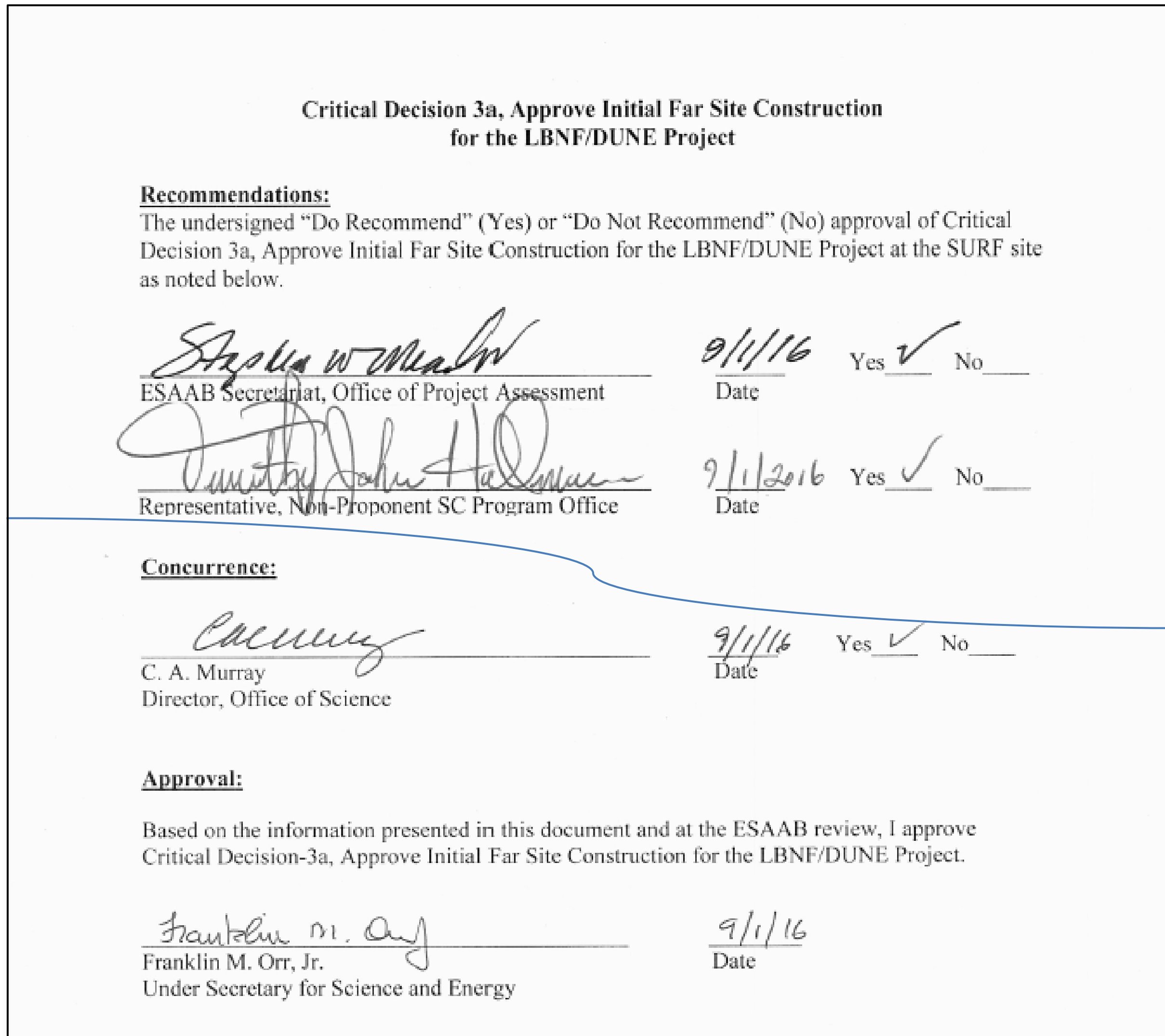


Single cryostat and portion of central utility cavern

- DUNE CD-1R 2015 (Conceptual Design Report)
  LBNF CD-3a 2016 – Approval of Initial Far Site Construction

- On September 1st 2016, DOE Under Sec'ty for Science and Energy **approved** the CD-3a milestone

- Signifies DOE's **strong commitment** to move the project forward, solidify international partnerships, and position DUNE to rapidly pursue its science objectives.



Critical Decision 3a, Approve Initial Far Site Construction for the LBNF/DUNE Project

Recommendations:
The undersigned "Do Recommend" (Yes) or "Do Not Recommend" (No) approval of Critical Decision 3a, Approve Initial Far Site Construction for the LBNF/DUNE Project at the SURF site as noted below.

ESAAB Secretariat, Office of Project Assessment — Date: 9/1/16 — Yes ✓ No ___

Representative, Non-Proponent SC Program Office — Date: 9/1/2016 — Yes ✓ No ___

Concurrence:

C. A. Murray
Director, Office of Science — Date: 9/1/16 — Yes ✓ No ___

Approval:

Based on the information presented in this document and at the ESAAB review, I approve Critical Decision-3a, Approve Initial Far Site Construction for the LBNF/DUNE Project.

Franklin M. Orr, Jr.
Under Secretary for Science and Energy — Date: 9/1/16

LBNF Groundbreaking 21/7/2017

→ Start of civil engineering works for LBNF

Première pierre pour l'expérience neutrinos internationale DUNE aux États-Unis

Le 21 juillet 2017 marque le début des travaux pour la construction d'un détecteur de neutrinos géant. L'expérience DUNE (*Deep Underground Neutrino Experiment*) est un projet international auprès de l'infrastructure LBNF (*Long Baseline Neutrino Facility*) dont le démarrage est prévu d'ici à 2026 au Fermilab, près de Chicago. En France, les chercheur.e.s de six laboratoires IN2P3 et CEA sont impliqués sur les prototypes de détecteurs (ProtoDUNE) qui serviront de modèle pour la construction de ces détecteurs de neutrinos de prochaine génération.

Le neutrino est une particule élémentaire particulièrement difficile à détecter. Il interagit peu avec la matière et traverse la Terre par milliards à chaque seconde, la plupart du temps sans laisser de trace. Son rôle pourrait être crucial pour comprendre l'origine de l'asymétrie matière-antimatière dans l'univers. La mise en évidence d'une violation de cette symétrie nécessite des expériences sur faisceau de nouvelle génération comme l'experience DUNE (*Deep Underground Neutrino Experiment*), qui doit être installé sur le faisceau de neutrinos LBNF. À son démarrage, vers 2026, ce faisceau de neutrinos sera le plus intense au monde.

DUNE sera composé de deux détecteurs qui observeront les neutrinos produits sur le parcours du faisceau. L'un proche de la source sera situé au Fermilab et l'autre installé 1300 km plus loin au laboratoire souterrain de Sanford, dans le Dakota du Sud. Ce détecteur lointain sera rempli par 70 000 tonnes d'argon liquide refroidi à -185°C.

Le prototype double-phase ProtoDune, en construction au CERN. © CERN

http://www.in2p3.fr/recherche/actualites/2017/nouvelle_experience_dune.html

http://news.fnal.gov/2017/07/construction-begins-international-mega-science-experiment-understand-neutrinos/

Strong commitment constantly reiterated: funding allocated for FY 2019 (95 M$) exceeded expectations and the budget recommended by the House of Representatives/Senate committees (80M$)

Creation of Far Detector consortia July-August 2018

Far Detector

- Plan that first far detector module will be single-phase and the second will be dual-phase

(Requires that we have cryostat design for both single and dual phase. Marzio is working toward common design for all but top of cryostat.)

- Based on this strategy, and after broad discussions, we decided to move forward with 9 far detector consortia:
  - Joint SP-DP: HV, DAQ, Slow controls and cryo instrumentation
  - Single Phase: APA, Photon Detection, TPC Electronics
  - Dual Phase: CRP, Photon Detection, TPC Electronics

Planning: first installed FD module single-phase, second module dual-phase

Schedule:

- Technical Proposal (interim-TDR) submitted to LBNC in May 2018 (soon public)
- Fall 2018-Spring 2019 ProtoDUNEs operation
- Technical Design Report (under work) to be completed by May 2019
- 2019: Start of Far Site caverns excavation
- 2022: Start of installation of first FD module
- 2023: Start of installation of second FD module
- 2024: Start of data taking
- 2026: Start of neutrino beam

DEEP UNDERGROUND NEUTRINO EXPERIMENT

The Volumes

Structure of the Technical Proposal

- **Volume 1: Introduction**
  - Executive Summary (Ed Blucher, Stefan Soldner-Rembold)
  - DUNE Physics (Albert de Roeck, Jon Urheim)
  - Simulation and Reconstruction Strategy (Ryan Patterson)
  - Computing Summary (Andrew Norman, Heidi Schellman)
  - Calibration Strategy (Sowjanya Gollapinni, Kendall Mahn)

~100 pages

- **Volume 2: Single-Phase DUNE Far Detector** (Mitch Soderberg)
  - Design Motivation and Overview
  - APAs (Dave Schmitz)
  - TPC Electronics (Mike Mooney)
  - HV System (Rob Plunkett)
  - Photon Detection System (Bob Wilson)
  - DAQ (Jim Brooke, Brett Viren)
  - Cryogenics Instrumentation and Slow Controls (Glenn Horton-Smith, Carmen Palormares)
  - Technical Coordination (Steve Kettell)

~300 pages

- **Volume 3: Dual-Phase DUNE Far Detector** (Dario Autiero, Dominique Duchesneau)
  - Design Motivation and Overview
  - CRPs (Dominique Duschesneau, Edoardo Mazzucato)
  - TPC Electronics (Slavic Galymov, Jamie Dawson)
  - HV System (Francesco Pietropaolo, Jae Yu)
  - Photon Detection System (Burak Bilki, Clara Cuesta)
  - DAQ (Jim Brooke, Brett Viren)
  - Cryogenics Instrumentation and Slow Controls (Glenn Horton-Smith, Carmen Palormares)
  - Technical Coordination (Steve Kettell)

~300 pages

Snapshot of Technical Proposal (interim-TDR)
Submitted in May 2015

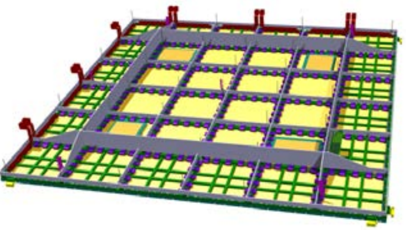
- Strong involvement of IN2P3 groups in DUNE (physics, computing, detector developments, coordination) *past*/present roles:
  - **D.Autiero *member of the DUNE Executive Committee*, Consortium leader for DP-electronics , ProtoDUNE-DP co-coordinator**
  - **D. Duchesneau *member of Speakers Committee*, interim CRP Consortium leader, ProtoDUNE-DP co-coordinator, technical lead in the DP photon detection consortium**
  - **S. Galymov *deputy coordinator of detector optimization task-force***
  - **Y. Karyotakis co-coordinator of joint SP-DP beamline instrumentation WG**
  - **T. Patzak *co-coordinator of LBL WG*, chair of Speakers Committee,**
  - **E. Pennacchio, ProtoDUNE-DP Computing Liaison**
  - **A. Tonazzo *co-coordinator of atmospheric neutrinos WG***

- Hardware responsibilities in WA105/ProtoDUNE-DP (WA105 MOU signed in 2015)
  - **APC+OMEGA+LAPP: light readout electronics**
  - **IPNL: Front-end analog cryogenic electronics, digital electronics, DAQ, online computing**
  - **LAPP: Charge Readout Planes hanging system, Charge Readout Planes mechanical frames design, beam instrumentation**
  - **LPNHE cathode HV feedthrough**

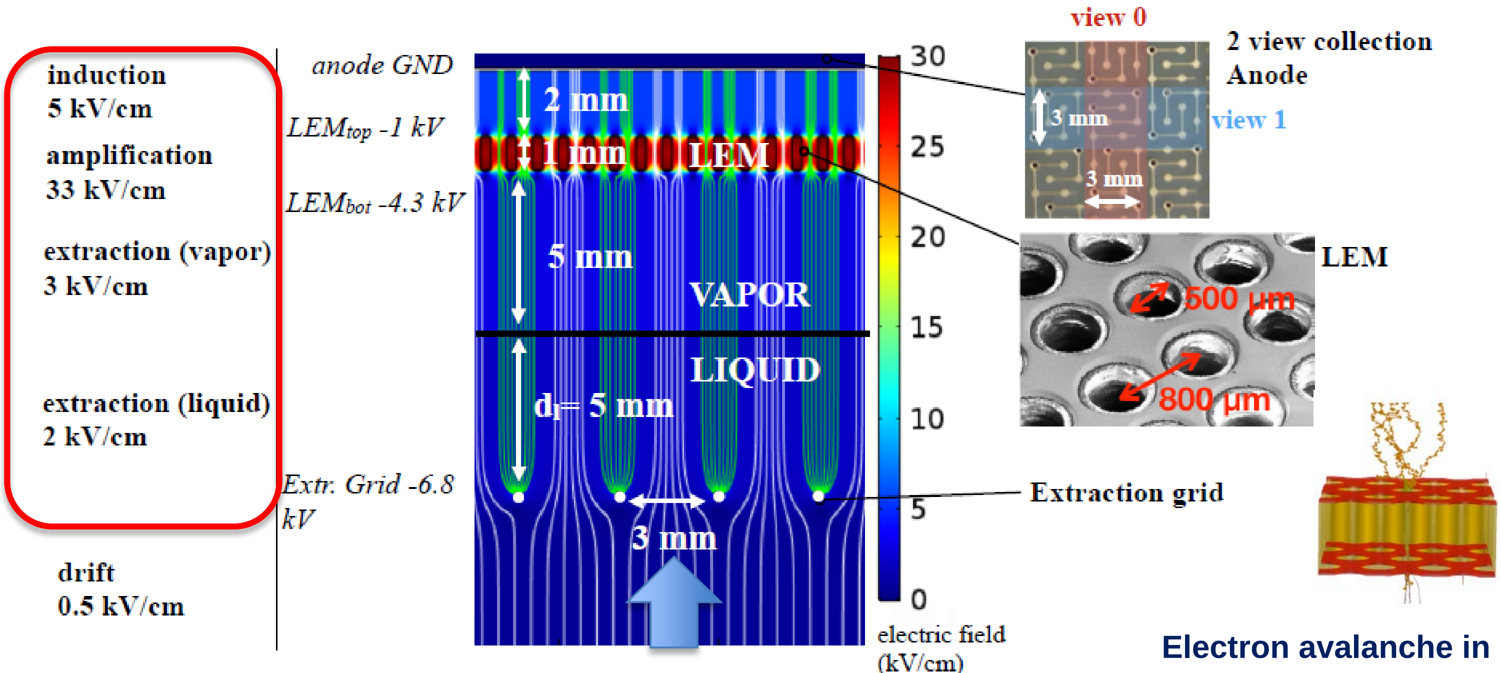
- CEA/Irfu responsibility of LEM/anodes production

- French groups involvement/leadership in DUNE Far Detector Consortia:
  - **Dual-phase Electronics (leadership)**
  - **Data Acquistion (joint SP-DP)**
  - **Dual-phase Charge Readout Planes (interim leadership)**
  - **Dual-phase Photon Detection System**

More information at the Journée DUNE France (January 2018): https://indico.in2p3.fr/event/16873/



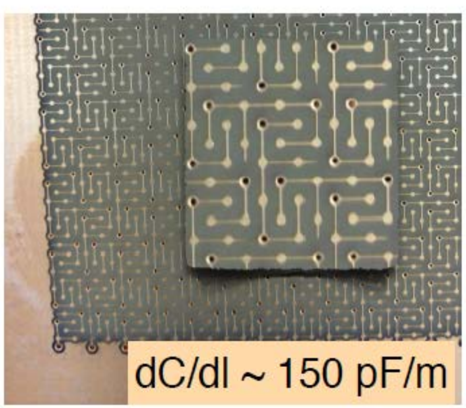
Charge Readout Plane integrating LEM-anode sandwiches

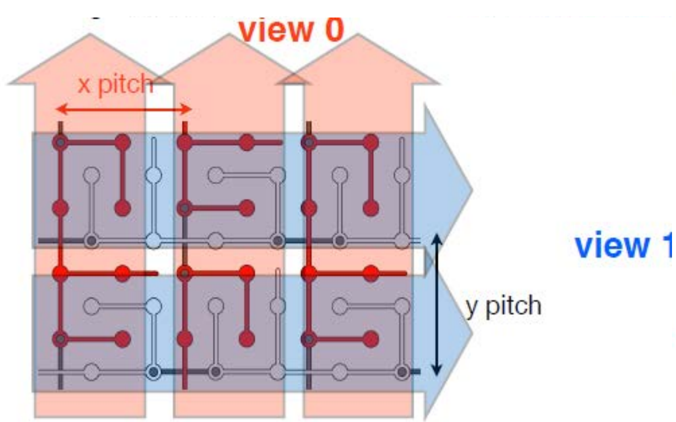


Electron avalanche in LEM hole

50x50 cm^2 LEM

50x50 cm^2 anodes with 2 collection views





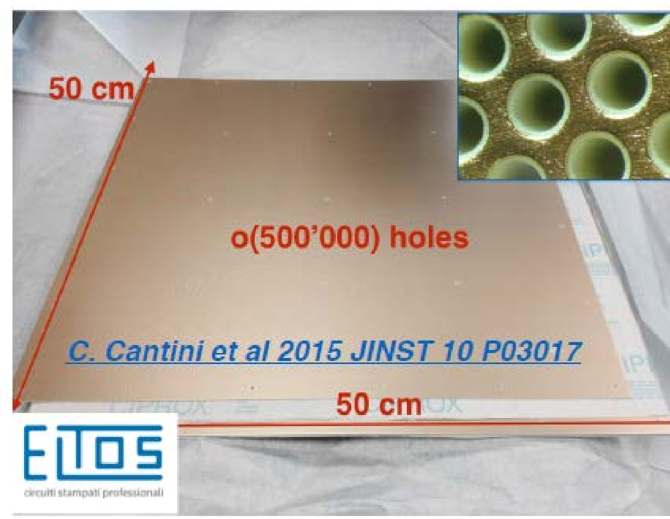
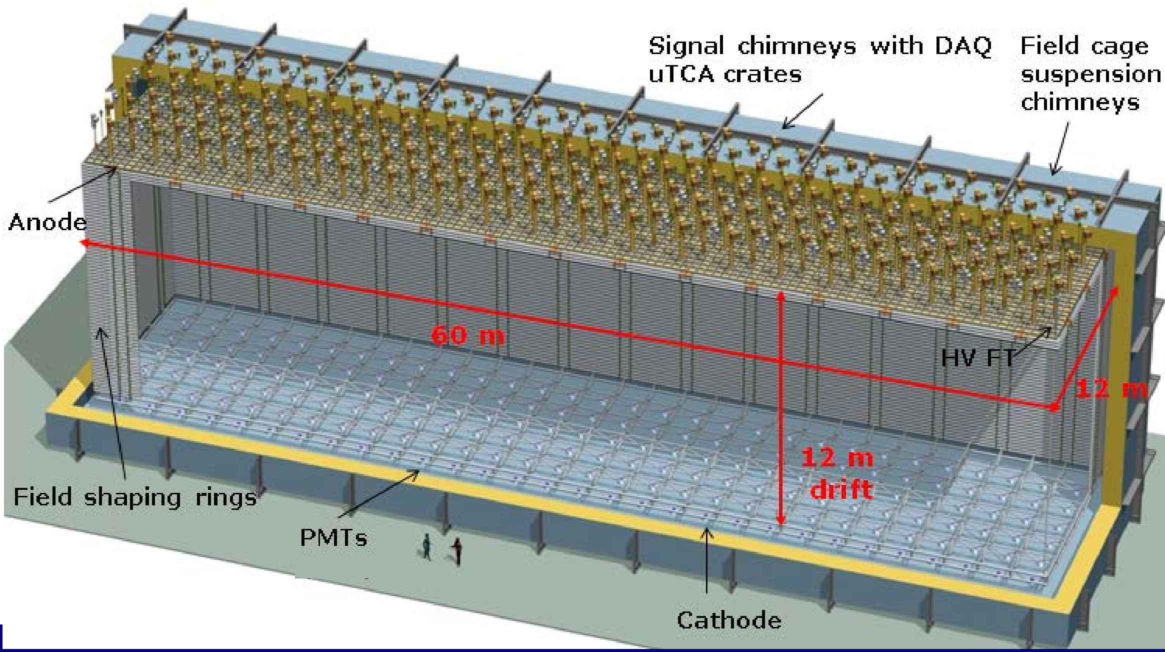


Table 1.2: Quantities of items or parameters for the 12.096 kt DP module

Item	Number or Parameter
Anode plane size	W = 12 m, L = 60 m
CRP unit size	W = 3 m, L = 3 m
CRP units	4 × 20 = 80
LEM-anode sandwiches per CRP unit	36
LEM-anode sandwiches (total)	2880
SFT chimney per CRP unit	3
SFT chimney (total)	240
Charge readout channels / SFT chimney	640
Charge readout channels (total)	153,600
Suspension feedthrough per CRP unit	3
Suspension feedthroughs (total)	240
Slow Control feedthrough per sub-anode	1
Slow Control feedthroughs (total)	80
HV feedthrough	1
HV for vertical drift	600 kV
Voltage degrader resistive chains	4
Cathode modules	80
Field cage rings	197
Field cage modules	288
PMTs (total)	720 (1/m^2)

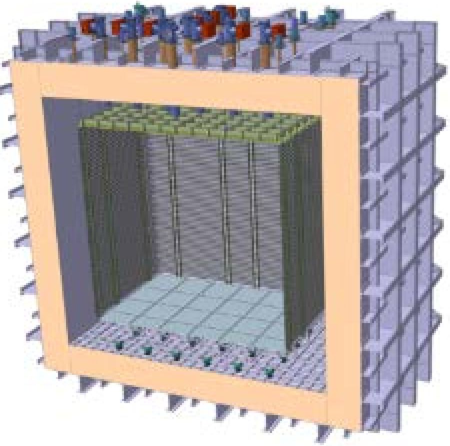
Dual-Phase DUNE FD: 20 times replication of Dual-Phase ProtoDUNE (drift 6m → 12m) DUNE Conceptual Design Report, July 2015

Active LAr mass:12.096 kton, fid mass:10.643 kton, N. of channels: 153600

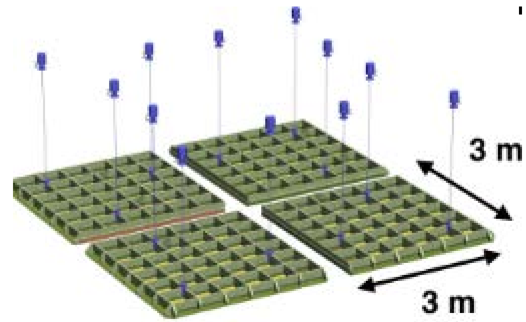


Advantages of dual-phase design:

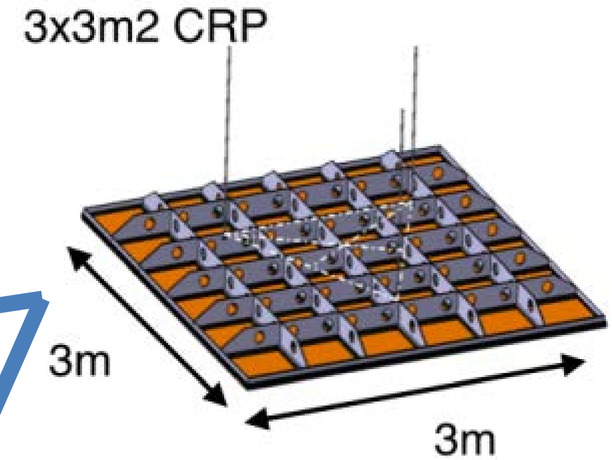
- Gain in the gas phase → robust and tunable S/N, lower detection threshold, compensation for charge attenuation due to long drift paths
- Finer readout pitch (3.125 mm), implemented in two identical collection views (X,Y) on 3m long strips
- Long drift projective geometry: reduced number of readout channels (153,600 for DP less than half of equivalent SP FD), absence of dead materials in the drift volume
- Fewer construction modules
- Full accessibility and replaceability of cryogenic front-end (FE) electronics during detector operation



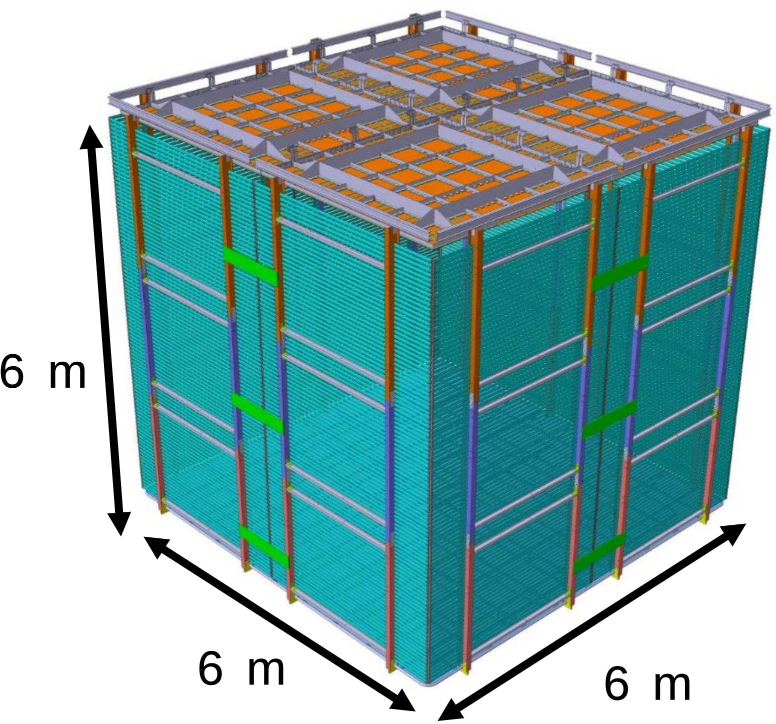
The Dual-Phase ProtoDUNE/WA105 6x6x6 m^3 detector is built out of the same **3x3m^2 Charge Readout Plane units (CRP)** foreseen for the 10 kton Dual-Phase DUNE Far Detector (same QA/QC and installation chains)



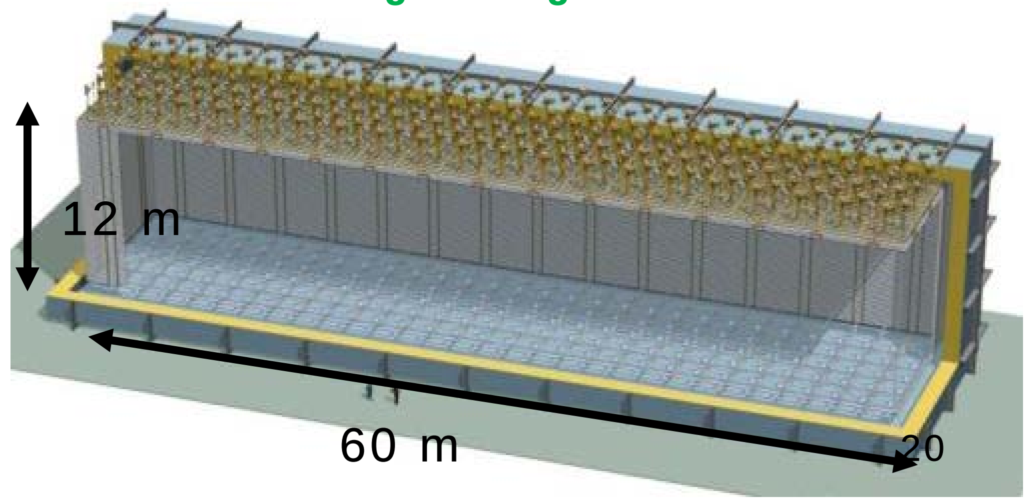
WA105: 4(2) CRP



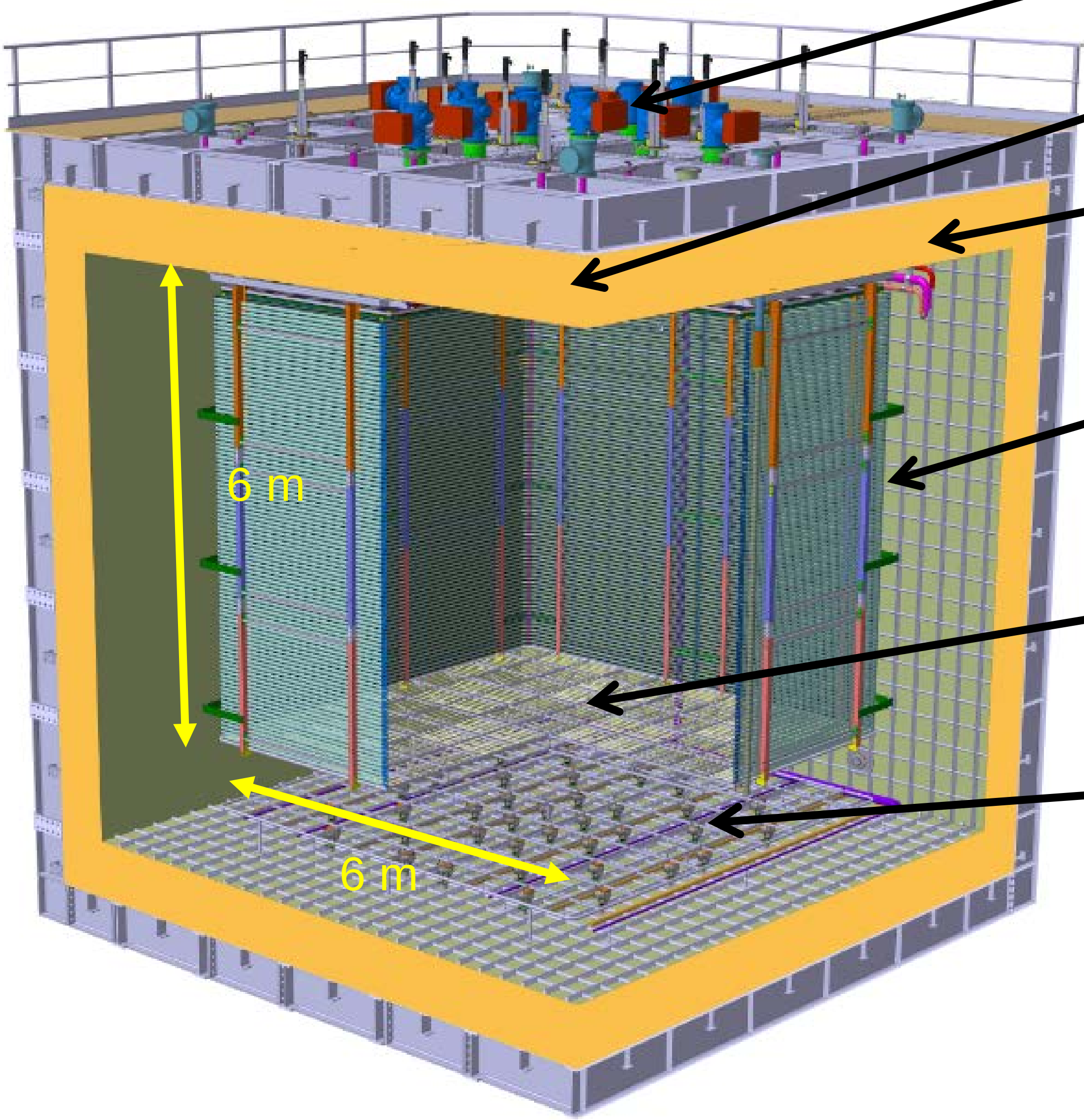
1920 channels/CRP
Accessible cold electronics in chimney



10 kton: 80 CRP + 288 field cage sub-modules + 80 cathode / ground grid modules



The DP-FD design described in the TP is based on ProtoDUNE-DP design



Digital electronics in uTCA crates

Cold FE electronics in SFT "chimneys"

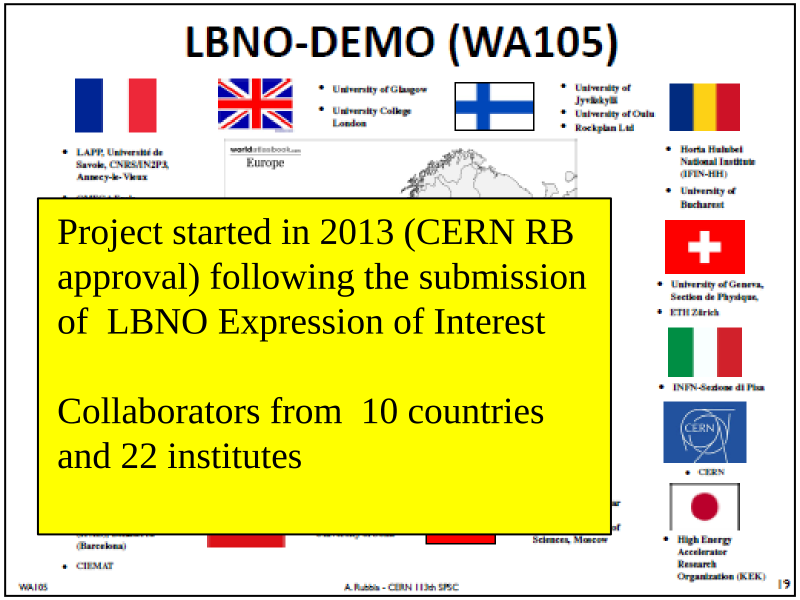
Charge Readout Planes

Field Cage sub-modules (common structural elements with SP)

Cathode modules

36 cryogenic photomultipliers Hamamatsu R5912-02mod with TPB coating

History of Dual-Phase ProtoDUNE / WA105



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

Collaborators from 10 countries and 22 institutes

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Technical Design Report

for large-scale neutrino detectors prototyp…

and phased performance assessment

in view of a long-baseline oscillation experi…

Collaboration

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

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2015-013 / SPSC-SR-158
31/03/2015

Progress report on LBNO-DEMO/WA105 (2015)

The WA105 Collaboration

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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. Nessi, and F. N…
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A. Blondel, Y. Karadzhov, and E. Noah
University of Geneva, Section de Physique, DPNC, Geneva, Switzerland

R. Bayes and F.J.P. Soler
University of Glasgow, Glasgow, United Kingdom

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

2015 Annual SPSC progress report 31st March 2015 SPSC-SR-158

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

WA105 project MOU fully signed, December 2015

Integration in the DUNE project as ProtoDUNE-DP December 2015; EOI call for ProtoDUNEs, January 2016

EUROPEAN ORGANIZATION FOR NUCLEAR RESEAR…

…dual phase (2016)

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L. Zambelli
LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France

CERN, Geneva, Switzerland

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

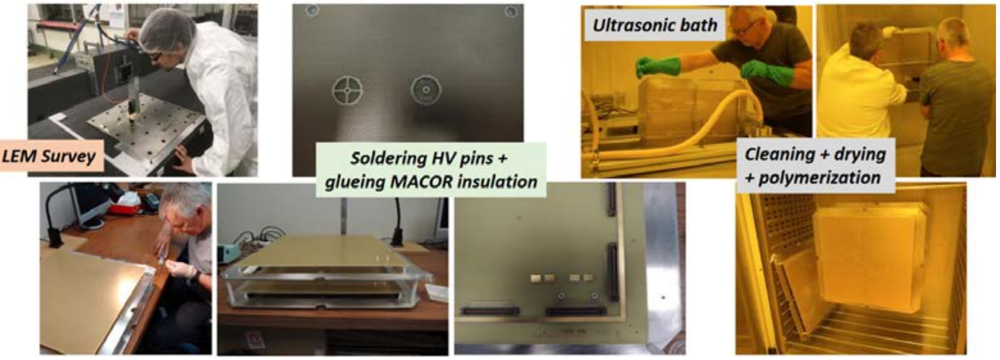
2016 Annual SPSC progress report, April 7th 2016
CERN-SPSC-2016-017
SPSC-SR-184

Systematic LBNC reviews since beginning of 2016

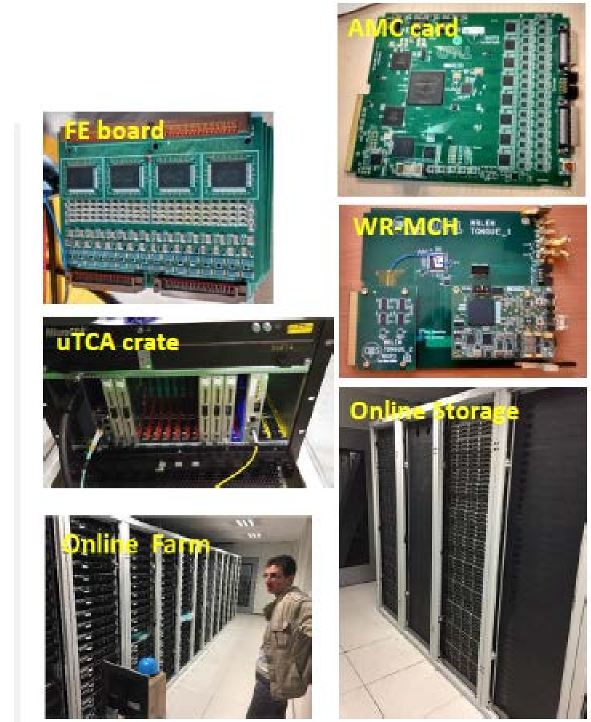
2017 Annual SPSC progress report, April 4th 2017
CERN-SPSC-2017-011
SPSC-SR-206

Technical Design Review April 2017

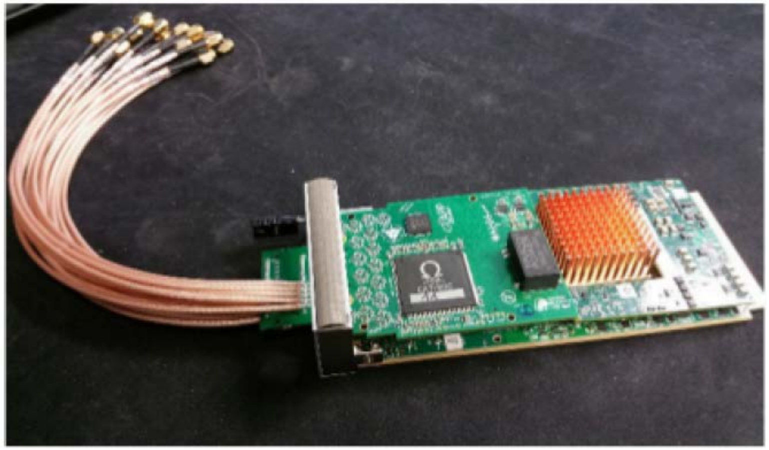
CEA/Irfu: LEM/anodes



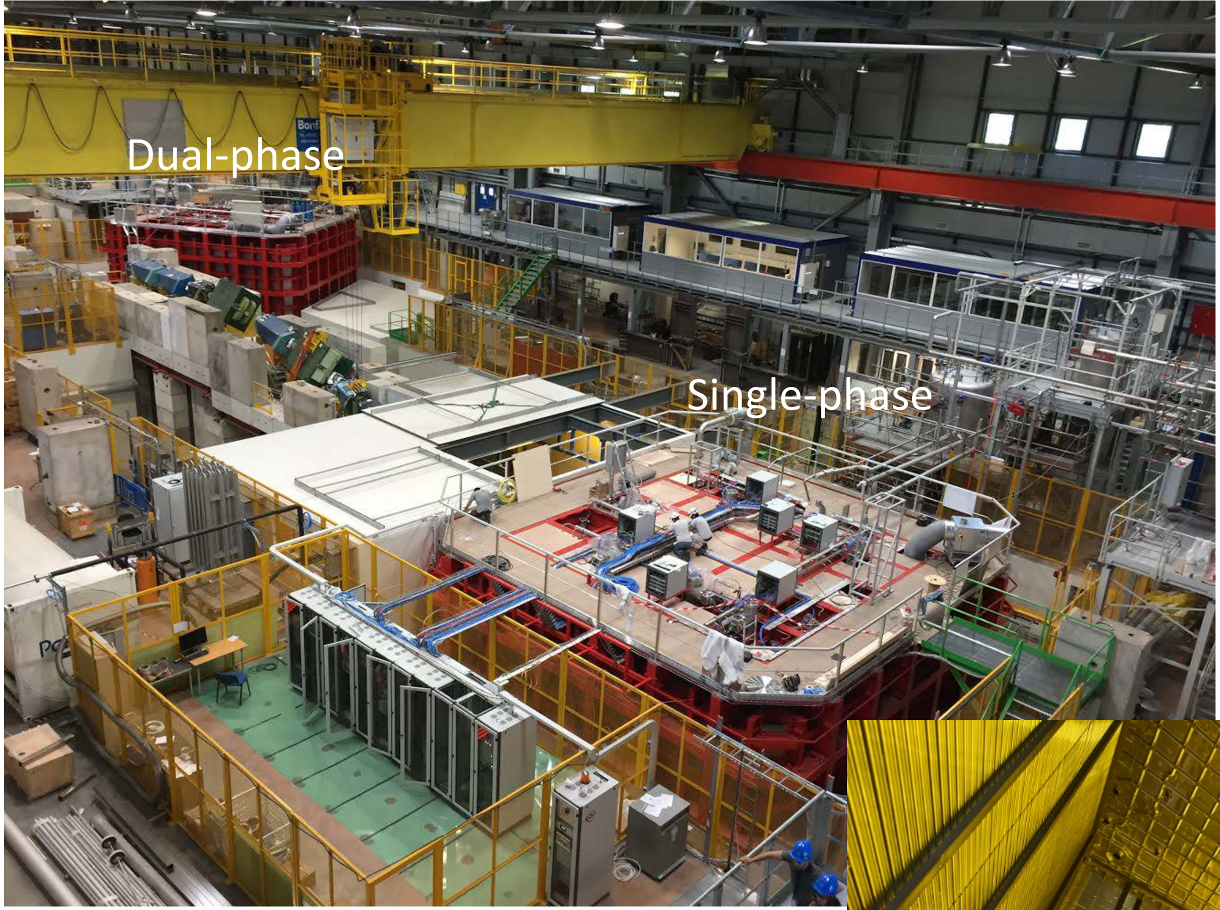
IPNL: charge readout analog/digital electronics, DAQ



APC/LAPP/OMEGA: Light readout electronics

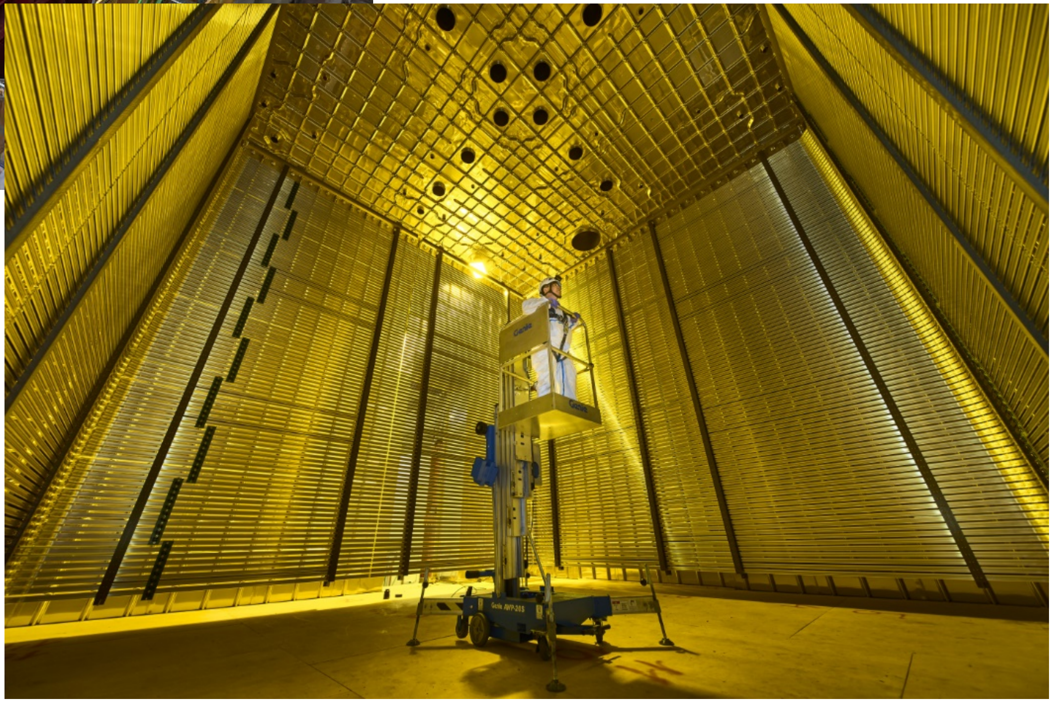


LAPP: Charge Readout Planes mechanics



ProtoDUNEs detectors at CERN EHN1

ProtoDUNE dual-phase under construction



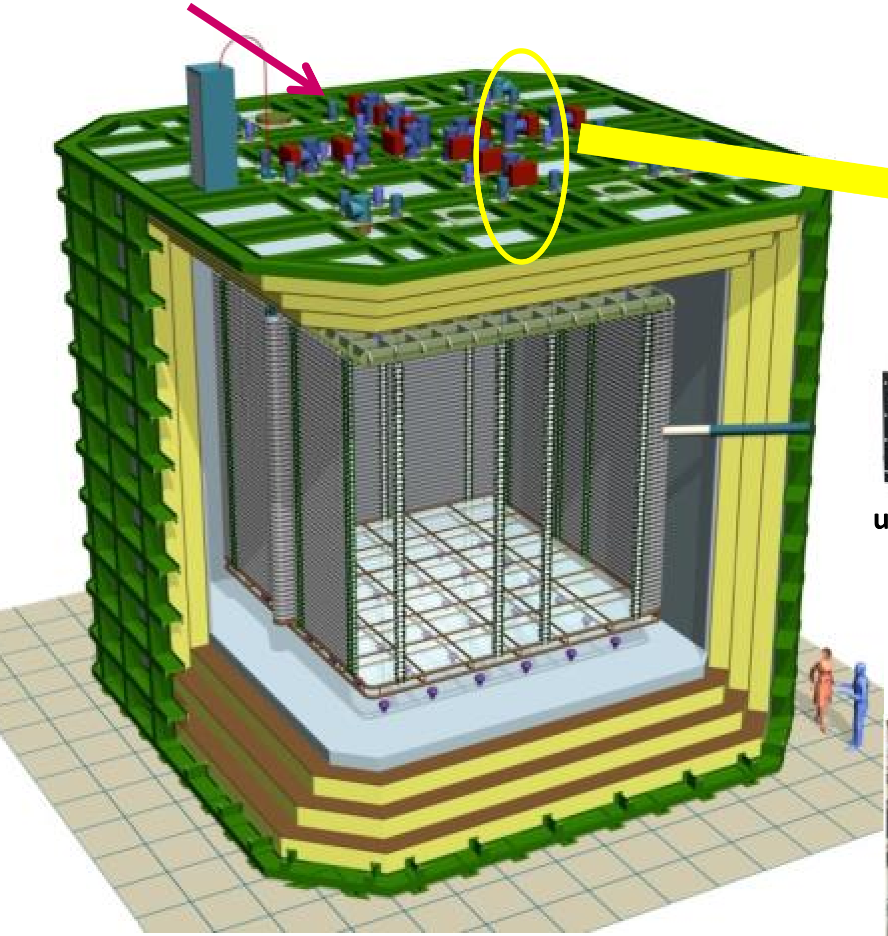
Detector closure expected in October
Data taking by the end of 2018

see also: http://news.fnal.gov/2018/06/dune-collaboration-grows-to-32-countries-prepares-for-operations-of-prototype-detectors/

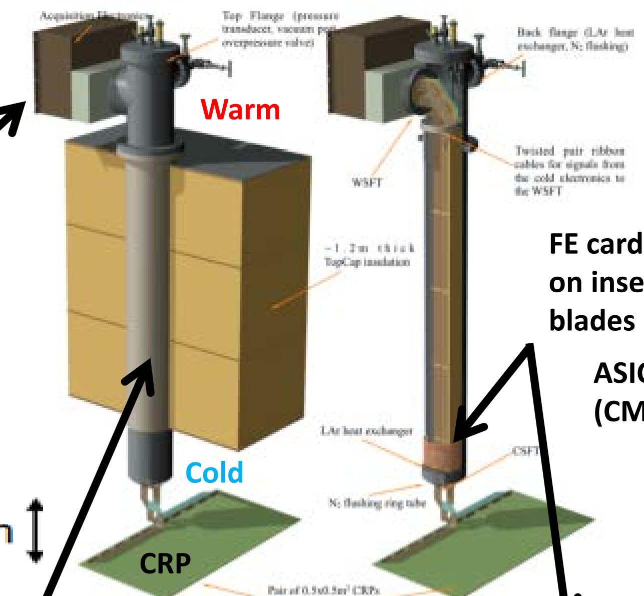
ProtoDUNE-DP accessible cold front-end electronics and uTCA DAQ system 7680 ch (IPNL)

Full accessibility provided by the double-phase charge readout at the top of the detector

- **Digital electronics at warm on the tank deck:**
  - Architecture based on uTCA standard
  - 1 crate/signal chimney, 640 channels/crate
  - → 12 uTCA crates, 10 AMC cards/crate, 64 ch/card
- **Cryogenic ASIC amplifiers (CMOS 0.35um) 16ch externally accessible:**
  - Working at 110K at the bottom of the signal chimneys
  - Cards fixed to a plug accessible from outside
  - →Short cables capacitance, low noise at low T

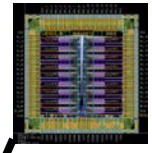


uTCA crate

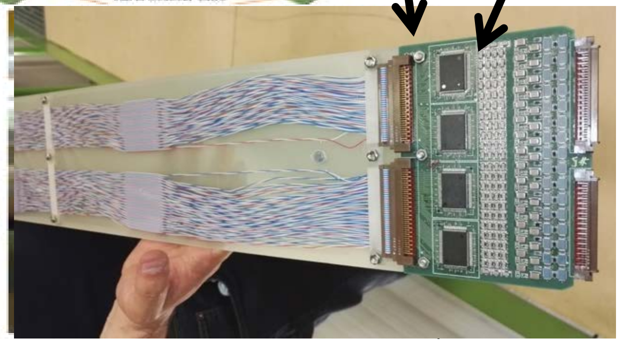


FE cards mounted on insertion blades

ASICs 16 ch. (CMOS 0.35 um)



Signal chimney

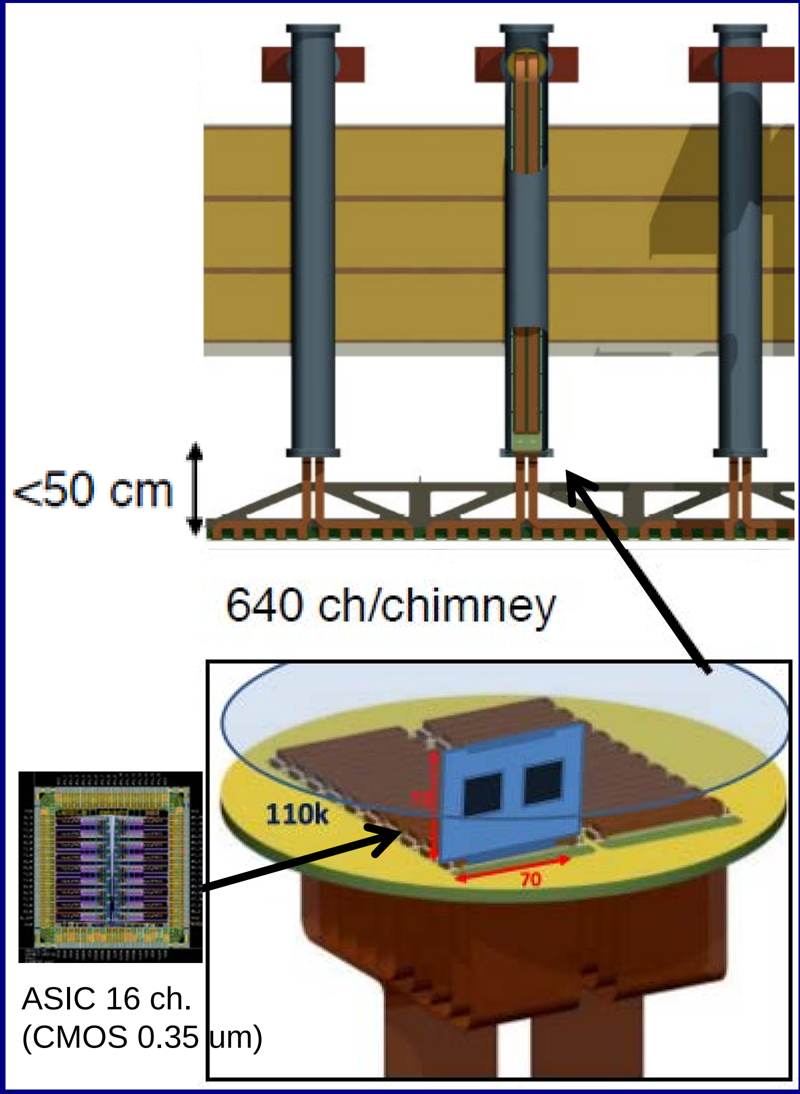


Cost effective and fully accessible cold front-end electronics and DAQ

Ongoing R&D since 2006→ production for 6x6x6 (7680 readout channels)

ASIC (CMOS 0.35 um) 16 ch. amplifiers working at ~110 K to profit from minimal noise conditions:

- FE electronics inside chimneys, cards fixed to blades accessible from outside
- Short distance cards-CRP<50 cm
- Dynamic range 40 mips, (1200 fC) (LEM gain =20)
- 1300 e- ENC @250 pF, <100 keV sensitivity
- Dual-slope gain for increased dynamics
- Power consumption <18 mW/ch
- Produced at the end of 2015 in 700 units (entire 6x6x6)



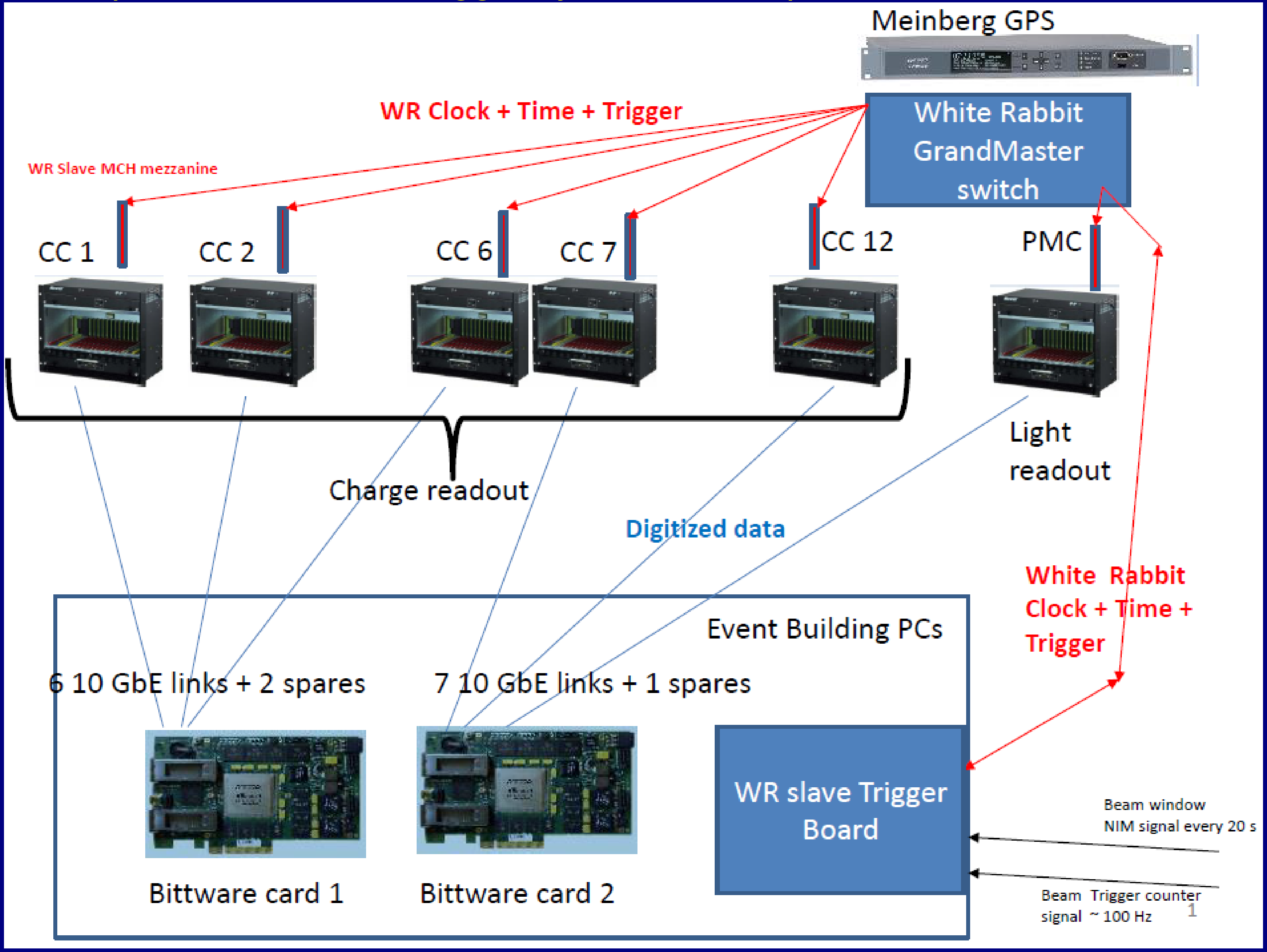
DAQ in warm zone on the tank deck:

- Architecture based on uTCA standard
- Local processors replaced by virtual processors emulated in low cost FPGAs (NIOS)
- Integration of the White-Rabbit time distribution chain (improved PTP)
- Network based back-end and storage/computing system
- Production of uTCA cards started at the end of 2015, pre-batch deployed on 3x1x1

→ Large scalability (150k channels for 10kton) at low costs

Global uTCA DAQ architecture for ProtoDUNE-DP

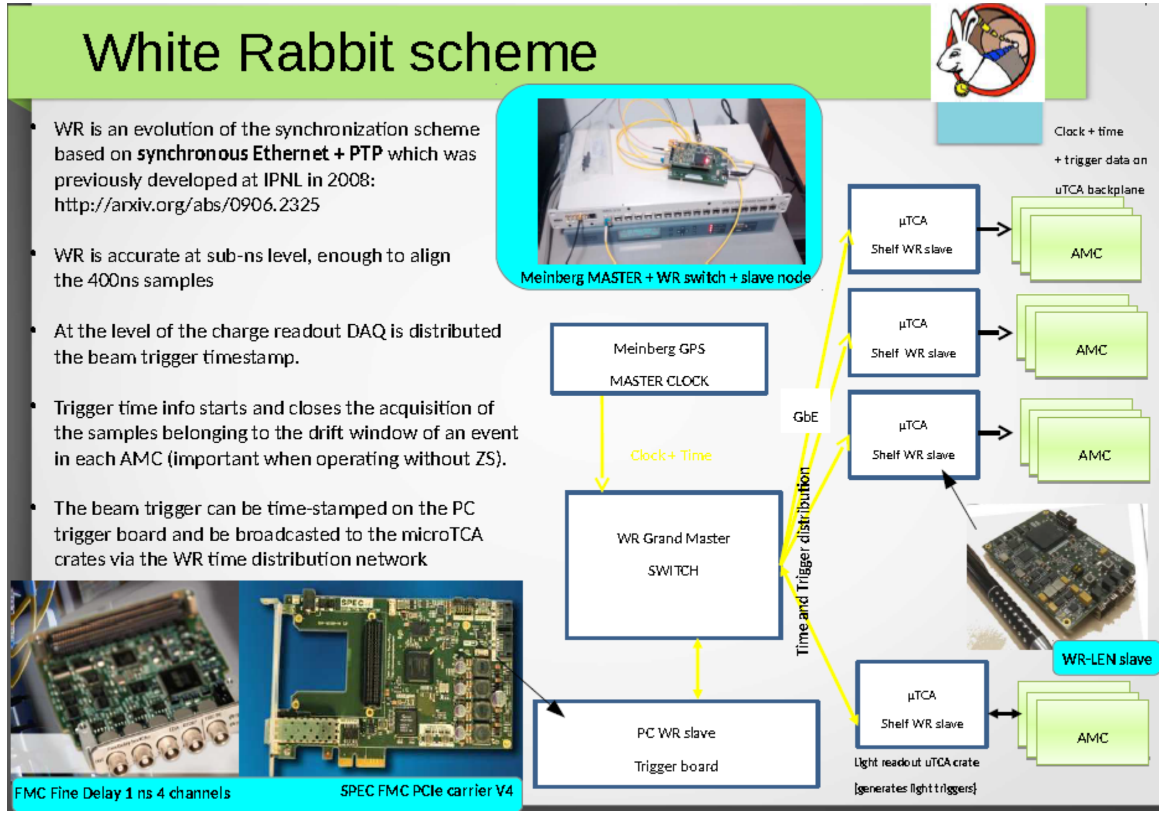
integrated with « White Rabbit » (WR) Time and Trigger distribution network
+ White Rabbit slaves nodes in uTCA crates +
WR system (time source, GM, trigger system, slaves)



White Rabbit trigger time-stamping PC (SPEC + FMC-DIO)

White Rabbit Grand-Master

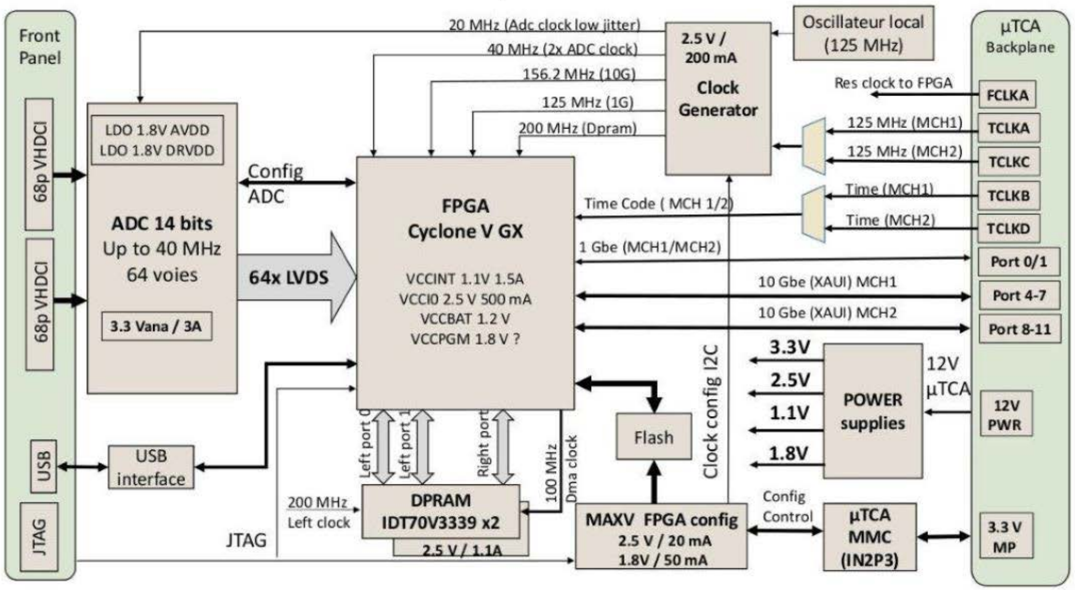
GPS unit



White Rabbit uTCA slave node based on WRLEN developed and produced for entire 6x6x6

Other components of the chain (GPS receiver, WR grandmaster, SPEC+ FMC-DIO + 13 WRLEN) available commercially

AMC_DAQ_WA105_V2



Charge readout AMC:

Components:
X8 ADC AD9257 14 bits, x2 Dual port memories IDT70V3339, ALTERA Cyclone V with NIOS

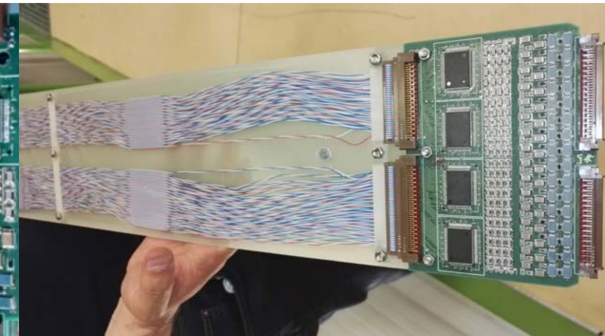
Features:
64 channels, 2.5 MHz sampling, 12 bits output, lossless Huffman-like compression (factor 10), 10 Gbit/s connectivity. Interface with the White-Rabbit and trigger timestamps transmission via dedicated lines and protocol on the uTCA backplane

- DAQ in protoDUNE-DP based on transmitting drift windows on the basis of external triggers
- Working mode foreseen for DUNE: continuous streaming
- 10 cards/crate → 640 channels/crate on a 10 Gbit/s optical link to DAQ back-end

Electronics components:

(R&D since 2006, long standing effort aimed at producing low cost electronics)

Main components ASIC amplifiers, ADCs, FPGAs, IDT memories already procured in 2015-2016. 3x1x1 pre-production batch in 2016.



Analog cryogenic FE:

- Cryogenic ASIC amplifiers DP-V3, 0.35um CMOS → production performed at the beginning of 2016
- 64 channels FE cards with 4 cryogenic ASIC amplifiers
- First batch of 20 cards (1280 channels) operational on the 3x1x1 since the fall 2016
- Production of remaining 100 cards for 6x6x6 completed on 2017 budget

Digitization cards:

uTCA 64 channels AMC digitization cards (2.5 MHz, 12 bits output, 10 GbE connectivity)

- 20 cards operational on the 3x1x1 since the fall 2016
- Production of remaining 100 cards for the 6x6x6 completed on 2017 budget

White Rabbit timing/trigger distribution system:

- Components produced in 2016 for the entire 6x6x6, full system operational on the 3x1x1 since the fall 2016

Integration exercise on the 3x1x1 m^3:

- Cryostat membrane vessel design and procurement
- Cryogenics
- LEM/anodes
- CRP hanging system
- Feedthroughs, signal chimneys
- VHV feedthrough
- Charge readout FE electronics + digital electronics
- Light readout system PMTs
- DAQ and online processing
- Slow Control

For many items benefit from immediate prototyping and integration on a smaller detector (3x1x1) (minimal size of RO unit in 6x6x6)

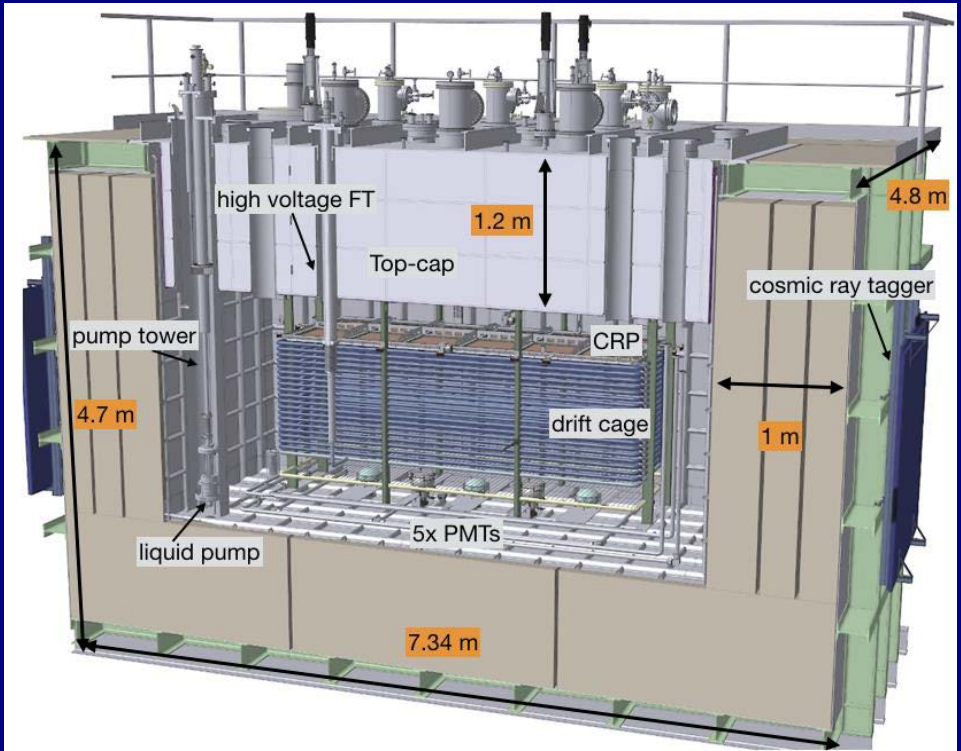
Completed: Fall 2016

Operating: spring-fall 2017

However:

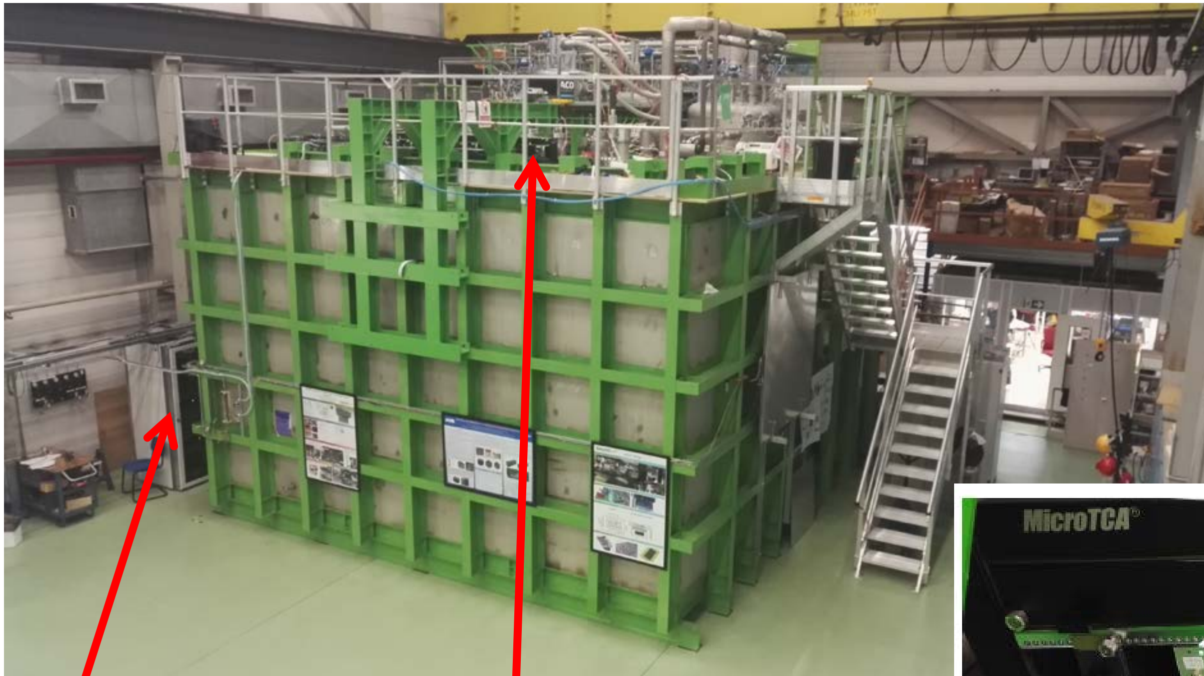
- CRP design of 6x6x6 completely different
- LEM design changed for 6x6x6
- Field cage/cathode design of 6x6x6 completely different

- ✓ **First DUNE cryostat prototype**
- ✓ **Anticipate legal and practical aspects** related to cryostat procurement (CERN-GTT collaboration)
- ✓ **Fully engineered versions of many detector components** with pre-production and direct implementation
- ✓ **Costs verification**
- ✓ First overview of the complete system integration: **set up full chains** for QA, construction, installation, commissioning



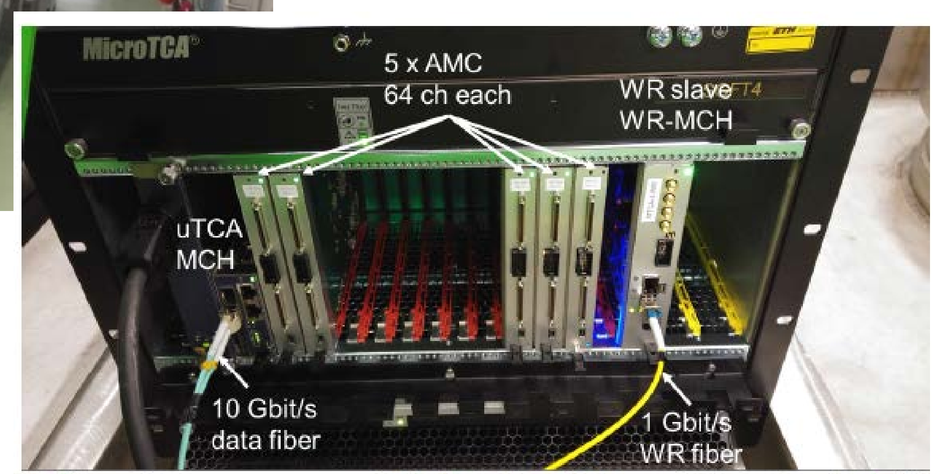
6x6x6: 12 uTCA crates (120 AMCs, 7680 readout channels)

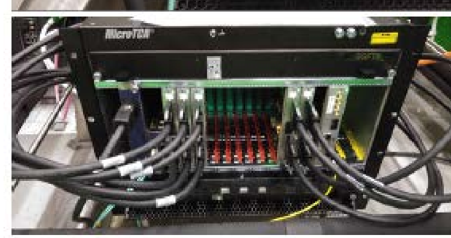
→ 3x1x1: 4 uTCA crates (20 AMCs, 1280 readout channels) Operational since fall 2016



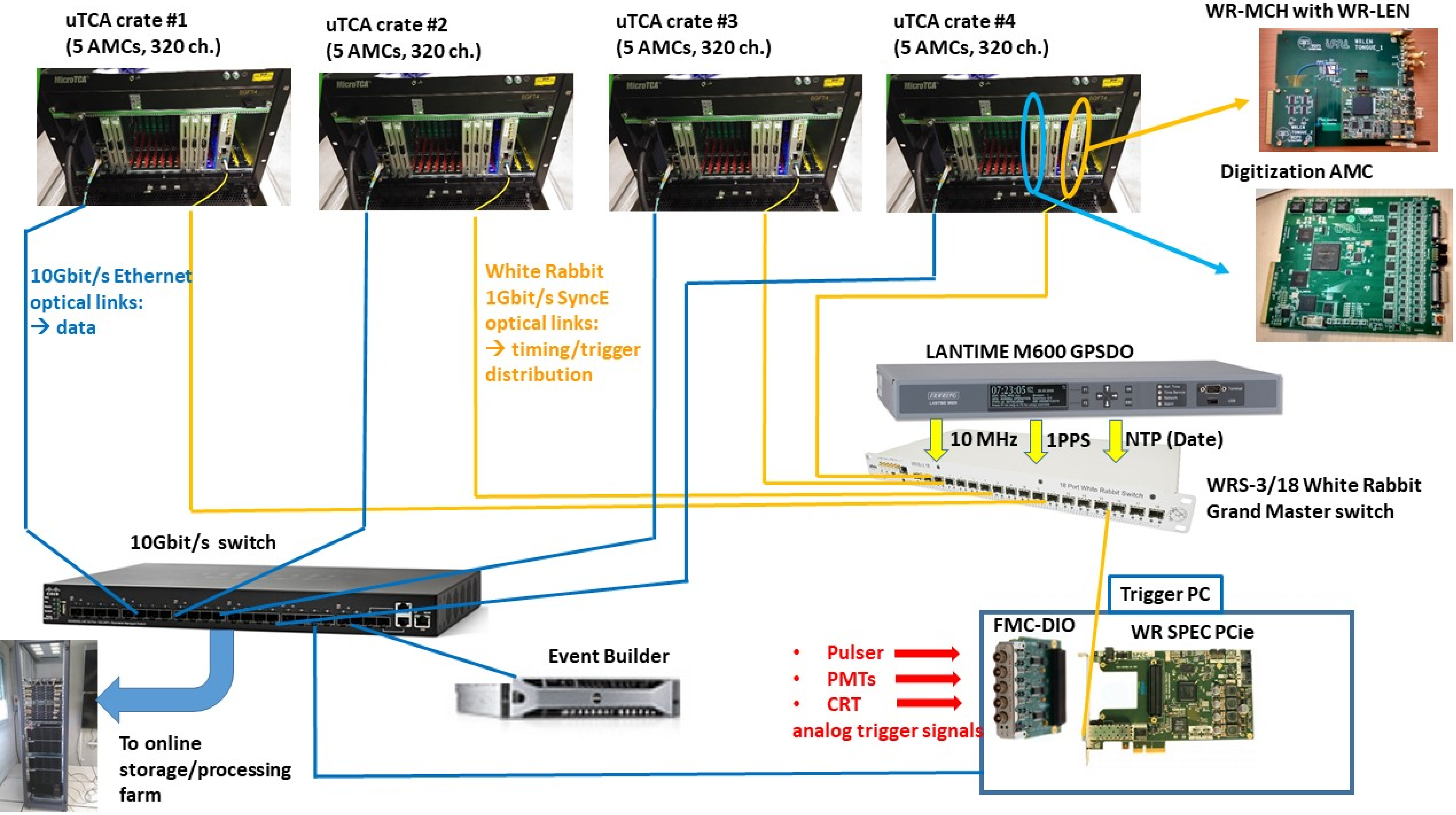
Signal Chimneys and uTCA crates

Event builder, network, GPS/White Rabbit GM, WR Trigger PC

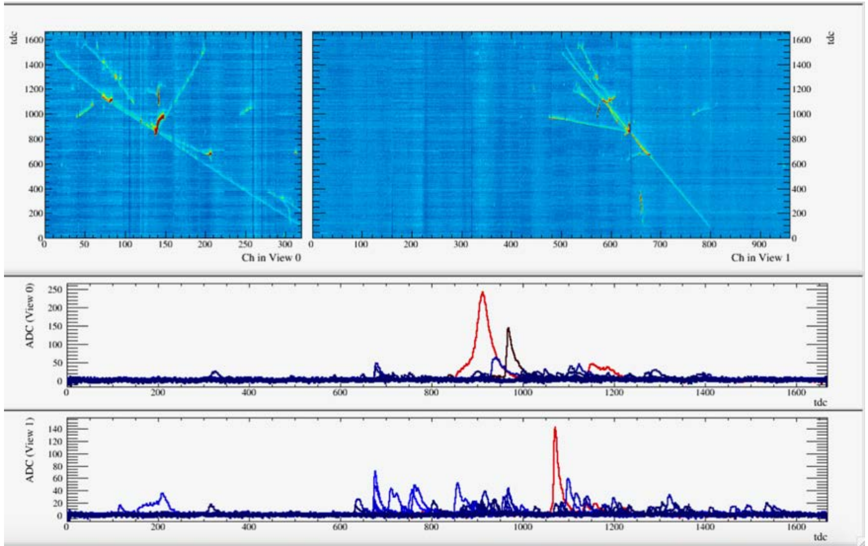


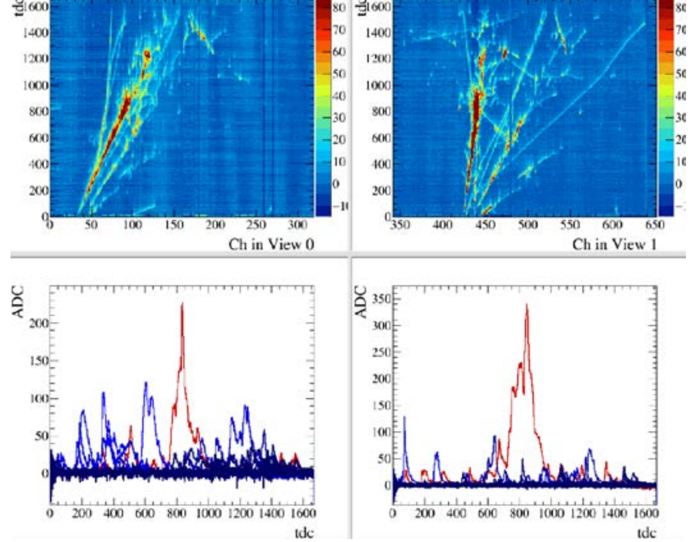


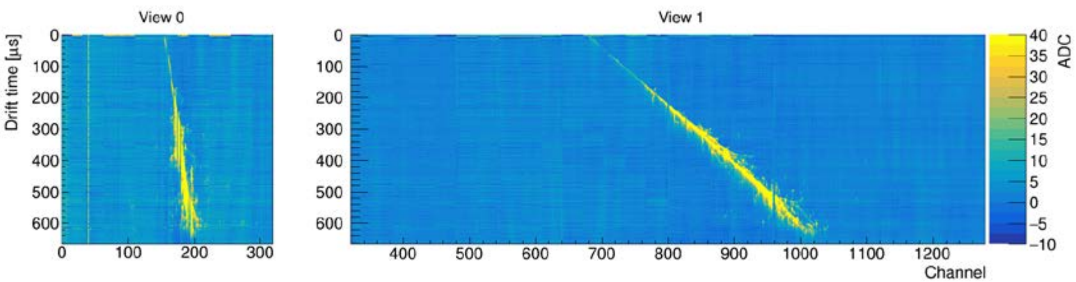
DAQ system of 3x1x1

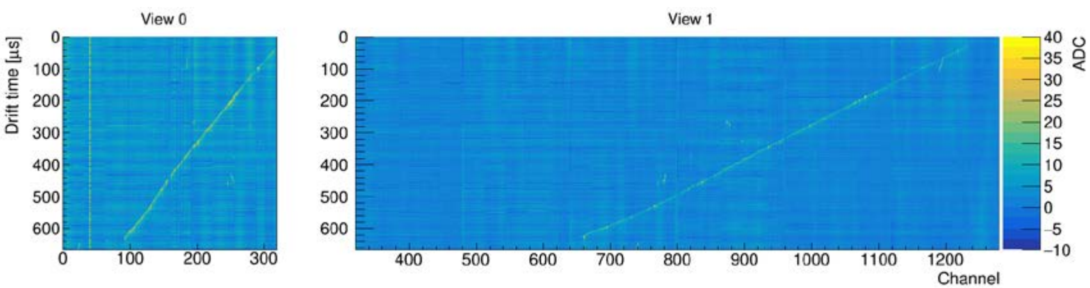


3x1x1 cosmic ray events:



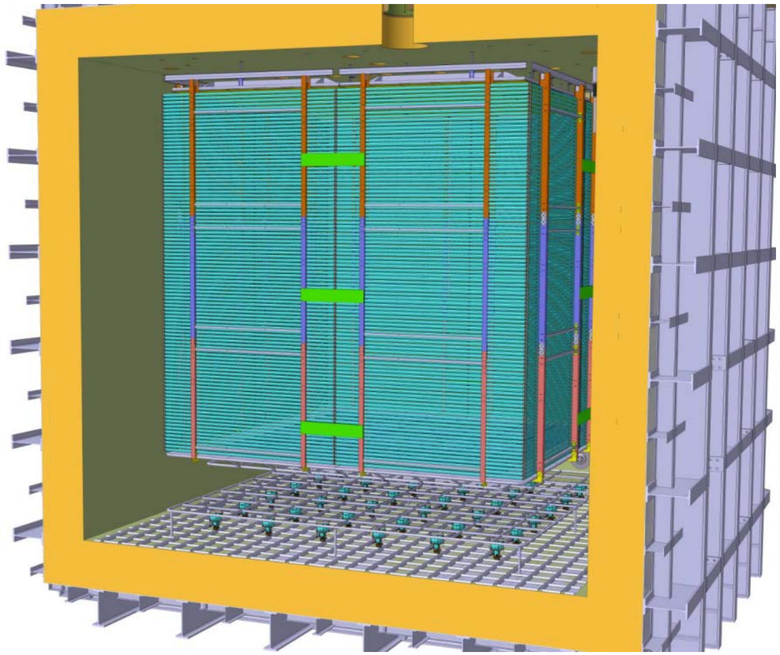






- Successful in proving the dual phase concept for a LArTPC at the 3m^2 readout scale.
- First application of complete electronics system, noise validation
- Detector working point limited by technical HV issues with the extraction grid
- LEM design improved for 6X6x6 (up to 3.5 kV stable operation)
- 60 pages paper recently submitted: https://arxiv.org/abs/1806.03317

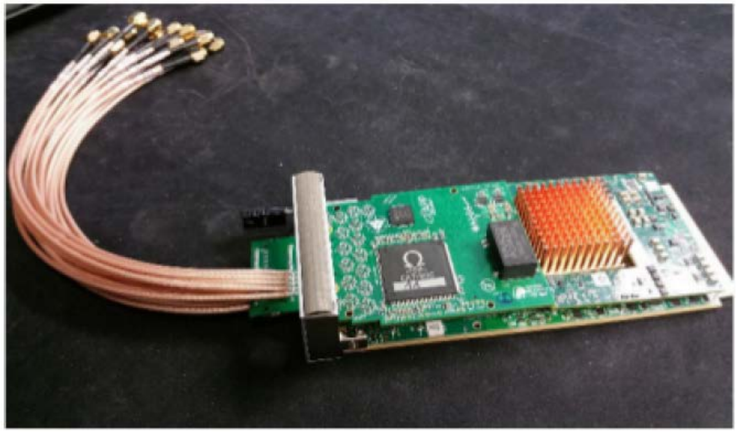
Electronics for the Light readout (APC-OMEGA-LAPP)



36 cryogenic photomultipliers Hamamatsu R5912-02mod at the bottom of the tank 1 PMT/1m^2
Assuming similar granularity → 720 PMTs for a 10 kton module

- Development (APC-OMEGA) of the trigger card mezzanine based on the PARISROC2 ASIC.

→ Mezzanine cards tested and produced



Finalization in progress of **uTCA light readout digitization boards** (APC+LAPP) based on Bittware S4AM kit (same card as used in the charge readout demonstrator made at IPNL in 2015),
→ 9 read channels/uTCA board, getting the timing information from WR and sending data to DAQ via uTCA network

- Foreseen for the 10 kton: full integration of trigger mezzanine card on final uTCA AMC card derived from the final charge readout

- Strong implications of IN2P3 groups in light readout analysis/simulations for 3x1x1, 6x6x6 and 10 kton.

Dual phase liquid argon TPC
$6x6x6\ m^3$ active volume
ProtoDUNE-DP at CERN

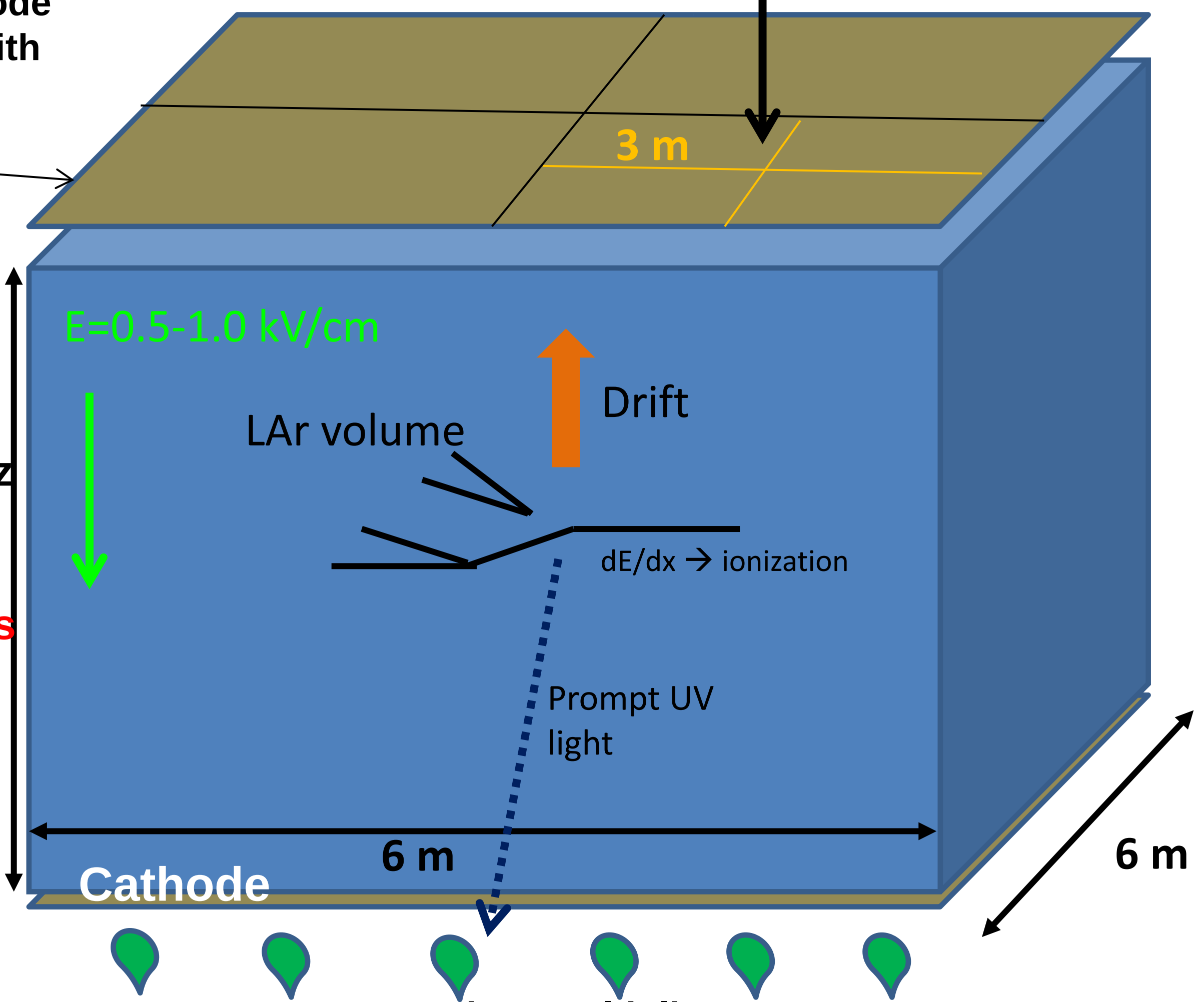
→ Event size: drift window of
7680 channels x 10000 samples ⇒ 146.8 MB

X and Y charge collection strips
3.125 mm pitch, 3 m long →7680 readout channels

Segmented anode in gas phase with dual phase amplification

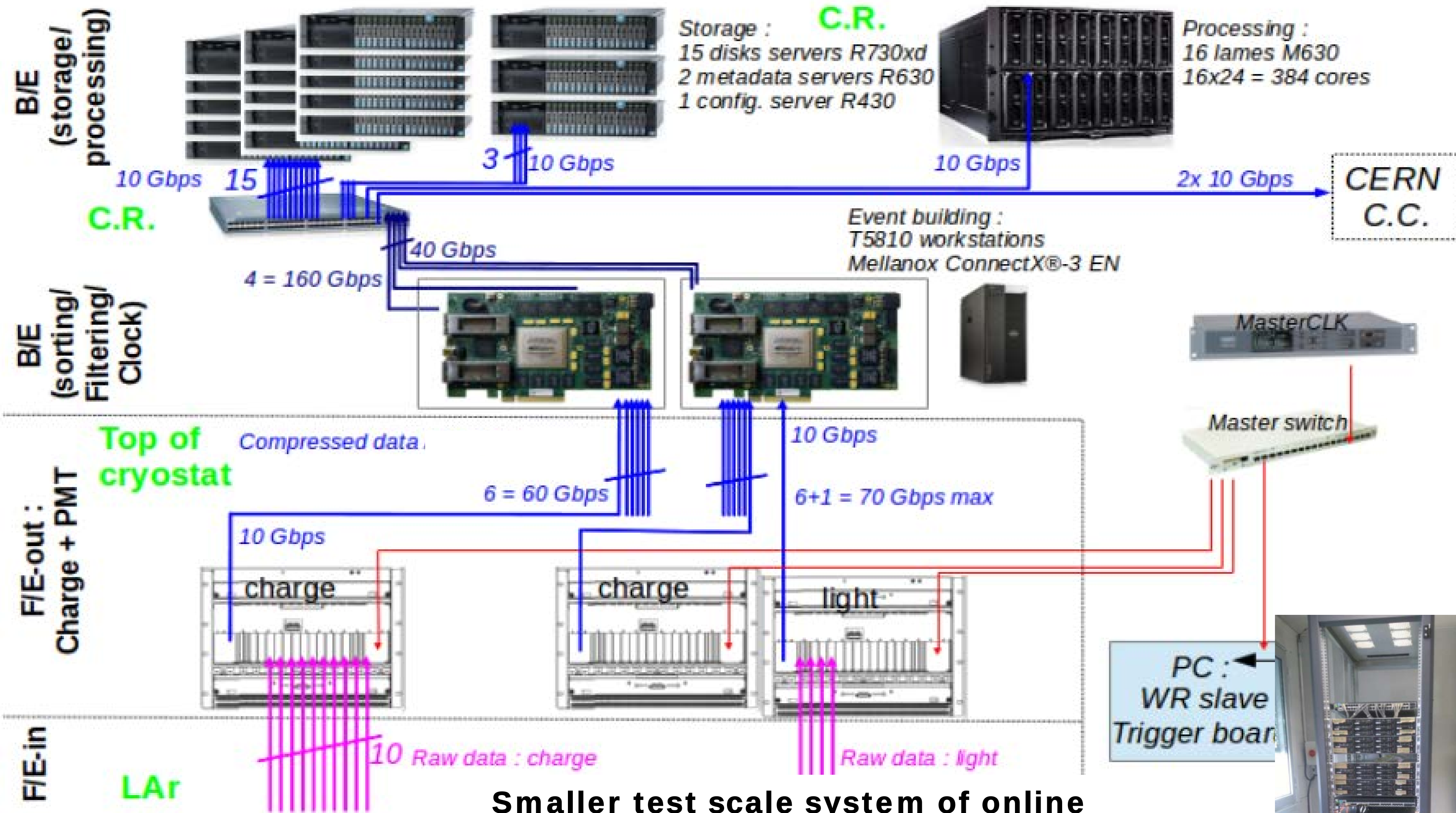
Drift coordinate
6 m = 4 ms
sampling 2.5 MHz (400 ns), 12 bits

→ 10000 samples per drift window



Photomultipliers

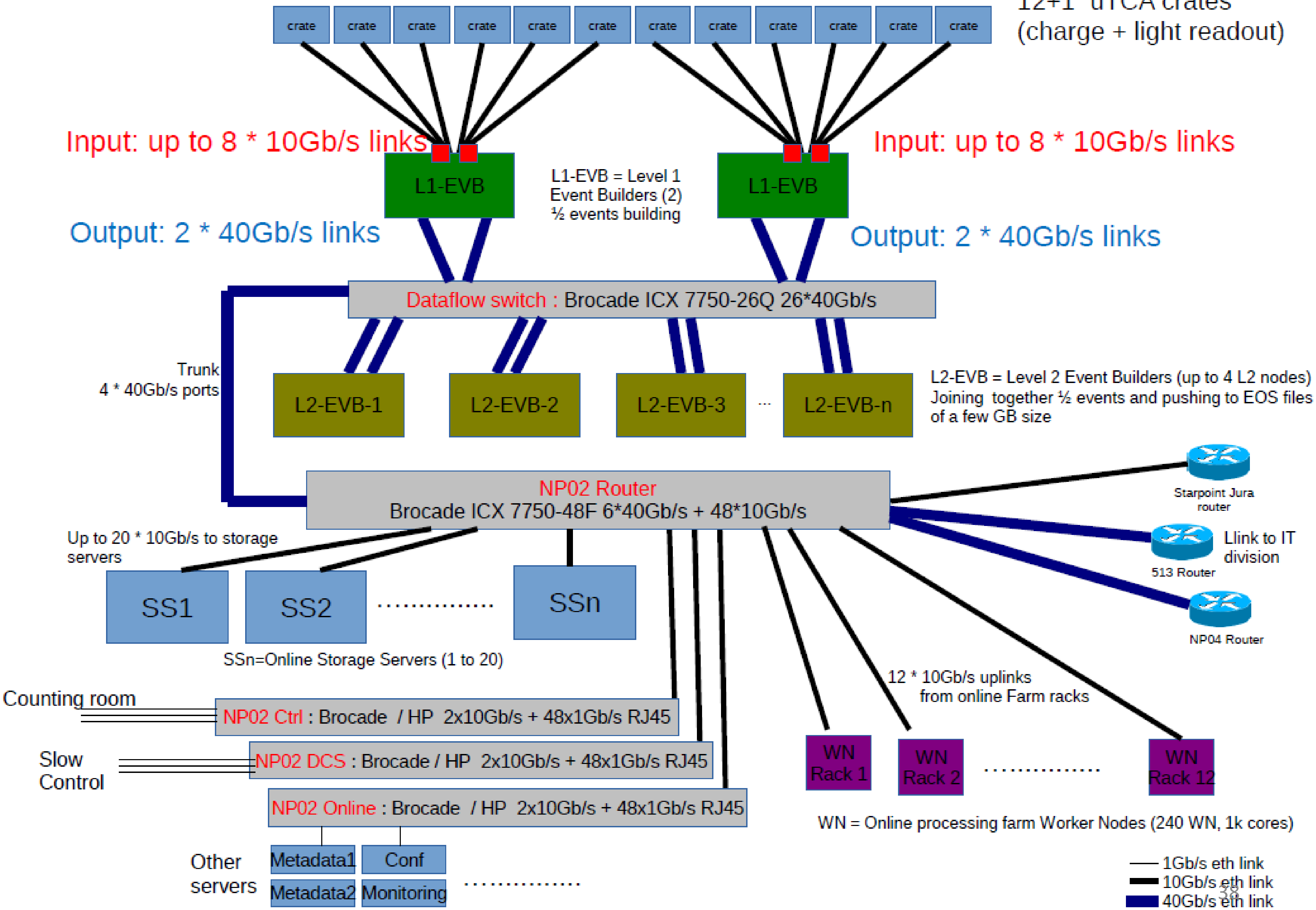
Online processing and storage facility: internal bandwidth 20 GB/s, 1 PB storage, 384 cores: key element for online analysis (removal of cosmics, purity, gain, events filtering)



Smaller test scale system of online storage/processing already installed and operative for 3x1x1 since last fall
→ Useful to perform tests to finalize the architecture of final online storage/processing facility.

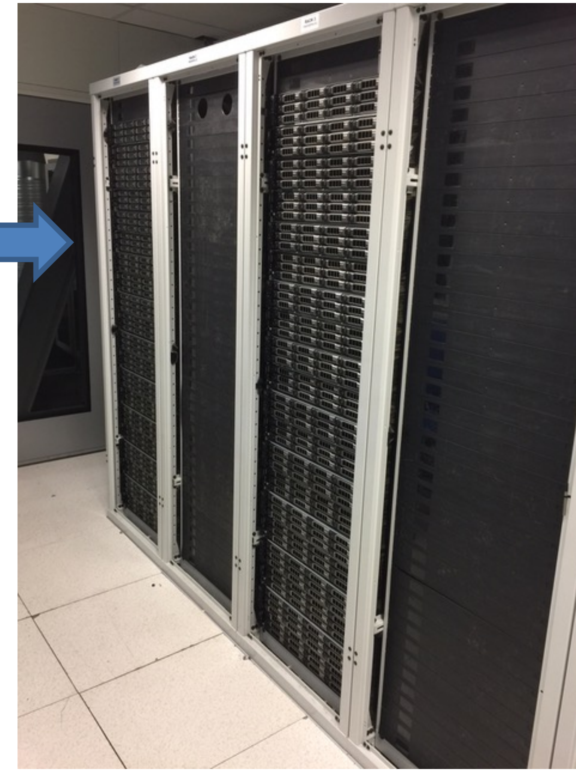
C.R. stands for Counting Room

Details of WA105 DAQ back-end network structure



- **High bandwidth (20GBytes/s) distributed EOS file system for the online storage facility**

→ Storage servers recovered from CCIN2P3: 20 machines + 5 spares, installed at CERN on September 10th (DELL R510, 72 TB per machine) : up to 1.44 PB total disk space for 20 machines, 10 Gbit/s connectivity for each storage server.



- **Infrastructure**: DAQ rooms (to host back-end nodes/storage servers), racks, cooling, power, counting rooms → made available by Neutrino Platform in Summer 2017
- **DAQ/online storage and processing facility network architecture:**

→ Designed in collaboration with Neutrino Platform and IT, Neutrino Platform procured the 40 Gbit/s DAQ switch and 10 Gbit/s router Network infrastructure (switches/routers). → installation completed by CERN by end of January 2018

- **Connectivity to central EOS storage at IT division:**

40 Gb/s link for ProtoDUNE-DP

- **Online computing farm:**

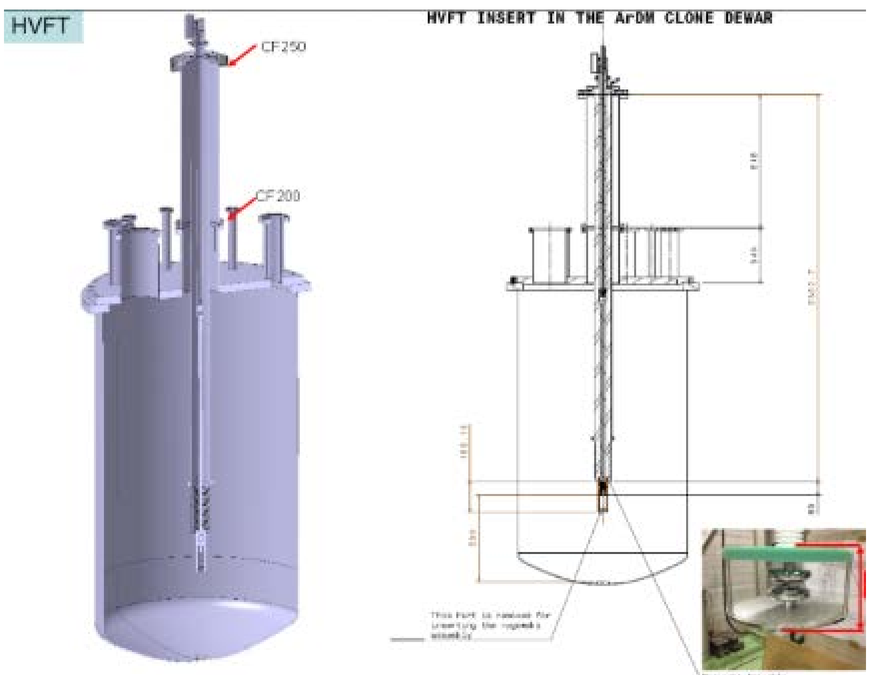
→ Procured by Neutrino Platform. ~1k cores installed in June in a dedicated room at EHN1 12 racks, 10 Gbit/s connectivity per rack

High voltage system for the drift field:

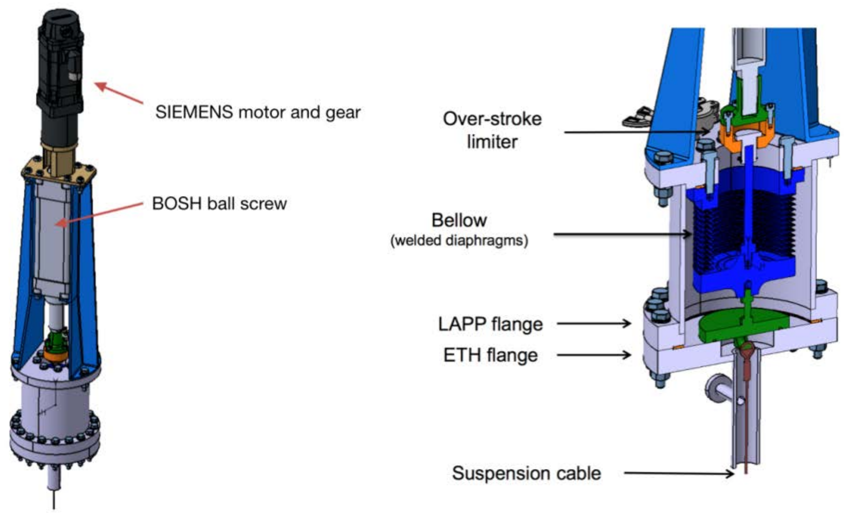
- 300 KV HV power supply already available
- HV feedthrough (with LPHNE contribution) already built and tested (nominal field of 6x6x6) at 300 kV in a dedicated LAr cryostat and deployed on 3x1x1 detector where it operated at lower field
- The achievement of 300 kV was an important milestone and world record.
- HV feedthrough design compatible with 600 kV, working on the power supply coupling

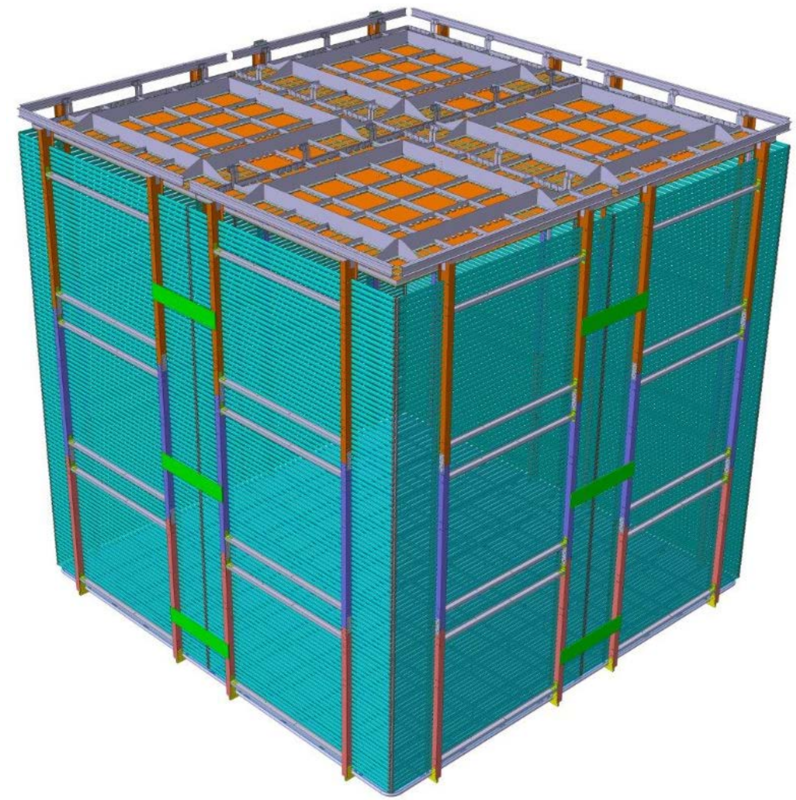
HV feedthrough→

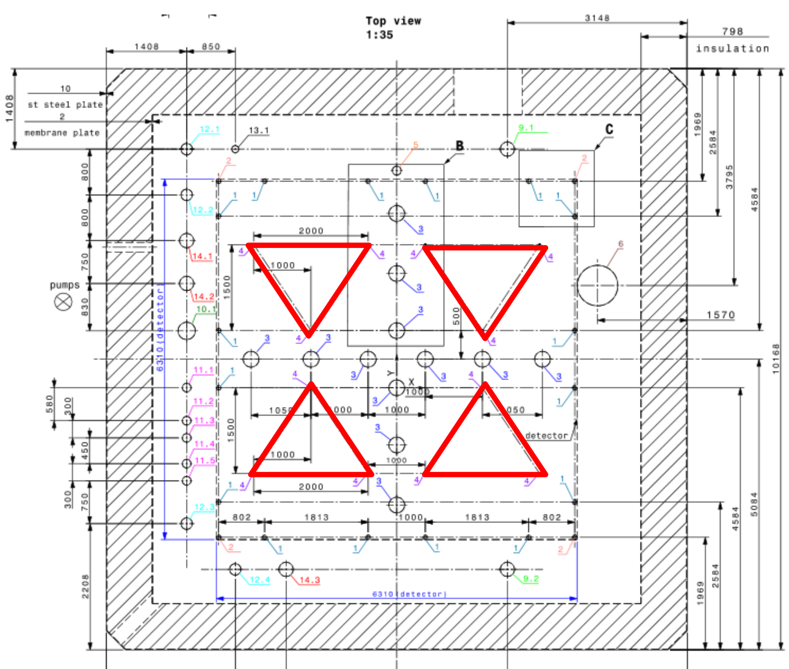
Test setup of HV feedthrough



Charge Readout Plane (CRP) suspension system and frame design (LAPP)





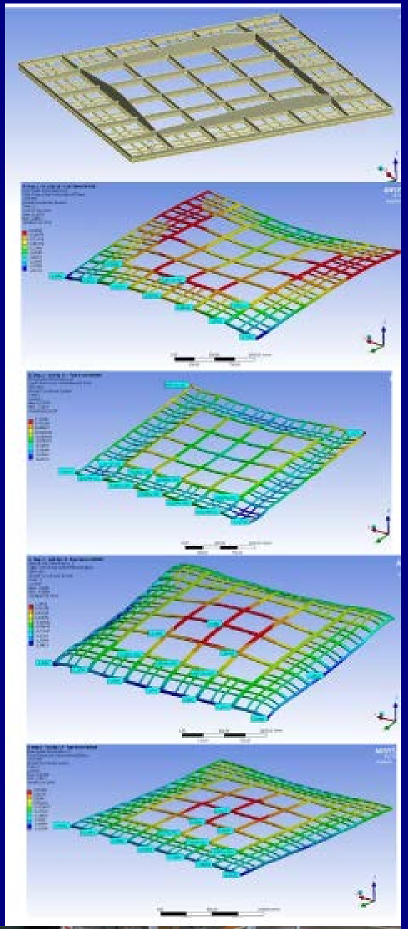


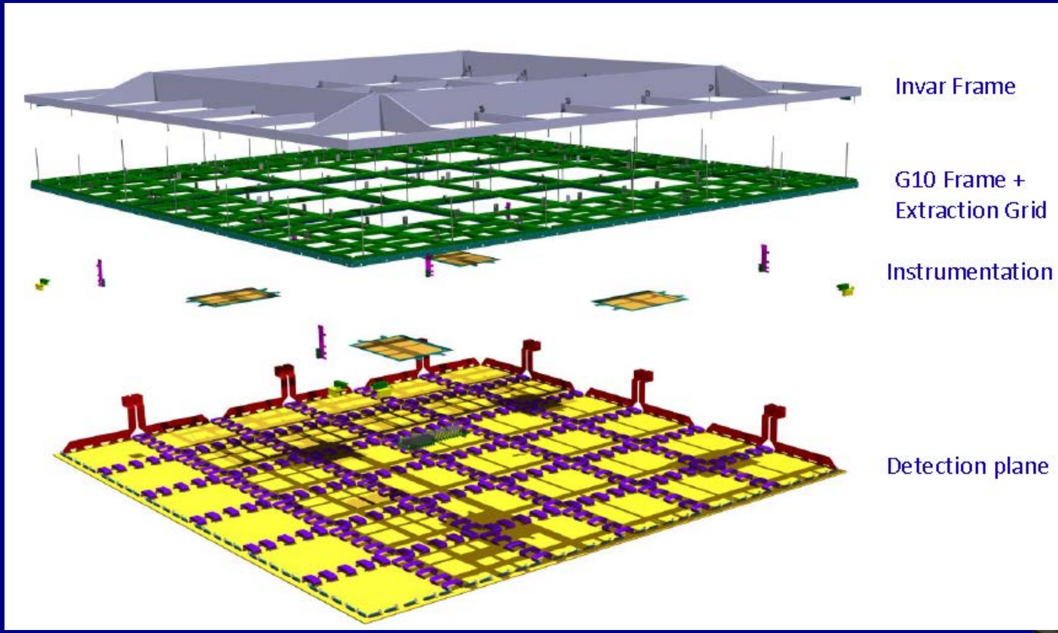
CRP hanging system feedthrough and motorization (subsample already operative on 3x1x1 for its CRP hanging) for adjustment of LEM readout plane with respect to the LAr level

← 3 suspension points per CRP

3x3 m² CRPs integrating the LEM-anode sandwiches (50x50 cm²) and their suspension feedthroughs (CRP specific to dual-phase technology: critical item)

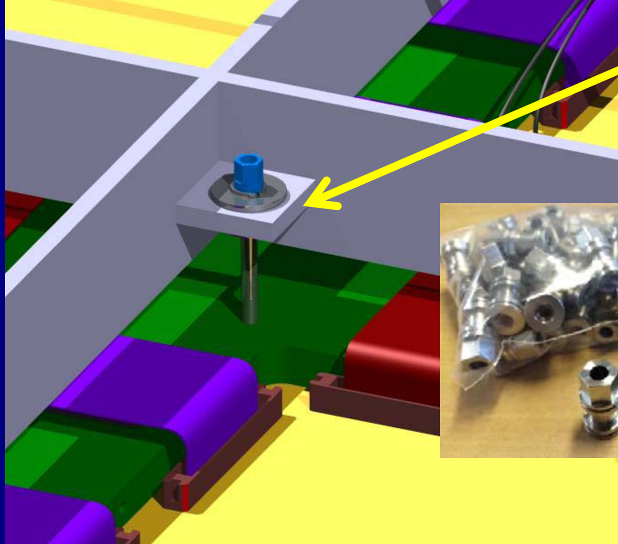
→ Invar frame + decoupling mechanisms in assembly in order to ensure planarity conditions +-0.5 mm (gravity, temperature gradient) over the 3x3 m² surface which incorporates composite materials and ensure minimal dead space in between CRPs



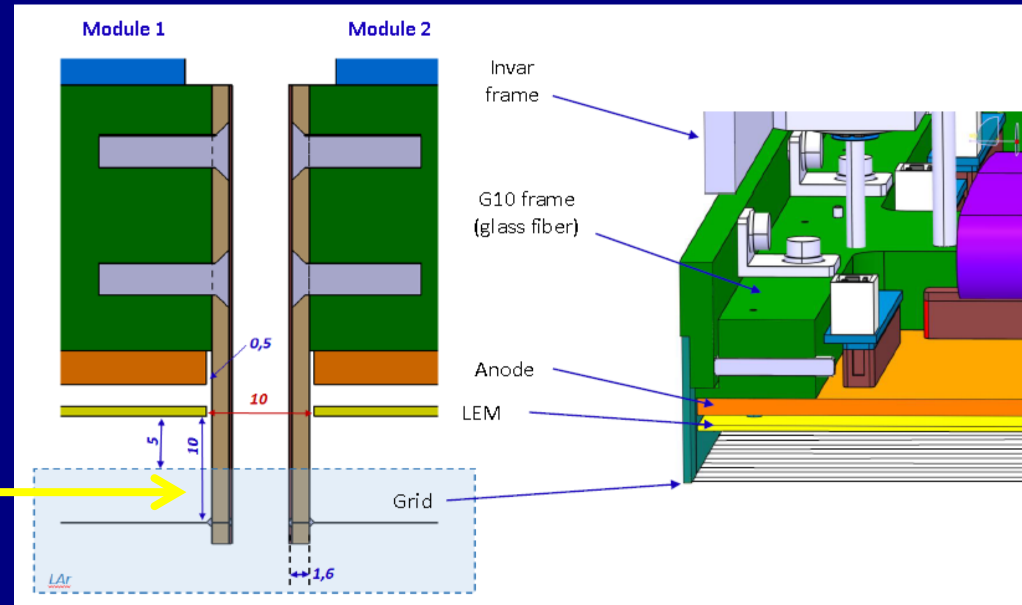


CRP mechanical structure design:

→ campaign of cold bath tests + photogrammetry on differential effects in thermal contraction, design of decoupling mechanism

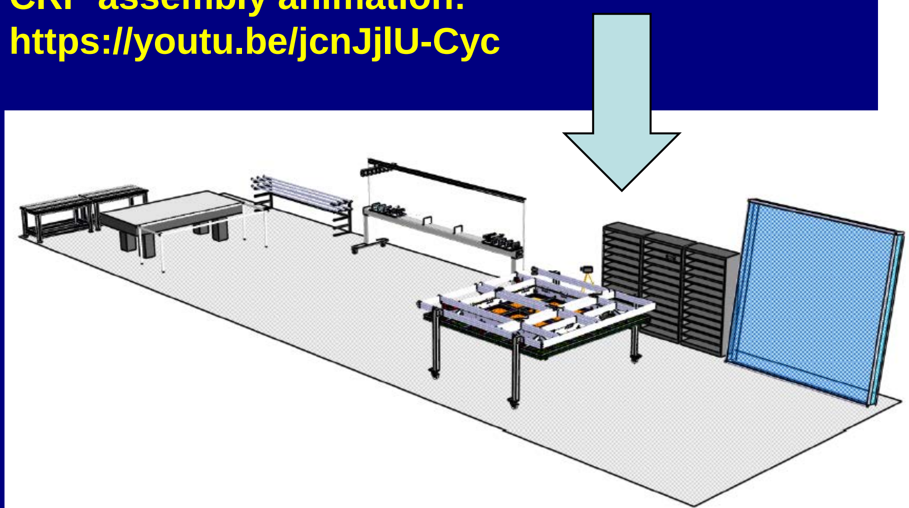


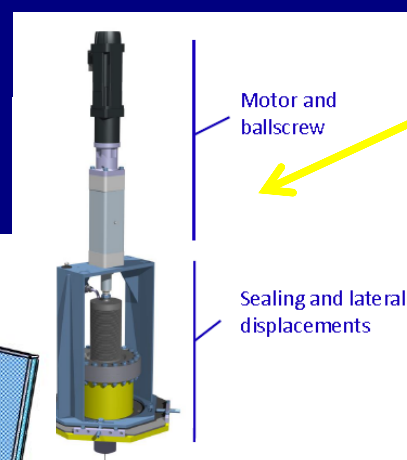
Thermal decoupling supports of G10 frame on invar frame



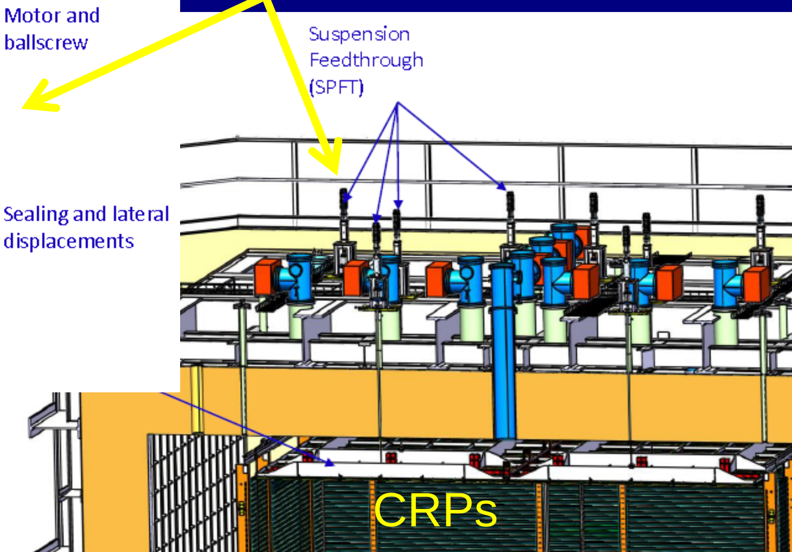
Integration of the grid of submerged extraction wires in the frame minimizing dead space in between CRPs. Tests for the wires system design

Tooling, assembly and installation procedures defined, Hall 185 equipment → CRP assembly animation: https://youtu.be/jcnJjlU-Cyc

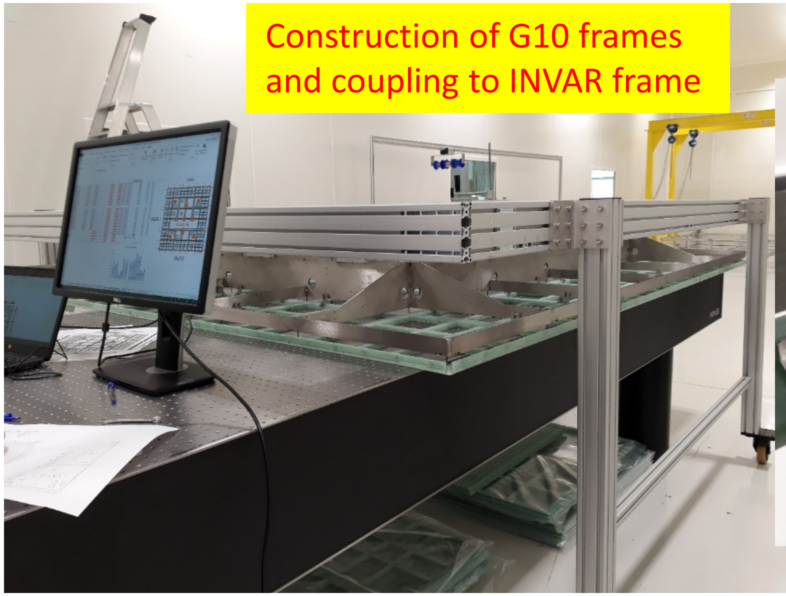




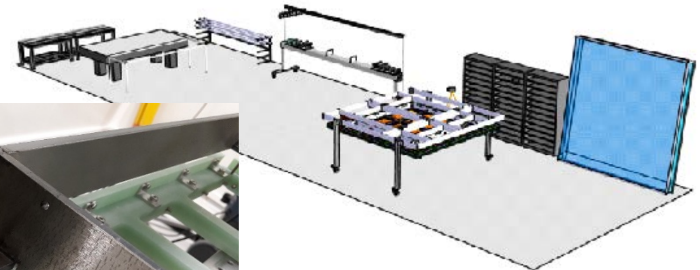
Suspension feedthroughs



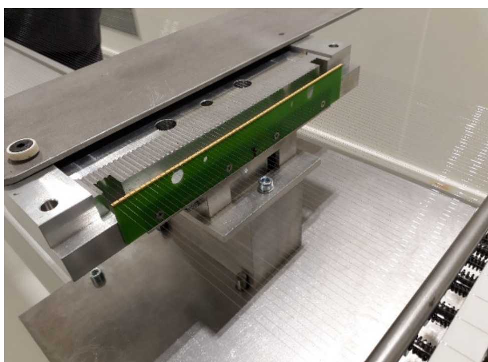
Charge Readout Planes assembled in the clean room in Hall 185 and then moved to the cold box test in Hall 182 and to the cryostat clean room buffer to EHN1



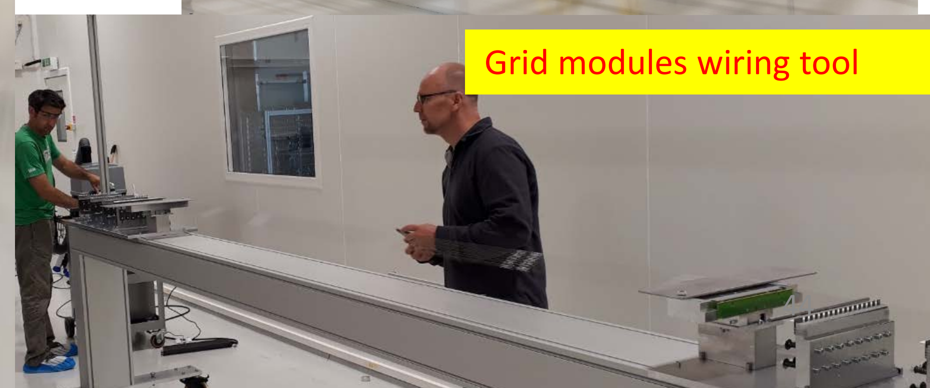
Construction of G10 frames and coupling to INVAR frame



One of the 50 decoupling supports

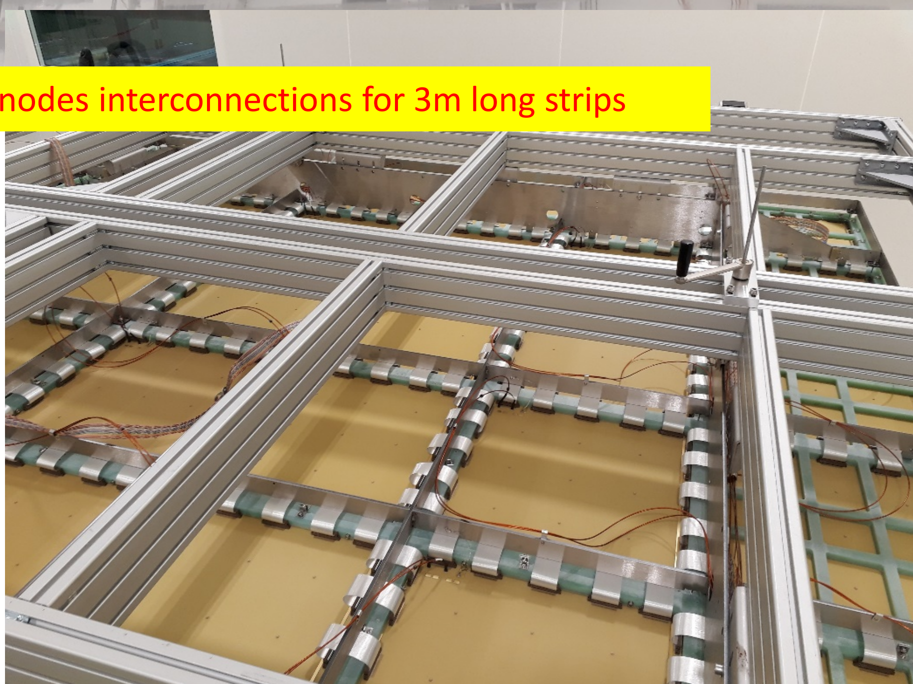


Grid module fabrication and storage

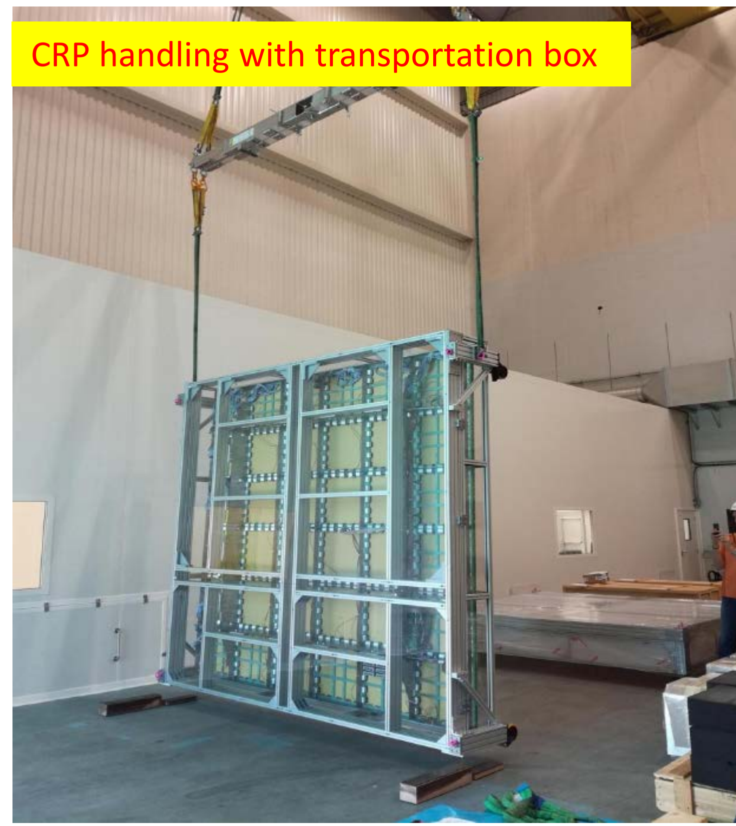


Grid modules wiring tool

CRP with LEM/anodes mounted during grid modules integration

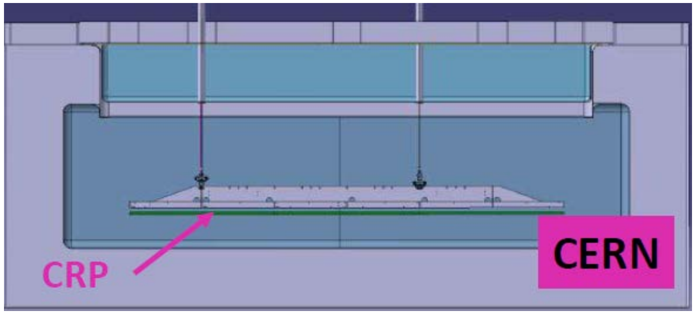


Anodes interconnections for 3m long strips



CRP handling with transportation box

CRP Cold Box test in Hall 182



→ ***Perform electrical and mechanical tests of each final CRP in nominal thermodynamic conditions:***

- Characterization of the HV operation of each LEM
- Characterization of the HV operation of the extraction grid
- CRP planarity test
- Test the tensioning of the extraction grid wires
- Test of the HV contacts and connections (LEM & grid)

First produced Charge Readout Plane inserted in the Cold Box on June 22nd and currently under test

- French collaboration growing. LAL recently joined

- Additional strong interest in contributing to the beam-line (IPNO, CEA/Irfu, LAL)

- Envisaged contributions to 10kton modules construction in the framework of the Far Detector Consortia (x20 productions/constructions performed for protoDUNE-DP) in line with the continuation of the protoDUNE-DP activities on a 10 kton module:

  - FE cryogenic electronics for charge readout
  - Digital electronics for charge and light digitization and readout based on integrated uTCA design and time distribution system
  - Signal feedthrough chimneys mechanics
  - Charge Readout Planes mechanics and motorization
  - LEM and anodes production (CEA/Irfu)
  - Groups involved on the digital electronics have also a strong commitment in the DAQ consortium in order to interface the FE electronics and contribute to the DAQ development. The DAQ consortium will organize the DP back-end to handle the very large data flow from FE in order to digest and analyze it on real time and issue global triggers for beam events, cosmic events + proton decay and SN burst events (DAQ is a big challenge)

- Structuring in view of IR project (DUNE was added to IR/TGIR roadmap in March 2018)

- In addition to hardware contributions we naturally had a long date strong involvement in Physics and Computing activities (details in the CSI report)

Current and envisaged physics contributions:

- Neutrino oscillations analysis (search for CP violation and determination of the mass hierarchy) and related systematics:
  - Neutrino interactions cross sections
  - Electron identification and π^0 background rejection
  - Events reconstruction (LarSoft/Pandora)
  - Neutrino energy measurement and nuclear effects
  - ν_τ CC background

- Light readout analysis/simulations

- 3 neutrinos phenomenology
  - ν_τ CC analysis, development of 3 flavors measurements/constraints

- Proton decay:
  - Events reconstruction and particles identification, nuclear effects

- n-nbar oscillations
  - Events reconstruction, nuclear effects

- SNa neutrinos:
  - Exploitation of dual-phase potential at low energy, online events selection, nuclear effects

- Most of these contributions are also developed in synergy with the French theorists, for instance on nuclear effects (for many topics) and n-nbar oscillations.

- 3 thesis in progress: A. Scarpelli (APC), T. Kock (IPNL), A. Chappuis (LAPP)

Computing

(more details in the CSI report):

- Already intensive activity to organize the online and offline computing for ProtoDUNE dual-phase in collaboration with CCINP3

- A. Pennacchio dual-phase computing liaison with FNAL and CERN

- Natural involvement in DAQ online computing activities for the 10 kton, preparation to handle a data volume of about 3PB/year (for two modules SP+DP)

- Support activities to analysis contributions within DUNE being organized with CCIN2P3 (already well supporting DUNE activities for ProtoDUNE) in a DUNE FD computing project. Possible contributions:

- CCIN2P3 as Tier-1 to host the raw data, and assure their reprocessing.
- CCIN2P3 can also be a Tier-2 center
- Contributions to massive Monte Carlo productions
- Working environment (as it is already happening) for collaborators to allow code development and data analysis
- Support to hardware/ production/ calibration databases connected to construction activities

Conclusions:

- DUNE is going to be the “ultimate” neutrino oscillations experiment based on conventional neutrino beam with world wide collaboration. It has unique capabilities relying on the spectral information, detailed reconstruction of final states, sensitivity to to ν_e and ν_τ appearance, precision measurements, 3 flavors phenomenology validation. It also offers a rich secondary physics program

- The IN2P3 groups have a long-standing involvement in the physics program explored by DUNE and in the related detector developments, first with the LAGUNA-LBNO design study and then within DUNE. This has been a long term investment.

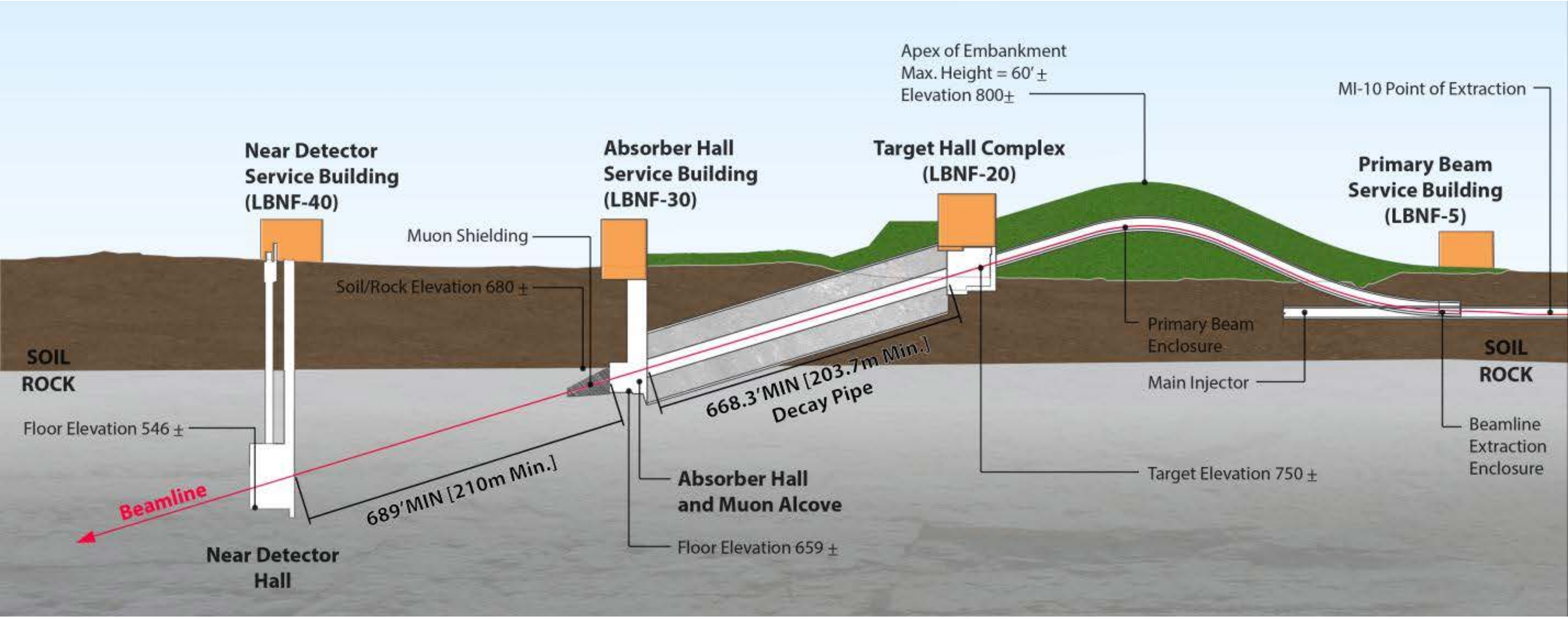
- They have contributed to DUNE since its birth, they are providing important contributions to ProtoDUNE-DP and they are fully integrated in the current DUNE activities and organization and Far Consortia leadership

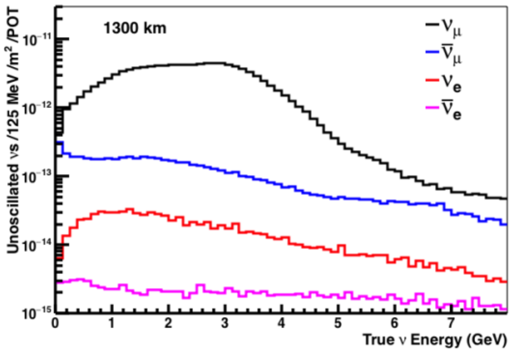
- We are completing the efforts on ProtoDUNE-dual phase in view of its running since the end of 2018 and after the editing of the Technical Proposal (Interim Design Report) we are completing the TDR

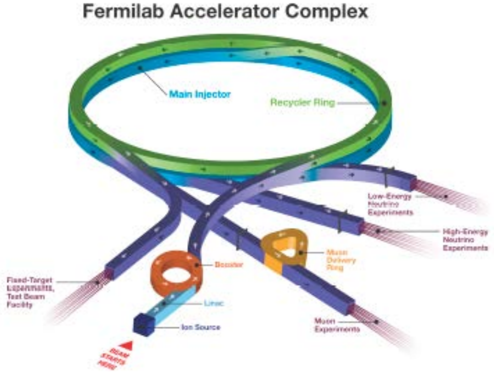
- We are looking forward, on building up on the current expertise and involvement, to providing hardware contributions to the DUNE FD within the already integrated consortia activities

- We have strong interests in providing as well strong contributions to the physics (CP violation/mass hierarchy analysis and systematic, neutrino interactions cross section, reconstruction and energy measurements, tau detection, light readout analysis, proton decay, supernova neutrinos, n-nbar oscillations and to the computing activities in collaboration with CCIN2P3

Long Baseline Neutrino Facility - LBNF



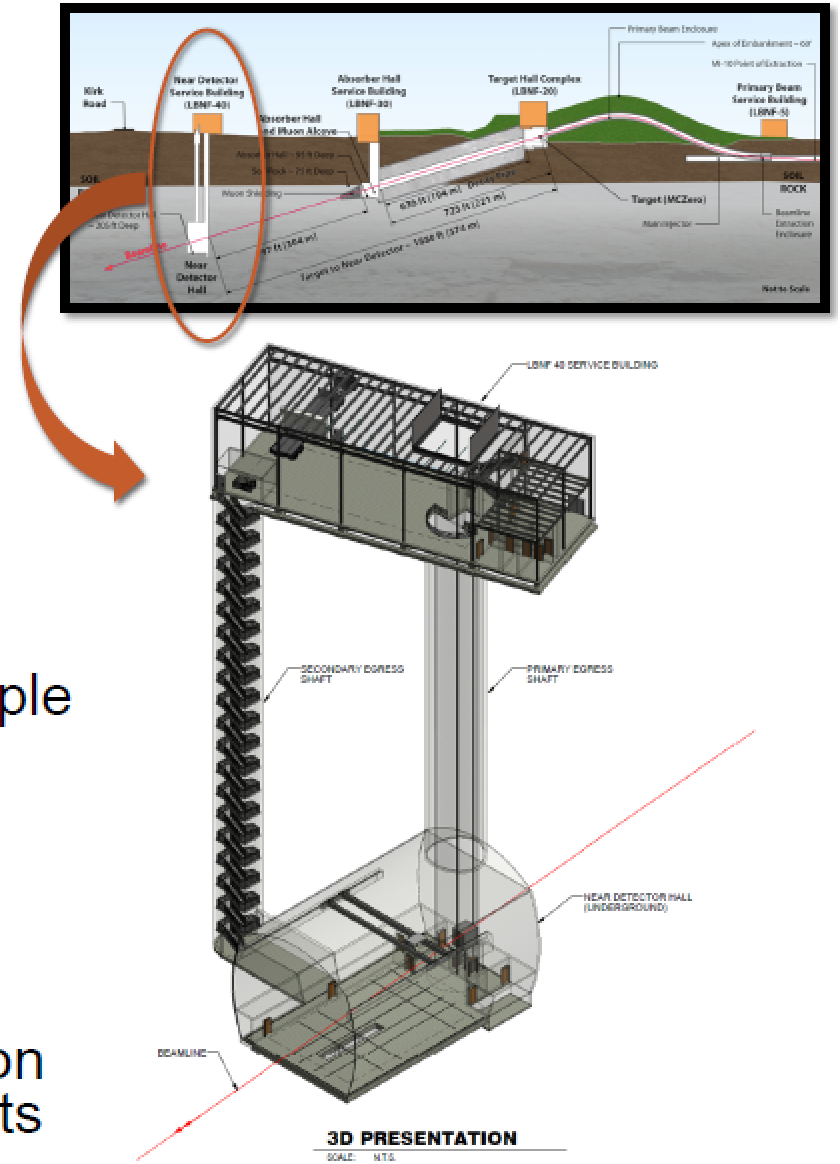




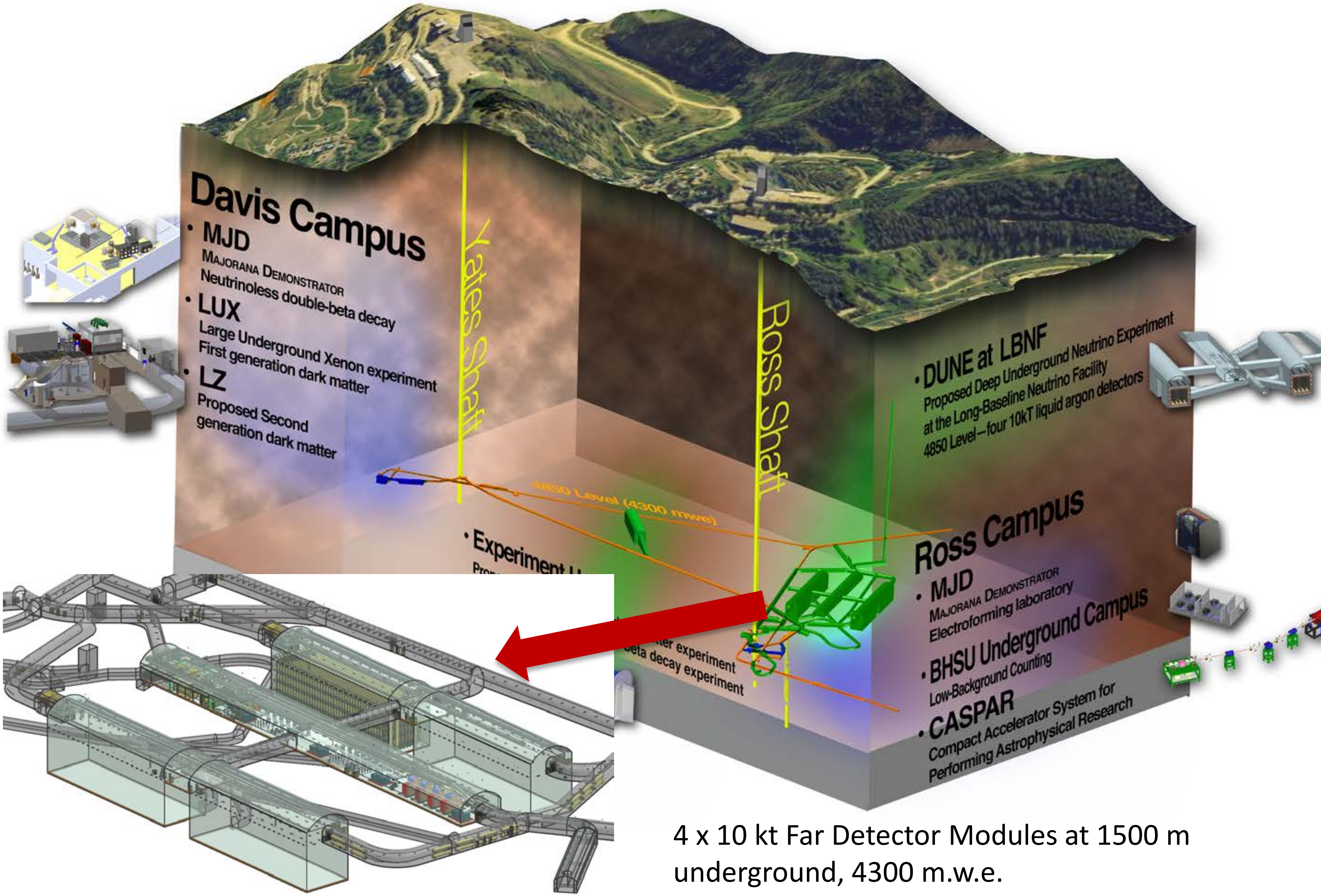
- 60 – 120 GeV protons
- Horn-focused neutrino beam line optimized for CP violation
- sensitivity using genetic algorithm
- Neutrino and Anti-neutrino running
- Initially 1.2 MW with 80 GeV protons
- Upgrade to 2.4 MW in ≈ 2033

DUNE Near Detector

- Primary purpose is to **constrain systematic uncertainty** for long-baseline oscillation analysis
  - Constrain flux, cross-section, and detector uncertainties
- DUNE ND design concept near final
  - Active ND Design Group
  - ND Conceptual Design Report (CDR) planned for 2019
- DUNE ND design concept is an integrated system composed of multiple detectors:
  - Highly segmented LArTPC
  - Magnetized multi-purpose tracker
  - Electromagnetic calorimeter
  - Muon chambers
- Conceptual design will preserve option to move ND for off-axis measurements



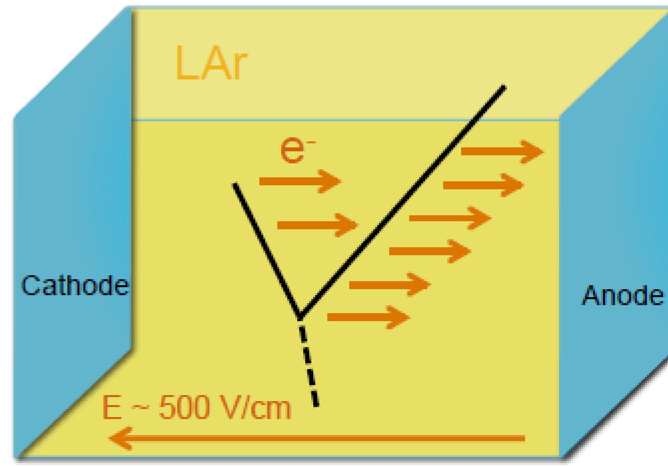
Sandford Underground Research Facility - SURF



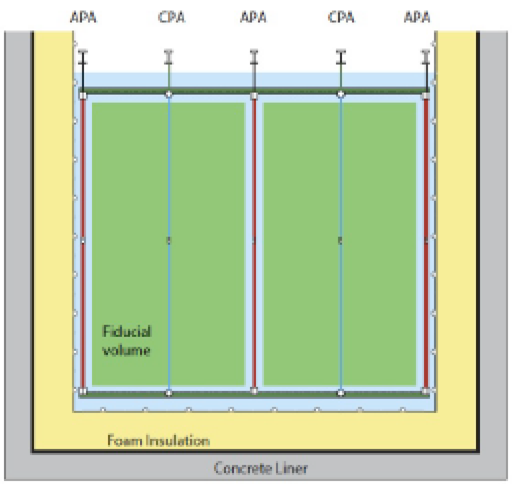
4 x 10 kt Far Detector Modules at 1500 m underground, 4300 m.w.e.

DUNE Far Detector

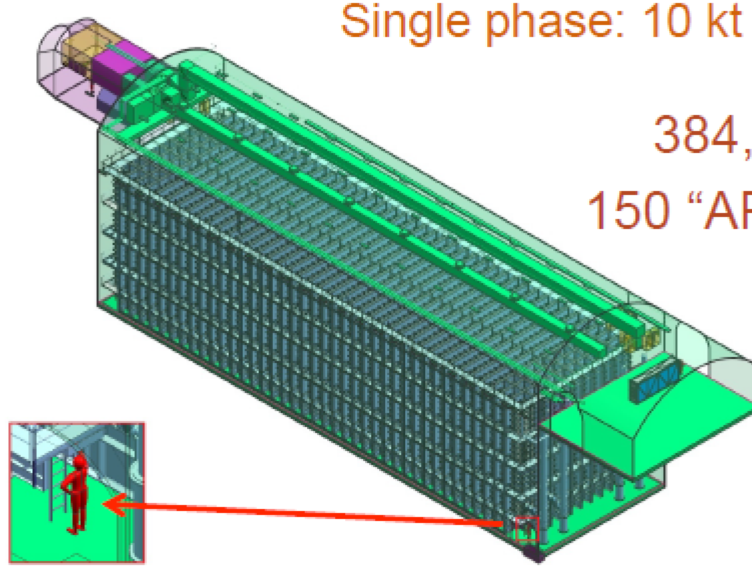
- 4 10-kt (fiducial) liquid argon TPC modules
- **Single-** and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical



Single phase: modular wire-plane readout



Single phase: 10 kt module



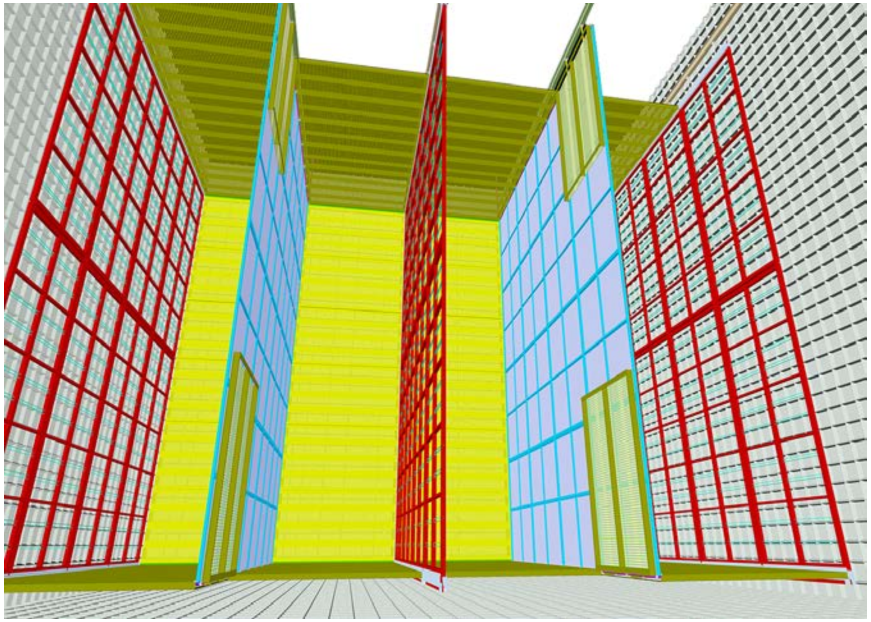
384,000 readout wires

150 “APAs” (2.3 m x 6 m)

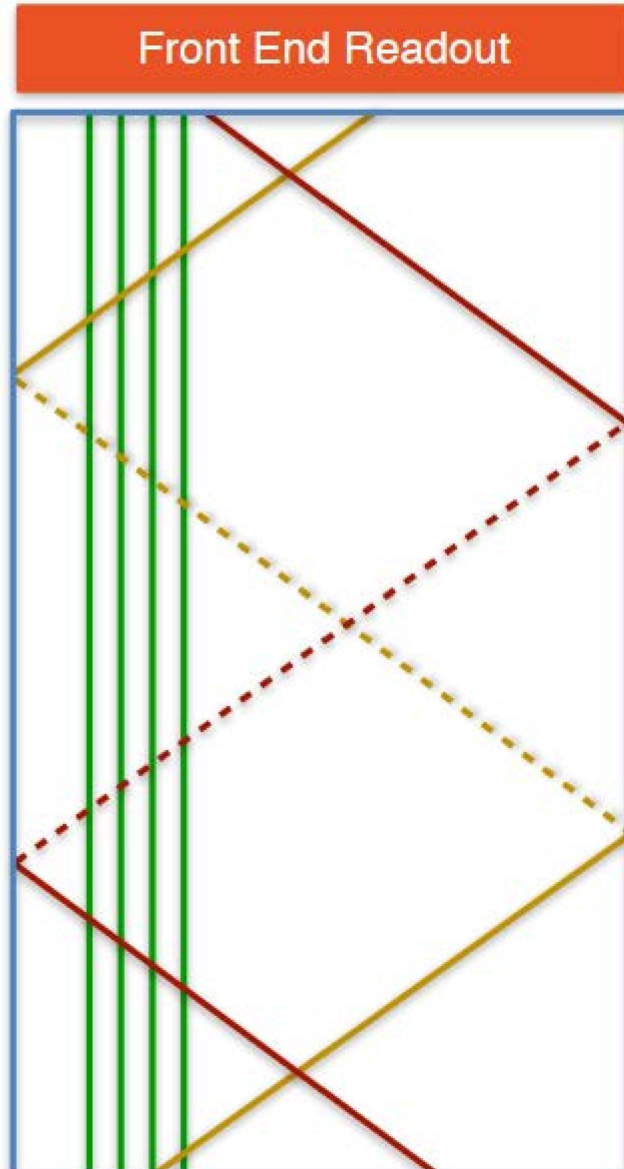
12 m high

15.5 m wide

58 m long

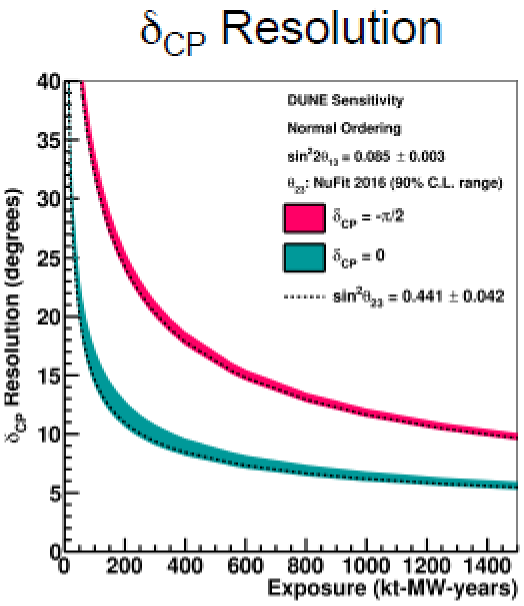


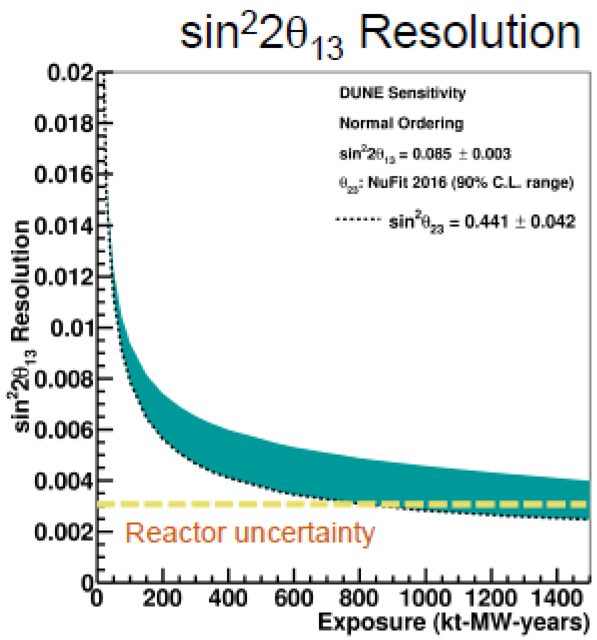
- Anode wires immersed in LAr
- Anode and Cathode Plane Assemblies (APA, CPA) suspended from cryostat roof
- Drift distance: 3.6 m, wire pitch: 5 mm
- 1 collection view + 2 induction views +-37.7° wrapped around APA to spare the number of channels
- 384,000 readout wires, 150 APA's
- 12 m high, 15.5 m wide, 58 m long
- Photon detectors: light guides+SiPMs, embedded in APAs

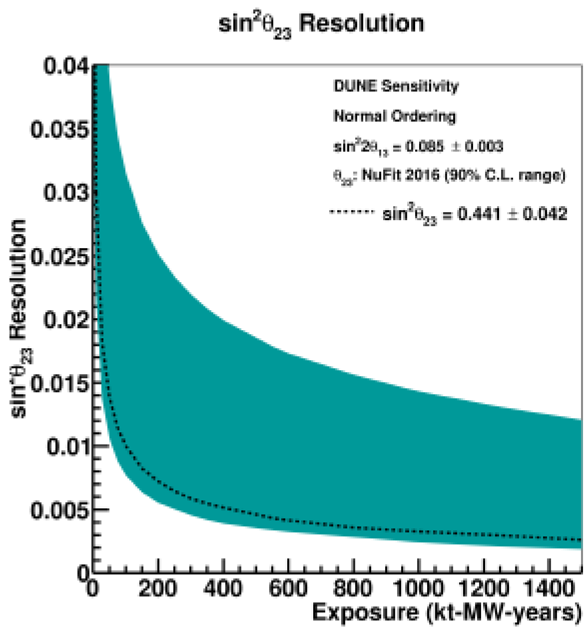


Oscillation Parameter Sensitivity

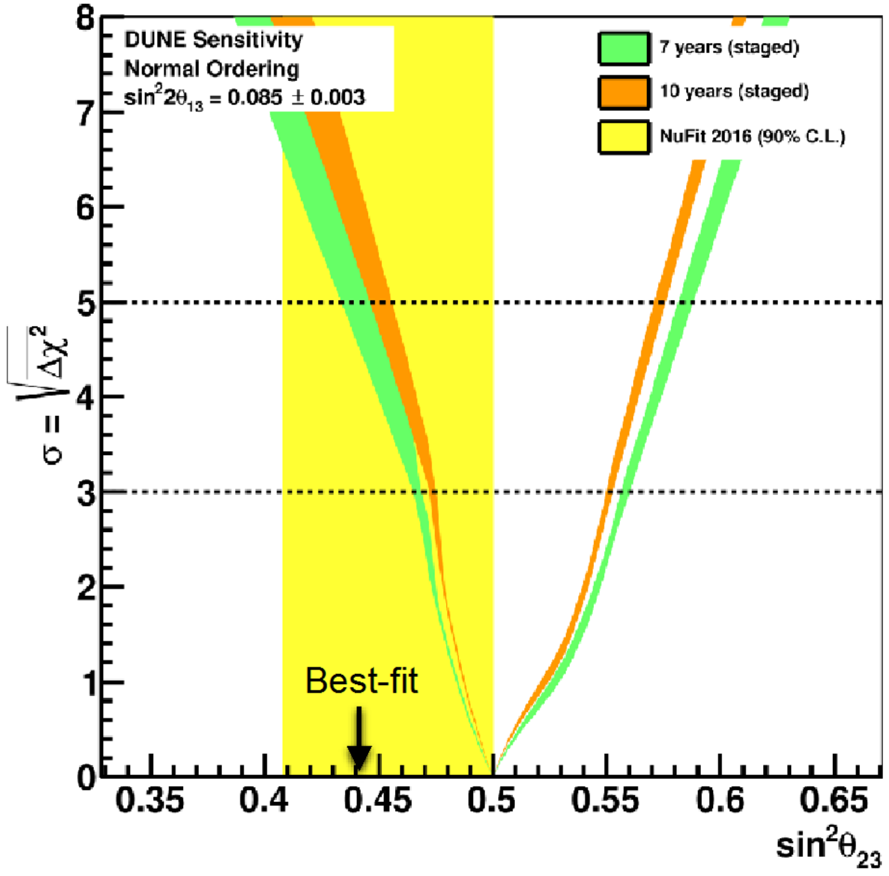
DUNE CDR:







Sensitivity to θ_{23} octant



DUNE CDR Systematics

- Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using signal and background normalization uncertainties.

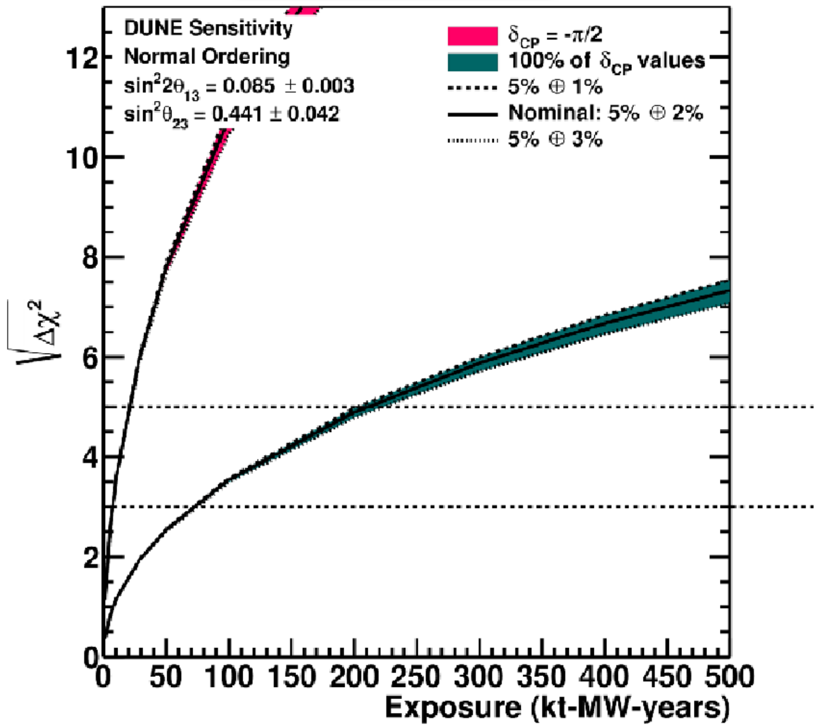
  Spectral uncertainty not included in this treatment.

- Signal normalization uncertainties are treated as *uncorrelated* among the modes (ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$) and represent the residual uncertainty expected after constraints from the near detector and the four-sample fit are applied.
  - $\nu_\mu = \bar{\nu}_\mu = 5\%$ → Flux uncertainty after ND constraint
  - $\nu_e = \bar{\nu}_e = 2\%$ → Residual uncertainty after ν_μ and $\nu/\bar{\nu}$ constraint
- Oscillation parameter central values and uncertainties are taken from NuFit 2016 (arXiv:1611.01514). Parameters are allowed to vary constrained by 1/6 of the $\pm 3\sigma$ range in the global fit.

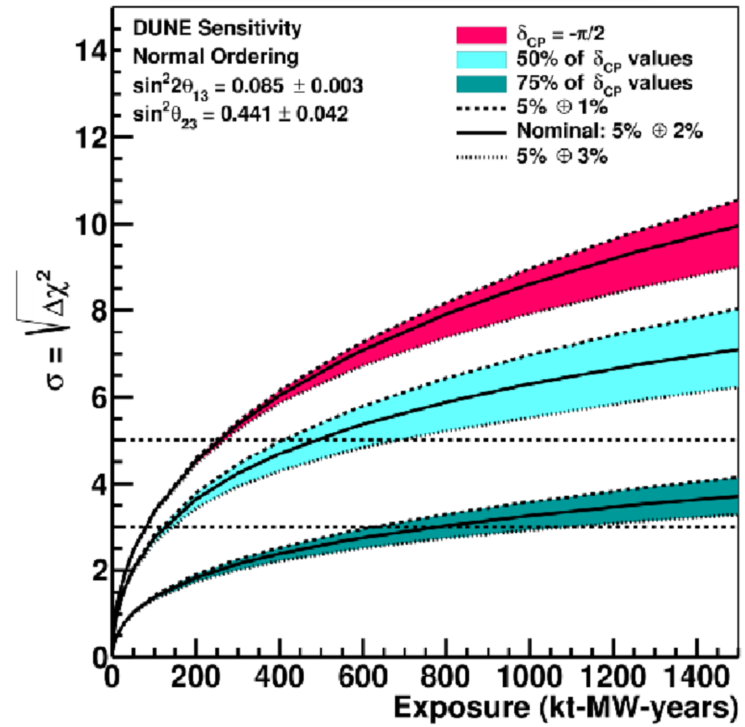
Effect of systematic uncertainties

- Width of sensitivity bands: 1-3% ν_e signal normalisation uncertainty
- Small impact on MH. For CP, important to keep uncertainty at ⎕2%

MH Sensitiivity

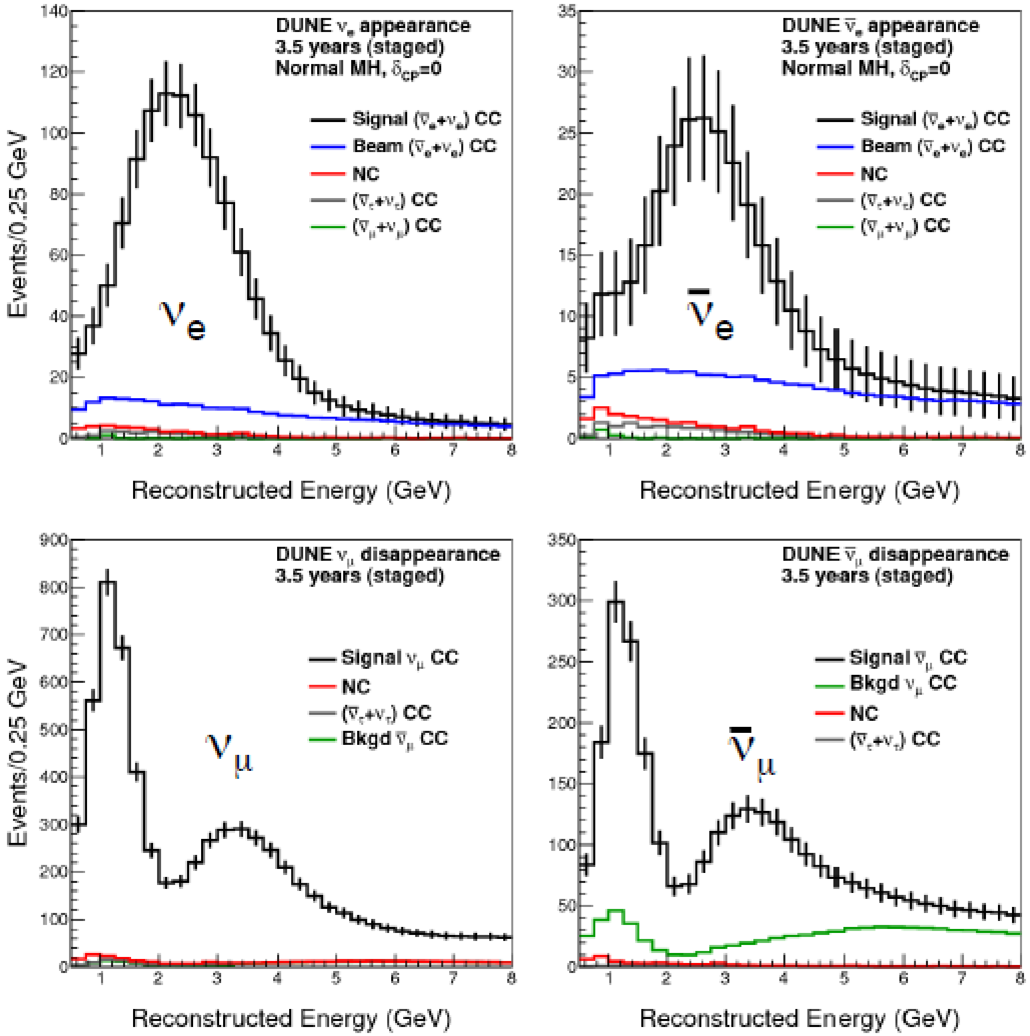


CP Violation Sensitiivity



Oscillation Sensitivity Calculations

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148



- 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
- 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
- GLoBES configurations arXiv:1606.09550

Automated reconstruction

- GEANT4 beam simulation of updated beam design
- Full LArSoft Monte Carlo simulation
  - Shared framework among many LArTPC experiments
  - GENIE event generator
  - GEANT4 particle propagation
  - Detector readout simulation including realistic waveforms and white noise
- Automated signal processing and hit finding
- Automated energy reconstruction
  - Muon momentum from range (contained) or multiple Coulomb scattering (exiting)
  - Electron and hadron energy from calorimetry
- Event selection using convolutional visual network (CVN)
- Oscillation analysis using CAFAna fitting framework
  - Shared framework with NOvA
- CDR-style systematics analysis (update coming in 2019)
- Results shown here are for single phase; dual phase analysis in progress