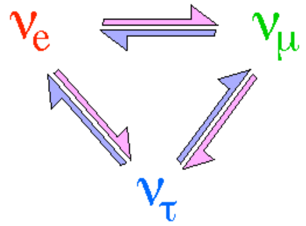
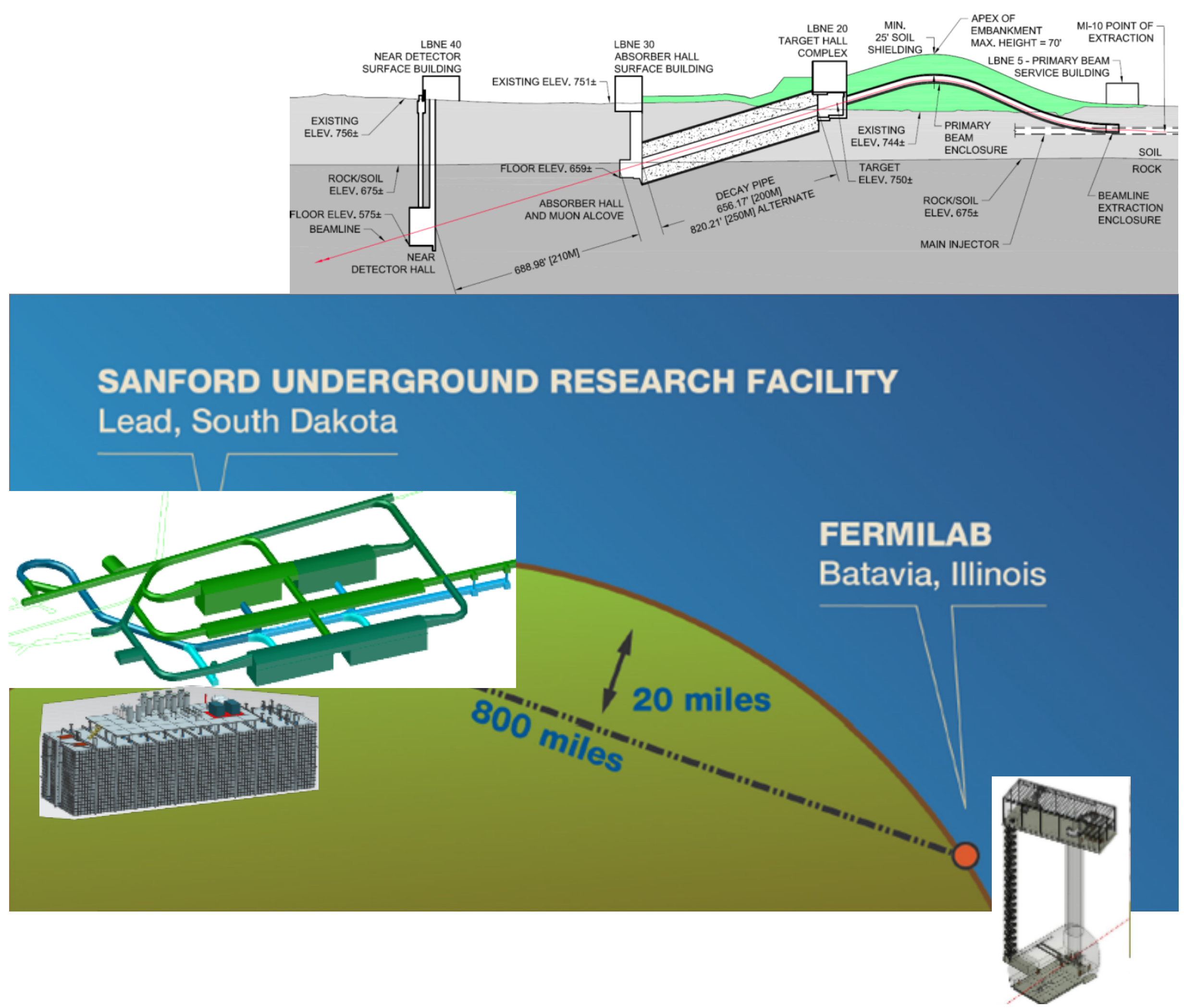


News from DUNE/LBNF

André Rubbia (ETH Zürich)



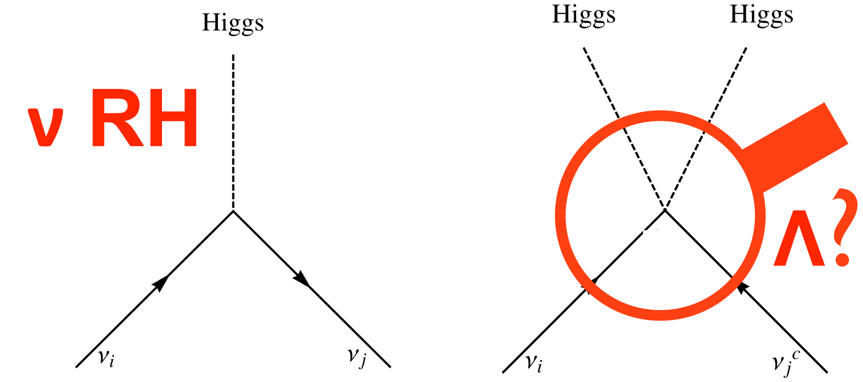
GDR Neutrino 2015, Clermont-Ferrand, June 2015

v1

Neutrinos at the frontier

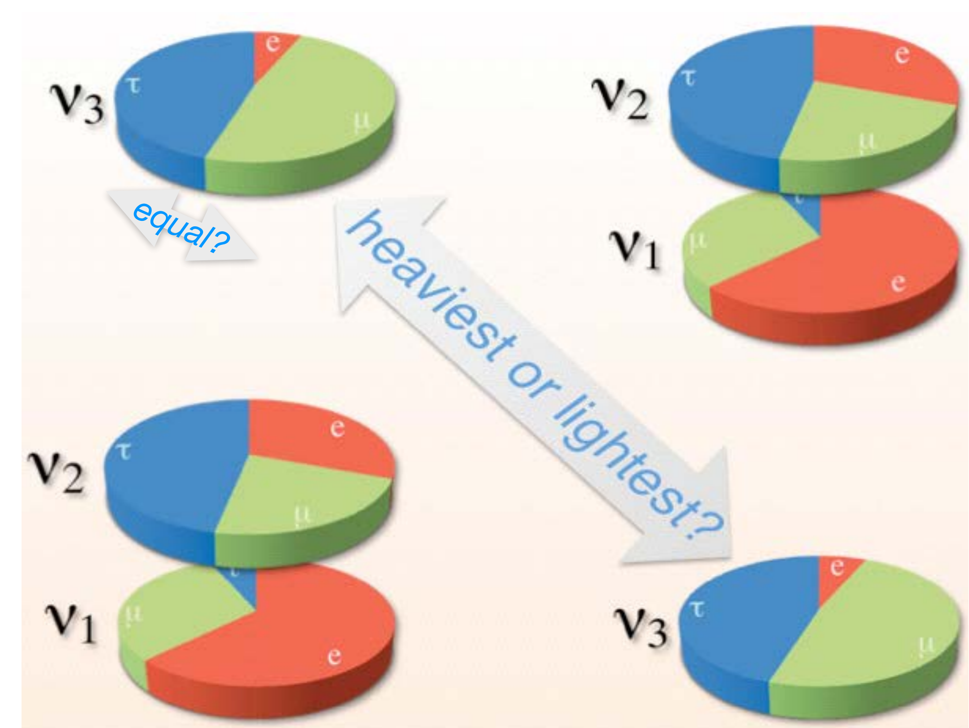
- **Neutrinos play a fundamental and special role in particle physics, astrophysics and cosmology**
- **Neutrino masses** → presently the <u>only</u> evidence of new physics beyond the SM – additional d.o.f. <u>must</u> exist: either **ν RH** and/or **new scale Λ** (>> TeV ?)
- **A window to questions related to a deeper description of physics and to the evolution of the Universe:**
  - Why are neutrino masses so small ?
  - **Why is the mixing matrix so different than the one of quarks? What does this picture suggest ?**
  - **How is the hierarchy of the ν mass eigenstates ?**
  - Which is the absolute mass of the lightest state ?
  - Are neutrinos Majorana particles ?
  - **P, CP, CPT are fundamental symmetries. "P is maximally violated by neutrinos but CP is saved" (W. Pauli). Is CP violated by neutrinos as well or is it a special feature of quarks ?**
  - Are there sterile neutrino states and is there mixing … ?

$$\underbrace{Y^{ij}\Psi_L^i\Psi_R^j\phi}_{-\mathcal{L}_{\mathrm{Dirac}}} + \underbrace{\frac{g^{ij}}{\Lambda}\Psi_L^i\Psi_L^{T,j}\phi\phi^T}_{-\mathcal{L}_{\mathrm{Majorana}}}$$



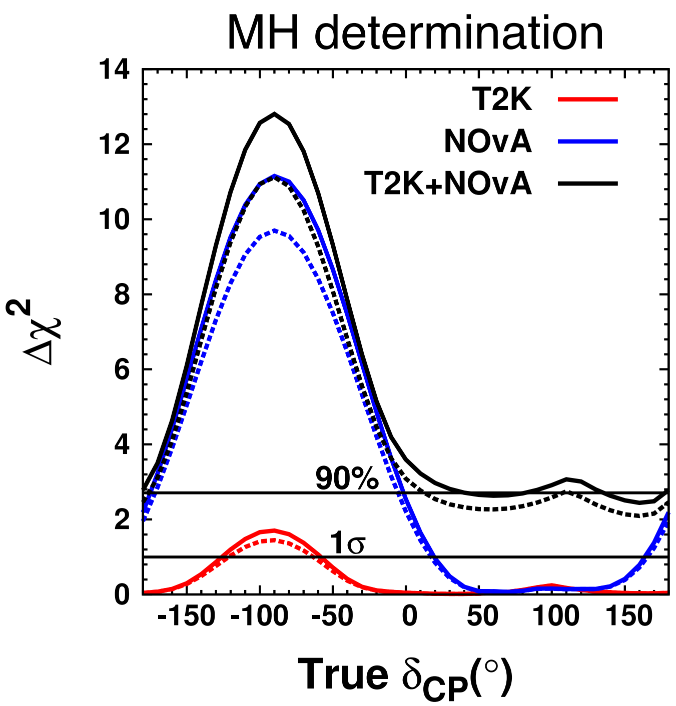
NuFIT 2.0 (2014)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

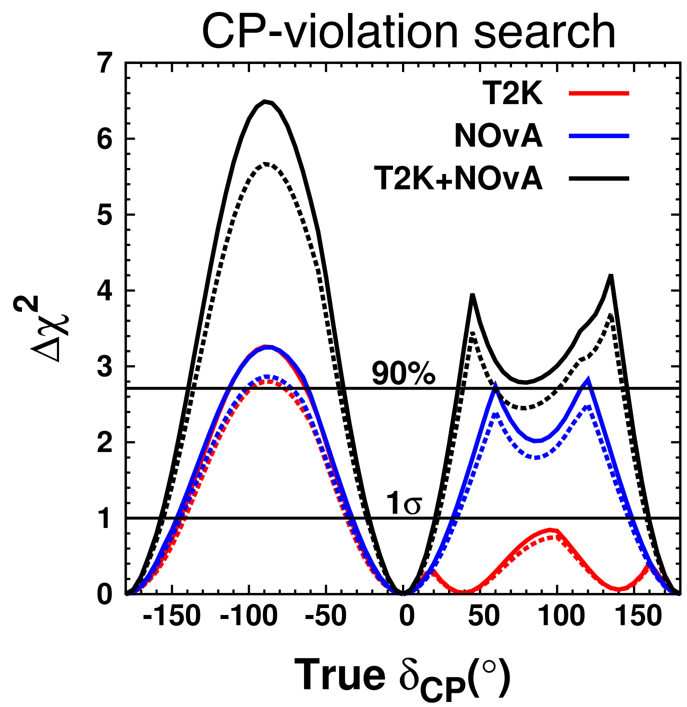


T2K and NOvA: the future until ≈2020

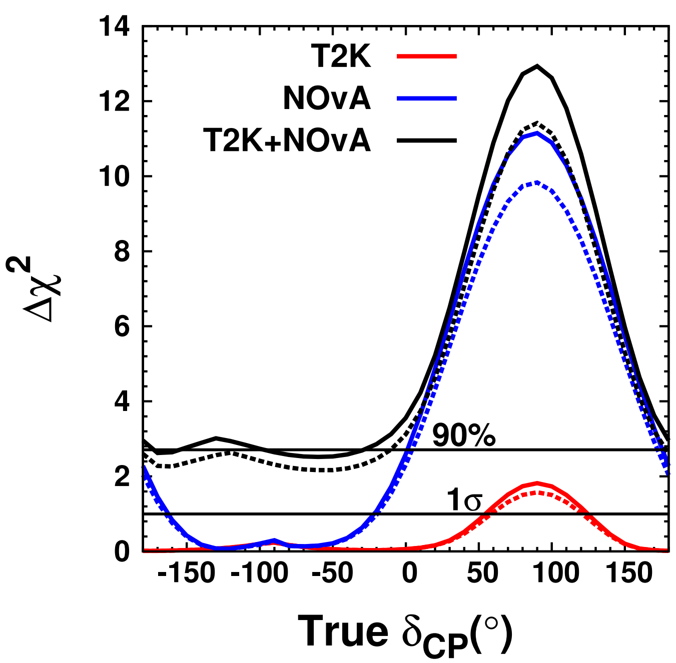
arxiv:1409.7469v1



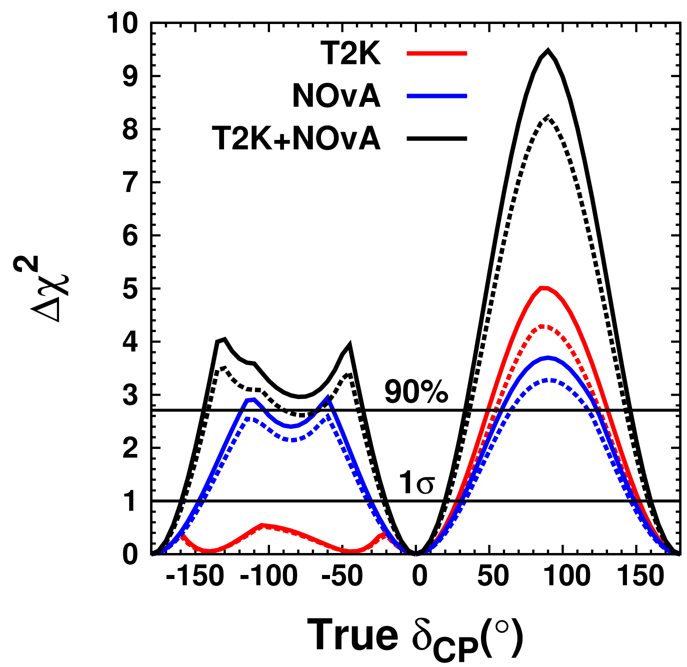
(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH



(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

Mass hierarchy determination:

- combined fit NOvA (6 years of nominal running) + T2K pot projection
- exploiting bigger matter effect (≈30%) at 830km(NOvA) comparing to 295km(T2K)
- strongly depends on true value of δ_{CP} and on true hierarchy (NH/IH)
- **>50% phase-space unreachable**

CP-violation discovery:

- combined fit NOvA (6 years of nominal running) + T2K pot projection
- **in the best case a 2.5σ(NH) hint**
- **>50% phase-space unreachable**

⇒New experiments needed beyond 2020 !

In Europe: LAGUNA, LAGUNA-LBNO, LBNO…

The European neutrino community has early on recognised the importance of this sector and has been strongly supported by CERN and ApPEC to prepare the new experiment with the LAGUNA and LAGUNA-LBNO design studies.

GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment, **2003**)

- New concept of Double Phase Liquid Argon TPC for CP-violation and future deep underground detector, up to 100 kton mass (hep-ph/0402110)

LAGUNA DS (FP7 Design Study **2008-2011**)

- ~100 members; 10 countries
- 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)

LAGUNA-LBNO DS (FP7 DS Long Baseline Neutrino Oscillations, **2011-2014**)

- ~300 members; 14 countries + CERN
- Fully engineered detector designs for 20/50 kt DLAr, 50 kt LSc, 540 kt WCD
- Infrastructure design, construction scheme and full costing

LBNO (CERN SPSC EoI for a very long baseline neutrino oscillation experiment, **June 2012**)

- An incremental approach with high level physics starting from phase 1 (MH + LCPV + Astro)
- ~230 authors; 51 institutions
- Design study is **concluded** and the deliverables are on the web

CERN-SPSC-2012-021, SPSC-EOI-007

LBNO-DEMO WA105 (@CERN first Collaboration meeting 16-17 **October 2014**)

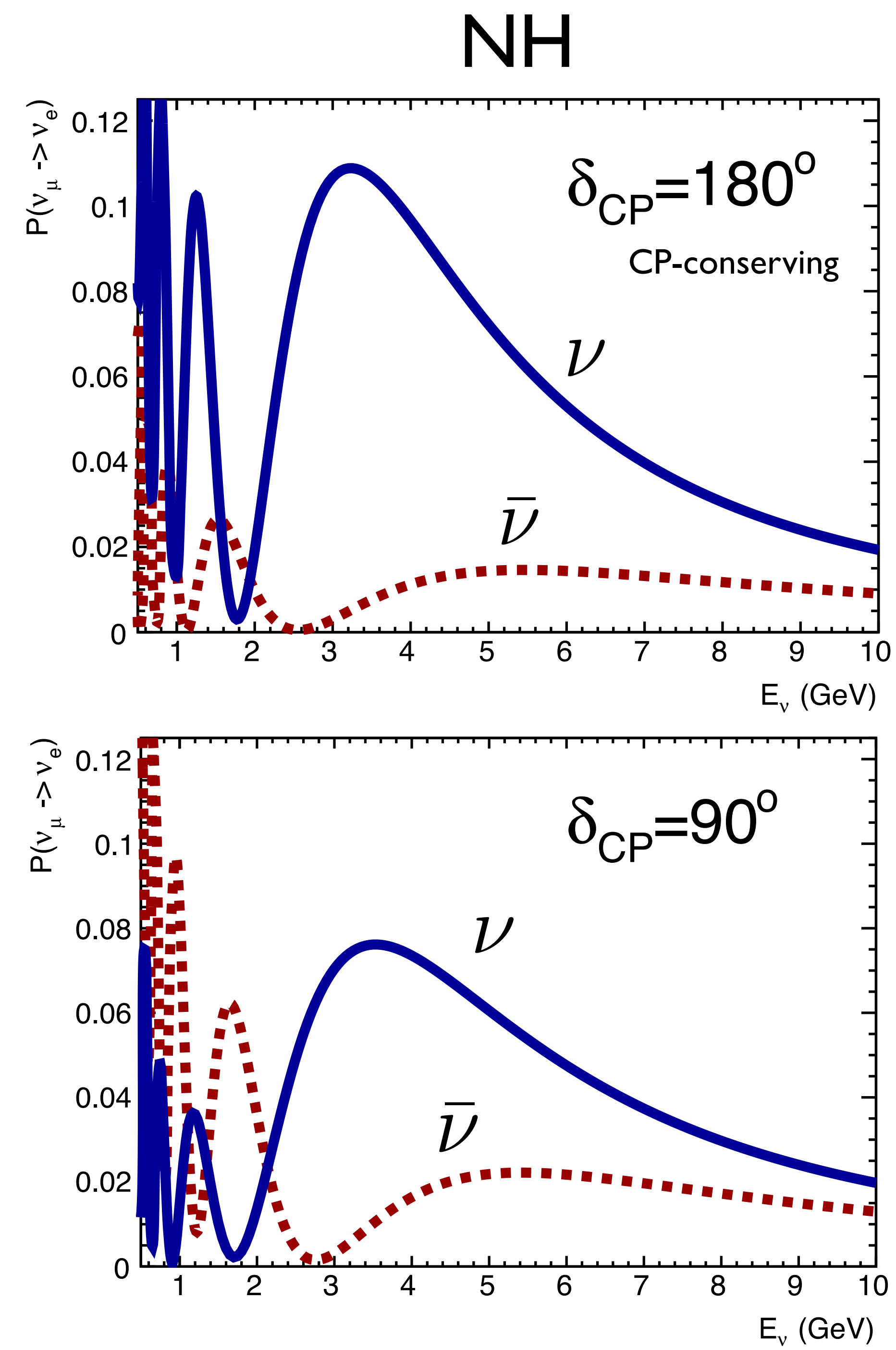
- kt-scale demonstrator for LBNO @ CERN: engineering and charged particle calibration

CERN-SPSC-2014-013, SPSC-TDR-004

LBNO physics goals

CERN-SPSC-2012-021,
SPSC-EOI-007

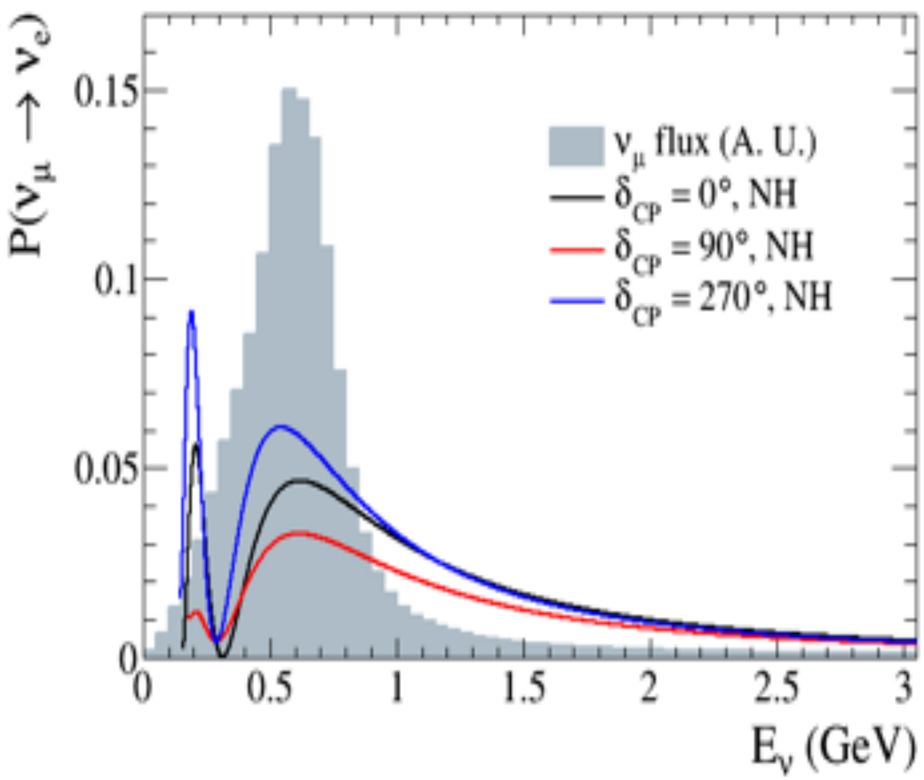
- **Long baseline neutrino oscillations**
  - $\nu\mu \rightarrow \nu e$ & $\nu\mu \rightarrow \nu\tau$ & $\nu\mu \rightarrow \nu\mu$ & νNC
  - Direct measurement of the energy dependence (L/E behaviour) induced by matter effects and CP-phase terms, independently for ν and anti-ν, by direct measurement of event spectrum, in particular covering 1st and 2nd oscillation maxima
  - Mass hierarchy determination at >5σ C.L. in first two years of running
  - CP-phase measurement and CPV "discovery" (⇒ 5σ C.L.)
  - Test of three generation mixing paradigm



- **A full astrophysics programme**
- Nucleon decays (direct GUT evidence)
- Atmospheric neutrino detection with complementary oscillation measurements and Earth spectroscopy
- Astrophysical neutrino detection and searches for new sources of neutrinos

A reminder: three strategies

T2HK: L = 295 km



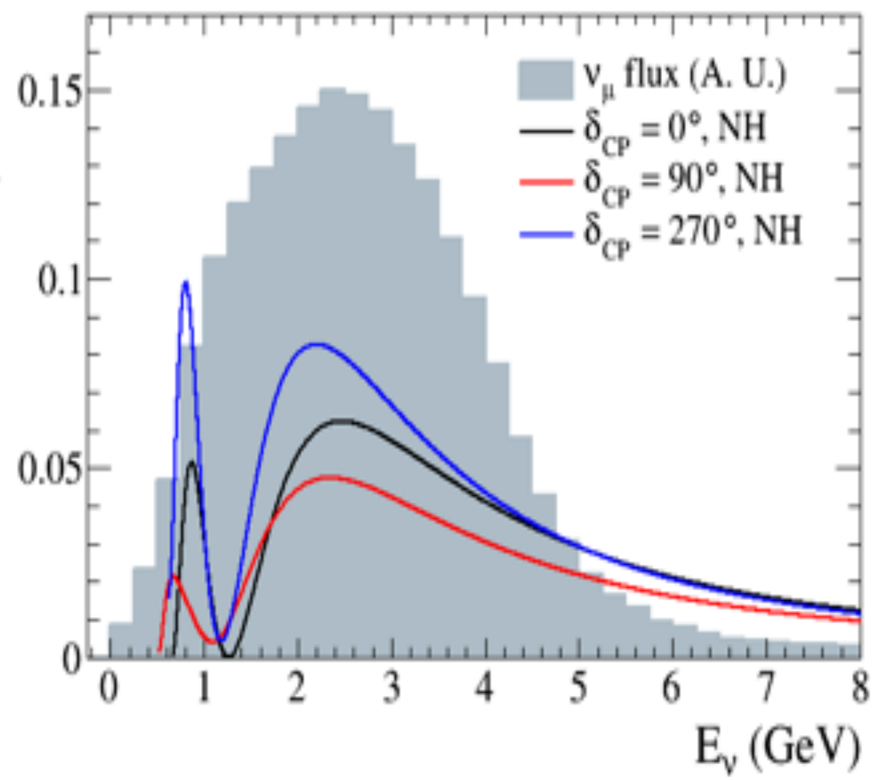
Off-axis narrow band sub-GeV beam:

- OA = 2.5 deg & <E_ν> = 0.6 GeV
- 30 GeV primary p beam
- Exposure 16E+21POT total

Covers 1st oscillation maximum

Short baseline → small matter effects → No MH from beam

LBNE: L = 1300 km



Wide-band neutrino beam

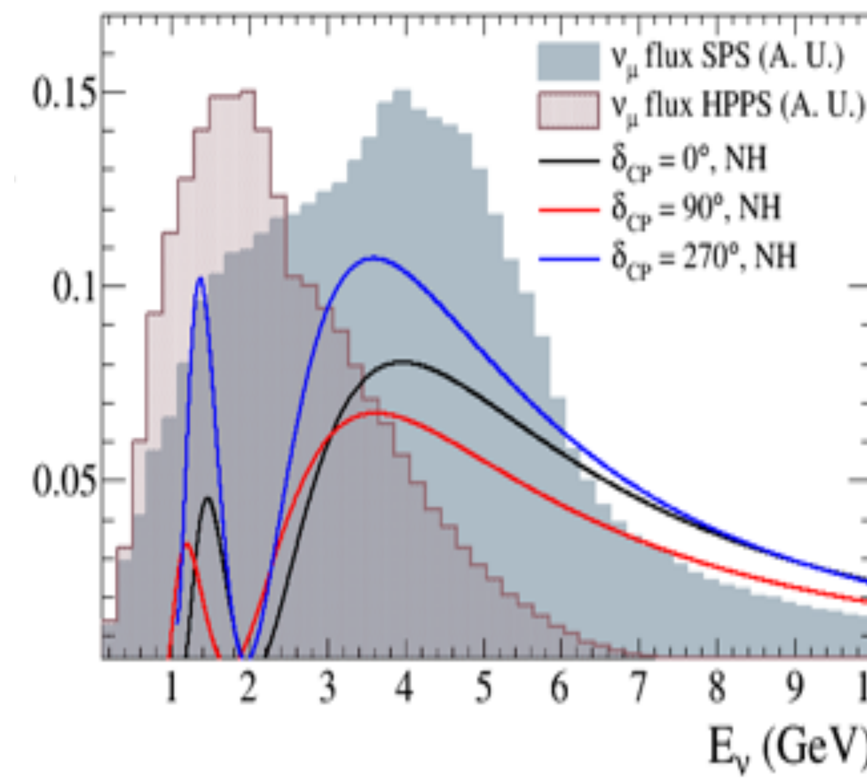
- 80 GeV primary p beam
- 1.2 MW, 9E+21POT total

Covers mostly 1st oscillation max → 2nd max is challenging (low flux x low cross section)

Significant matter effects → MH

DUNE: L = 1300 km

LBNO: L = 2300 km



Wide-band neutrino beam

Two optimizations:

- 400 GeV p beam (Phase I): 750 kW, 1.5E+21POT total
- 50 GeV p beam (Phase II): 2 MW, 30E+21POT total

Can cover both 1st and 2nd max

Huge matter effects → quick MH

Entering the “global” era (2014)

- **CERN European Strategy:**
  CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects **outside Europe**.

European Strategy for Particle Physics

- **US P5 report:**
  Recommendation 12 : In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context

June 2014: CERN decides to freeze further developments of LBL (and SBL) neutrino beams in Europe
May 2015: CERN-DOE agreement signed at the White House

An Experimental Program in Neutrinos, Nucleon Decay and Astroparticle Physics Enabled by the Fermilab Long-Baseline Neutrino Facility

LOI-PAC-P-1062

January 2015

LBNF/DUNE is a merger of all previous efforts (LBNE, LBNO) and any other interested parties to build, operate, exploit

- A new **wide-band neutrino beam** pointing to SURF at a distance of **1300 km** from FNAL, utilizing **1.2 MW** protons from PIP-II by ~**2026**, and with a capability for an upgrade to **2.4 MW** protons with PIP-III by ~**2030**.
- A **40-kt fiducial mass liquid argon TPC** located deep underground at SURF 4850L, with the aim for an initial 10-kt deployed by **~2021/2022**.
- A **high-resolution/fine-grain near detector** with the ability to constrain the systematic errors for the LBL oscillation programme, enabling as well a generational advance in neutrino studies with unprecedentedly large statistics of neutrino interactions measured with very high precision.

DUNE international Collaboration

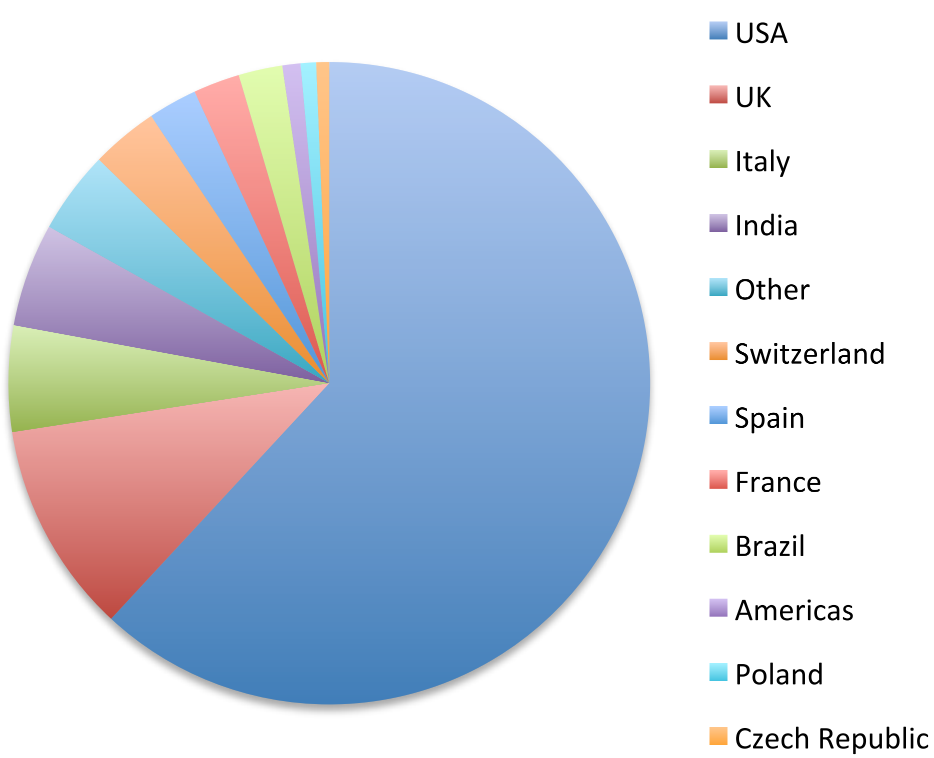
A rapidly evolving scientific collaboration

- **Collaboration rules adopted in April**
  - Now have full management structure and executive committee
  - Ten task forces were set up to prepare DOE CD-1 documents
  - Review of documents involving ~75 members of the collaboration
- **First formal collaboration meeting April 16th-18th 2015**
  - Over 200 people attended in person

The DUNE Collaboration

As of today:

769 Collaborators



from

144 Institutes, 25 Nations

Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, France, Germany, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, Spain, Switzerland, Turkey, UK, USA

DUNE now has broad international support

LBNF/DUNE Conceptual Design Report (CDR)

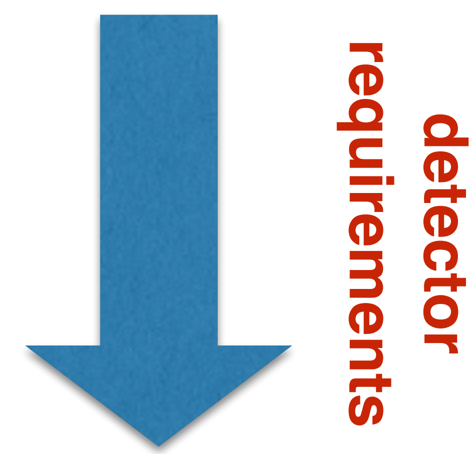
- DOE CD-1 Review July 2015
- To update the scope and vision and to inform all stakeholders of that new international vision
  - Vol. 1 – Introduction and Executive Summary
  - Vol. 2 – Physics (FD+ND)
  - Vol. 3 – LBNF
  - Vol. 4 – DUNE (FD,ND,prototypes)
- Science goals drive the detector requirements.

Conceptual Design Report
The Deep Underground Neutrino Experiment

Volume w: LBNF/DUNE Physics

April 20, 2015

≈50 pages



Conceptual Design Report
The Deep Underground Neutrino Experiment

Volume 4: The Deep Underground Neutrino Experiment

April 20, 2015

≈150 pages

Top-level Science Objectives

- **The LBNF/DUNE scientific objectives are categorized as**
  - A primary science program, addressing the key science questions highlighted by P5 report and CERN ESPP
  - A high-priority ancillary science program that is enabled by the construction of LBNF and the DUNE
  - And additional scientific objectives, that may require developments, e.g. of the LArTPC technology.

- **The primary science program defines the high-level requirements for LBNF and DUNE**
  - The ancillary program provides further requirements, specifically on the design of the near detector, required for the full scientific exploitation of LBNF/DUNE

DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astro-particle physics – aim for discoveries:

- **1) Long-baseline Neutrino Oscillation Physics**
  - CPV in the leptonic sector
    [ultimate sensitivity requires high precision]
  - Mass Hierarchy
  - Precision Oscillation Physics (θ_{23} octant, …) & testing the 3-flavor paradigm
- **2) Nucleon Decay**
  - Targeting SUSY-favored modes, e.g. $p \to K^+ + \bar{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse super-nova, sensitivity to ν_e

DUNE Ancillary Science Program

Enabled by the intense LBNF beam and the DUNE near and far detectors

- **Other physics with BSM sensitivity**
  - Neutrino non-standard interactions (NSIs)
  - Search for sterile neutrinos at the near and far sites
  - Measurements of tau neutrino appearance
- **Oscillation physics with atmospheric ν's**
- **Rich neutrino Physics in the near detector**
  - Inclusive & exclusive ν cross section measurements
  - Studies of nuclear effects, FSI etc.
  - Measurements of the structure of nucleons
  - Neutrino-based electroweak theory measurements (e.g. $\sin^2\theta_W$)
- **Search for signatures of Dark Matter**
  - Search for Heavy Neutrinos

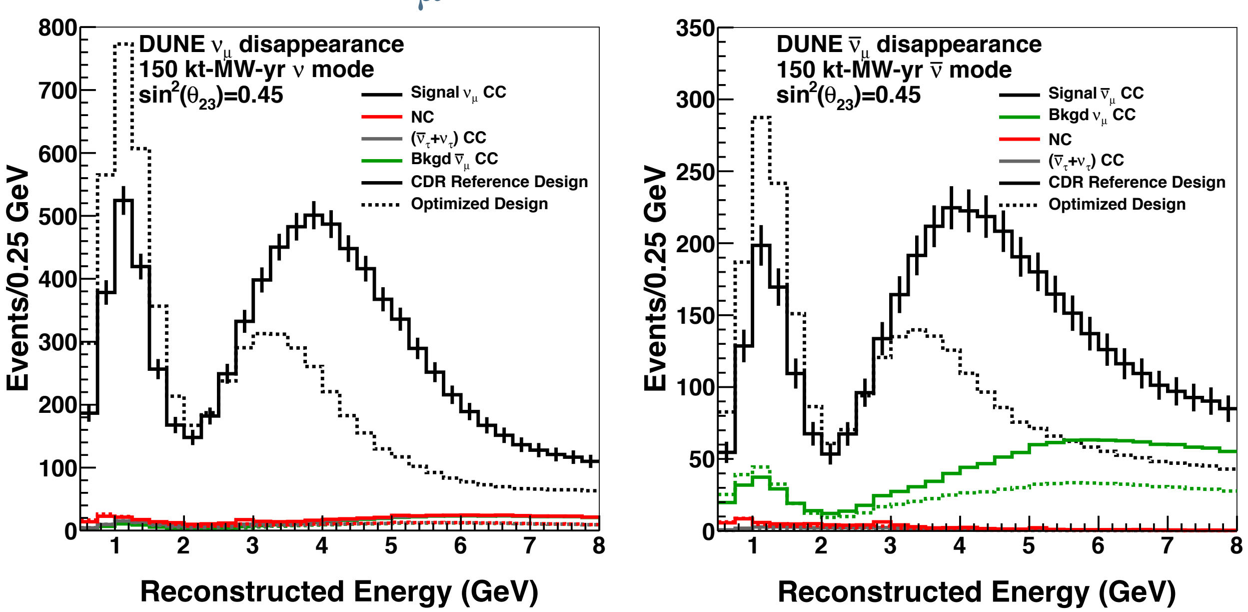
LBL oscillation strategy

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

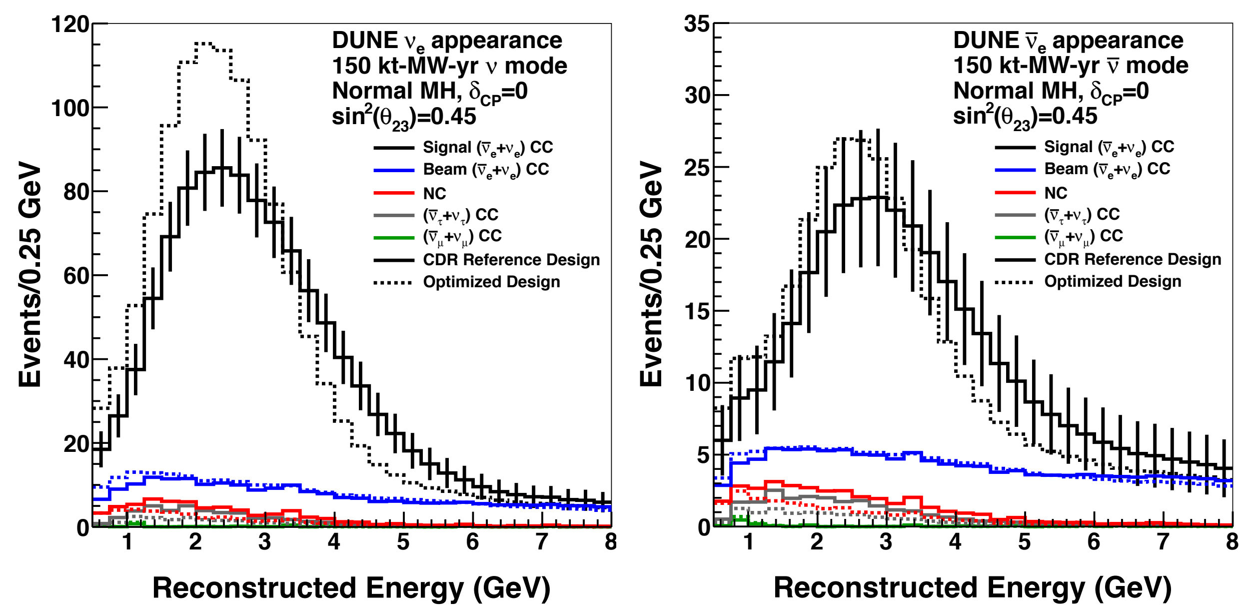
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Study $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and $\nu_\mu \rightarrow \nu_x$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_x$) over range of energies
    - MH & CPV effects are separable

Systematic errors to be negligible compared to statistical power reached over lifetime of experiment

ν_μ disappearance



ν_e appearance



LBL oscillation strategy (II)

CPV & MH : Systematic errors presented in CDR

After fits to both near and far detector data and all external constraints.

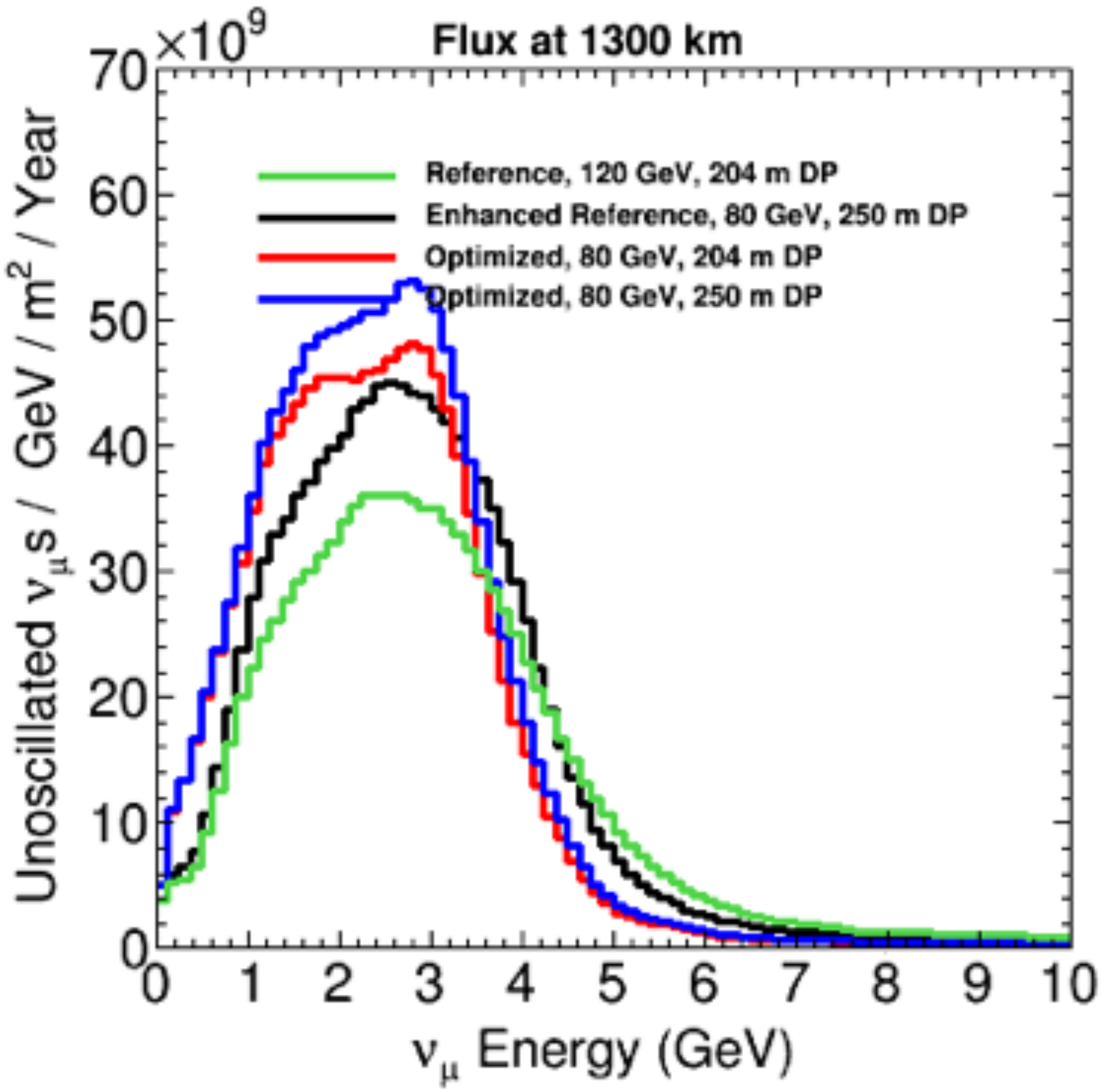
Signal: **5%** (abs. νμ norm.) ⊕ **2%** (νe norm.) for both neutrinos and antineutrinos sample

Background processes:

From CDR Volume 2 "Physics":

Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

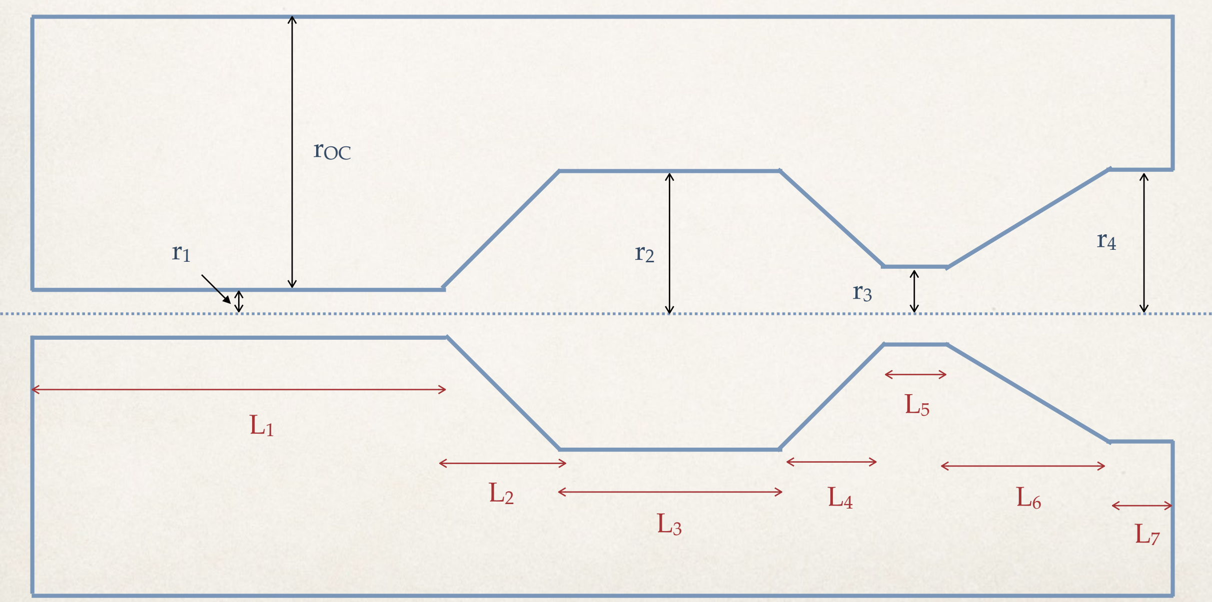
Beam Focusing Optimisation



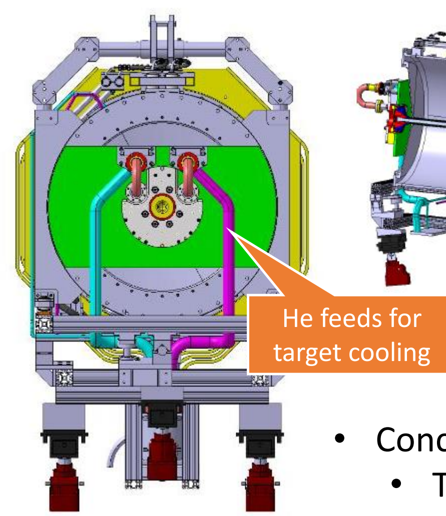
Optimised beam is crucial for reaching ultimate sensitivities – less important in the initial phase of experiment

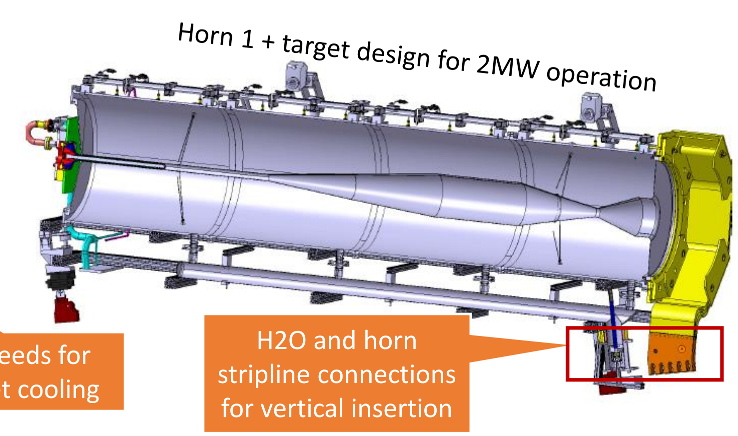
arXiv:1412.0593

- The "Optimized" fluxes on previous slides are the output of a genetic algorithm inspired by LBNO and developed by that optimizes CP sensitivity. I've done several versions of this algorithm including one LBNO-style Horn 1:



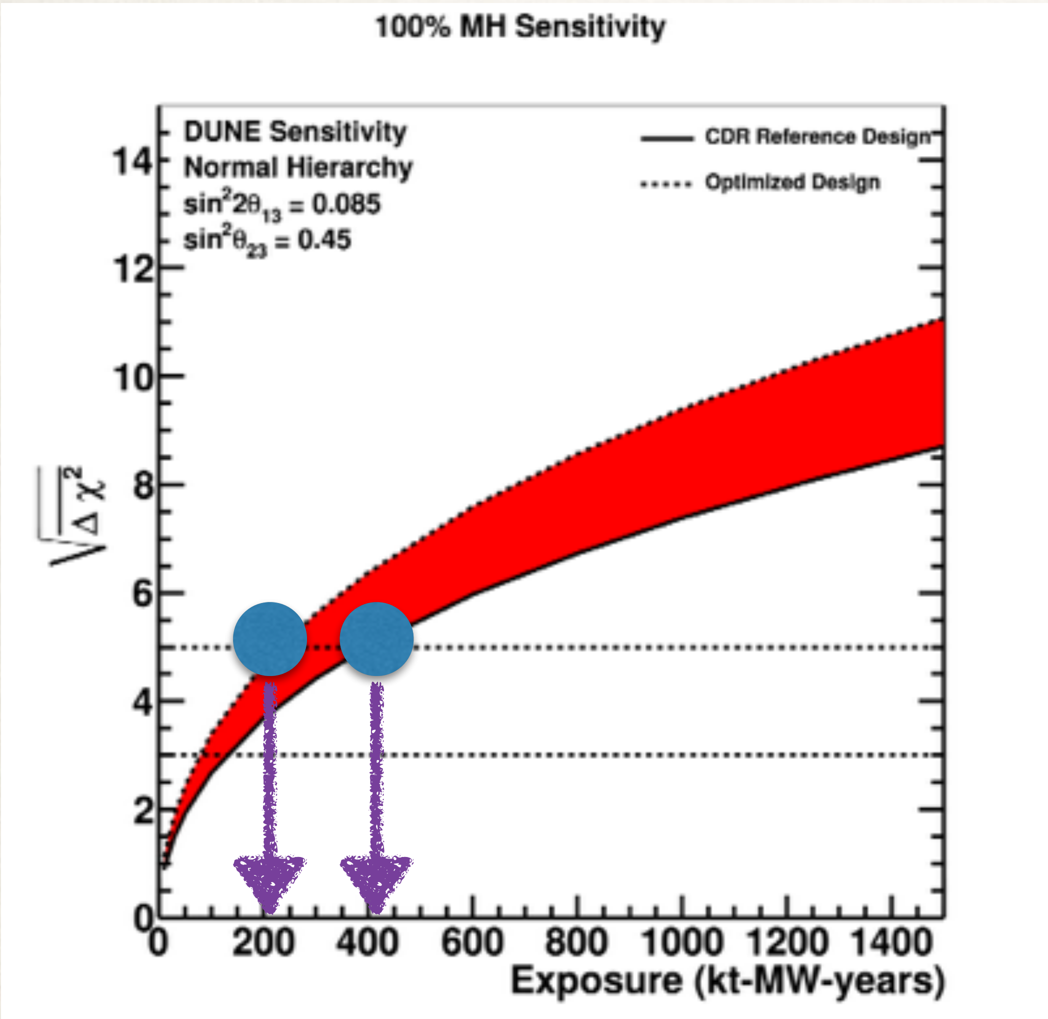
Horn concept **(LAGUNA-LBNO/CERN)**



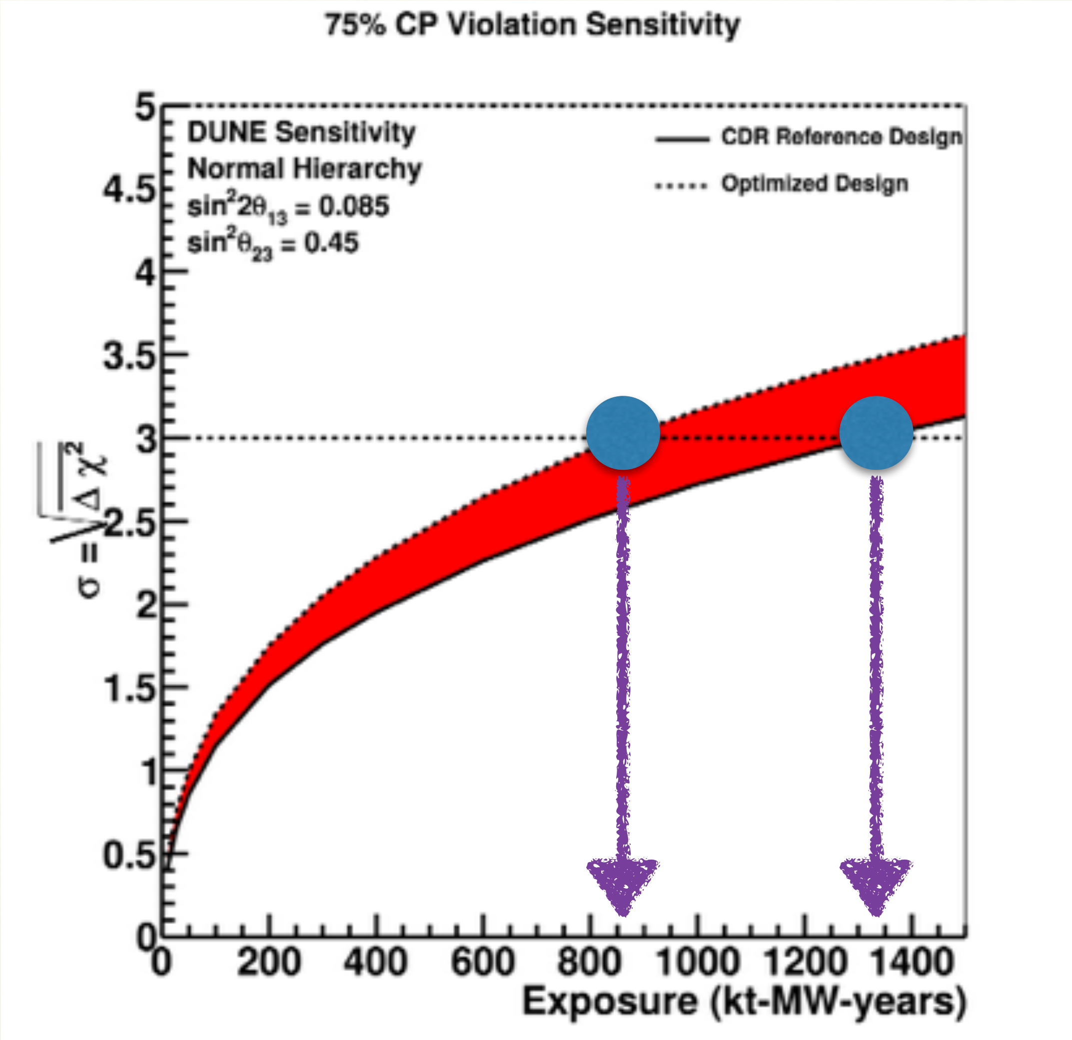


- Conceptual design has been developed
  - Thermal and structural analysis
- Water-cooling system for both 750kW and 2MW operation
- PS requirements for the desired currents

MH & CPV sensitivity reach



- Current estimates show 5 sigma sensitivity to mass hierarchy for all values of δ_{CP} by 400 kt-MW-years with reference beam



- Will reach P5 goal of 3 sigma coverage of 75% of δ_{CP} phase space by 850-1300 kt-MW-years, depending on beam design

MH & CPV milestones vs exposure

Rapidly reach scientifically interesting sensitivities:

e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :

Reach 3σ CPV sensitivity with 60 – 70 kt.MW.year

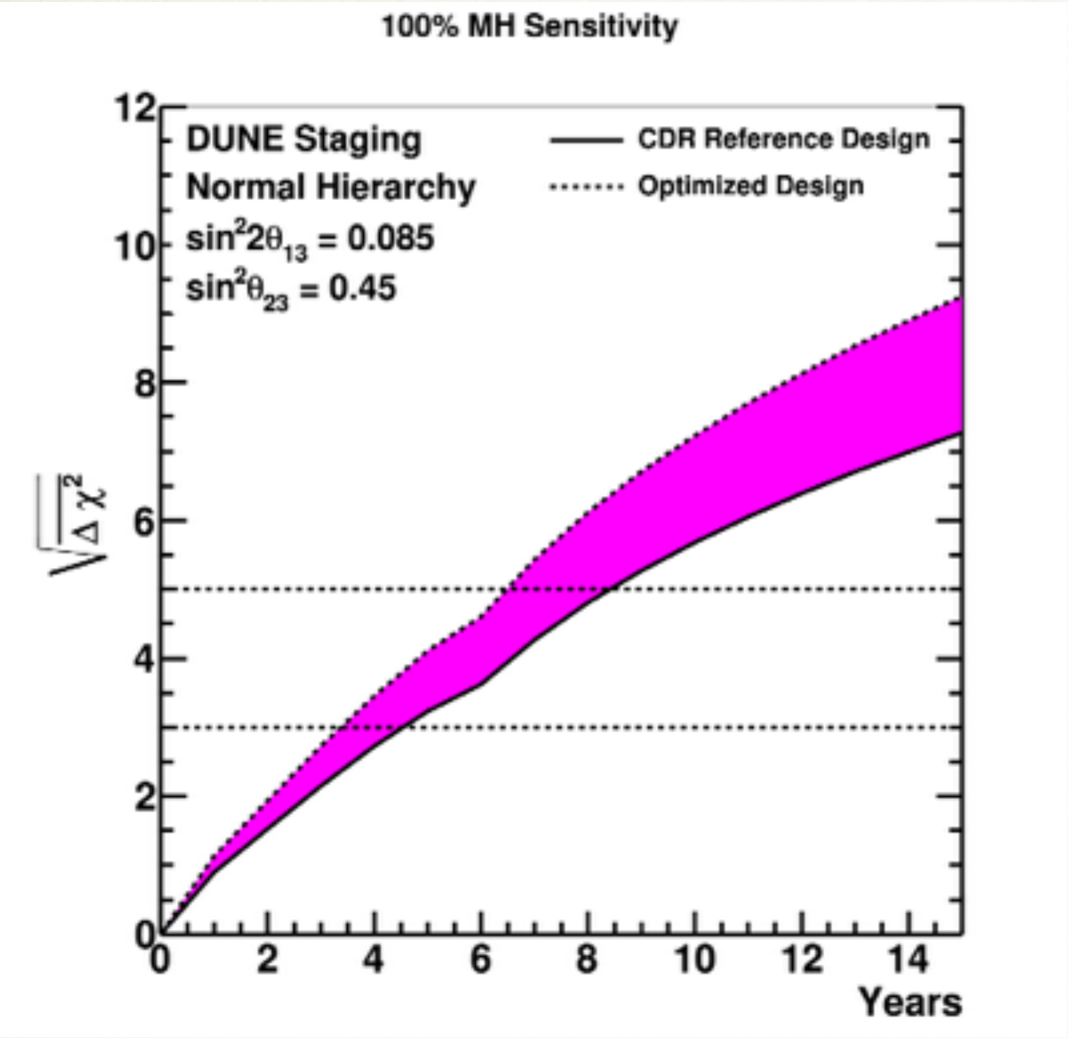
e.g. in best-case scenario for MH :

Reach 5σ MH sensitivity with 20 – 30 kt.MW.year

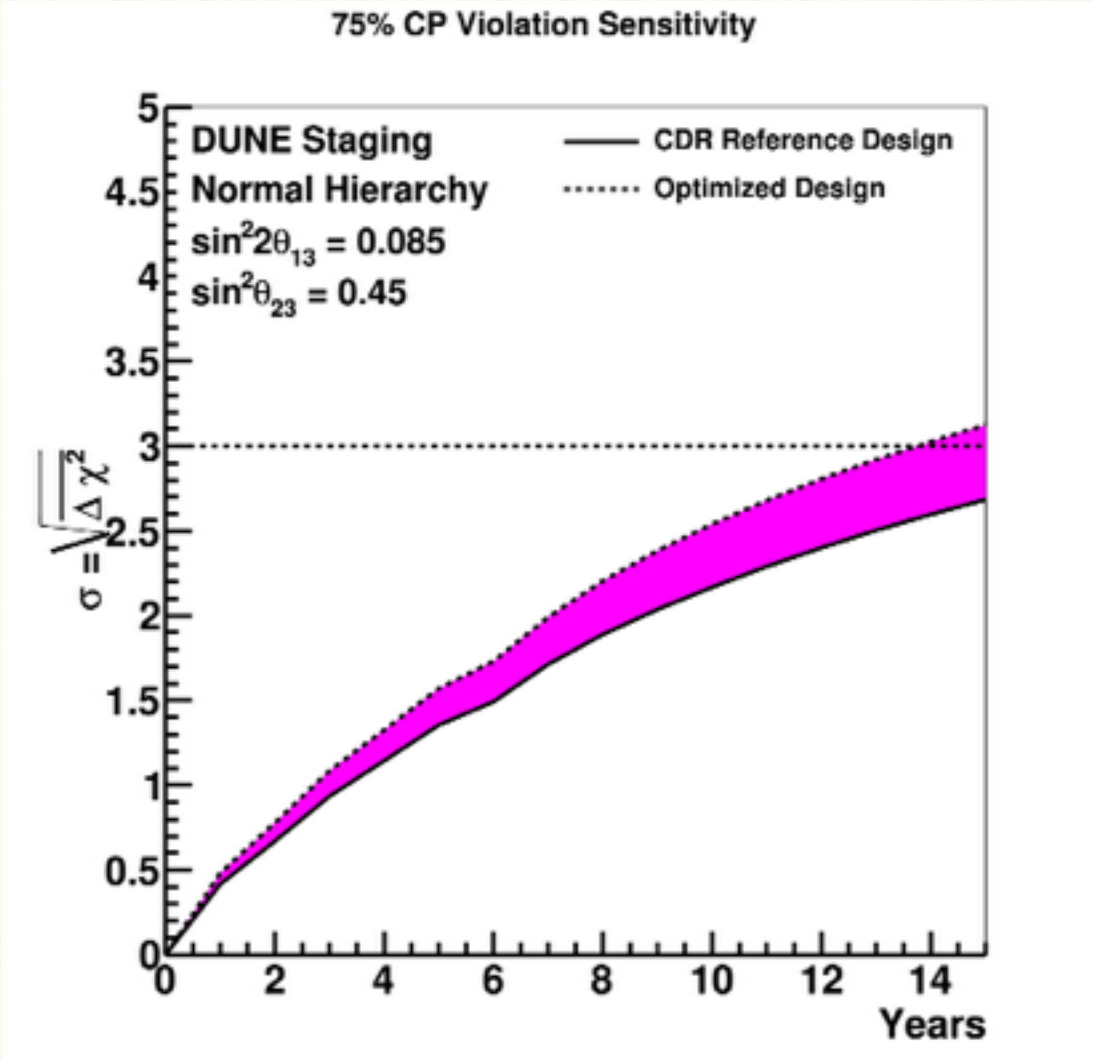
Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

➡ **Potential for early physics discovery**

MH & CPV sensitivity vs years

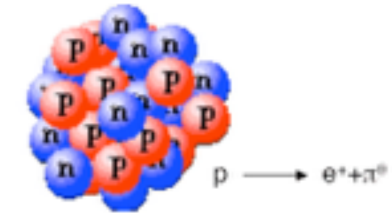


- Sensitivity versus years assuming staged increases in detector mass, beam power and near detector constraints



- If CP violation is near maximal, a signal will be seen within a few years of running

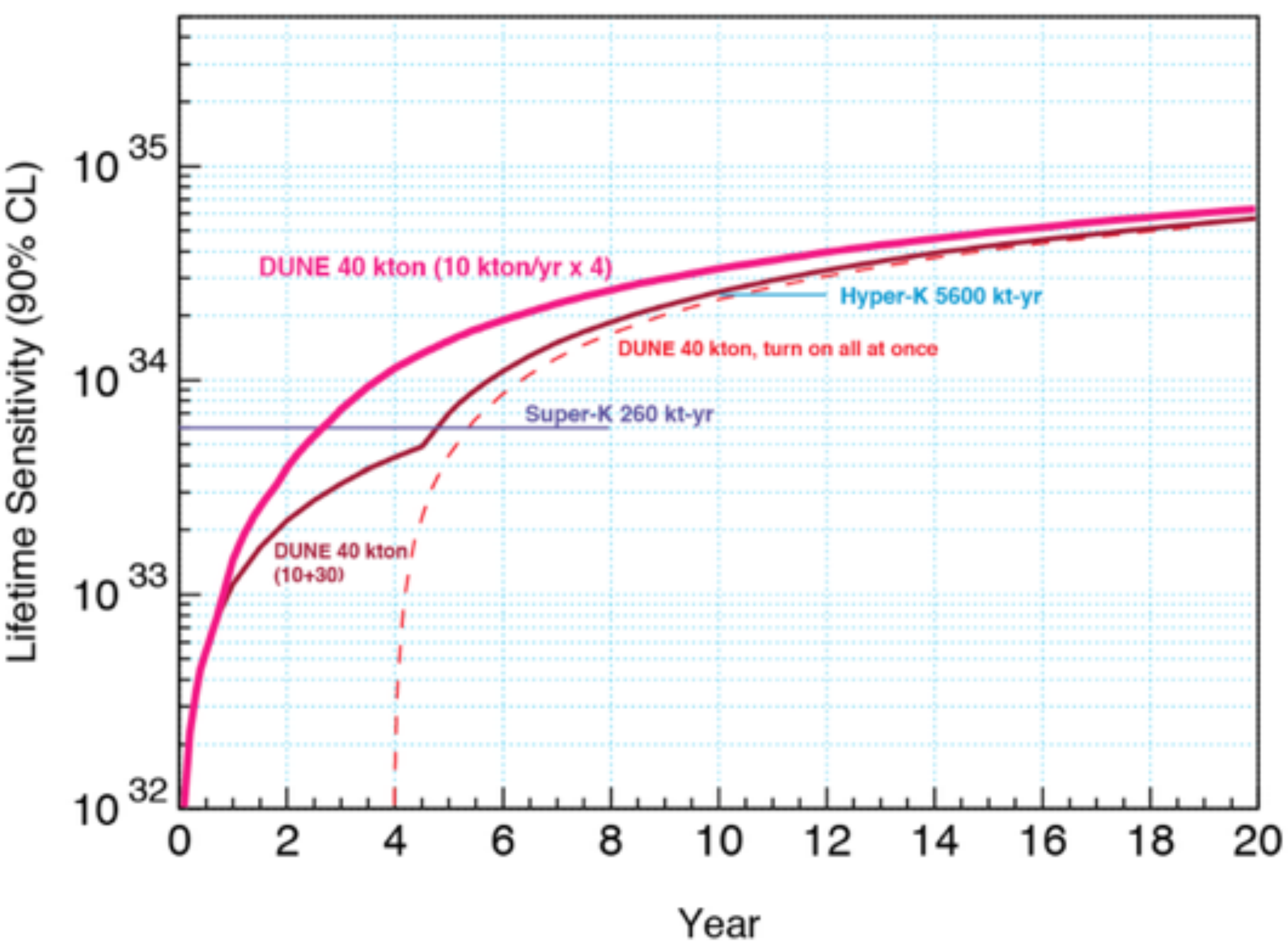
Nucleon decay



Generational advance in detection method:

Exploit tracking and calorimetry for unbiased, exclusive final state reconstruction of decay products with precise kinematics

$$p \to K^+ + \bar{\nu}$$



For a 20kton exposure of 10 years (200 kton×year)

JHEP 0704 (2007) 041

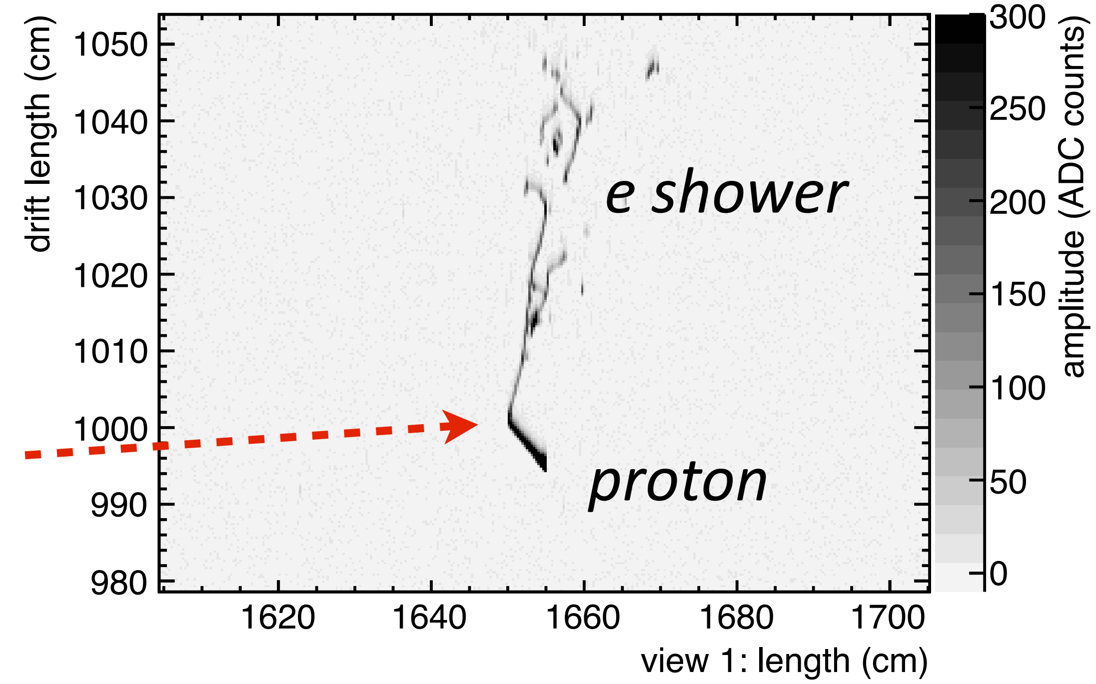
Mode	Lifetime (90%C.L.)
$p \to \nu K^+$	**$>3\times10^{34}$ yrs**
$p \to e^+\gamma$, $p \to \mu^+\gamma$	**$>3\times10^{34}$ yrs**
$p \to \mu^-\pi^+K^+$	**$>3\times10^{34}$ yrs**
$n \to e^-K^+$	**$>3\times10^{34}$ yrs**
$p \to \mu^+K^0$, $p \to e^+K^0$	$>1\times10^{34}$ yrs
$p \to e^+\pi^0$	$>1\times10^{34}$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

Expect ≈linear sensitivity improvement with exposure until 1000 kton×year

Atmospheric neutrinos

Mode	Events/20kt/yr
ν_eCC	1440
$\bar{\nu}_e$CC	310
ν_μCC	2440(w/o osc)
$\bar{\nu}_\mu$CC	680(w/o osc)
νNC	640

MC: ν_eCC



- **Neutrino oscillation physics complementary to long baseline beam**
- Clean ν_e & ν_μ CC over all range of energies (GeV,MultiGeV)
- Good neutrino energy and angular reconstruction
- Recoil hadronic system on an event-by-event basis
- Statistical separation of ν and anti-ν by exclusive final states
- $\nu_\mu \rightarrow \nu_\tau$ appearance significance >3σ after 3 years exposure (≈12 ν_τ CC / year)

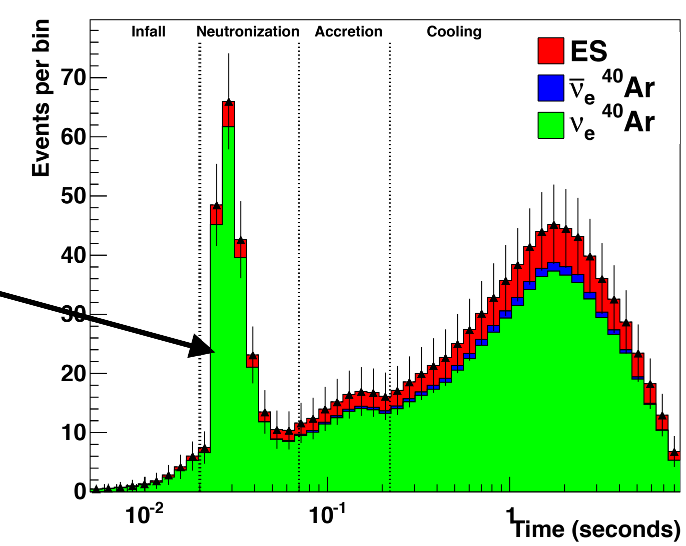
Supernova burst neutrinos

For 40 kton and a SN explosion at the distance of 10 kpc : (no oscillations included!)

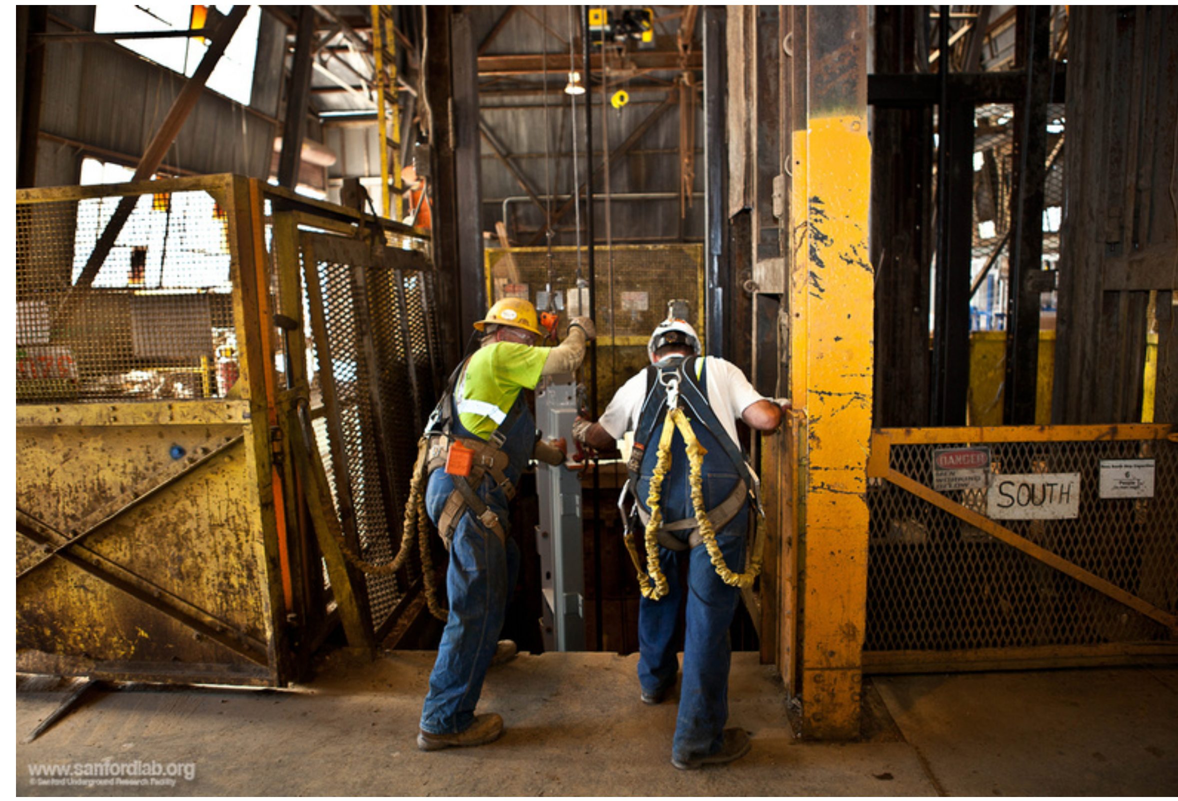
JCAP 0310 (2003) 009
JCAP 0408 (2004) 001

		Events (GKVM):
$\nu_e\ ^{40}Ar \rightarrow e^-\ ^{40}K^*$	(E_ν > 1.5 MeV)	3350
$\bar{\nu}_e\ ^{40}Ar \rightarrow e^+\ ^{40}Cl^*$	(E_ν > 7.48 MeV)	160
$\nu_x\ ^{40}Ar \rightarrow \nu_x +\ ^{40}Ar^*$		4200
$\nu_x\ e^- \rightarrow \nu_x\ e^-$		260

- Unique sensitivity to electron neutrino flavour (most other SN-detectors detect inverse beta decays)
- Combined analysis of all reaction modes
- Oscillation (both standard and collective) will potentially have a large effect
- Neutrino mass via TOF



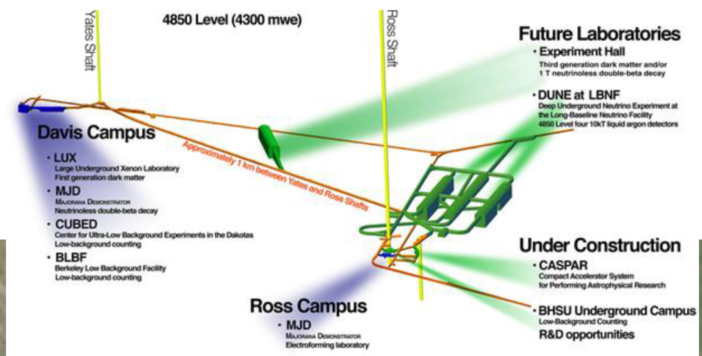
Sanford Underground Research Facility



Sanford
Underground Research Facility

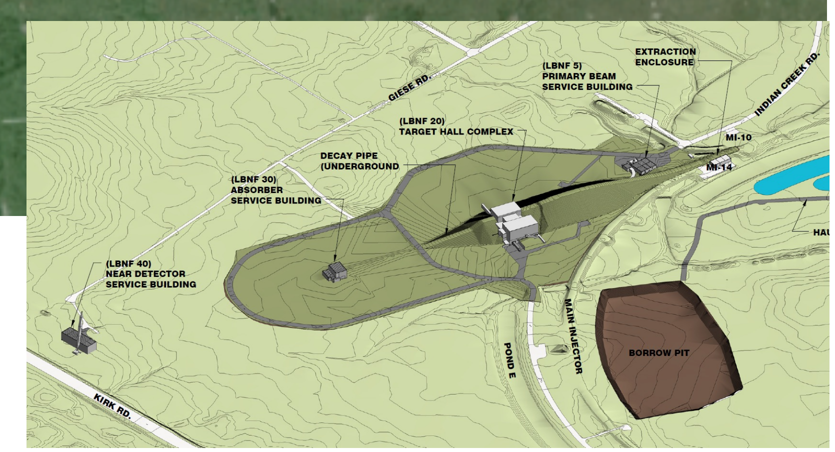
- Experimental Facilities at 4850 ft level
- Two vertical access shafts for safety
- Ross shaft refurbishment in process and is ~50% complete
- Over $100M invested from private and state funds
- Facility donated to the State of South Dakota for science in perpetuity
- Working two 12 hour shifts/day in order to be done by 2017

Near and Far sites: tentative timescale



Far site

2016:	CD-3a approval
2017-2021:	Excavation caverns + construction
2022:	Completion of conventional facilities



Near site

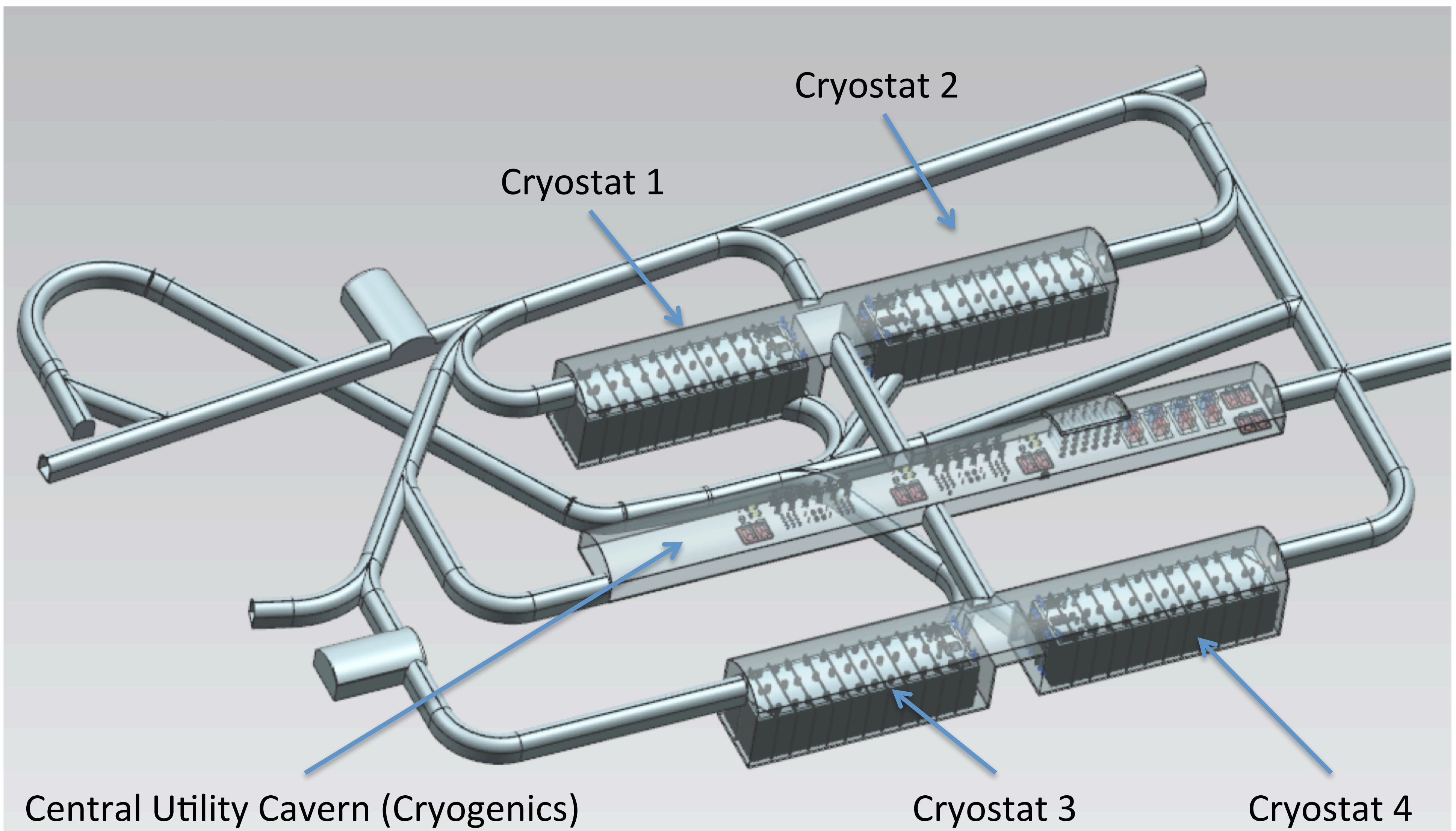
2018:	CD-3b approval
2020-2025:	Civil engineering + construction
2026:	Completion of conv. facilities

Cavern configuration… major change

New analysis based on strategic and technical input taking into account findings of LBNE & LBNO

➡ **four caverns hosting four independent 10-kt FD modules**

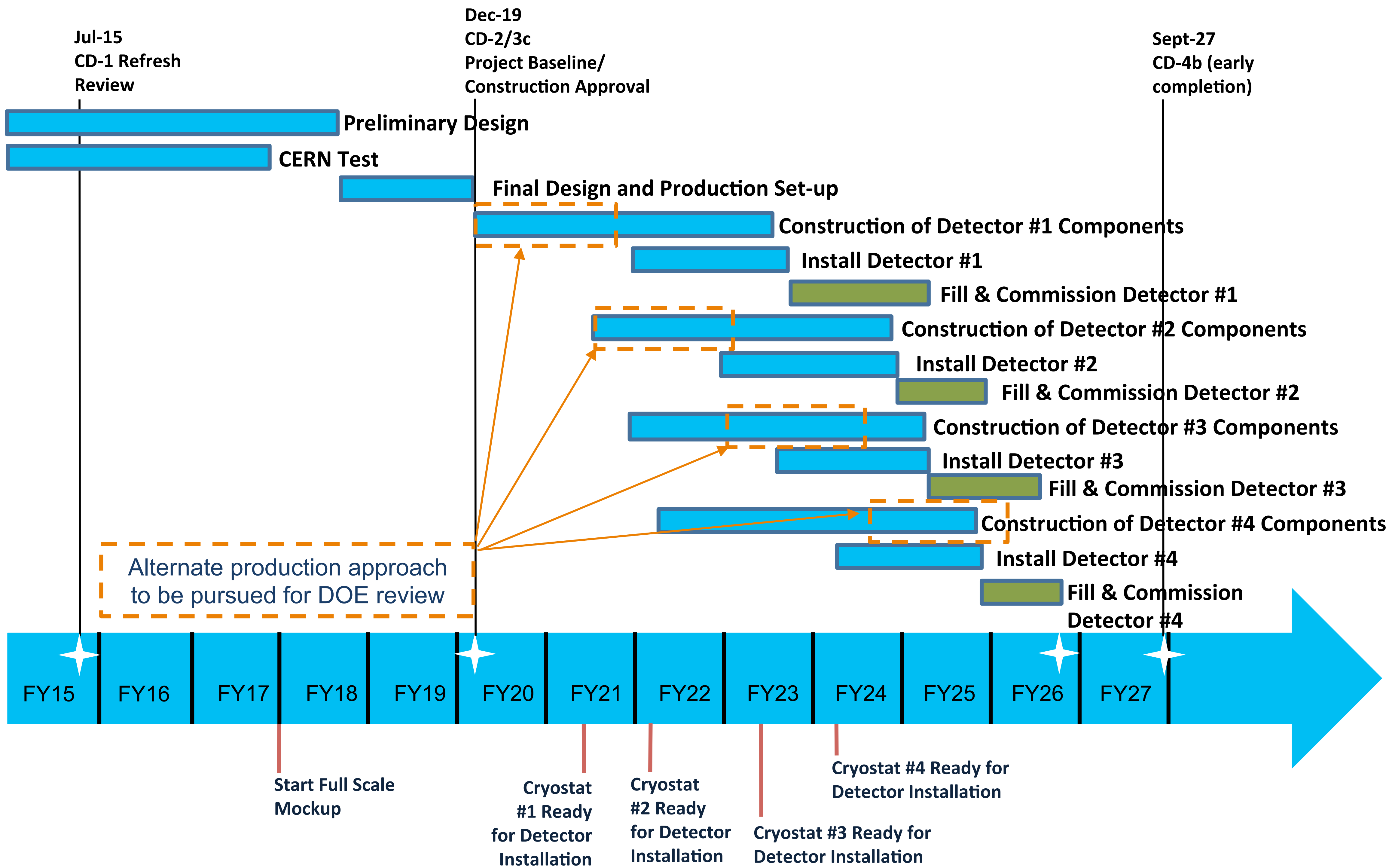
Each 10-kt cavern: 19.3m (w) x 66.2m (l) x 16.9 (h)



- Two parallel caverns each have two 10 kt detector pits with a laydown space in between
- The CF utilities and cryogenics are in a separate parallel chamber, thus no conflict with cryostat & detector install

Far Detector : tentative timescale

2016: CD-3a approval
2021: Cryostat #1 ready for installation
2023: Cryostat #1 ready for commissioning



New design for membrane tanks

x 700

- **GTT membrane technology for effective underground storage of ultra pure liquid argon → many years of studies now materialising**
- **Today: WA105 prototype**
  - Inner dimensions: 3x3x2 m^3
- **Next steps:**
  - SBN ND, single phase proto
  - WA105 8x8x8 m^3
- **DUNE 10 kton inner dimensions:**
  - 15.1(W)x14.0(H)x62m(L)

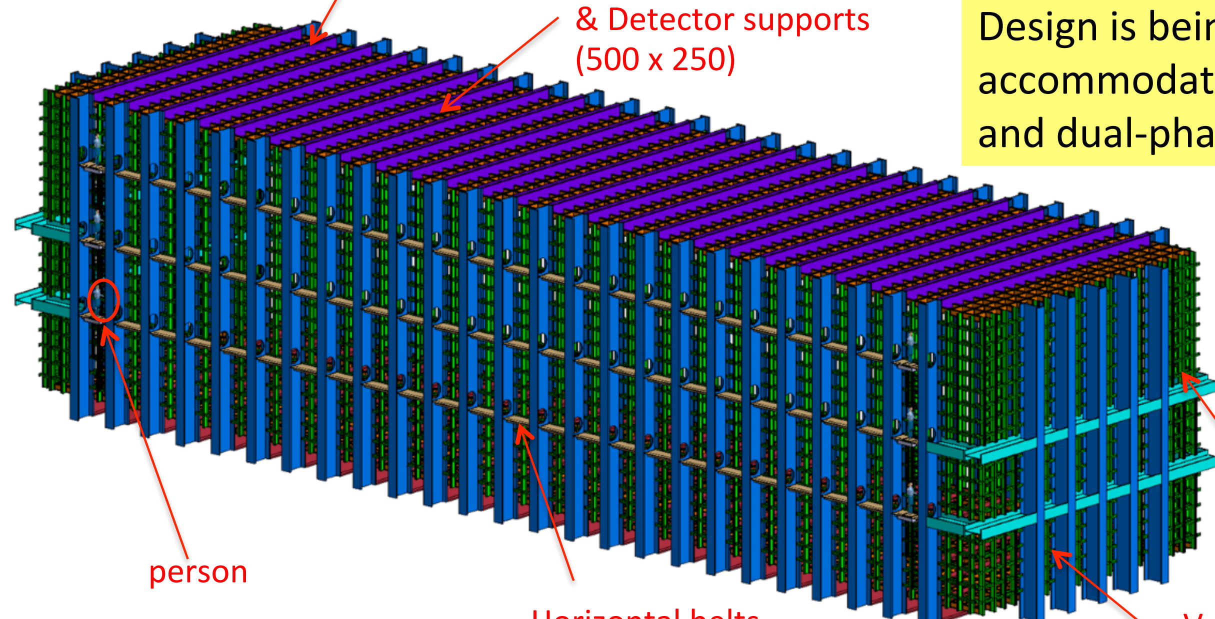
Steel-Frame Cryostat

Inner dimension (liquid+gas):

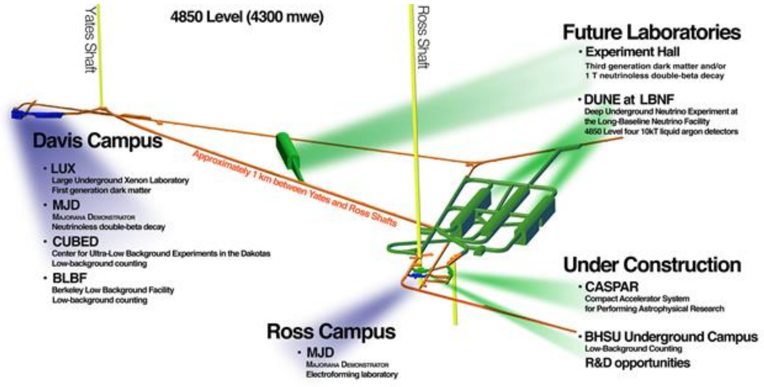
- L = 62.00 m
- W = 15.10 m
- H = 14.00 m

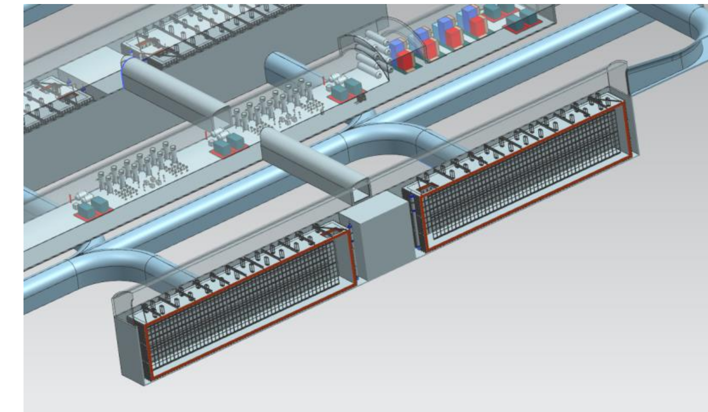
LAr = 17'432 tons (95% liquid)

Design is being developed to accommodate both single- and dual-phase detectors.



Far Detector





Detector Capabilities:

- Full reconstruction of neutrino (accelerator, atmospheric, and supernova) interactions and nucleon decays
- Photon collection for event timing (non-accelerator)

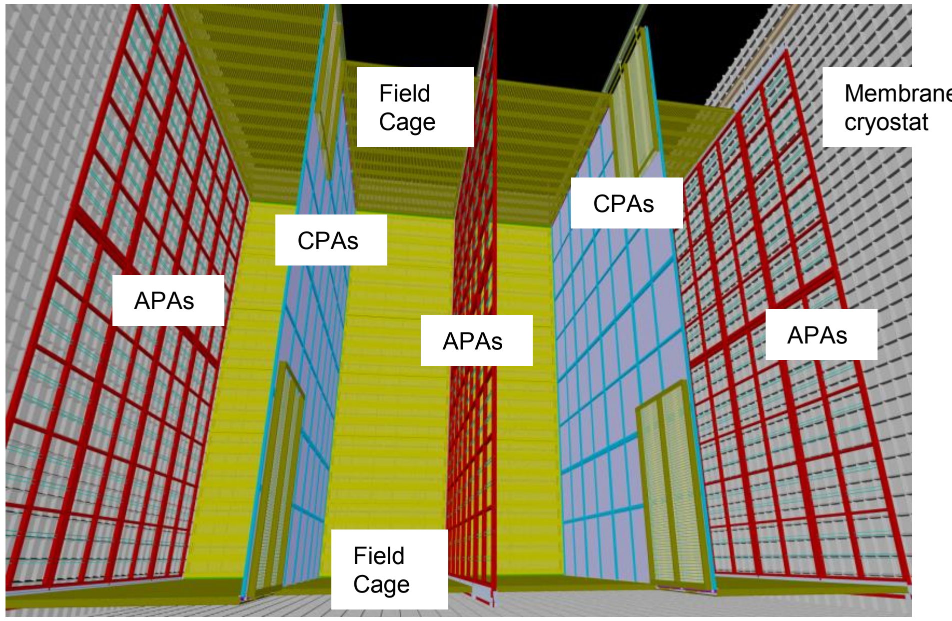
DUNE is considering two options for readout of ionization signals:

- **Single-phase wire-plane readout**
  - Ionization signals (collection + induction) read out in liquid volume
  - As used in ICARUS, ArgoNEUT/LArIAT, MicroBooNE
  - Single-phase prototype to be proposed at CERN (June 2014)
- **Dual-phase readout**
  - Ionization signals amplified and detected in gaseous argon above the liquid surface
  - Being developed by the WA105 collaboration
  - If demonstrated, potential advantages over single-phase approach

Design of 10-kt far detector modules

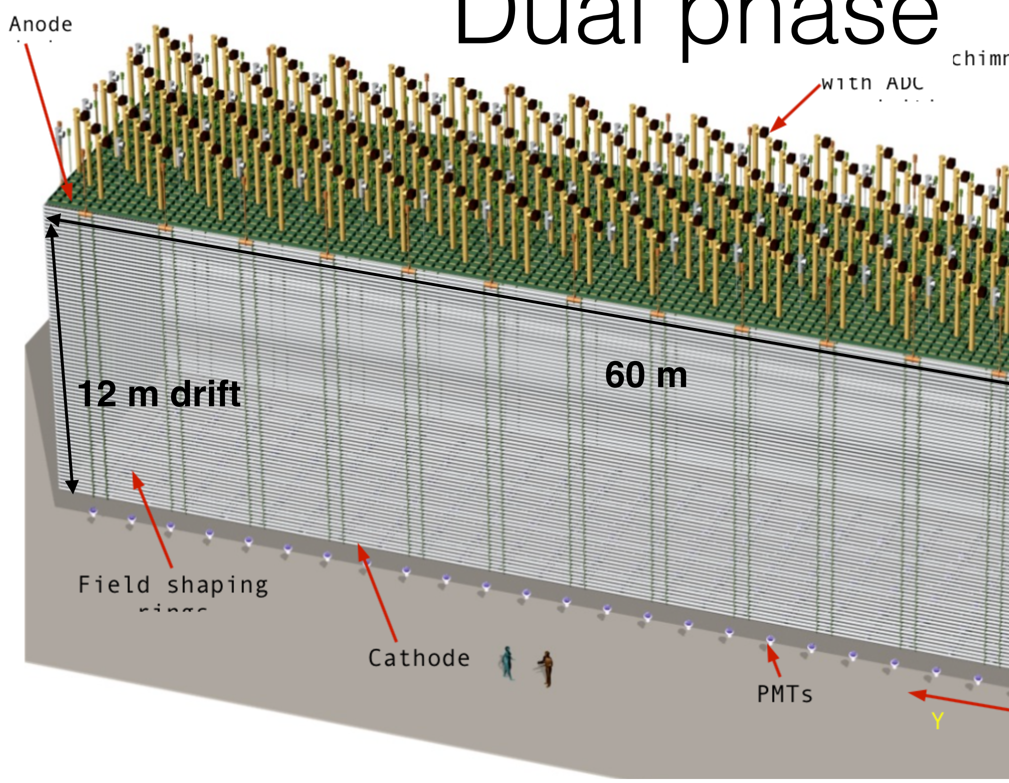
- **One 10-kt module 58m x 12m x 14.4m (~20x ICARUS)**
- **Reference design**
  - Alternating CPA/APA assemblies, 2.3m(w)x6.3m(h) modules
  - 4 wires planes (1 grid + 1 collection + 2 inductions), 4.8mm readout pitch, 3.6m drift path
  - **150 APAs** and **200 CPAs** / 10 kton
  - **384,000** ionisation readout channels
  - Embedded PD
  - Active mass **14’128 tons**, fiducial **10’200 tons**

Single phase



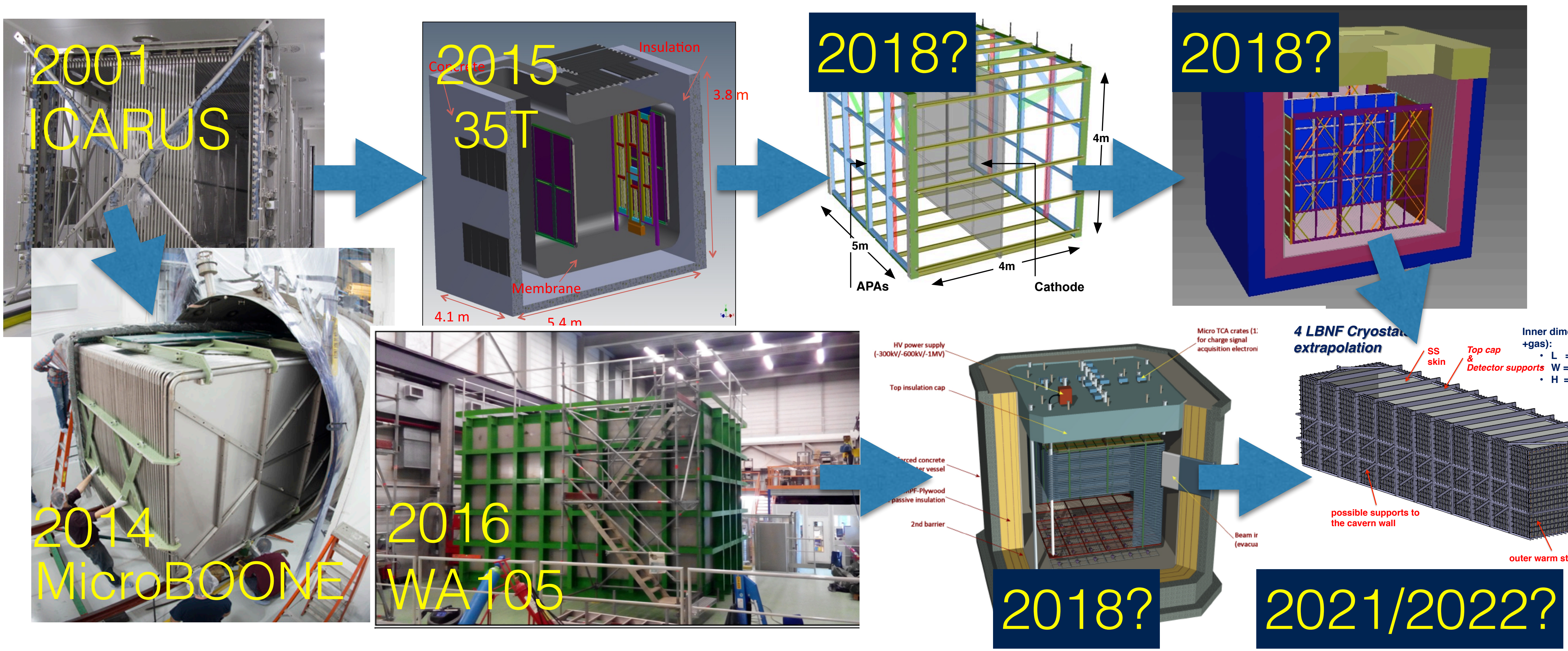
- **Alternate design**
  - 3x3m^2 CRP modules placed at the gas-liquid interface
  - 2 perpendicular “collection” views, 3mm readout pitch
  - **45 CRPs** / 10 kton
  - **153,600** ionisation readout channels
  - Hanging field cage and cathode - decoupled from CRP plane
  - Decoupled PD (w/ no. 720 8” PMT)
  - Active mass **12’096 tons** (**10’643 fiducial**) for 12m drift [15’120 tons (13’444 fiducial) for 15m drift]

Dual phase



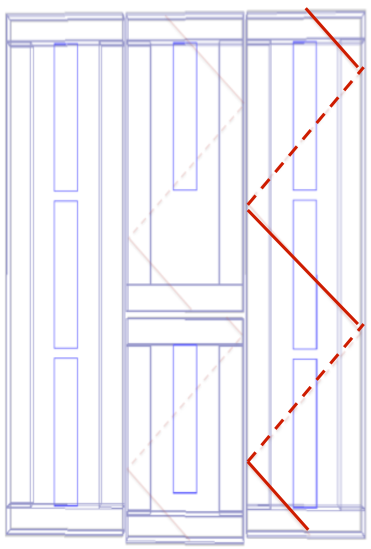
Far detector development path

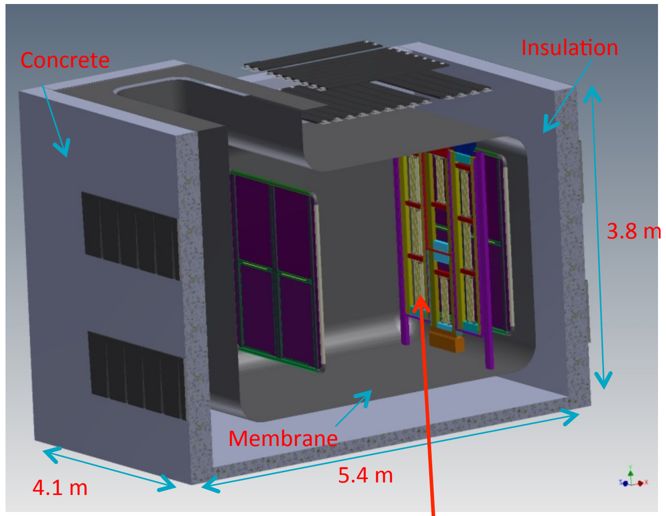
CERN Neutrino Platform (WA105 & single phase proto) and FNAL SBN provide the necessary development and prototyping for the DUNE FD reference and alternative designs.

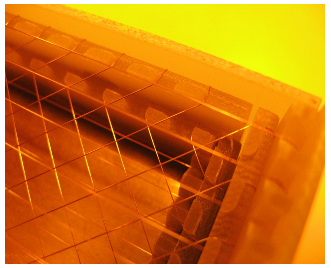


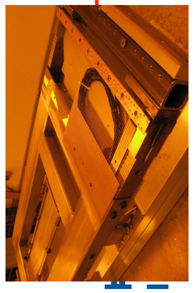
35 ton @ FNAL phase 2

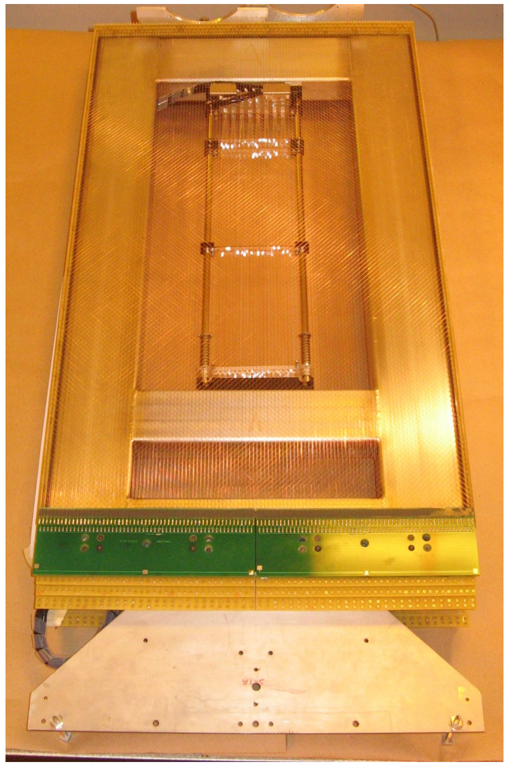
- 2.5m x 1.5m x 2m active volume
- Two drift volumes (long/short)
- 4 APA modules (8 sets of wires)

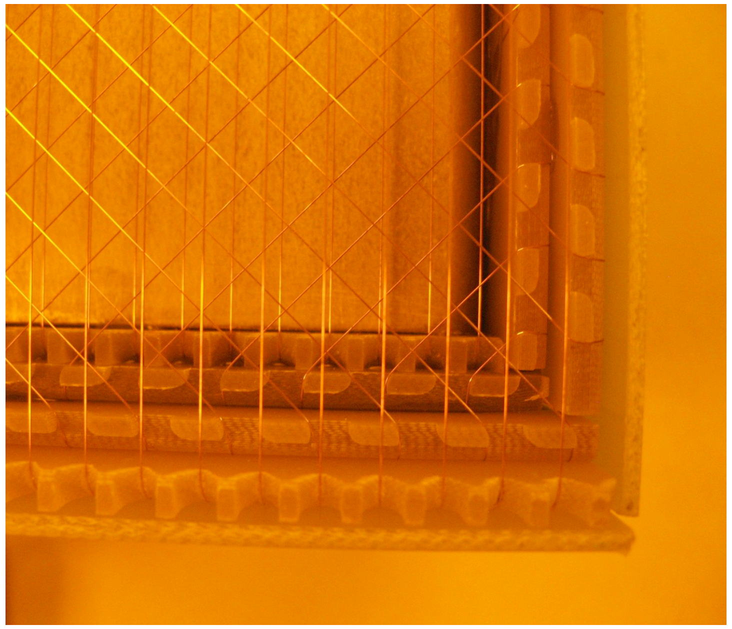




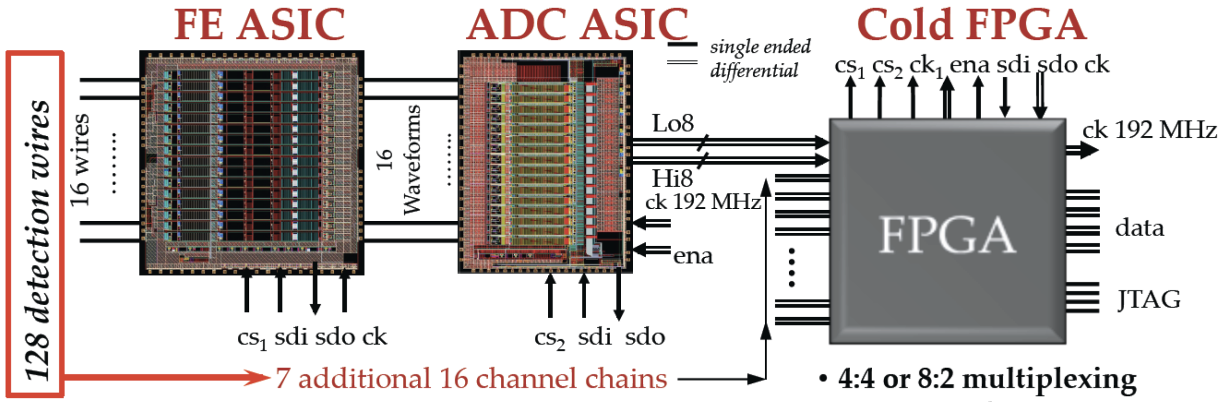








- Modular TPC performance:
  - wrapped wires
  - gaps between modules
  - tracks crossing APAs
- Bar+SiPM photon detectors
- Field Cage: FR4 printed circuit board
- Electronics/DAQ
  - cold pre-amp and ADC
  - triggerless operation (continuous readout)
  - zero suppression development



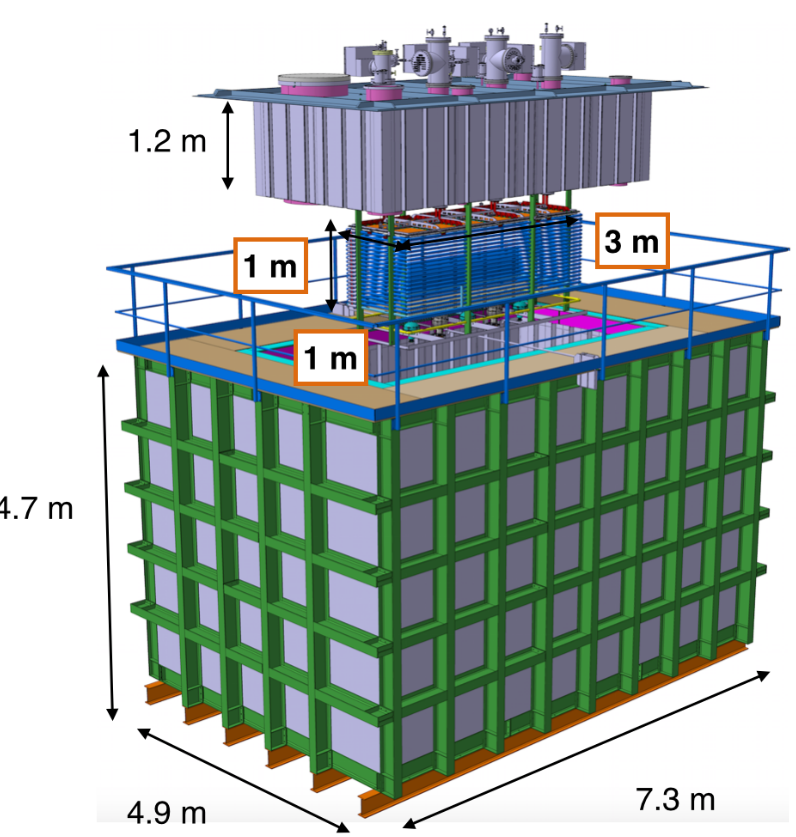
- low-noise analog amplification
- programmable gain, shaping, coupling, …
- charge calibration over all chips, channels and temperatures to 1%

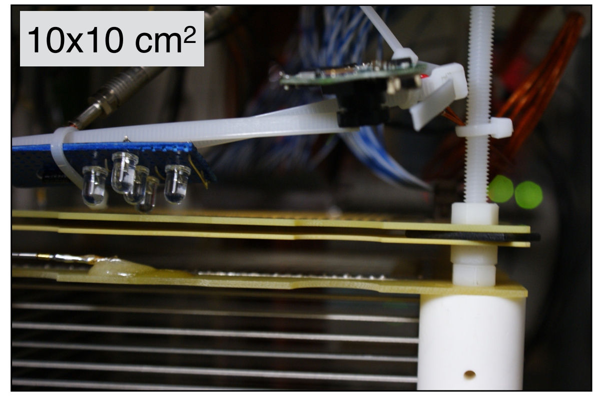
- ADC 12-bit 2MS/s sampling rate
- built-in FIFO
- serialized outputs
- 2 x **8:1 multiplexing**

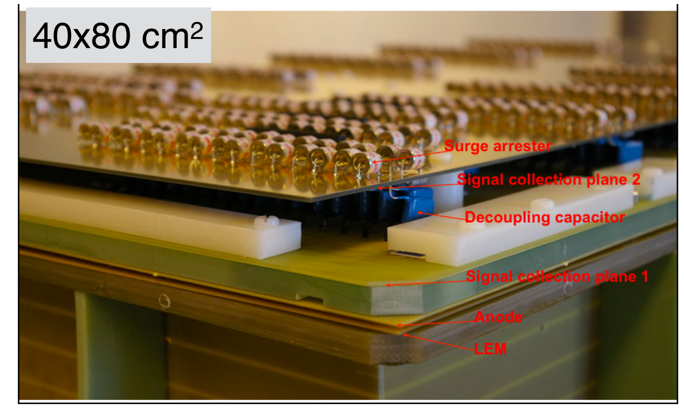
- **4:4 or 8:2 multiplexing** (total 32:4 or 64:2)
- timestamp
- compression
- zero suppression
- neighbor triggering
- *support non-reduction transparent mode*
- *max output data rate 960Mbit/s or 1.92Gbit/s with overhead of 8B/10B*

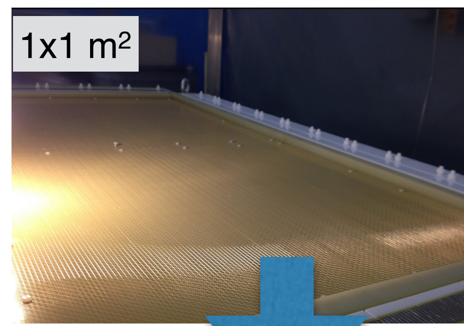
WA105 3x1x1m3 @ CERN

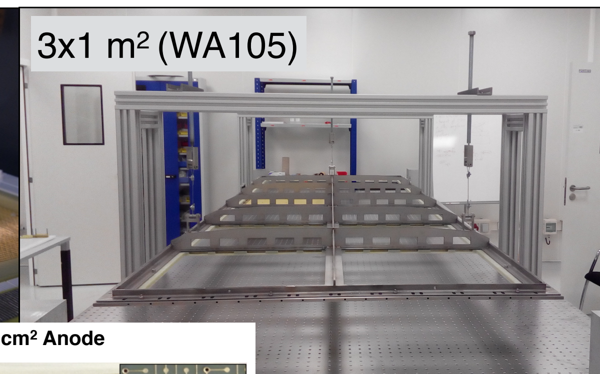
LAr-Proto
(3x1x1 m³ active 24 ton LAr total)

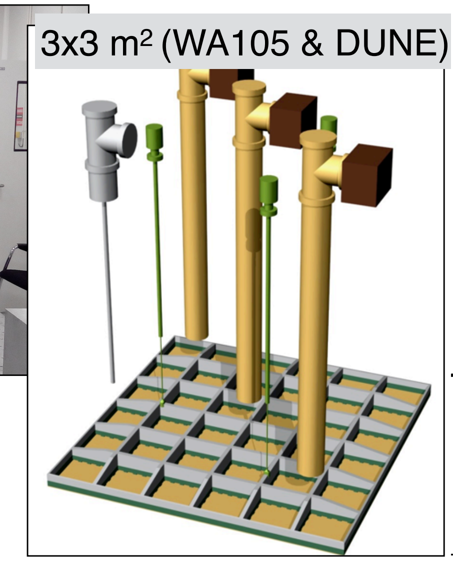


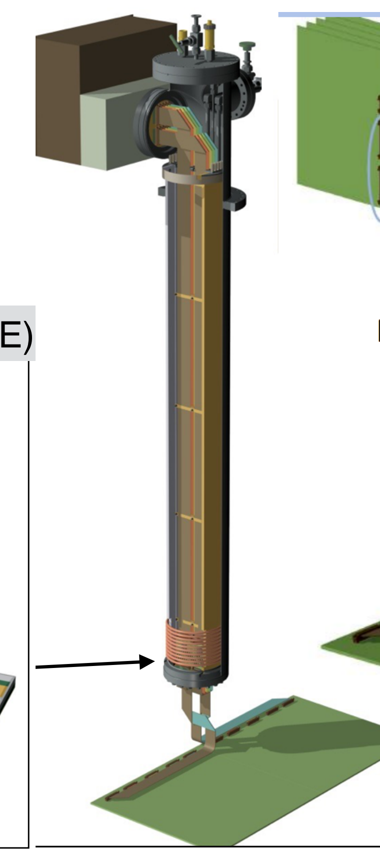


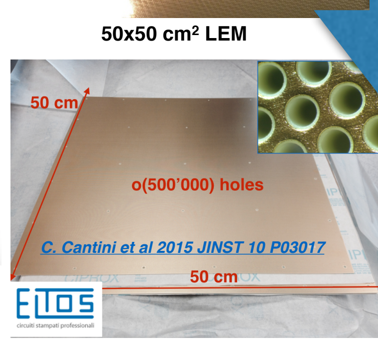


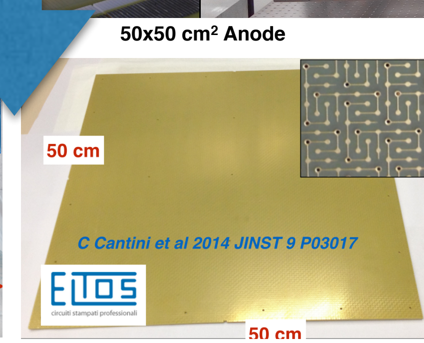




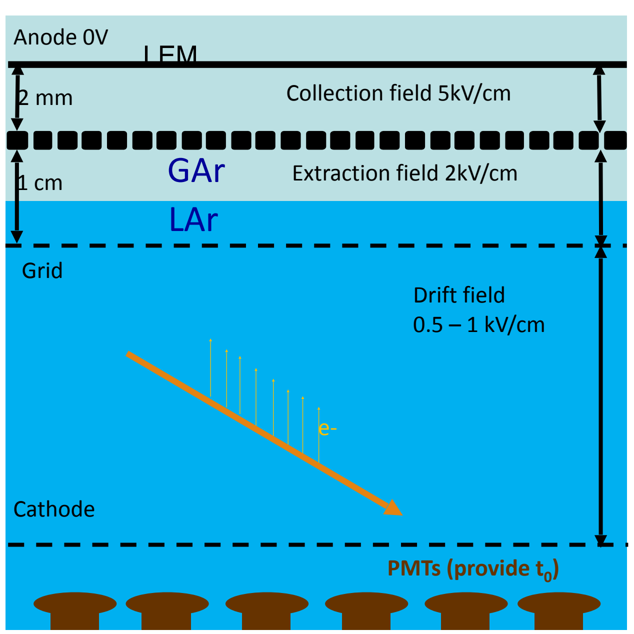








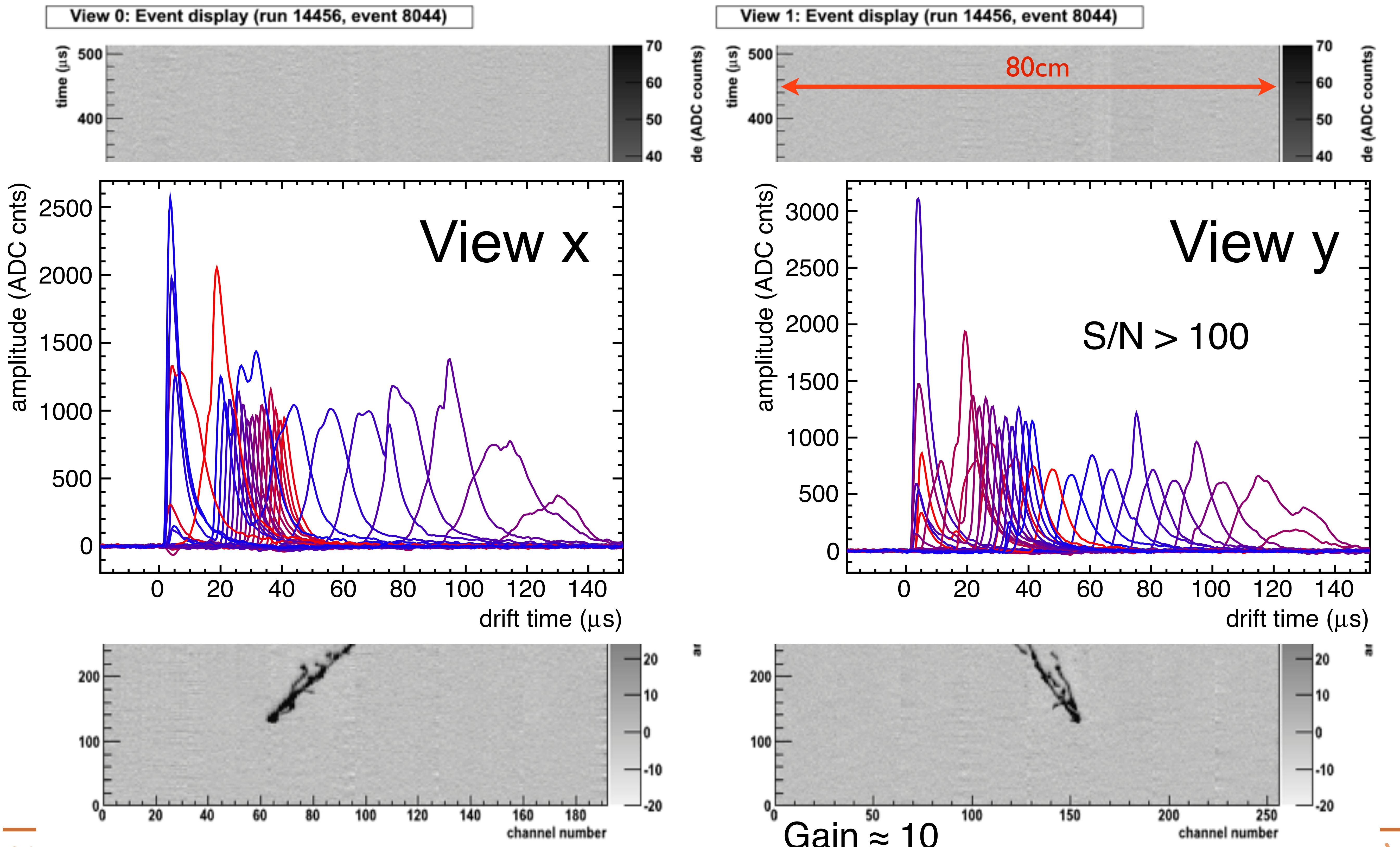
80 units for DUNE 10kton



- **Double phase ionisation readout (several years of R&D on small prototypes), field cage, PMT based light readout**
  - Extraction, amplification in holes (GEM-concept), segmented anode 3mm pitch, 2 x-y collection views
- **Accessible cold F/E electronics (lower risk than immersed electronics)**
- **17m3 cryostat under construction at CERN Blg 182**
- **Detector in procurement phase → integration in 2015**
- **Gas purging ≈ 2015?; Cryogenic operation ≈ 2016?**
- **Performance demonstration with cosmic rays**

CR events in dual-phase 200L proto

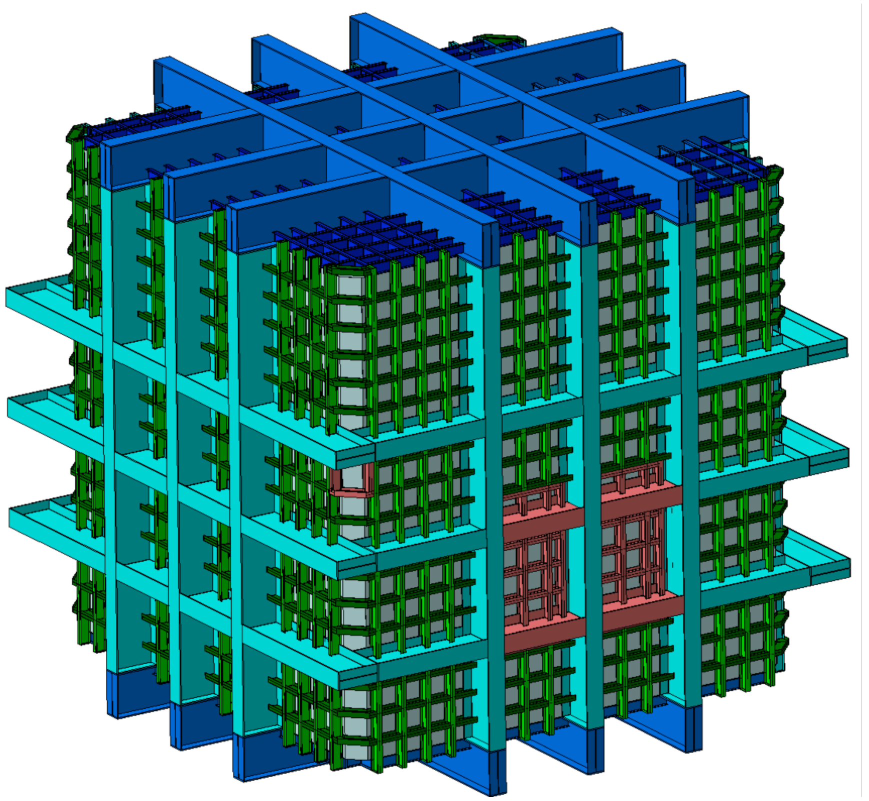
If demonstrated on large scale, potential advantages over single-phase approach →
Allows finer readout pitch, lower energy thresholds and better pattern recognition



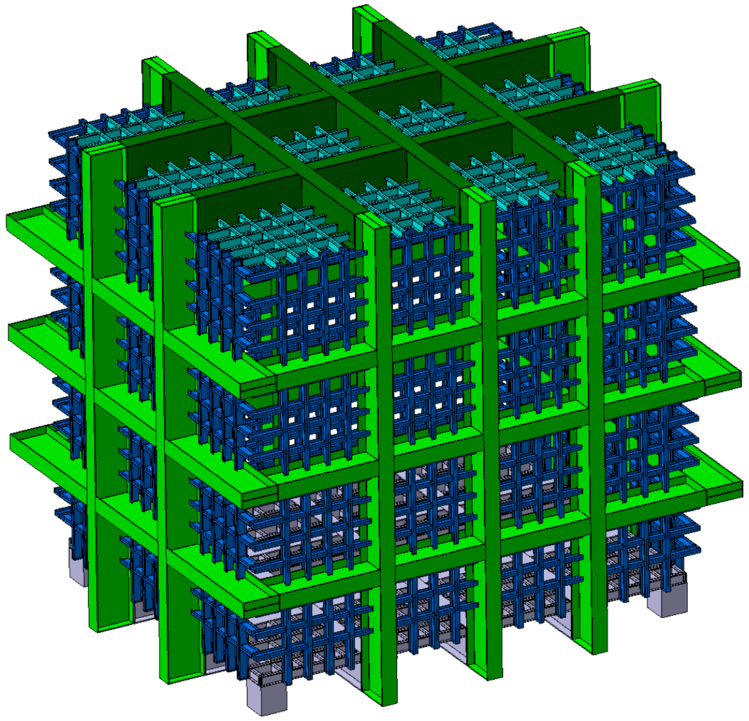
Large-scale prototypes @ CERN

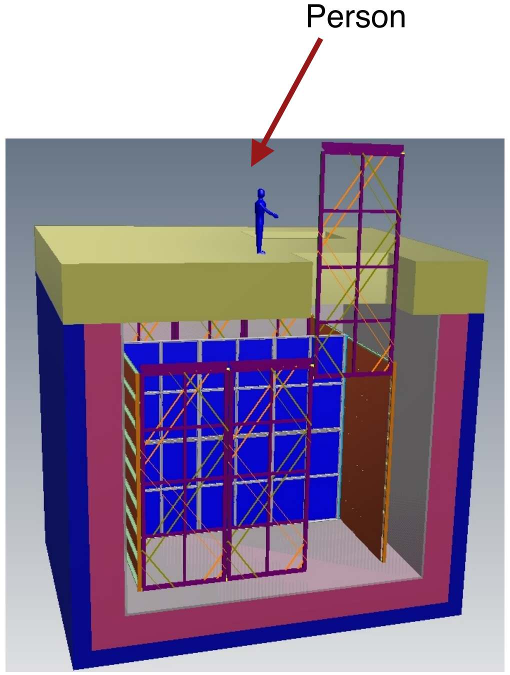
- **WA105 is approved for a 6x6x6m3 (300-ton) demonstrator.**
- **A single-phase prototype TDR was just submitted to SPSC committee (250-ton).**
- **<u>A) Prototype construction and commissioning:</u>**
  - Measure and benchmark detector performance of full scale detector components
  - Develop manufacturing capabilities at multiple sites
  - Test installation procedures and operation of full scale detector components
- **<u>B) Beam test at the new EHN1 extension</u>**
  - Assess Detector systematic uncertainties
  - Validate and tune MC simulations to data
  - Test reconstruction tools and PID
  - Study pion interactions, muon capture, anti-proton annihilation, ...

WA105 8x8x8 (524 m^3)



Single Phase Test Prototype (485 m^3)





The WA105 collaboration

WA105

22 institutes, 130 physicists

UNIVERSITY of OULU

UCL

Sofia University St. Kliment Ohridski, Bulgaria

CERN

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Ciemat
Centro de Investigaciones Energéticas, Medioambientale[s y Tecnoló]gicas

University of Jyväskylä

ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ РОССИЙСКОЙ АКАДЕМИИ НАУК
INSTITUTE FOR NUCLEAR RESEARCH OF RUSSIAN ACADEMY OF SCIENCES

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

Institut de Física d'Altes Energies IFAE

LPNHE PARIS

lapp

University of Glasgow

UNIVERSITÉ DE GENÈVE

cea SACLAY

ipnl

APC

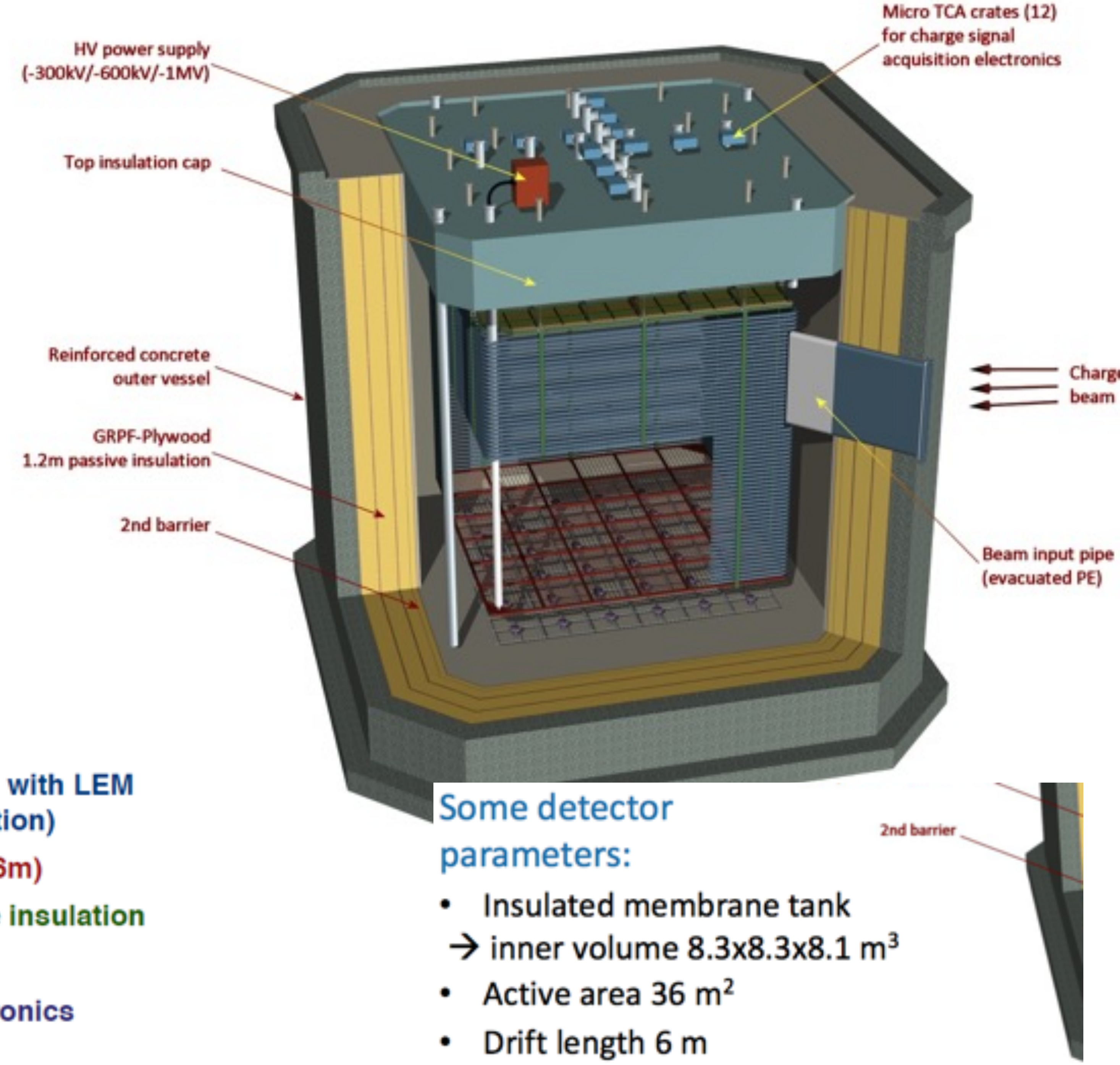
IN2P3
Institut National de Physique Nucléaire et de Physique des Particules

WA105 6x6x6m3 demonstrator

WA105

Technical proof-of-principle:

- ✳ Purity in non-evacuated tank
- ✳ Large hanging field cage structure
- ✳ Very high voltage generation
- ✳ Large area charge readout
- ✳ Accessible cold front-end electronics
- ✳ Long term stability of UV scintillation light readout



1. Longest drift in LAr (up to 6m)
2. Ionisation e- transverse and longitudinal diffusion
3. e- attenuation and its compensation by charge multiplication with LEM operating in gas phase (LEM gain uniformity/stability/calibration)
4. HV operation in the range 300kV-600kV (or 0.5-1 kV/cm over 6m)
5. Validation of the corrugated membrane cryostat with passive insulation
6. ≤100ppt O2-equivalent impurities in LAr in such a tank
7. Low-noise accessible ionisation charge signal readout electronics operating at low temperature (~110K)
8. Reachable and optimisation of S/N ratio
9. Verification of possible effects of positive ions (surface! - n/a underground)
10. Robust light readout (UV aging resistant), immersed electronics
11. First calibration of a LAr TPC with beam e-/μ/hadrons

Some detector parameters:

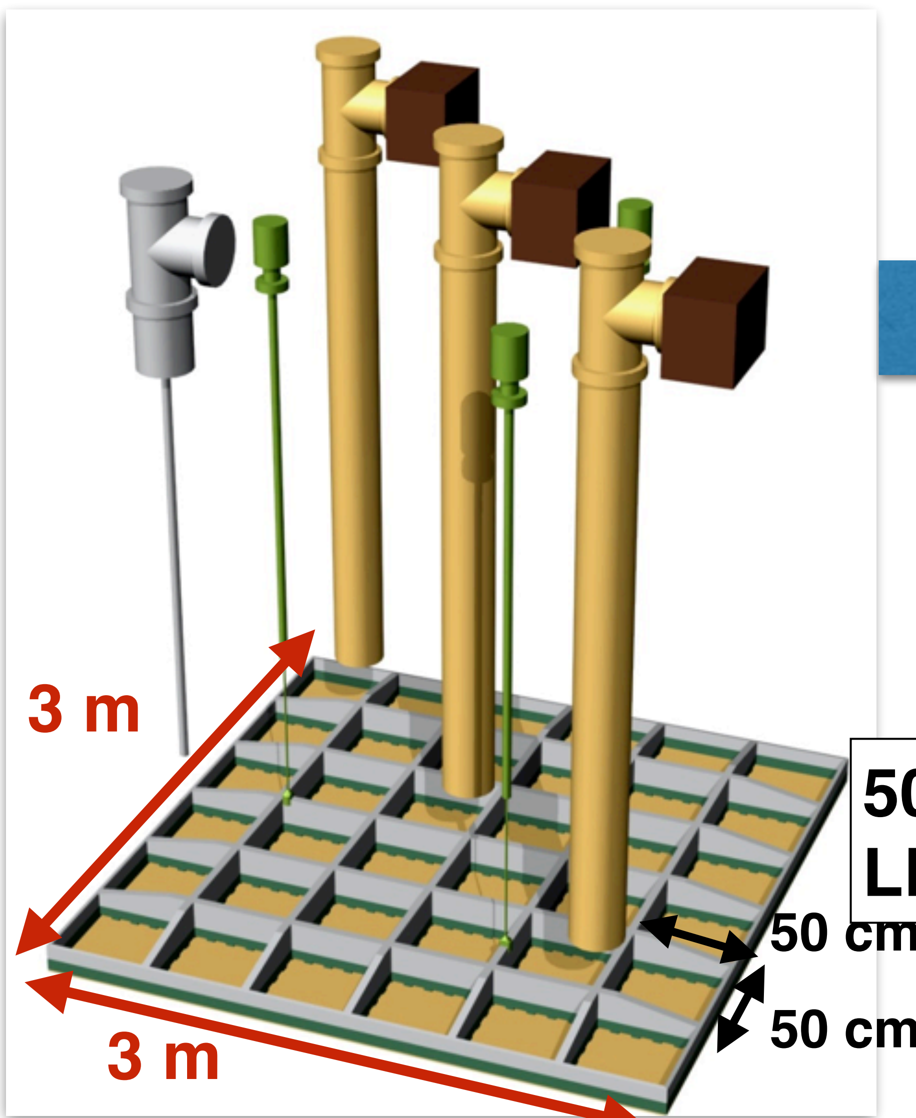
- Insulated membrane tank
  → inner volume 8.3x8.3x8.1 m^3
- Active area 36 m^2
- Drift length 6 m
- Total LAr mass 705 ton (~300 ton active)
- Hanging field cage & readout plane
- # of signal channels: 7680 in 12 signal FT
- # of PMTs: 36

WA105 6x6x6m3: Charge readout plane

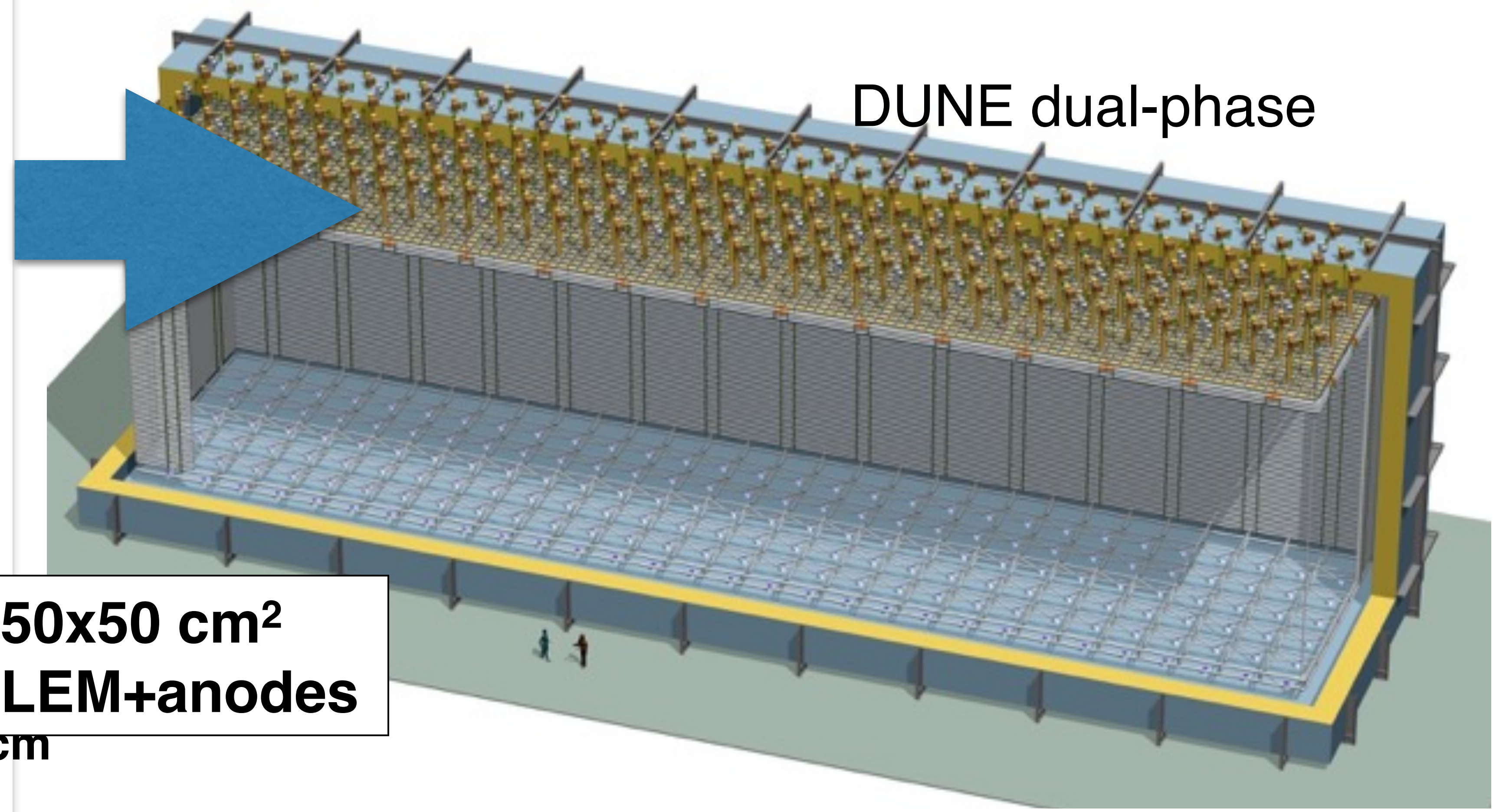
The extraction grid LEM and anodes are all combined in **independent modules of square meter scale** adjustable to the LAr level: **the charge readout plane (CRP)**

extraction grid-LEM and anode all in one single module

example of a 3x3 m² CRP



50x50 cm²
LEM+anodes

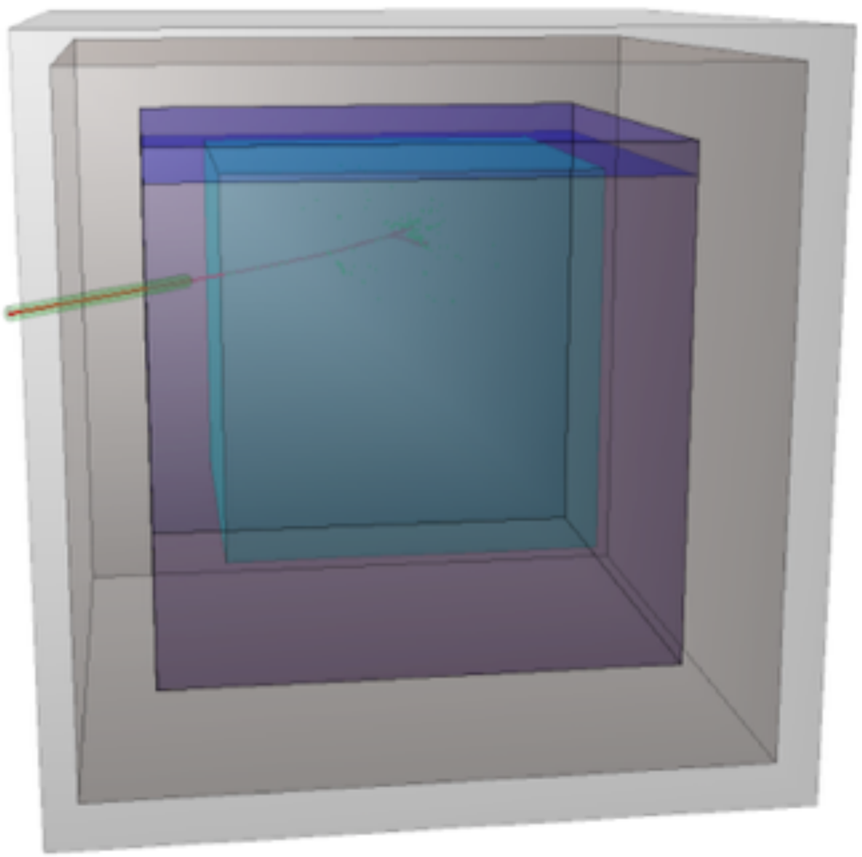


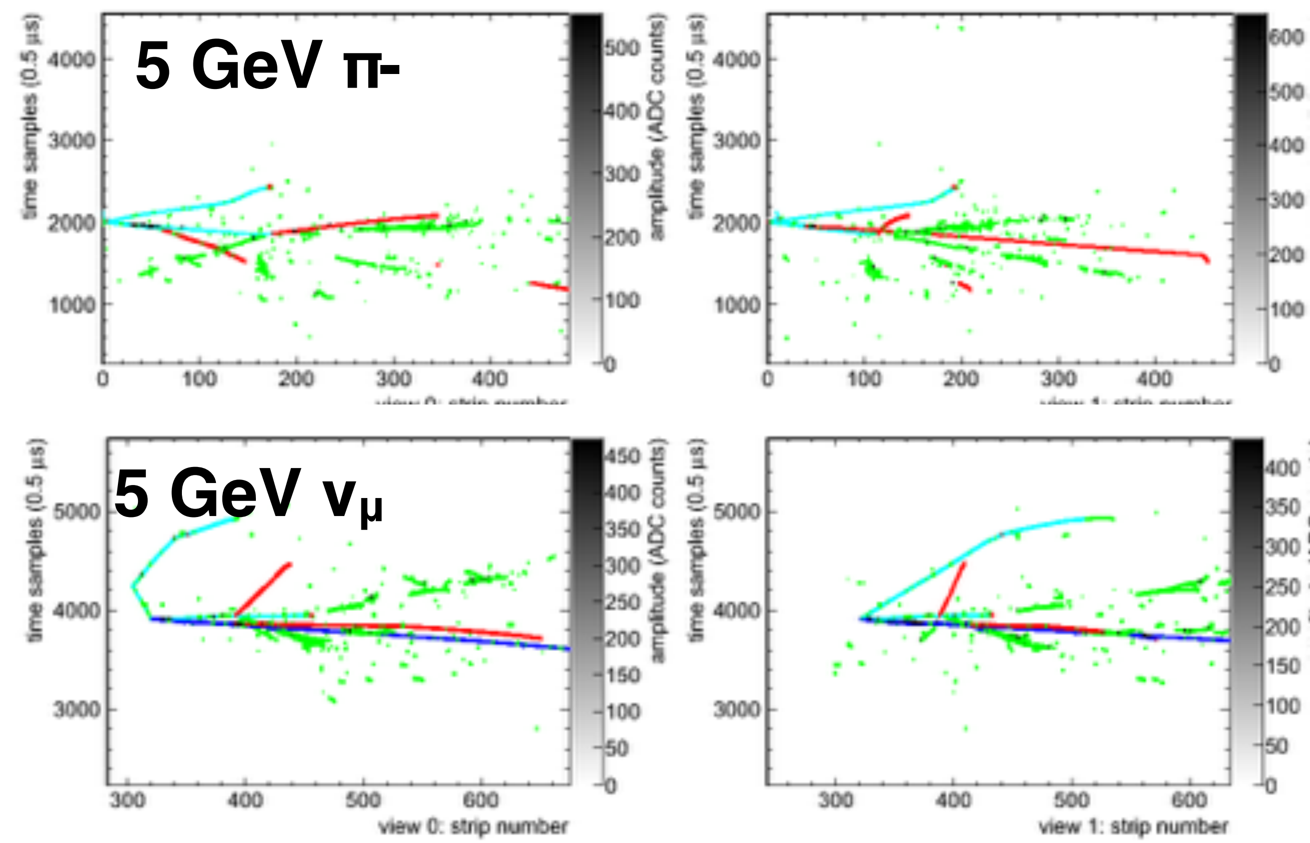
Important physics milestone

WA105

Test reconstruction on fully contained events from charged particle beam (well defined primary particles and energies)

pions, electrons/positrons, protons, muons





- LAr TPC provide a fully active homogeneous medium
- High granularity 3x3 mm^2 ← two orders of magnitude better than most granular calorimeters
  - e.g., CALICE AHCAL prototype has 3x3 cm^2
- Additional handle from dE/dx

Opportunity to provide unprecedented measurements of hadronic shower development to HEP community

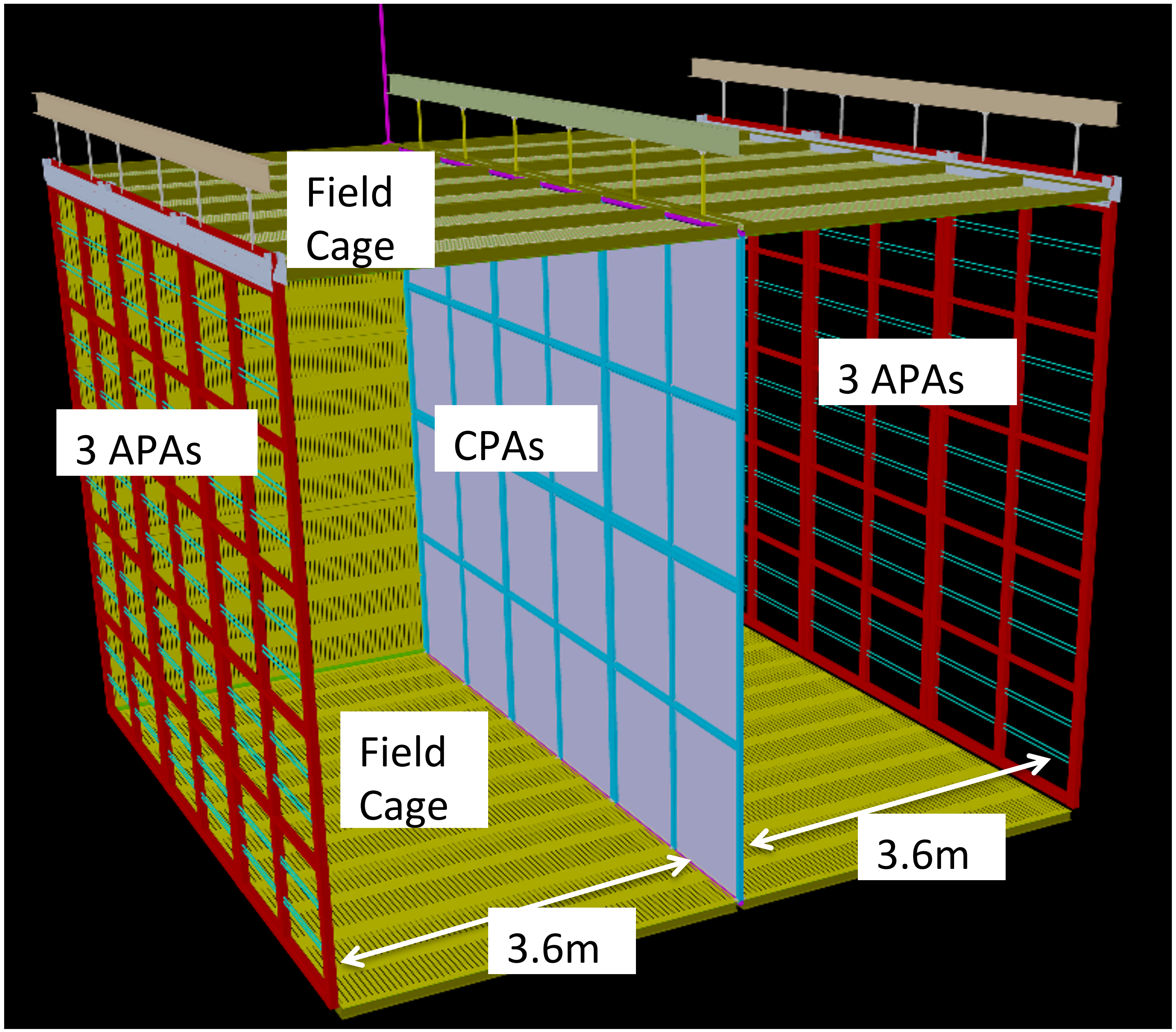
Some goals

- Development of automatic event **reconstruction**
- **test NC background rejection** algorithms on "ν_e free" events
- Charged **pions** and proton **cross-section** on Argon nuclei.

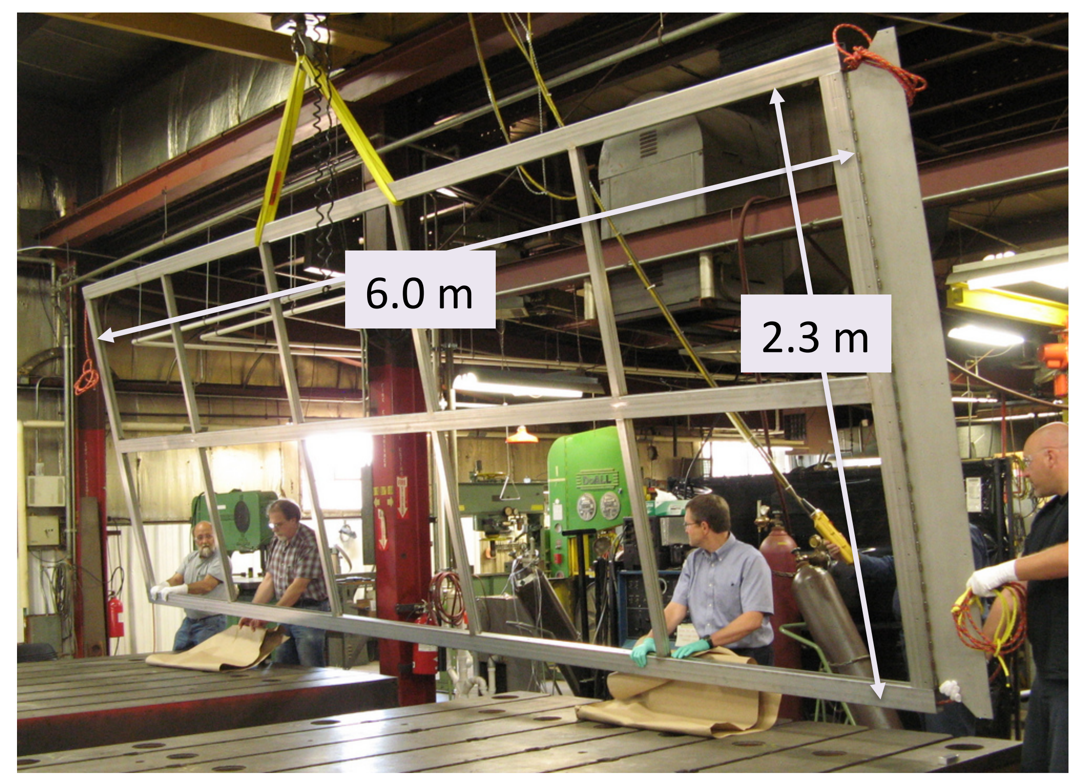
Single-phase test prototype (WA10x)

US-UK driven effort

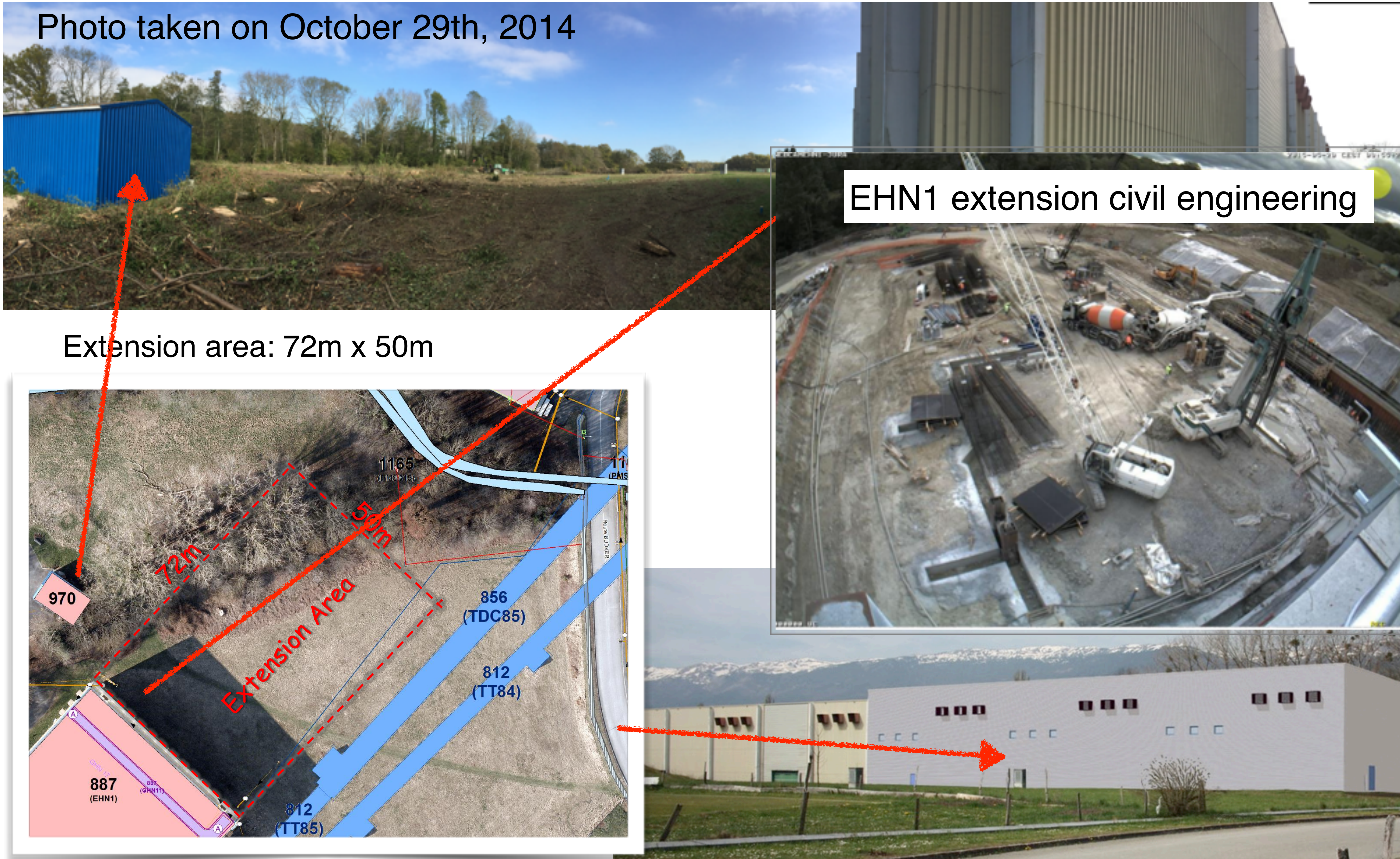
internal dimensions: **7.8 m (Transv) x 8.9 m (Parallel) x 8.1 m (Height)**
external dimensions: **10.6m (Transv) x 11.7 m (Parallel) x 11.0 m (Height).**



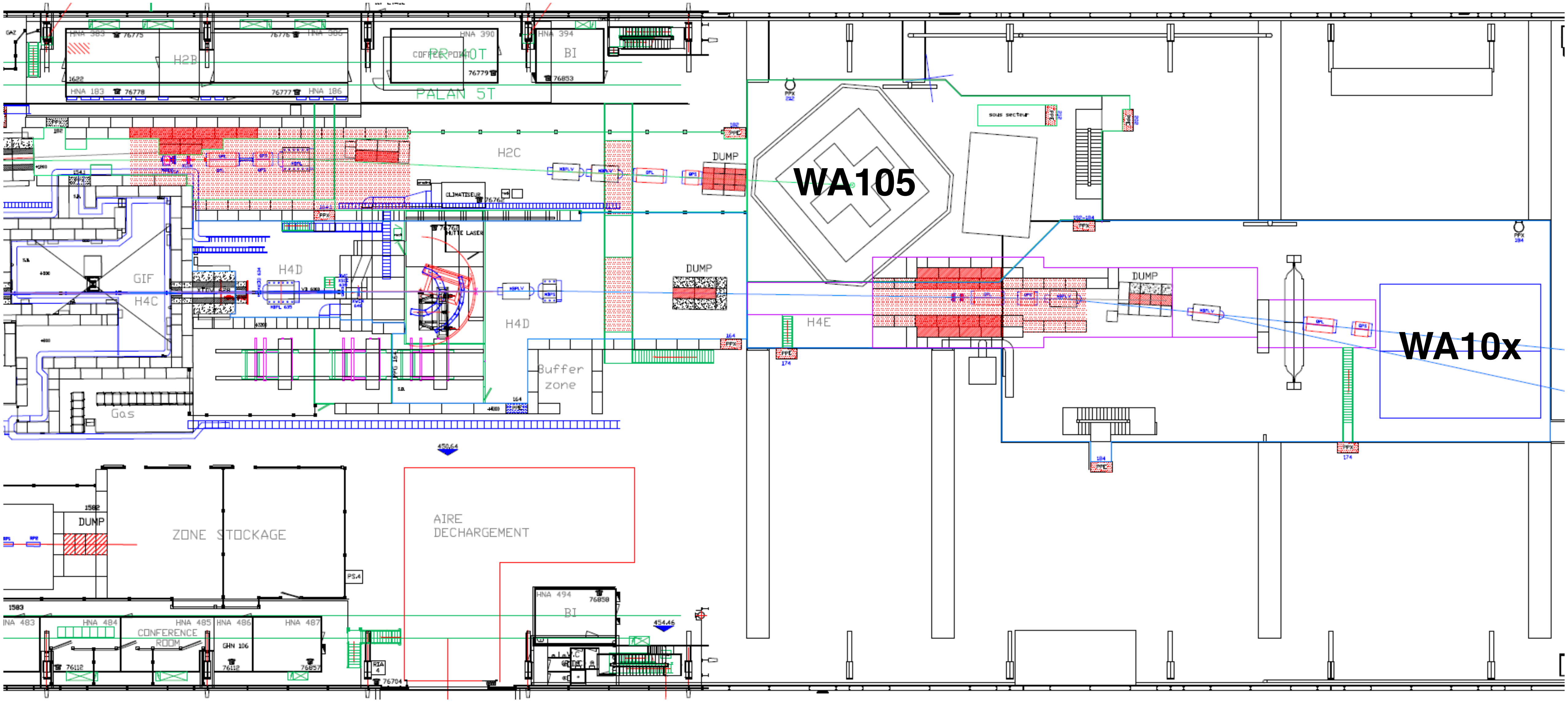
Test detector components
- Full scale
- Same design as for DUNE 10 kt single phase



North Area Extension (EHN1-X)

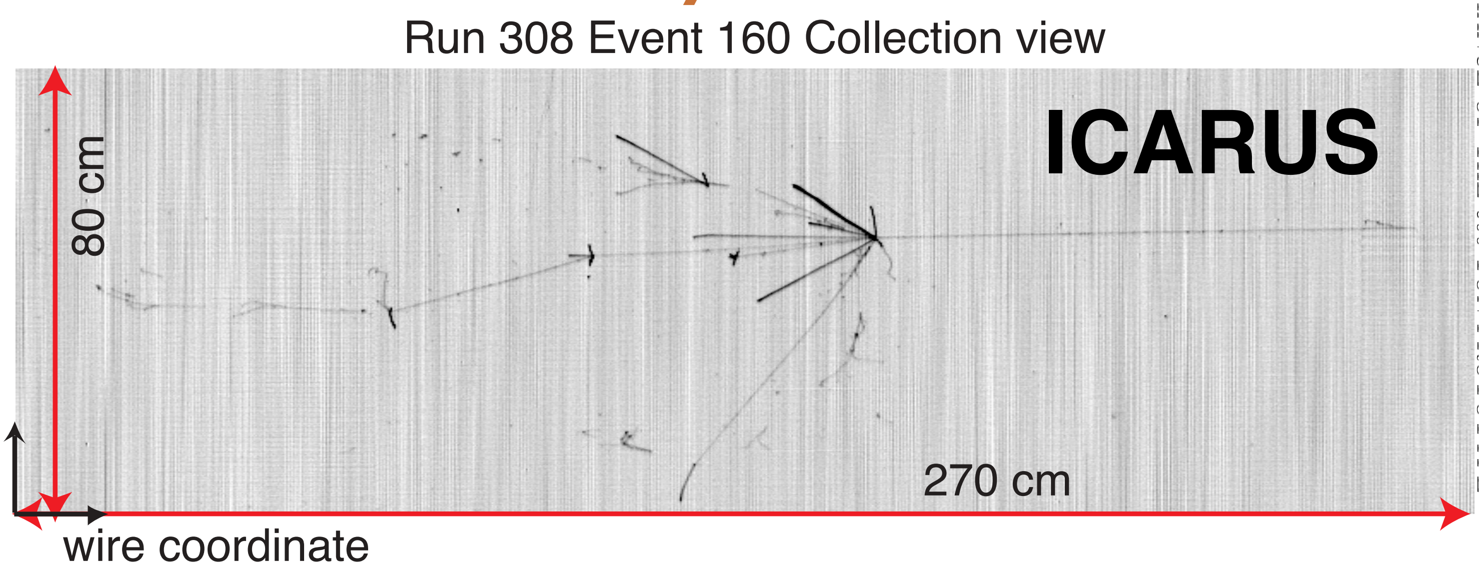


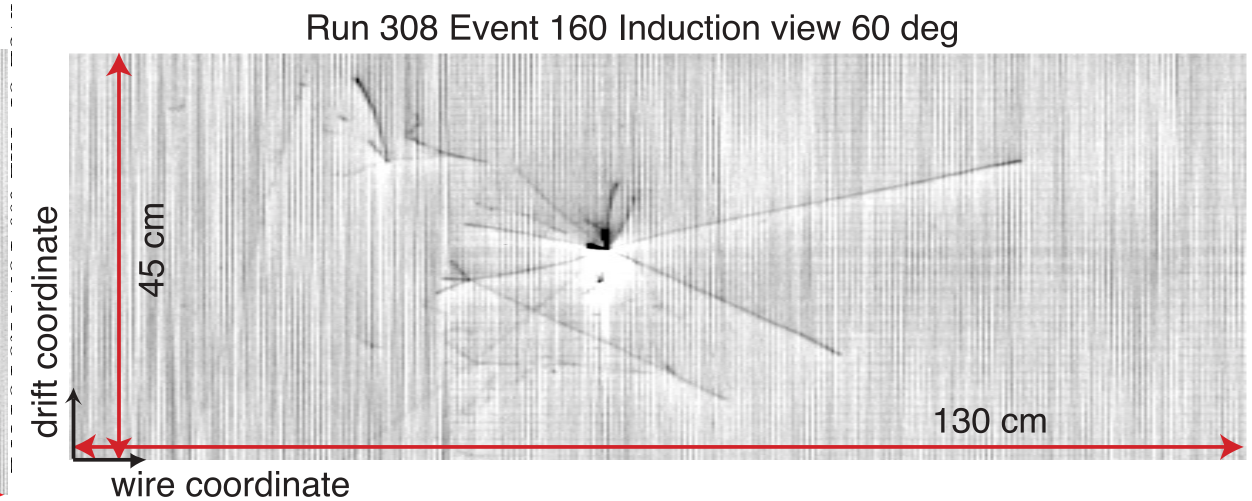
H2/H4 VLE Extension - beam layout

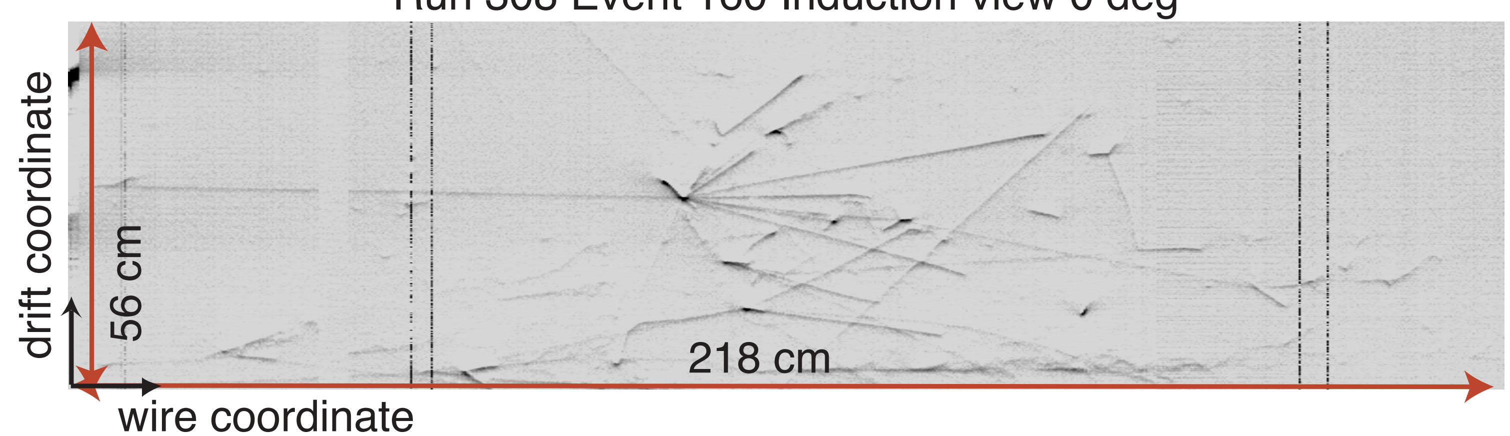


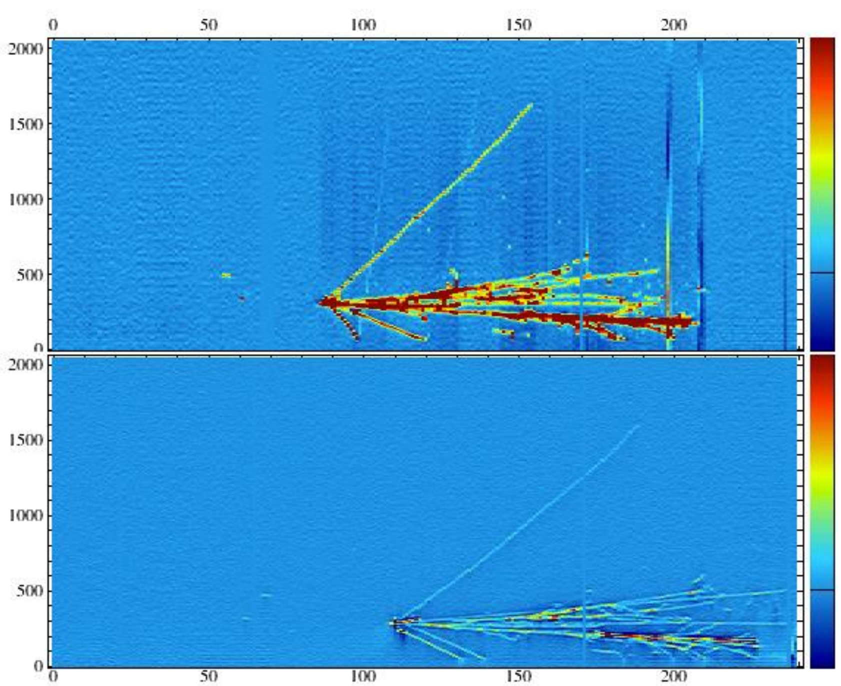
- **H2** extension to **WA105** cryostat: **1(0.5) ÷ 12 GeV** tertiary beam
- **H4** extension to **DUNE** cryostat: **1(0.2) ÷ 7 GeV** tertiary beram
- Beam characteristics:
  - Use secondary beam of 80 Gev (π/p, or e) to produce the tertiary low-energy beams on a secondary target
  - VLE beams : mixed **hadrons** ($\pi^{\pm}$, $\mu^{\pm}$, $K^{\pm}$, p), ~pure **electron** ($e^{\pm}$) beams

Software / reconstruction / simulation

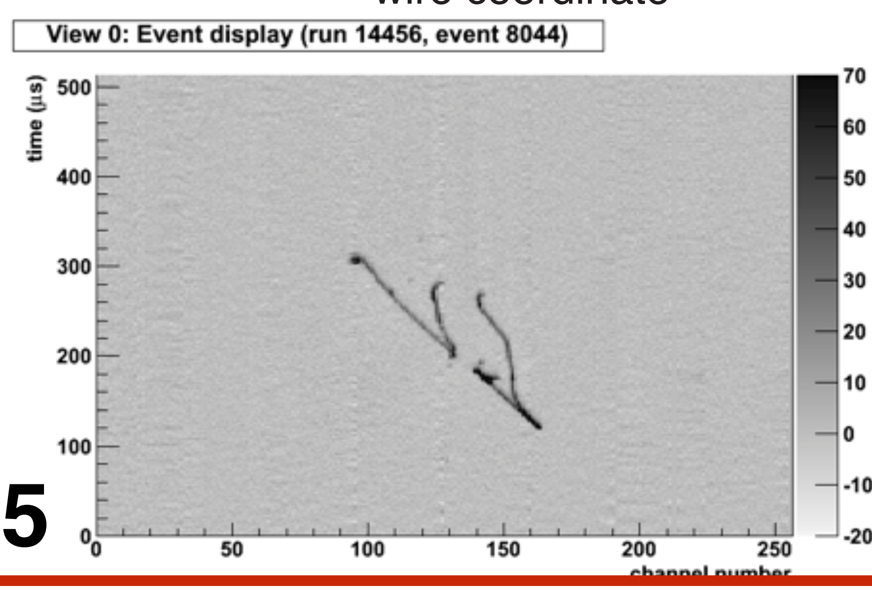


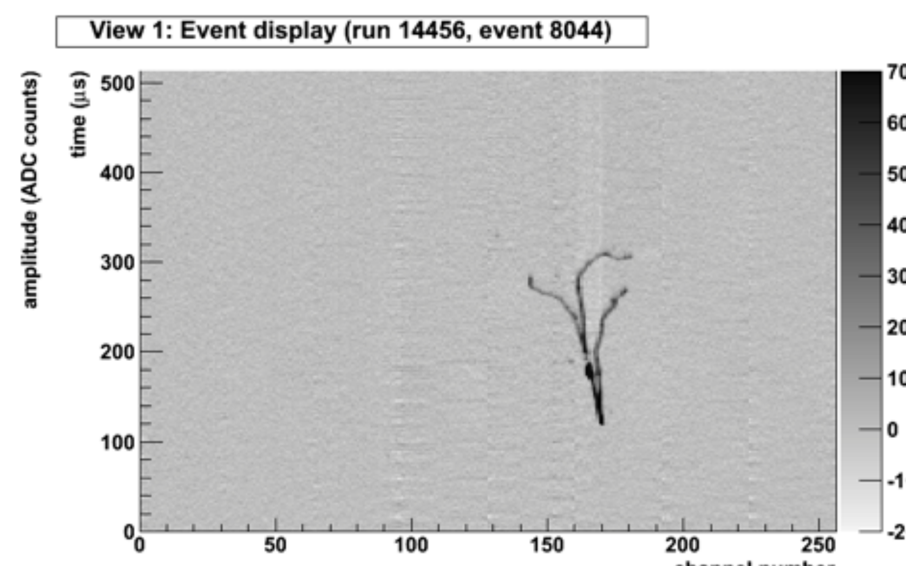






ArgoNEUT

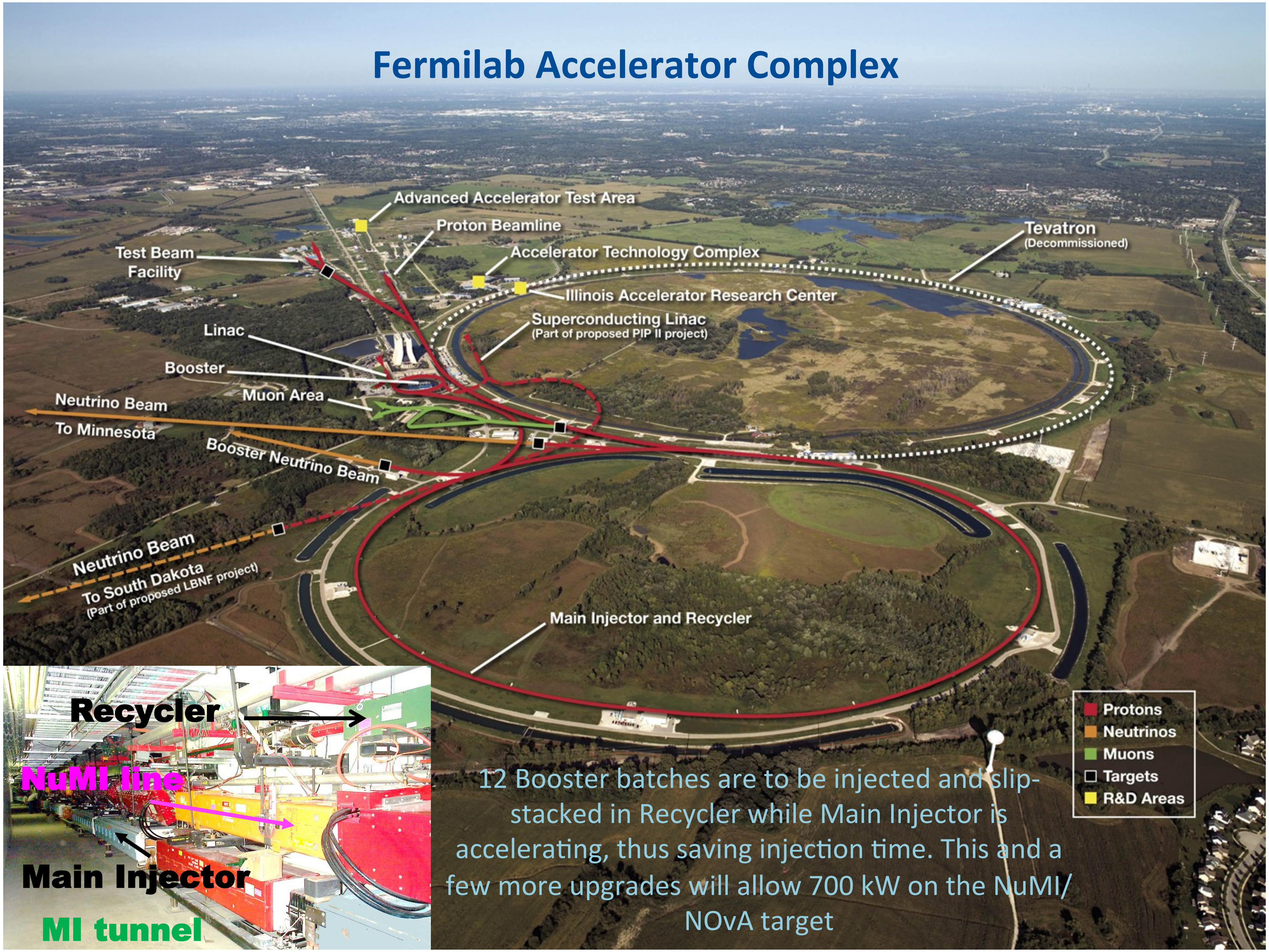




WA105

Unified SW/comparison of performance is critical

FNAL accelerator complex



12 Booster batches are to be injected and slip-stacked in Recycler while Main Injector is accelerating, thus saving injection time. This and a few more upgrades will allow 700 kW on the NuMI/NOvA target

Accelerator improvement plans (PIP, PIP-II)

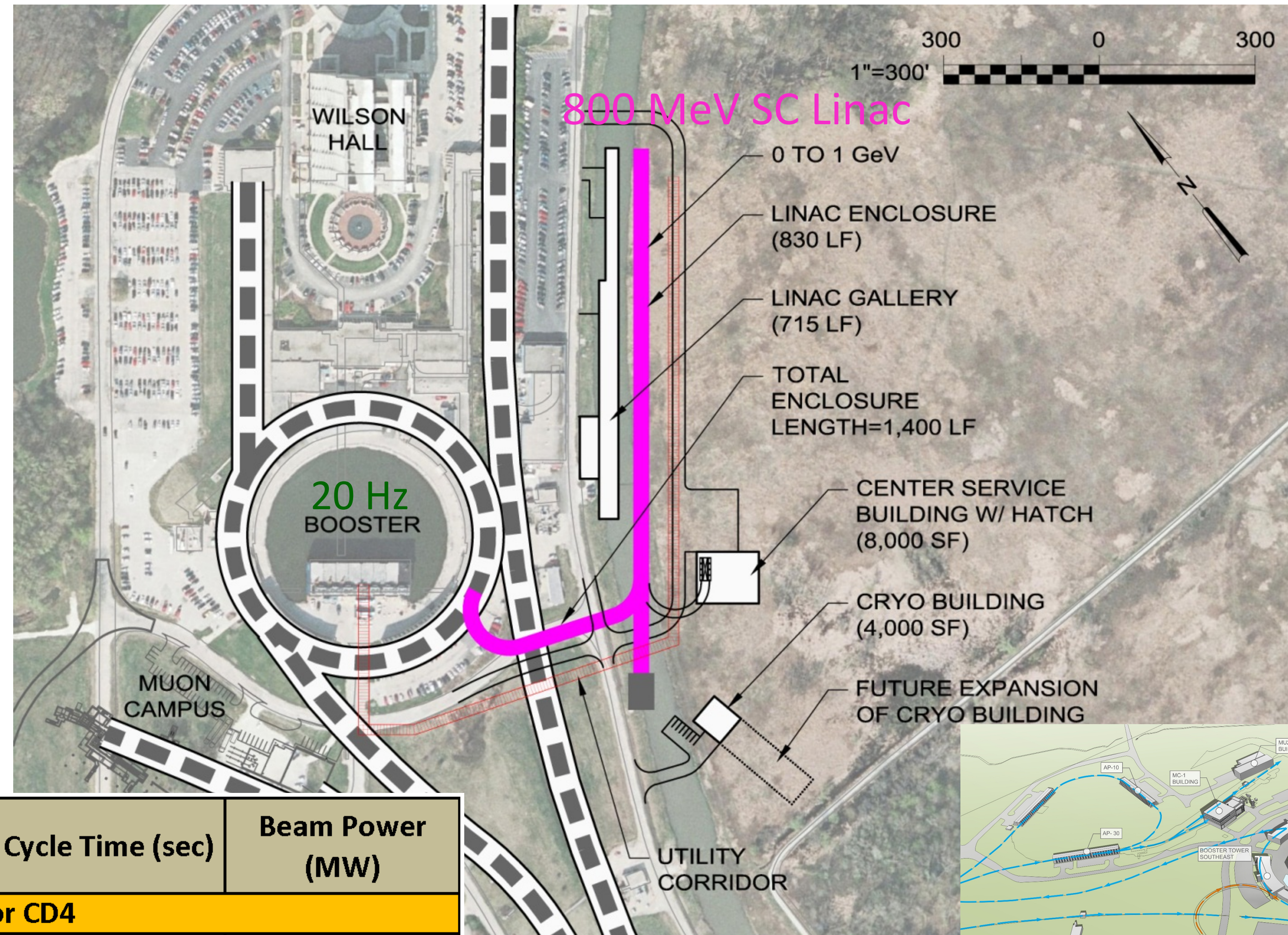
- Since November 2014, the Main Injector (MI) has been delivering 2.4×10^{13} ppp at 120 GeV every 1.333 s by using the Recycler as a proton stacker (6 batches, no slip- stacking).
- On March 5th, 2015 it switched to 2+6 operation, delivering during the past month ~425 KW average beam power.

On April 27th, 2015 achieved new MI Beam Power record of 483 KW (running without SY120).

- Plan to demonstrate 4+6 operation in June 2015, before the summer shutdown and achieve 575 kW in Nov. 2015. (19 re-furbished Booster RF stations, 7.5 Hz operation).
- Achieve 700 KW with 6+6 operation - Feb. 2016 (20 re-furbished Booster RF stations, 9 Hz operation).
- PIP-II: 1.2 MW (~ 2024) – 800 MeV superconducting Linac, 20 Hz Booster, MI cycle time of 1.2 s.

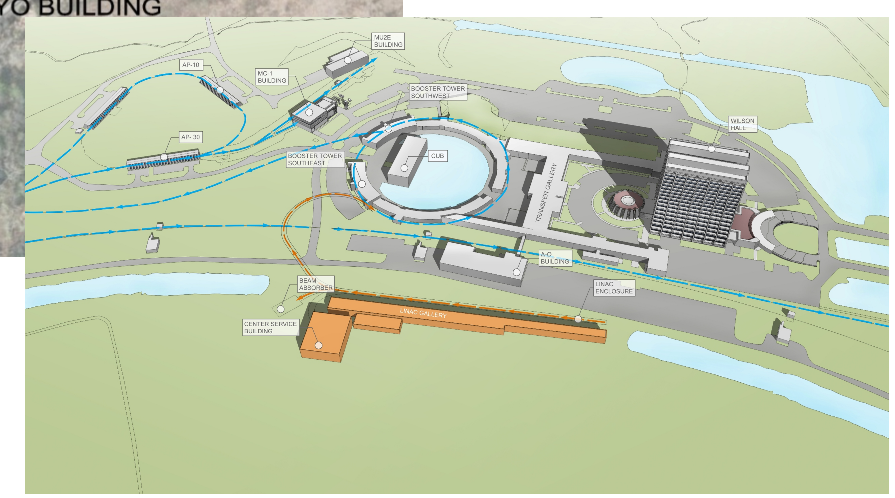
Proton Improvement Plans – PIP-II & III

- PIP-II:
  New SC linac
  800 MeV protons →
  1.2 MW by ~**2024**
- PIP-III:
  Plan for 2.4 MW
  protons with by
  ~**2030**
  (Linac or RCS)



CD-0 review planned for June 2015

Beam Power
(1.03 – 1.2) MW
p momentum
(60-120) GeV/c



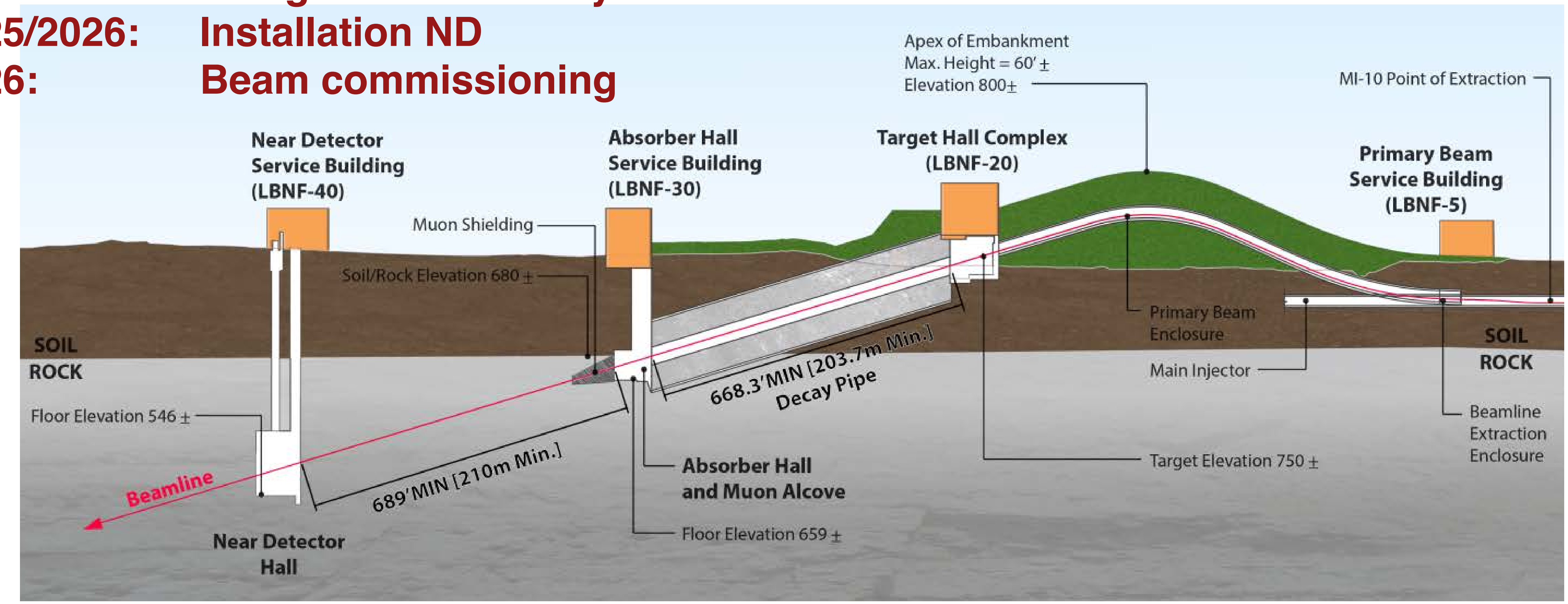
Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for CD4			
Proton Beam Energy (GeV):			
60	**7.5E+13**	**0.7**	**1.03**
80	**7.5E+13**	**0.9**	**1.07**
120	**7.5E+13**	**1.2**	**1.20**
≤ 2.4 MW Operation - Ultimate Maximum Value LBNF Final Phase			
Proton Beam Energy (GeV):			
60	**1.5E+14**	**0.7**	**2.06**
80	**1.5E+14**	**0.9**	**2.14**
120	**1.5E+14**	**1.2**	**2.40**

(1.1 – 1.9)x10^{21} POT/yr

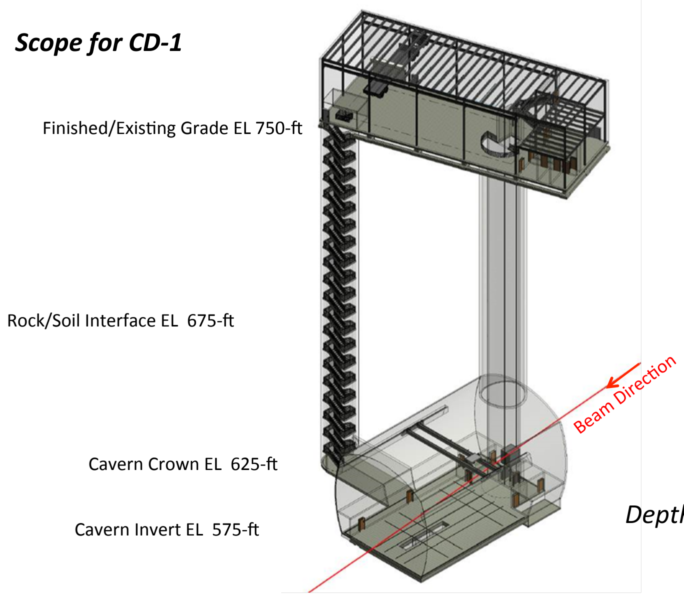
Pulse duration: 10 ms
Beam size at target: tunable 1.0-4.0 mm

LBNF neutrino beamline

2019: CD-2 approval
2021-2025: Design and assembly
2025/2026: Installation ND
2026: Beam commissioning



NEAR HALL

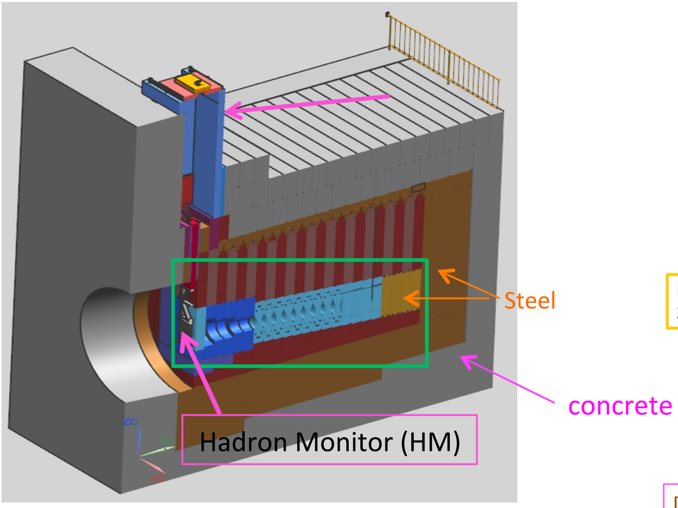


Option to be considered after CD-1:

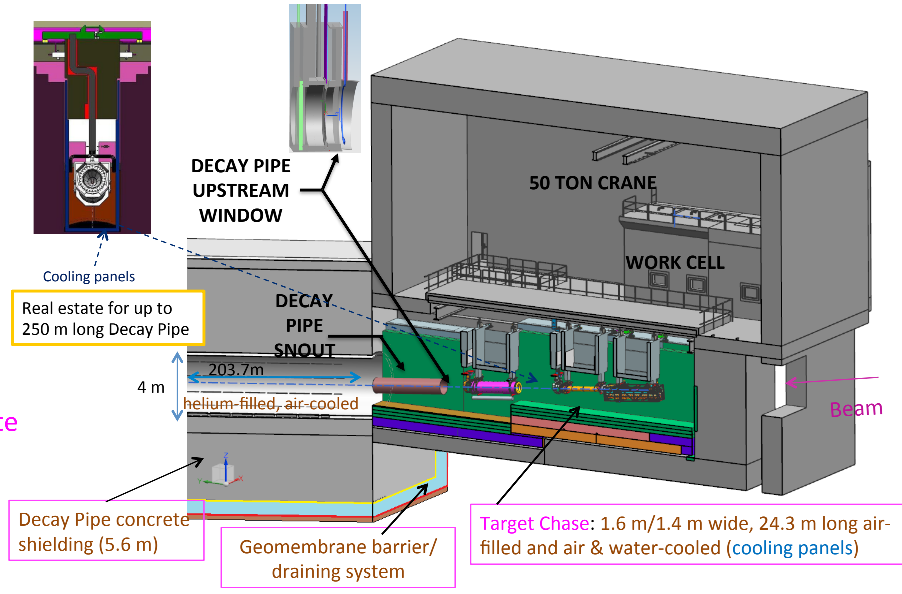
Excavate ~x2 larger underground cavern to provide future facility for additional neutrino detector / experiment

Depth ≈ 200 feet (or ≈61m)

HADRON ABSORBER

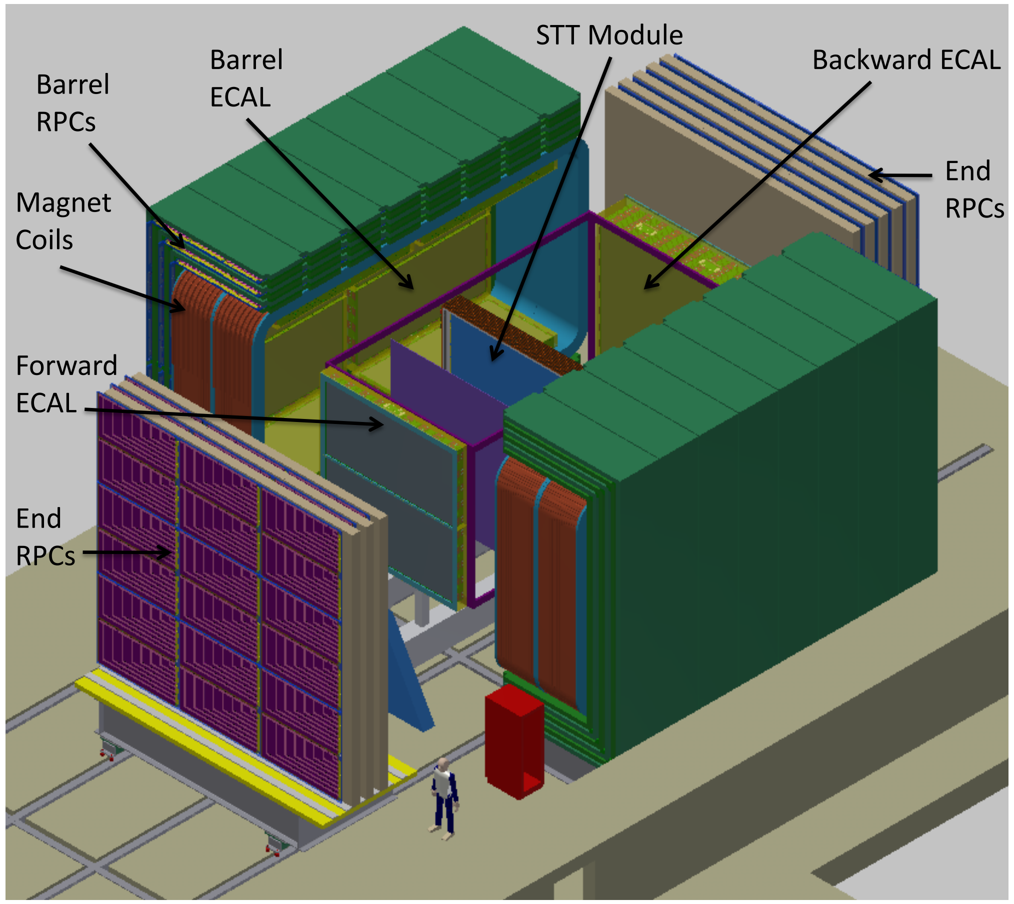


TARGET HALL



DUNE Near Detector

- A highly-capable neutrino detector which provides the required information for LBL goals and a rich physics program on its own.
- Fine-grained tracker (FGT) magnetised neutrino near detector.
- A LAr TPC target may be added for comparison with FD [need measures for event pileup at high beam power].
- May be advantages of deploying a high-pressure gaseous argon TPC [upgrade of the FGT tracker]
- O(100millions) νμ CC events expected per 10 ton target



Performance Metric	FGT
Dipole magnetic field	0.4 T
Average target/tracker density	$\rho \sim 0.1$ g/cm^3
Target/tracker Volume	3.5m x 3.5m x 6.4m
Target/tracker Mass	8 t
Vertex Resolution	0.1 mm
Angular Resolution	2 mrad
E_e Resolution	5%
E_μ Resolution	5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
NCπ^0/CCe Rejection	0.1%
NCγ/CCe Rejection	0.2%
CCμ/CCe Rejection	0.01%

Recent Director's Review (June 2-4)

- ***Findings (Detector section)***
  - *The conversion of LBNE/LBNO to LBNF and DUNE has brought significant changes and new opportunities for the detectors. International collaborators will now make major contributions to the near detector and the far detector.*

- ***Executive Summary:***
  "The committee determined that the project is developing well and has a strong, capable project teams in place to develop and execute the project. All of the charge questions were answered positively. The consolidated and reconfigured project has developed rapidly and is progressing well. The committee feels that the DUNE/LBNF will be prepared for the DOE CD-1 refresh review."

Outlook

- DUNE/LBNF is becoming a highly motivated, experienced and well-organised international team that has the necessary expertise to accomplish this program.
- DUNE/LBNF have developed a clear plan for reaching the P5 goals in a timely manner
  - The FNAL accelerator complex is being upgraded to continue to provide the most powerful neutrino beams and a MW-class neutrino beam will be constructed.
  - The design and prototyping towards the deployment of four 10-kt far detector modules at SURF 4850L is ongoing.
  - The performance of the more conservative single-phase design will be assessed in the single phase prototype at CERN and the dual-phase design will be tested on a large scale by the approved WA105 programme. The dual-phase design, if demonstrated, will bring improved performance for the far detector consecutive modules.
  - The near detector will provide the capability to constrain the systematic errors for the LBL goals and will bring a generational advance in neutrino measurements due to its high-granularity, high-precision and very large statistics.
- DUNE will address many of the most interesting open questions in neutrino physics, and will likely lead to new discoveries, e.g. CP-violation in the leptonic sector.

Thank you !