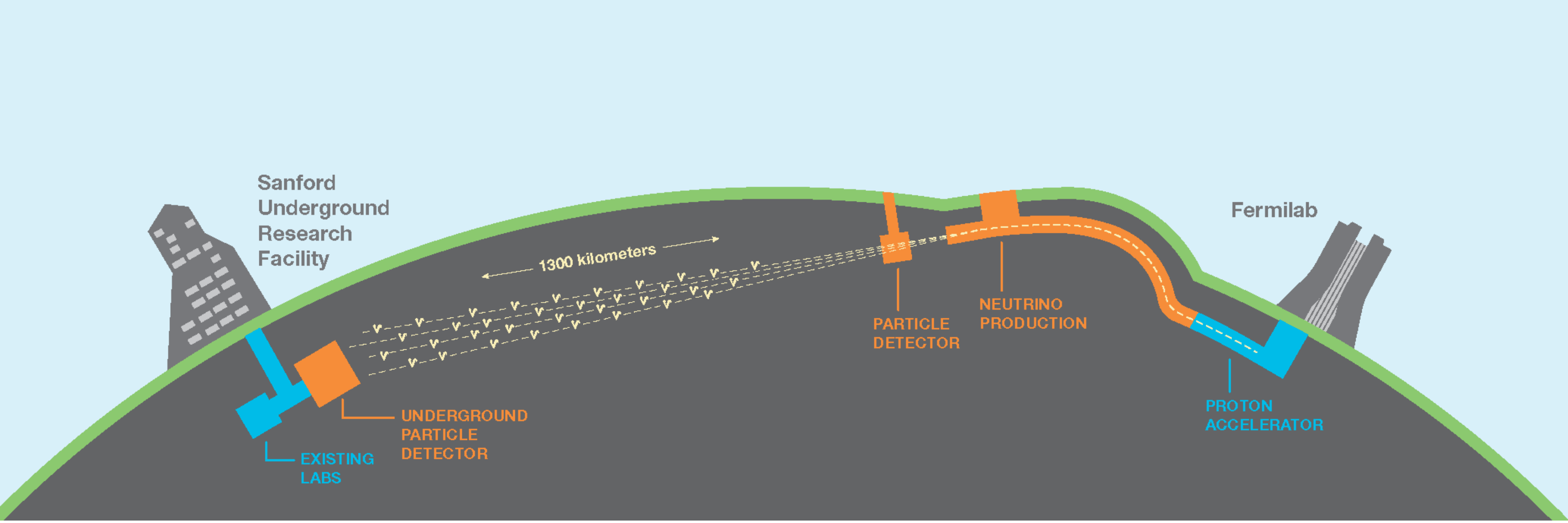
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Michelle Stancari
on behalf of the DUNE collaboration

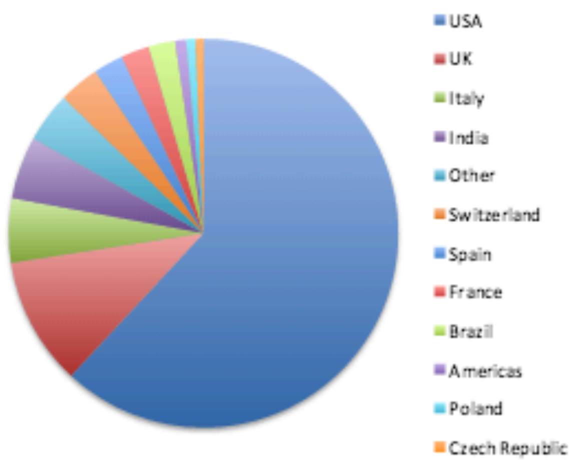
Les Rencontres de Physique de La Vallée d'Aoste
March 12, 2016

DEEP UNDERGROUND NEUTRINO EXPERIMENT

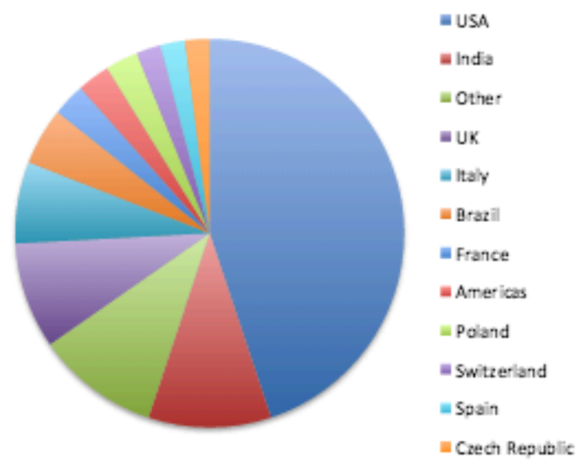
An Experimental Program in Neutrinos, Nucleon Decay and Astroparticle Physics enabled by the Fermilab Long-Baseline Neutrino Facility



~800 Collaborators



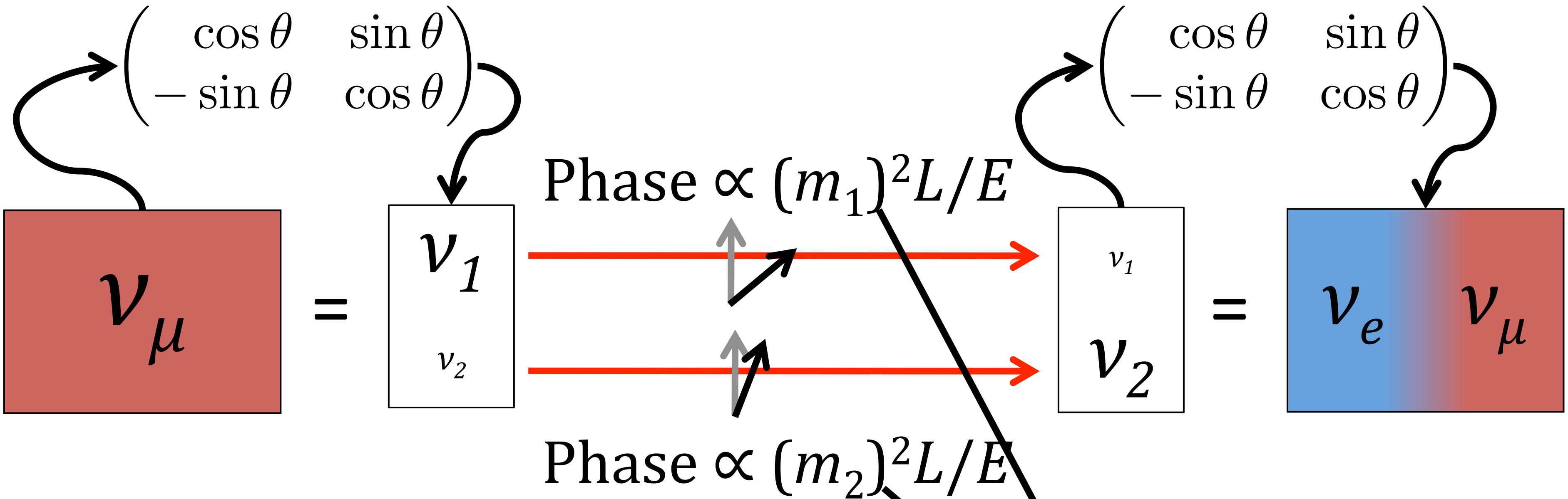
144 Institutes from 26 Nations



Science Program

1. Long Baseline Neutrino Oscillations

Neutrino Oscillations Simplified



Electron Neutrino Appearance Probability

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

The PMNS Mixing Matrix

Flavor

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

Mass

$c_{13}=\cos\theta_{13}$; $s_{13}=\sin\theta_{13}$

Pontecorvo

Sov.Phys.JETP 6:429, 1957

Sov.Phys.JETP 26:984-988, 1968

Maki, Nakagawa, Sakata

Prog.Theor.Phys. 28, 870 (1962)

What We Know

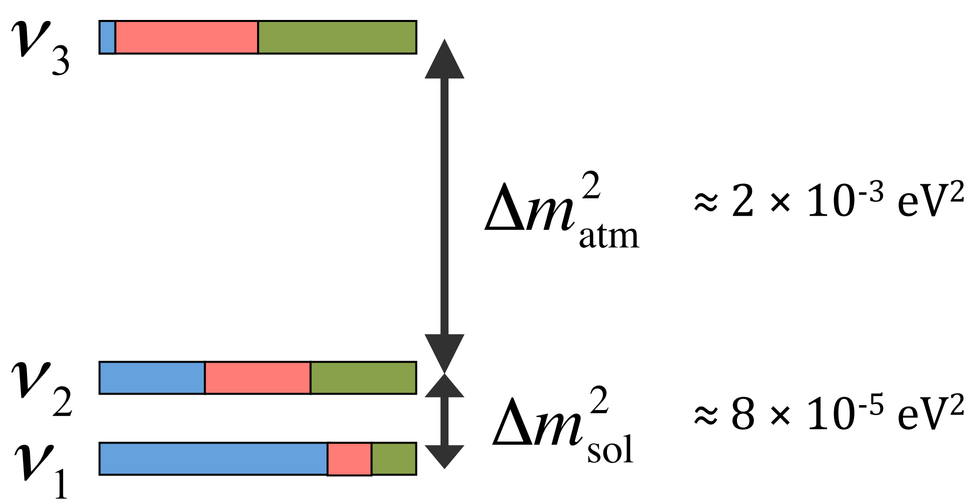
atmospheric, accelerator ν_μ	short baseline reactor, accelerator ν_e	solar, long baseline reactor

Flavor

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

Mass

$\theta_{23} \approx 45°$ $\theta_{13} \approx 9°$ $\theta_{12} \approx 34°$



What We Don't Know

atmospheric accelerator ν_μ	short baseline reactor accelerator ν_e	solar long baseline reactor

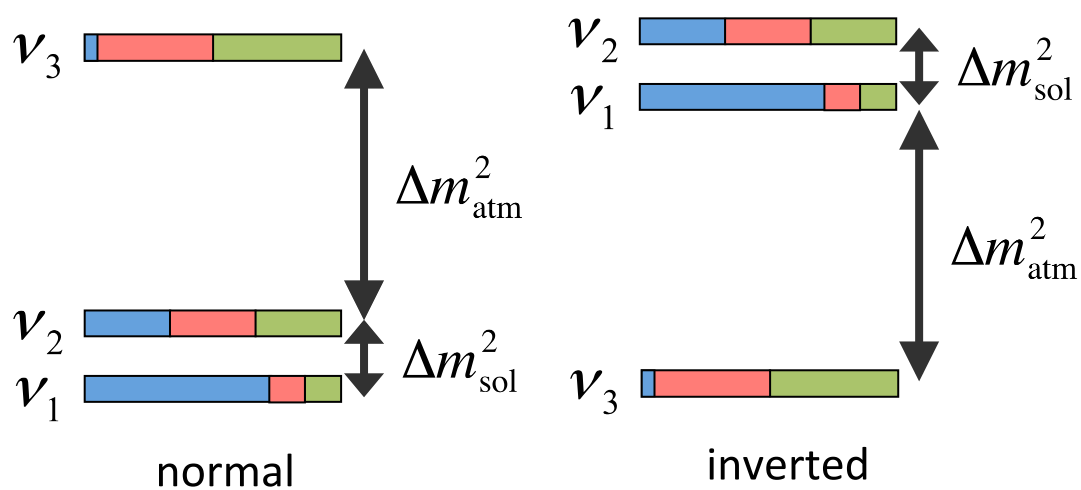
Flavor

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

Mass

Phase δ_{CP}, and potentially CP violation

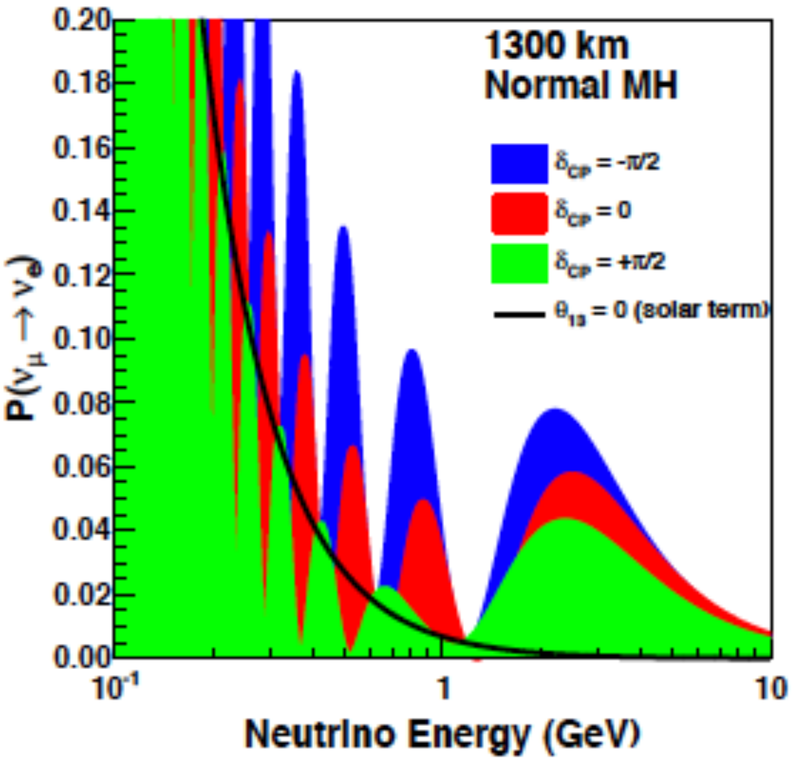
The "mass hierarchy" (MH)



$\nu_\mu \rightarrow \nu_e$ Appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$
$$a = G_F N_e/\sqrt{2},$$



Measure MH and δ_{CP} by combining neutrino and anti neutrino data:
ν->anti-ν : δ_{CP}->-δ_{CP}, a->-a

DUNE CDR "physics volume"
arXiv:1512.06148v2

Science Program

1. Long Baseline Neutrino Oscillations:

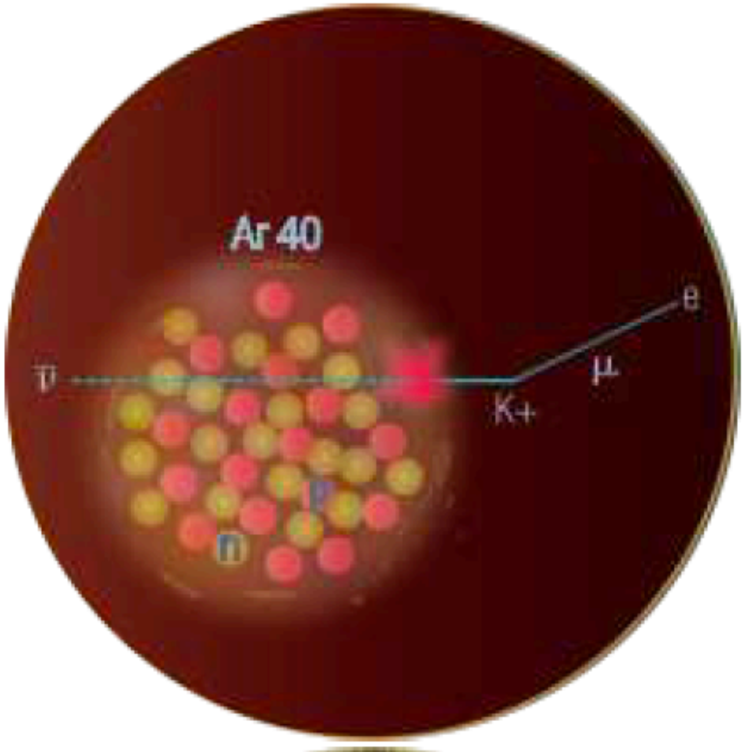
combination of “long baseline” and “wide-band” beam optimizes sensitivity

- High discovery potential for leptonic CPV
- Guaranteed determination of MH
- Test of 3-flavour oscillation paradigm

More details in Phys Rev D91, 052015 (2015)

Science Program

1. Long Baseline Neutrino Oscillations
2. Proton Decay
   - direct observation of a nucleon decay would be monumental.
   - “Deep underground” to reduce backgrounds
   - Decay channels with kaons



Science Program

1. Long Baseline Neutrino Oscillations
2. Proton Decay
3. Neutrino Astrophysics, including supernova neutrino bursts

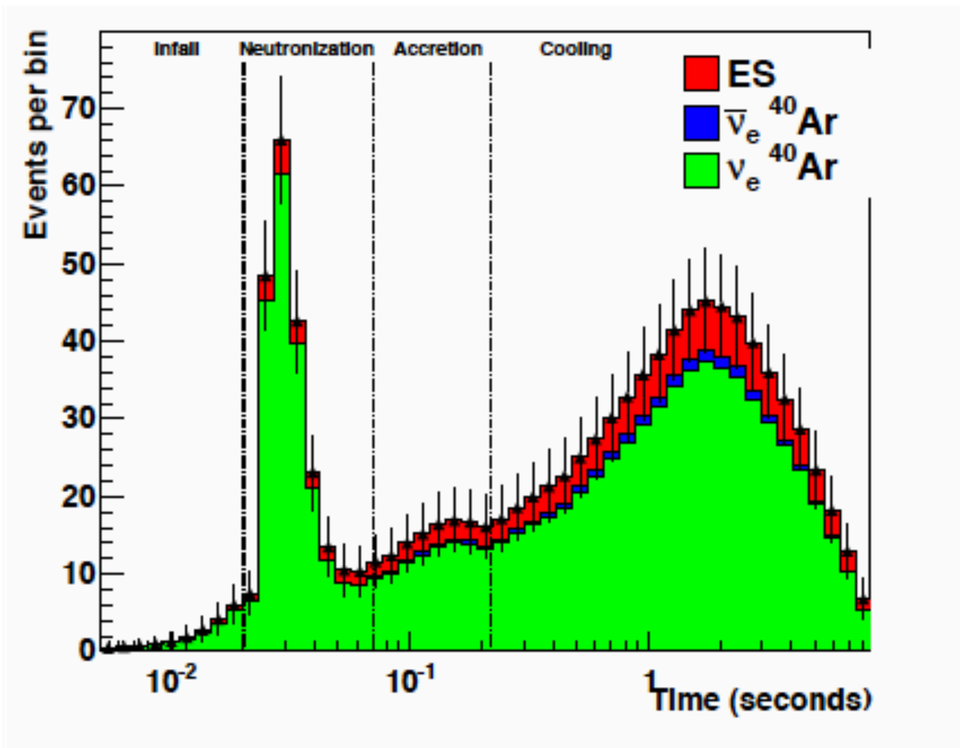
- Liquid argon detector can measure the ν_e component of a supernova burst. The details of the core collapse process are encoded in the distribution of neutrino energy and arrival time.

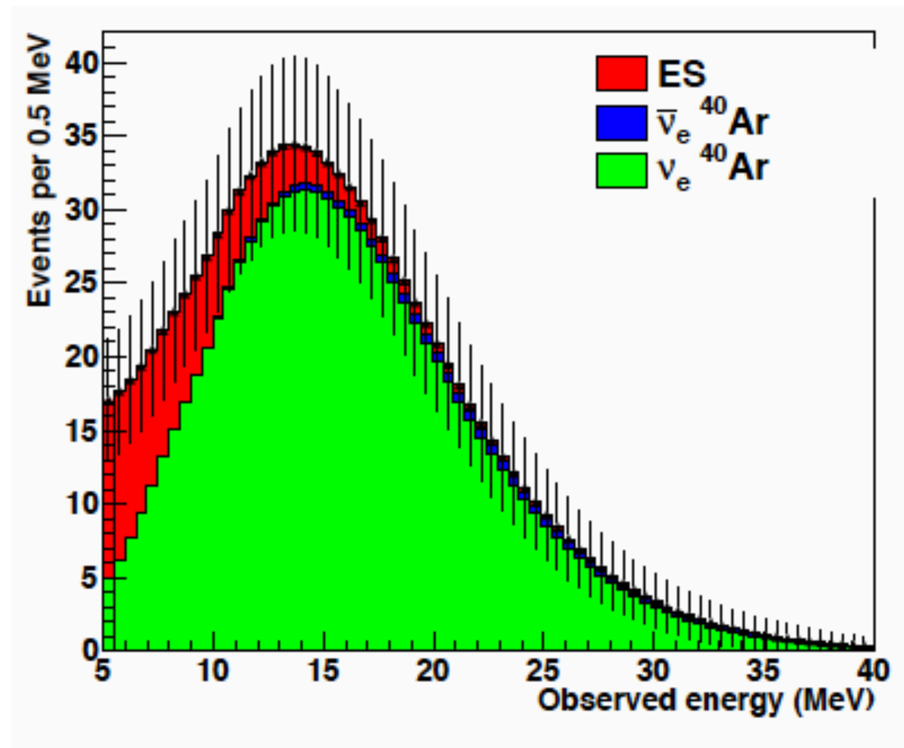
Science Program

DUNE CDR "physics volume"
arXiv:1512.06148v2

The details of the core collapse process are encoded in the distribution of neutrino energy and arrival time.

A neutronization burst during the collapse produces a burst of electron neutrinos

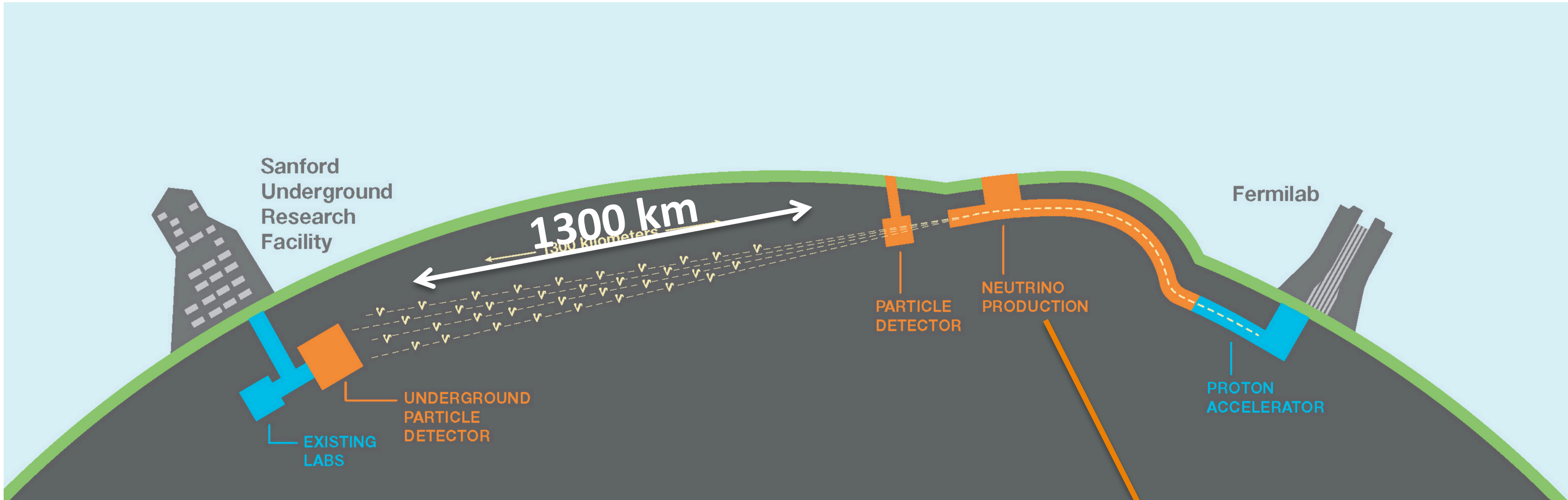




Science Program

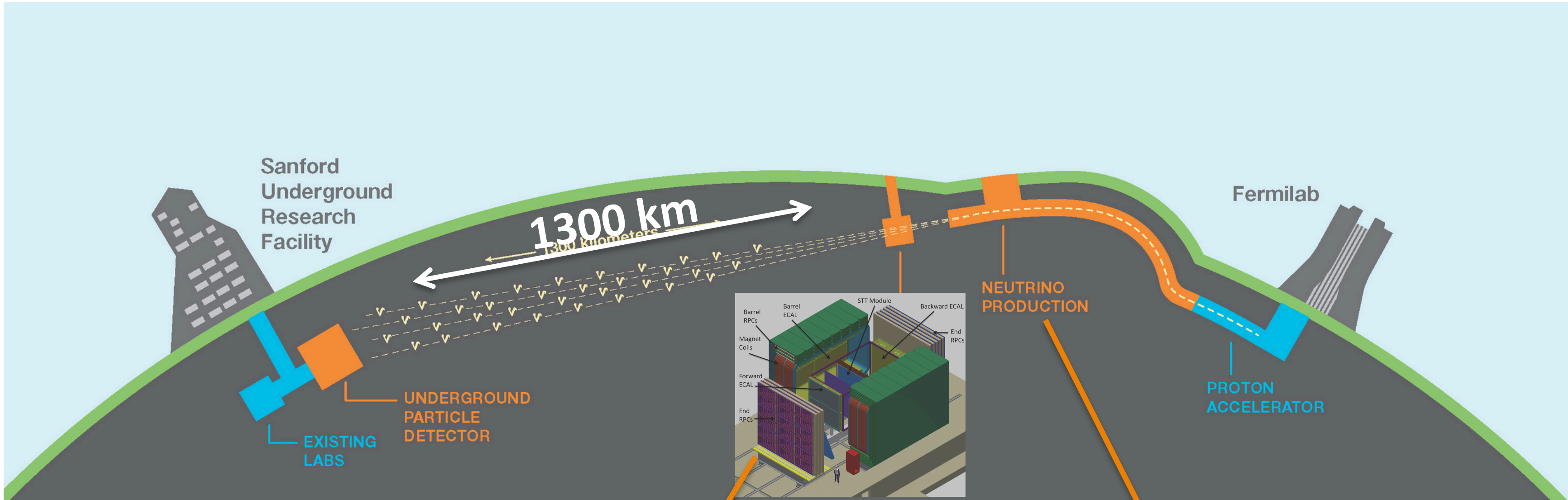
1. Long Baseline Neutrino Oscillations
2. Proton Decay
3. Neutrino Astrophysics, including supernova neutrino bursts
4. Atmospheric neutrinos
5. Precision measurements of neutrino interactions with the near detector

DUNE experimental strategy



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

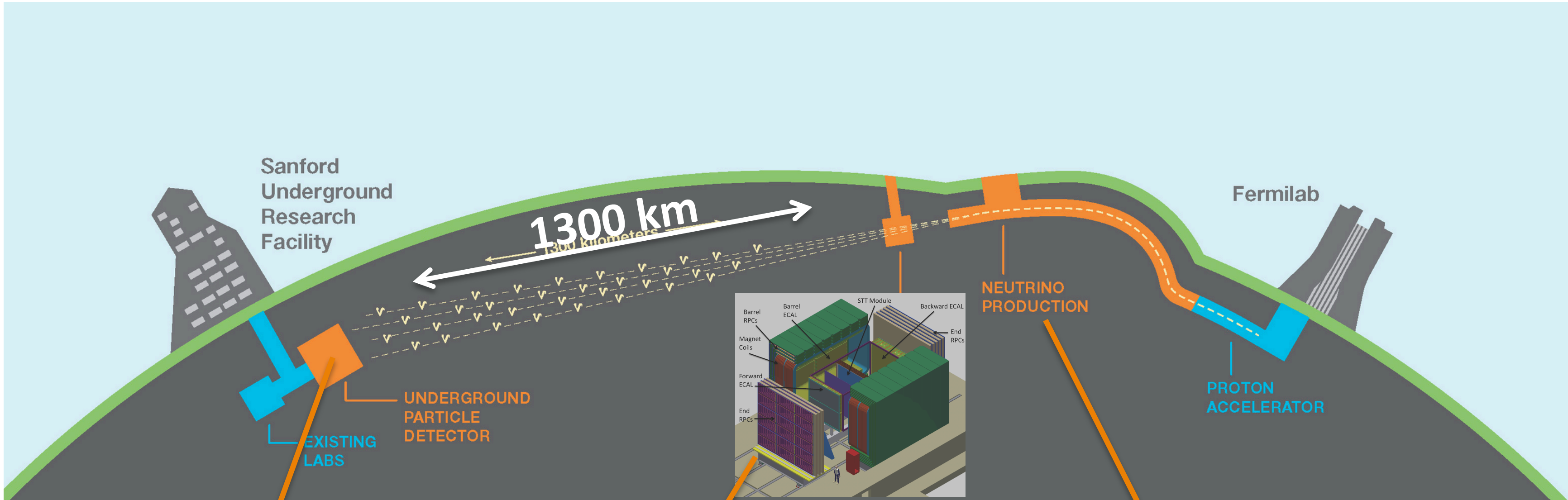
DUNE experimental strategy

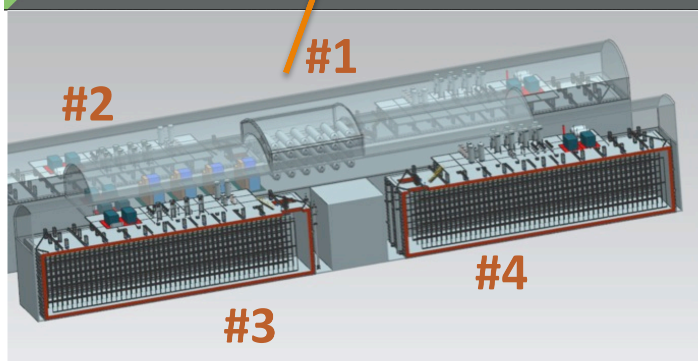


High precision near detector at 574 m

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

DUNE experimental strategy





High precision near detector at 574 m

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

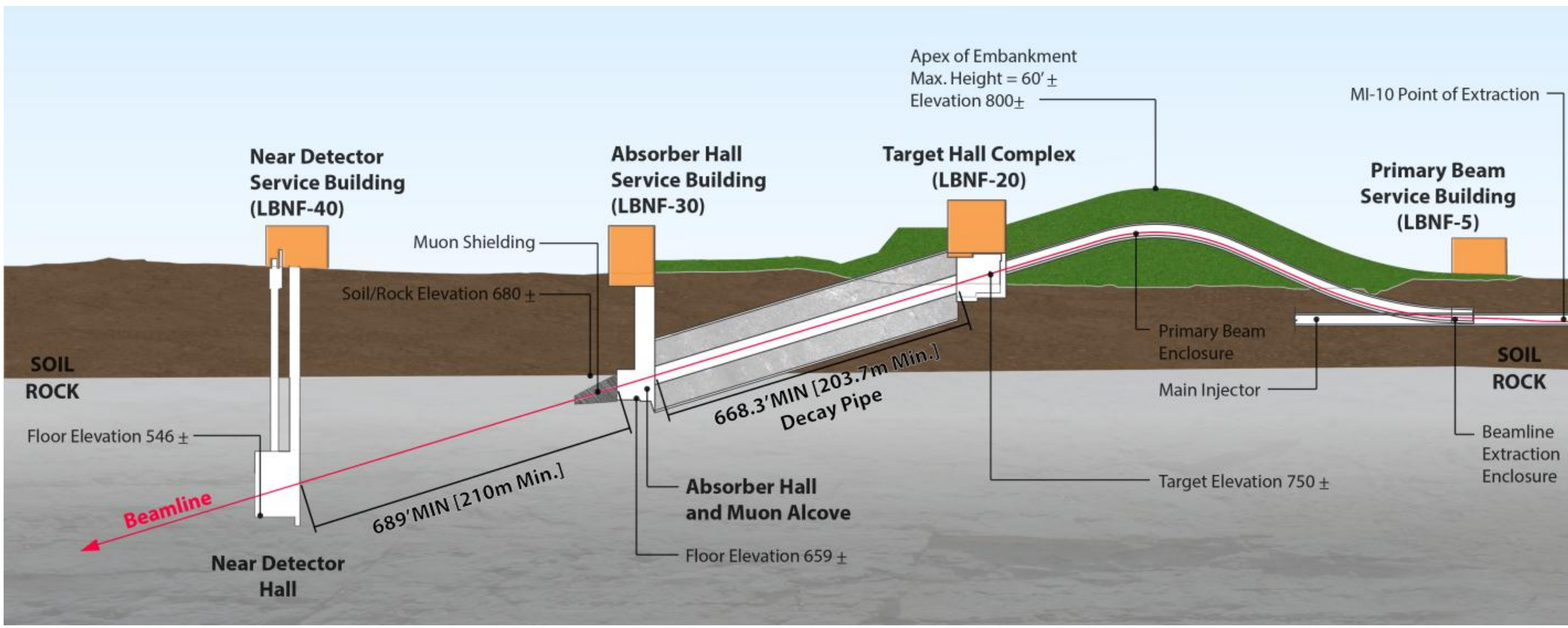
- Four identical cryostats deep underground
- Staged approach to four independent 10 kTon LAr detector modules
- Single phase and dual phase readout under consideration

Sanford Underground Research Facility

Fermi National Accelerator Laboratory

DUNE/LBNF Near Site

- Primary proton beam 60-120 GeV extracted from Main Injector
- Initial 1.2 MW of beam power, upgradable to 2.3 MW
- Intense period of work to optimize horn focusing system and decay pipe geometry (Referenced and optimized designs)
- Near Detector hall at 574 m depth



DUNE/LBNF Neutrino Beam

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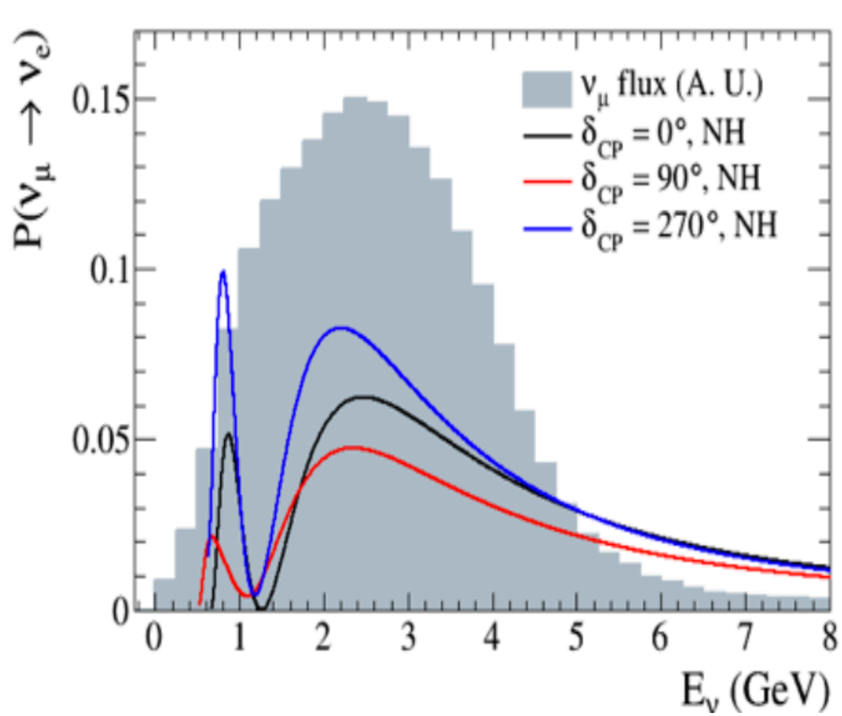
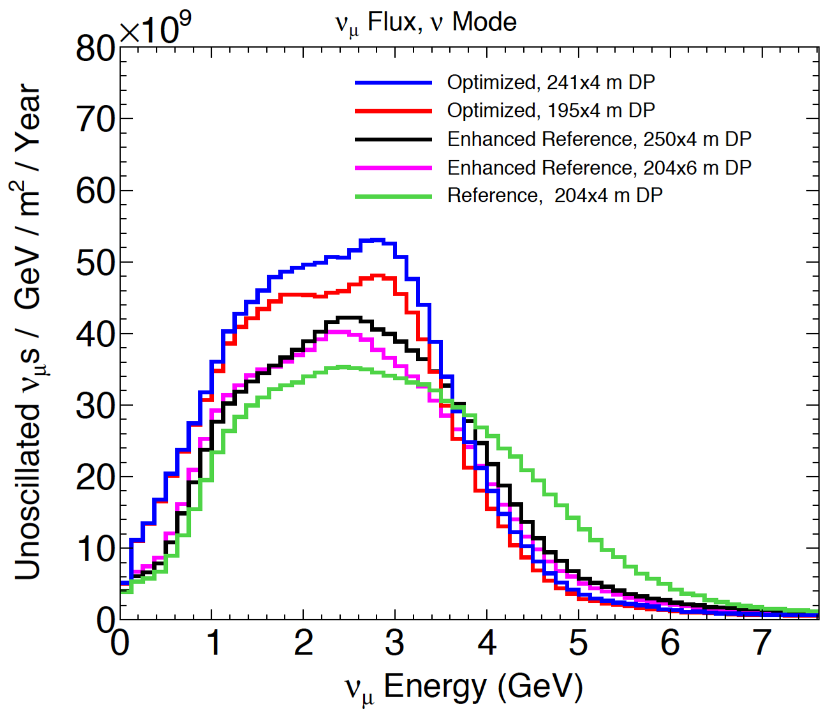




DUNE CDR “LBNF volume”
arXiv:1512.05823

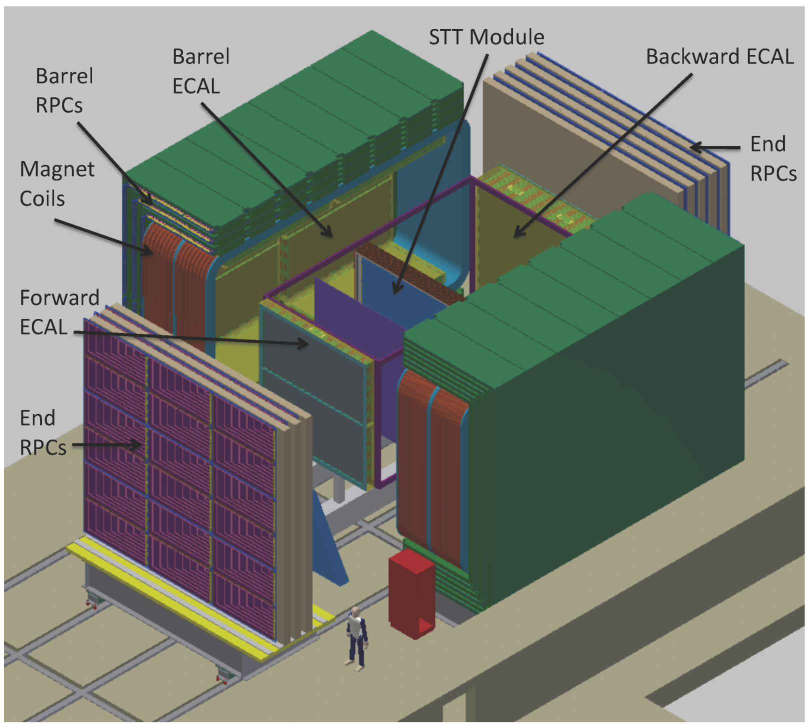
DUNE CDR “physic
arXiv:1512.06

Near Detector

DUNE CDR "detector volume"
arXiv:1601.02984

The near detector will measure
- CC ν_μ events (normalization and energy spectrum)
- CC ν_e and NC pi0 (backgrounds)
- Neutrino interaction properties

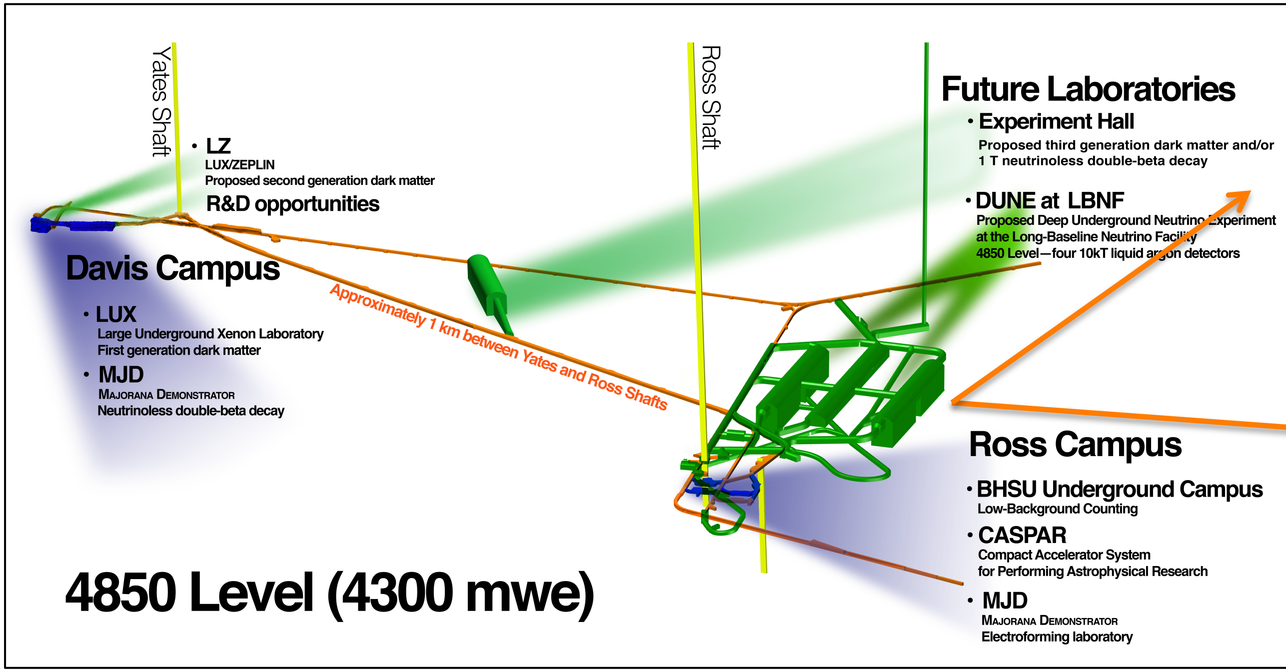
10^7 interactions per year - high precision!

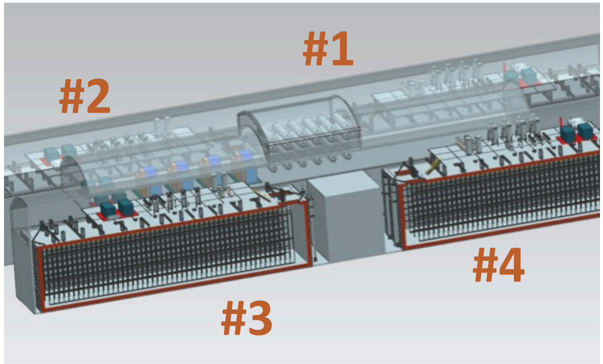


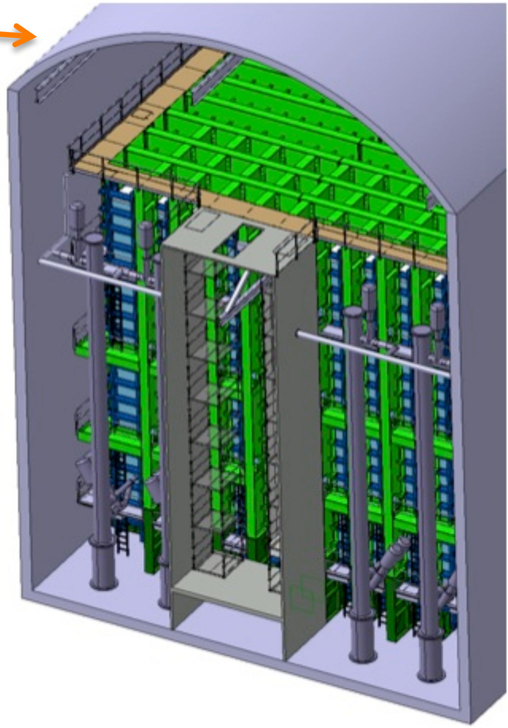
Reference design
- Fine grained tracker inside 0.4T magnetic field (straw tubes)
- Lead-scintillator ECAL
- RPC muon tracker

Other designs under consideration
- Magnetized LArTPC
- High Pressure GArTPC

Far Detector at SURF

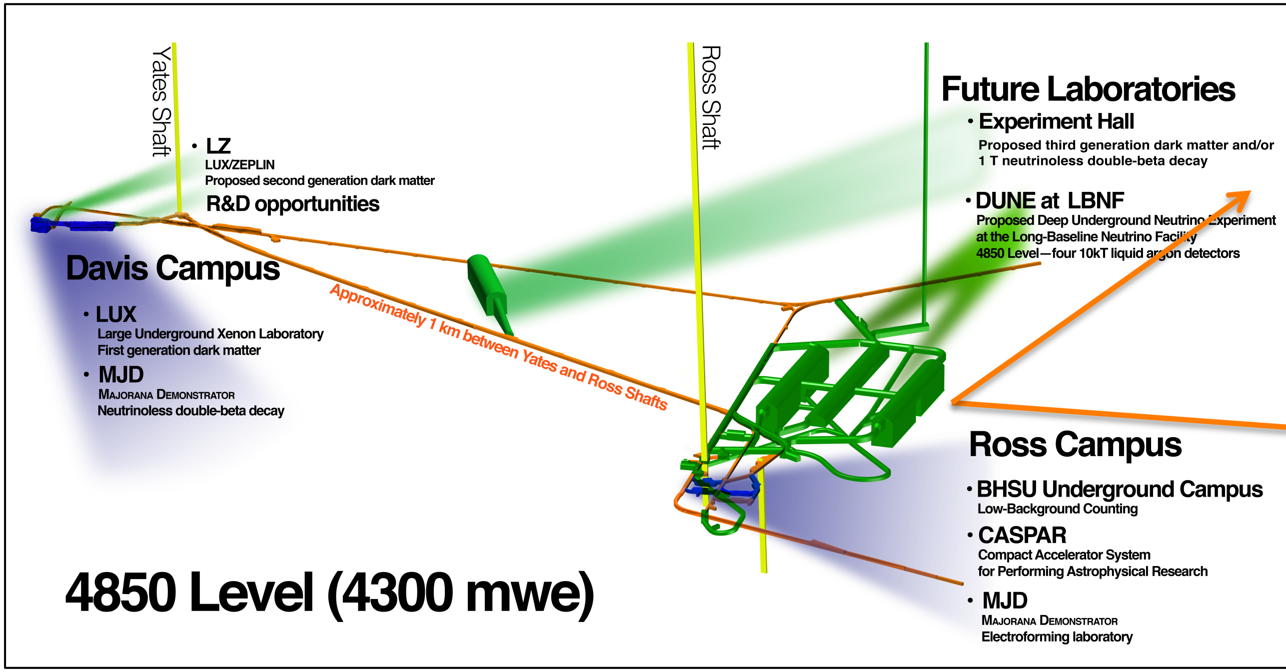


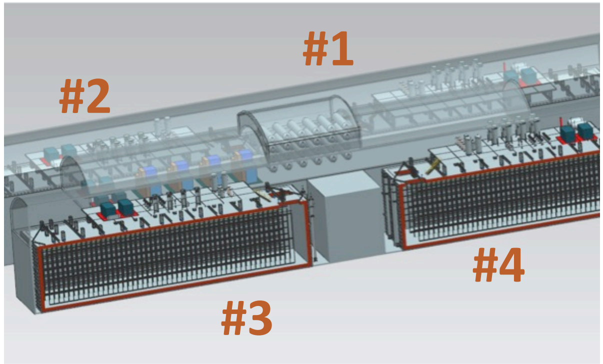


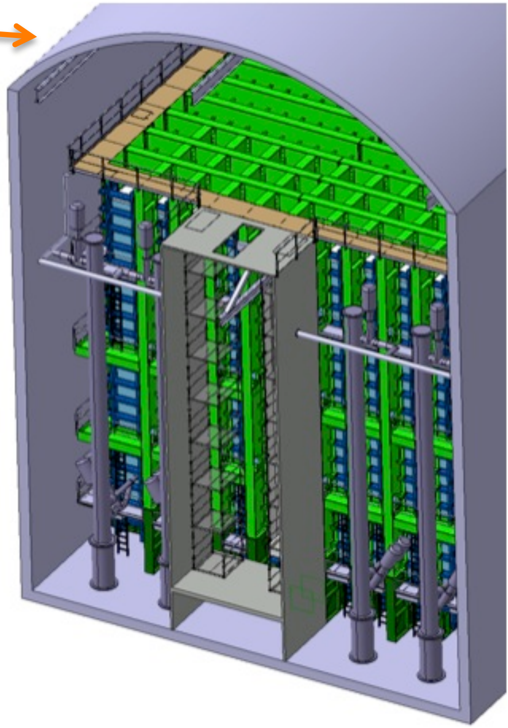


- Liquid argon (LAr) is both the interaction target and the detector.
- 40 kTon fiducial volume, divided into 4 modules (staged construction), each 17 kTon total volume
- 4 identical cryostats that can accommodate single phase or dual phase style detectors

DUNE Far Detector at SURF

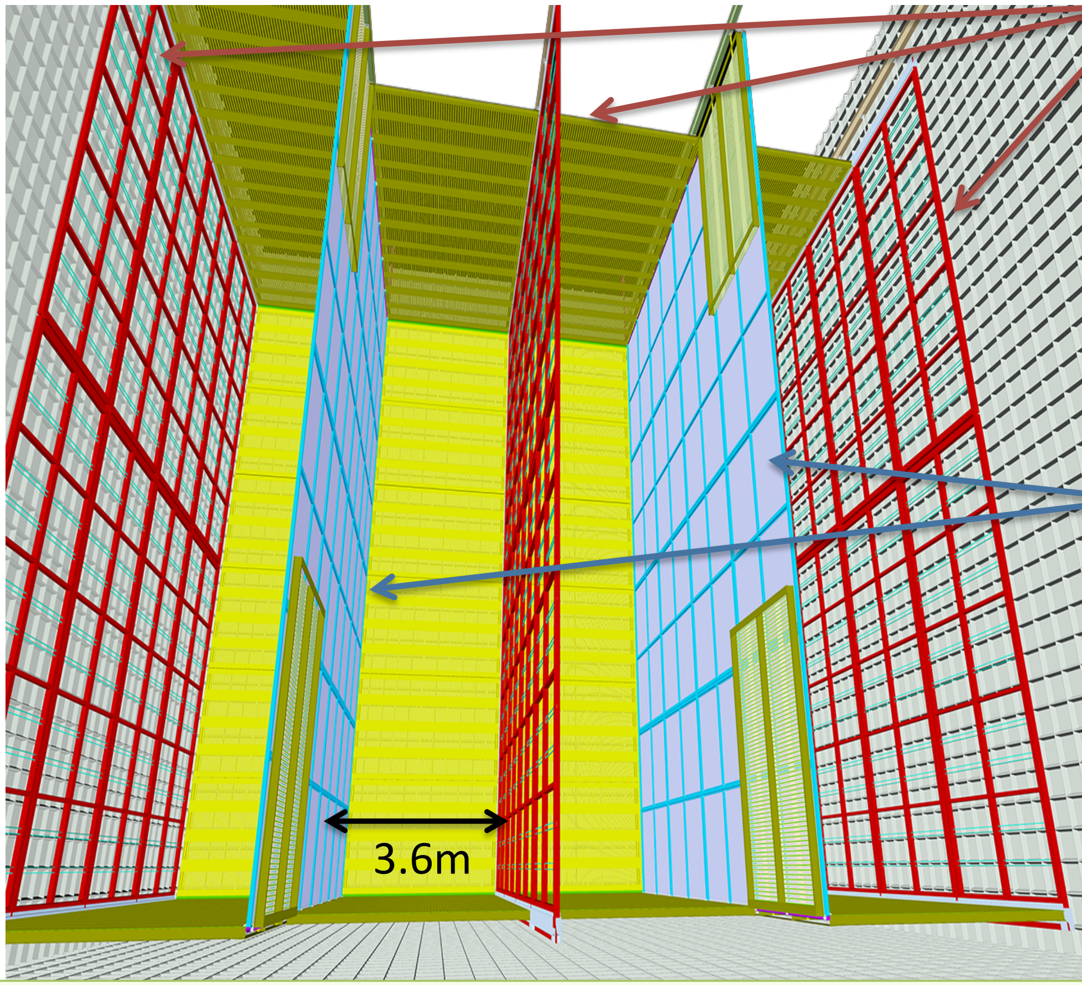






- The first module will be a single phase TPC (live in 2024). Its design is mature and the basis for the engineering prototype at CERN
- Subsequent modules can incorporate design changes that are demonstrated by ongoing R&D efforts, including a dual phase TPC option

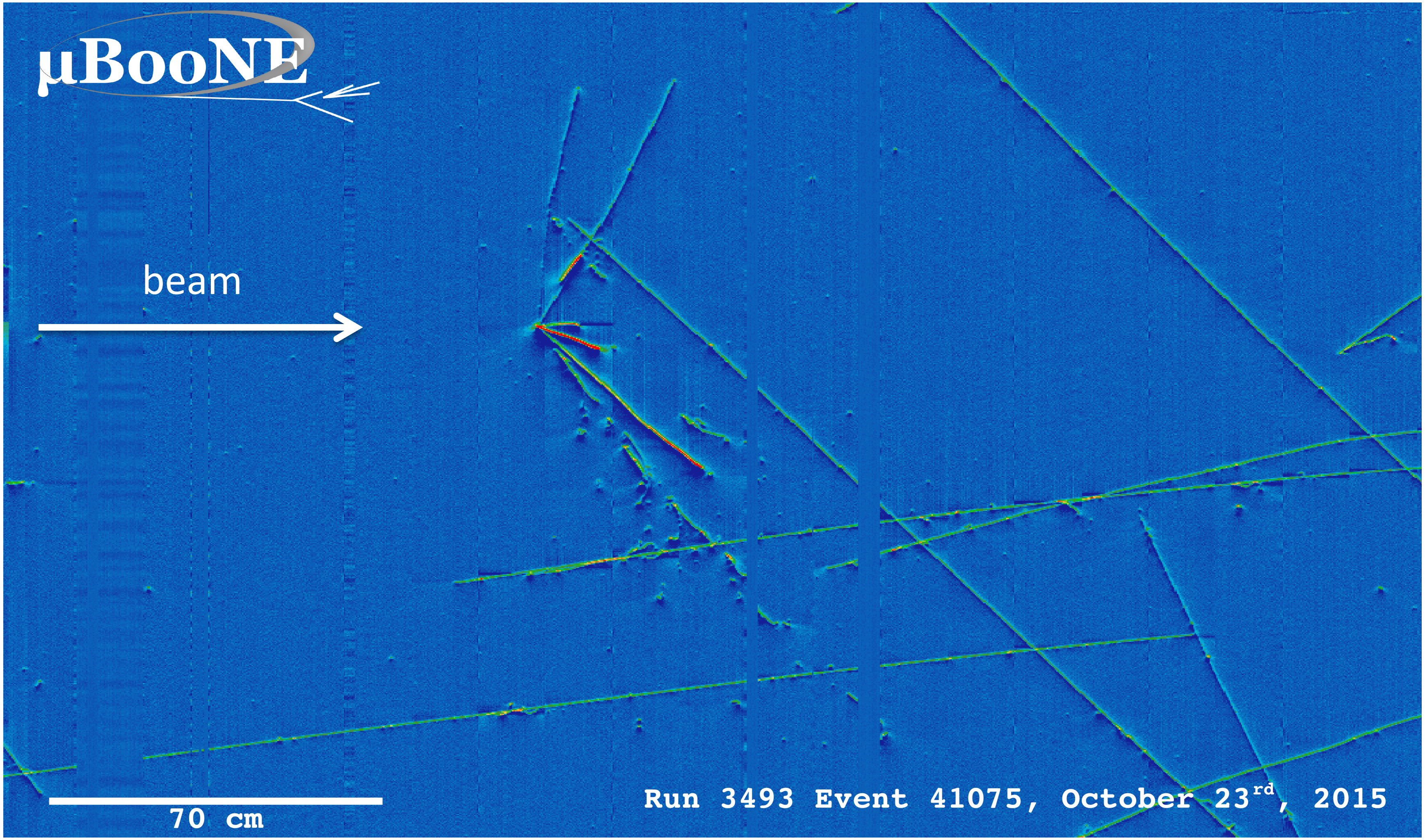
Single Phase LAr Detector



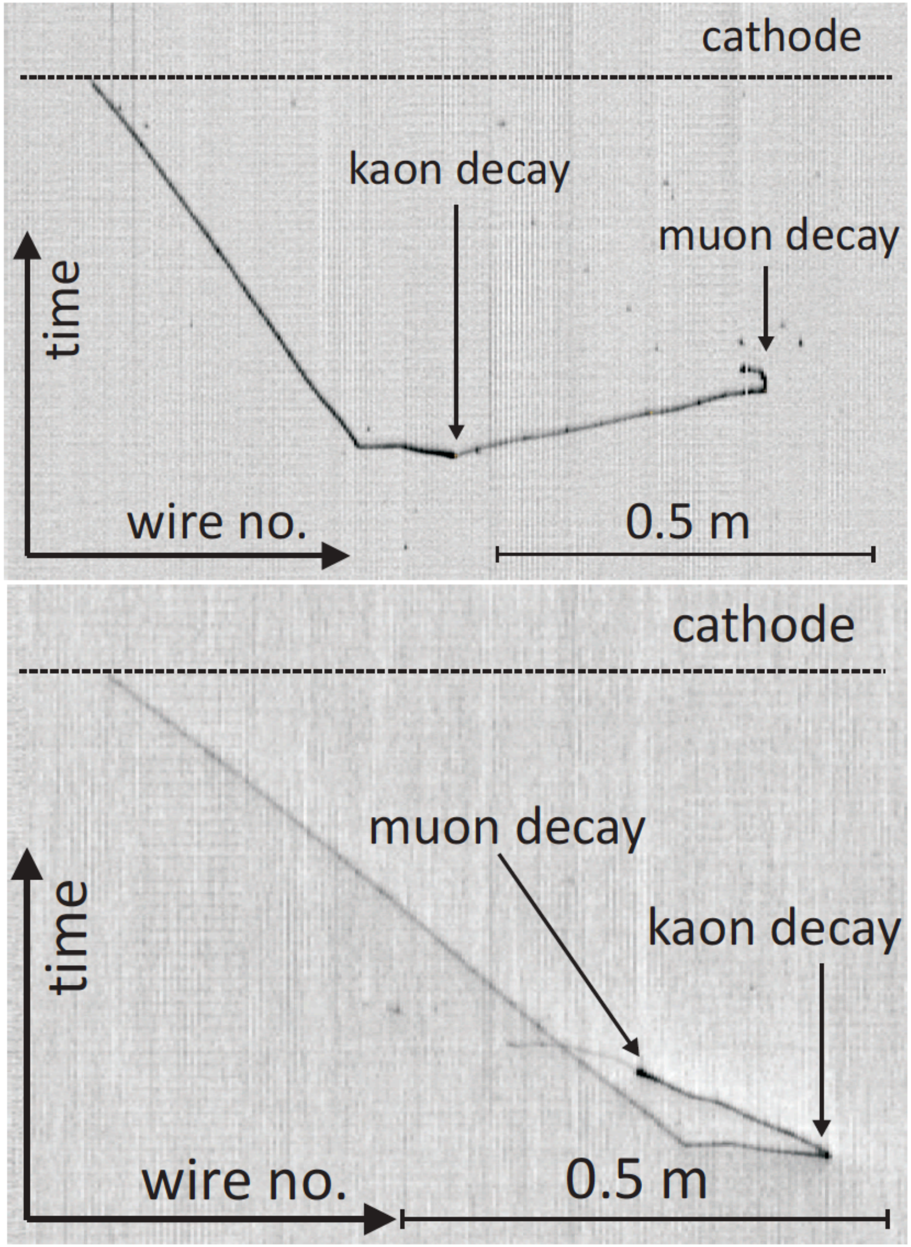
Active volume: 12 m x 15 m x 58 m (2x3x22 units)

Time Projection Chamber

- Anode Plane Assemblies (APAs) with three instrumented wire planes on each side (one collection and two induction) to readout ionization charge
- Drift field of 500 V/cm (cathode planes: 180 kV)
- Four drift regions 3.6 m each
- Photon Detection System (not shown) integrated into APAs to measure scintillation light for non-beam event timing


μBooNE
beam
70 cm
Run 3493 Event 41075, October 23rd, 2015

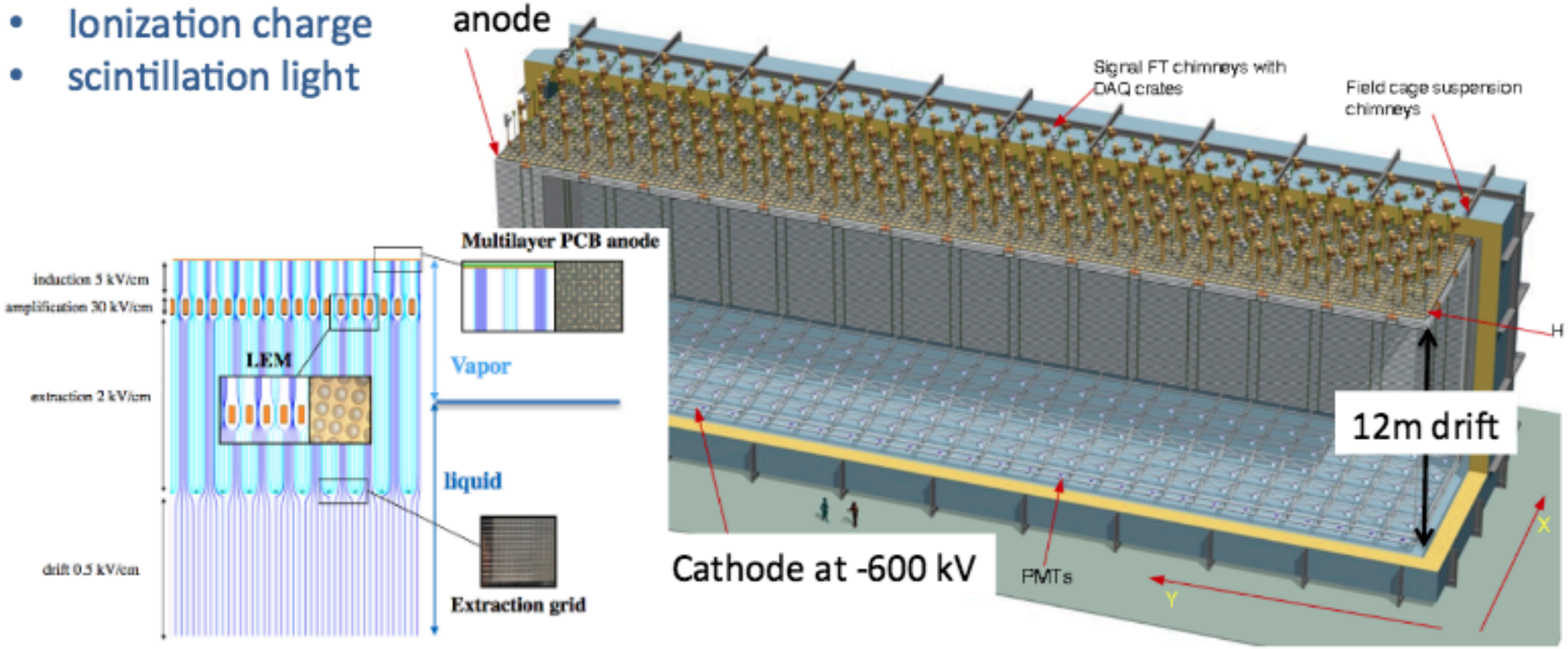
Cosmogenic induced kaons observed by the ICARUS detector



Adv. High Energy Phys., vol. 2013, p. 260820, 2013

Dual-Phase LAr Detector

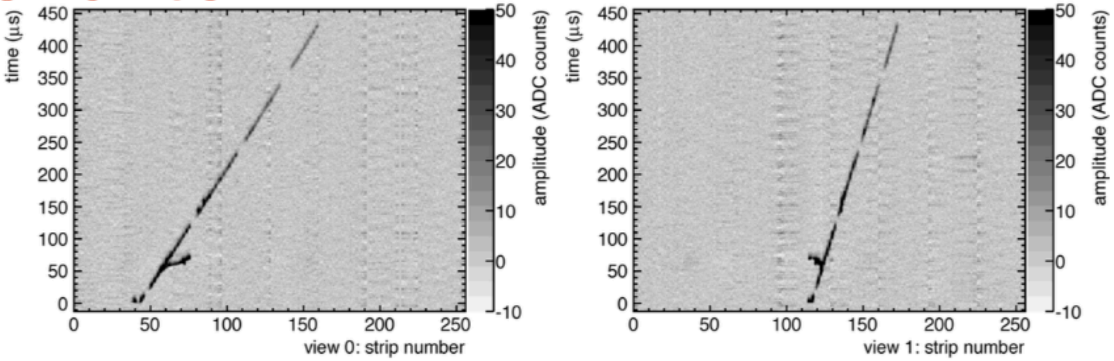
Readout of
- Ionization charge
- scintillation light



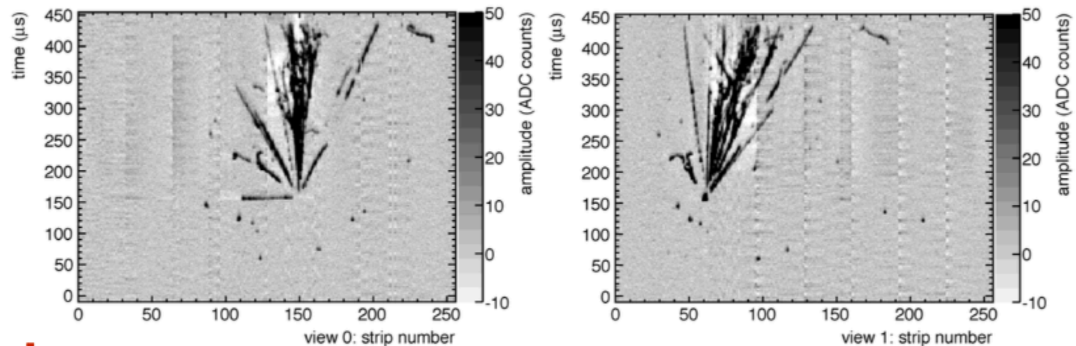
Ionization charge extracted into Ar gas phase
charge amplification via large electron multipliers (LEM) before readout
[2 dimensional charge collection]

→ If demonstrated, could be used as alternative design for 2nd or subsequent 10 kt far detector modules

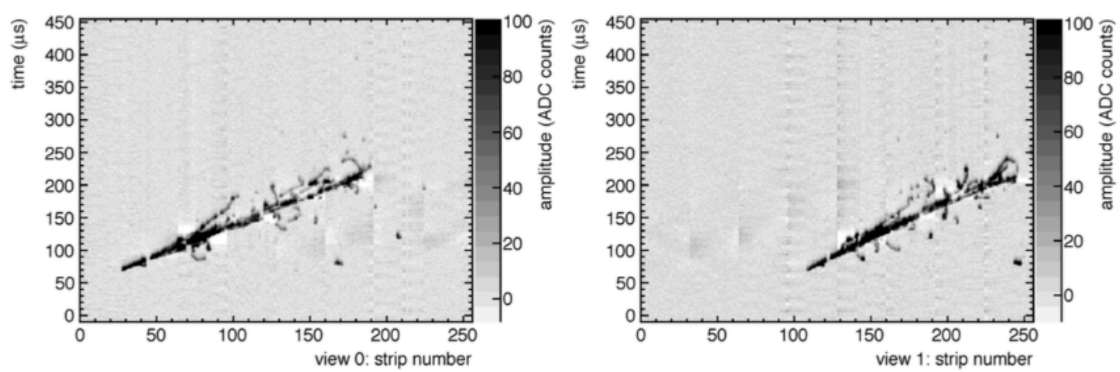
cosmic muon



HADR shower



EM shower

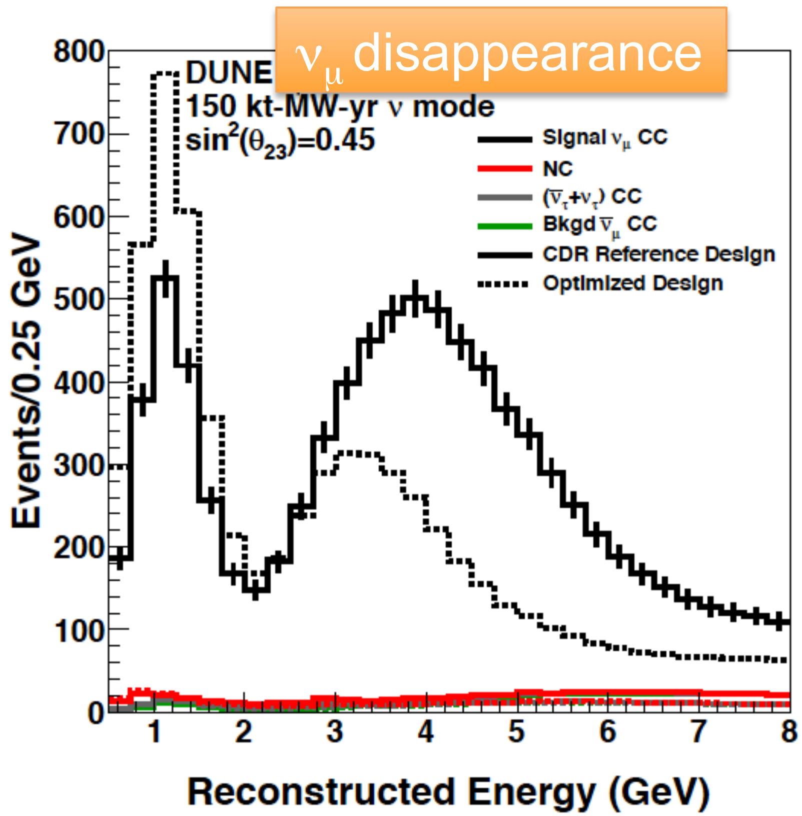


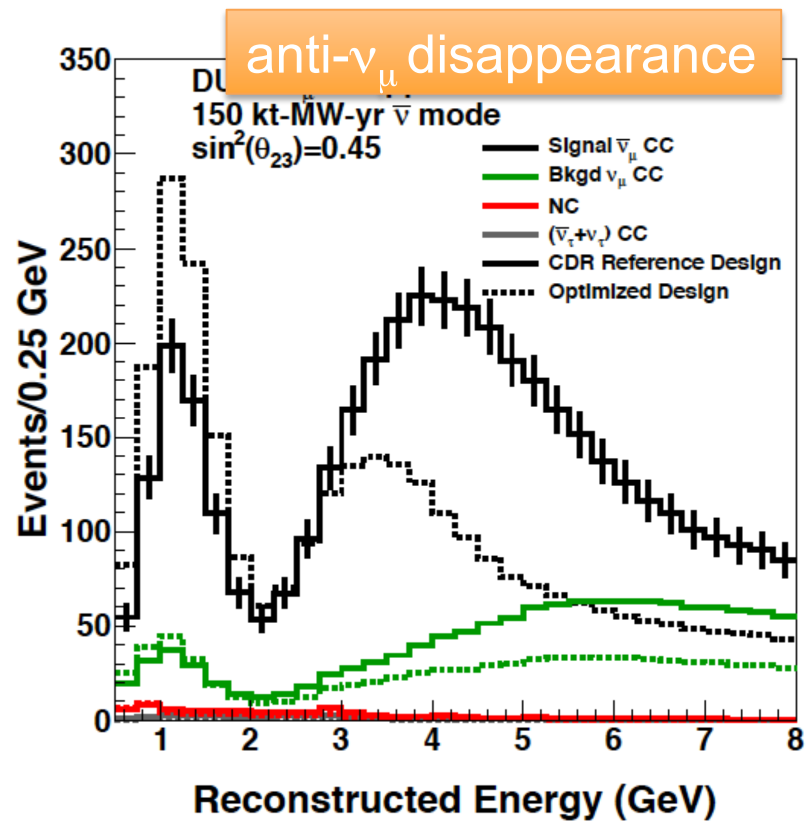
Zurich 200 liter prototype

arXiv: 1301.4817v1

measurements – oscillation physics

- Simultaneous fit to all four event spectra to extract MH and δ_{CP} (ν_μ, anti-ν_μ, ν_e, anti-ν_e)
- Plots below assume normal MH and δ_{CP}=0
- 10 years of DUNE running is roughly 300 kTon*MW*years





DUNE CDR “physics volume”
arXiv:1512.06148v2

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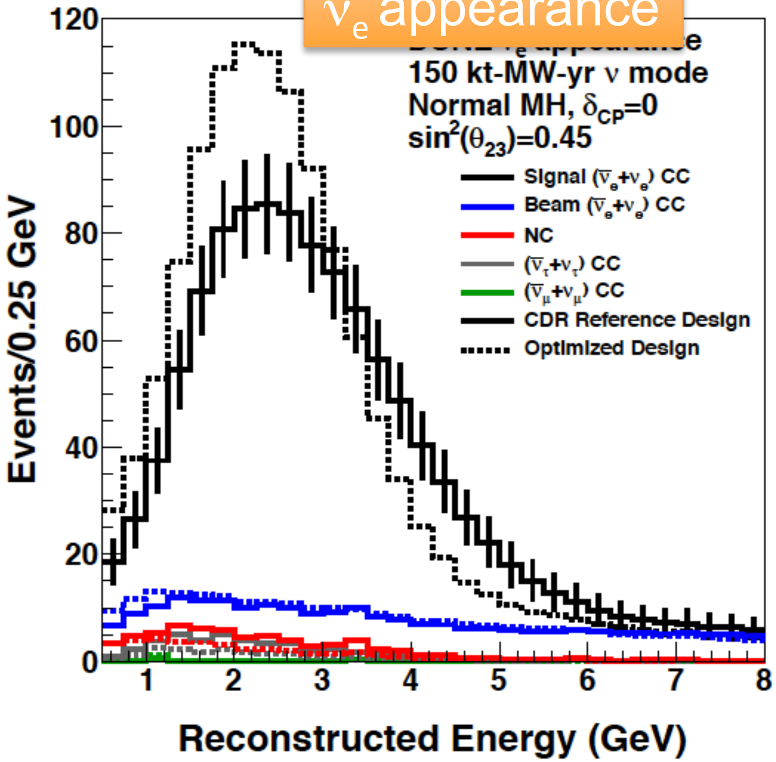
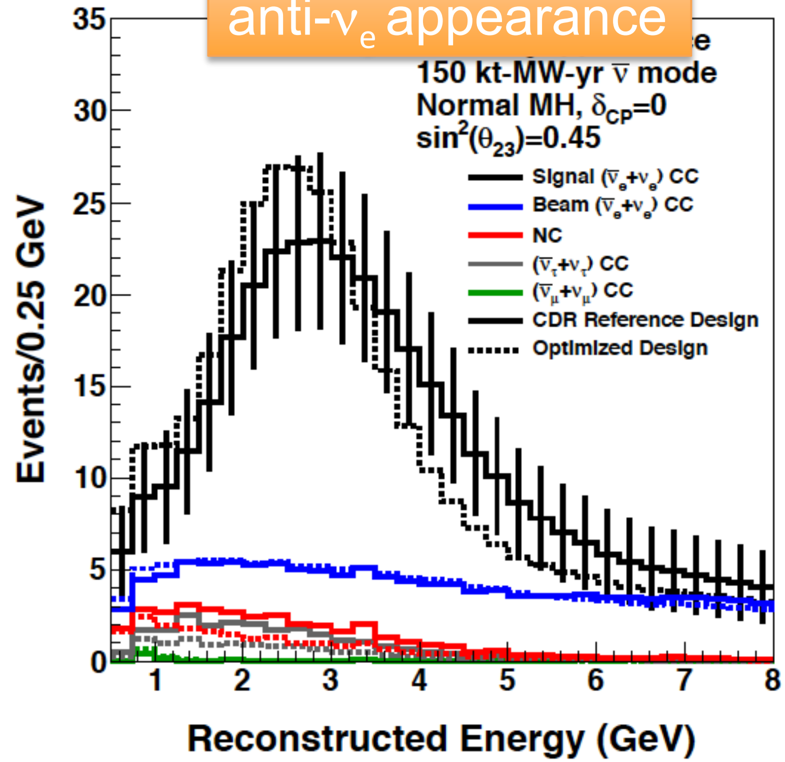
ν_e appearance



anti-ν_e appearance



DUNE CDR "physics volume"
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Expected number of events in the far detector. 5 years running, δ_{CP}=0, normal MH (inverted)

	Neutrino beam	Anti-neutrino beam
ν_μ signal	7929	2639
ν_μ background	29	18
ν_e signal	945(521)	168(436)
ν_e background	243	127

DUNE CDR "physics volume" arXiv:1512.06148v2

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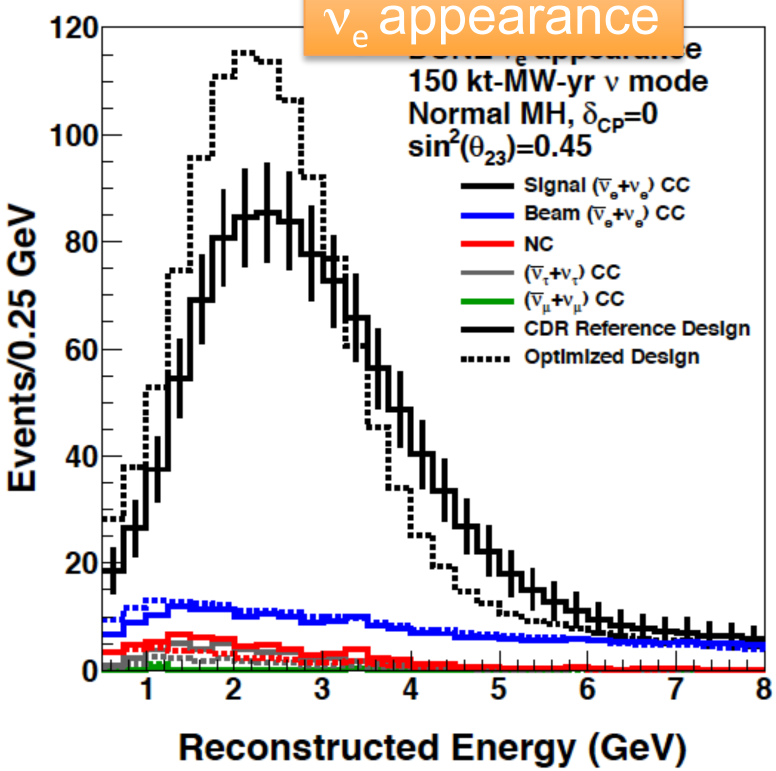

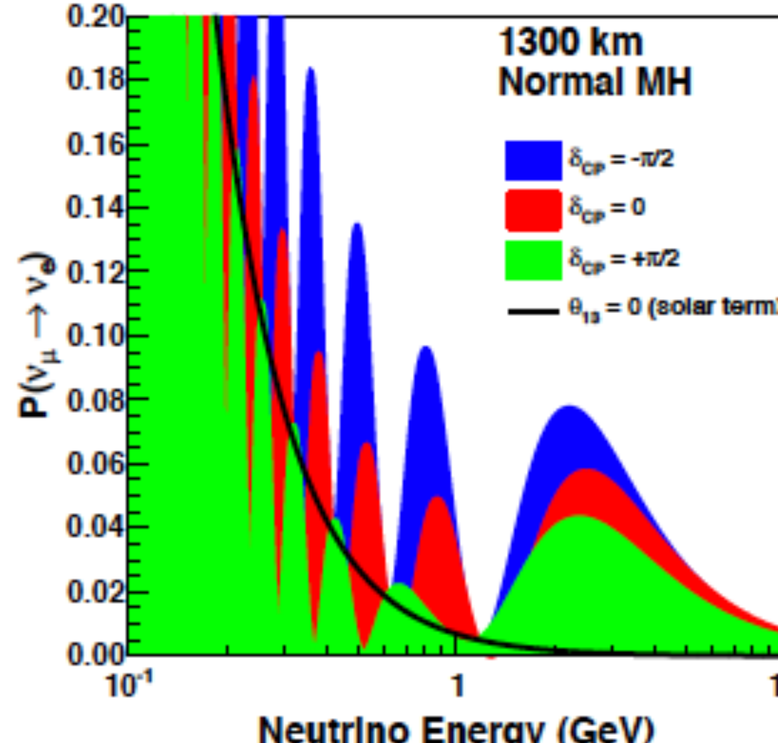

DUNE CDR "physics volume"
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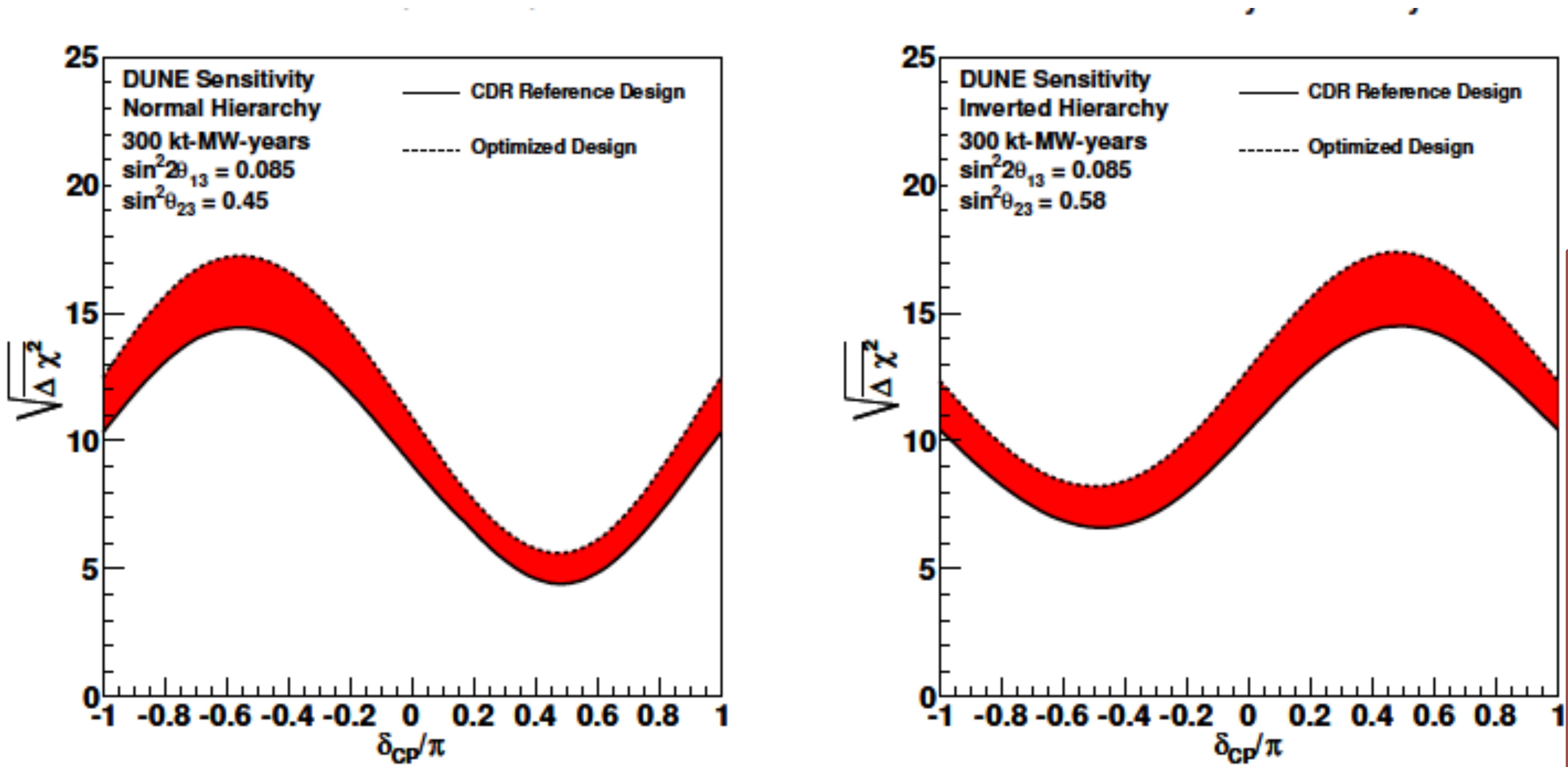
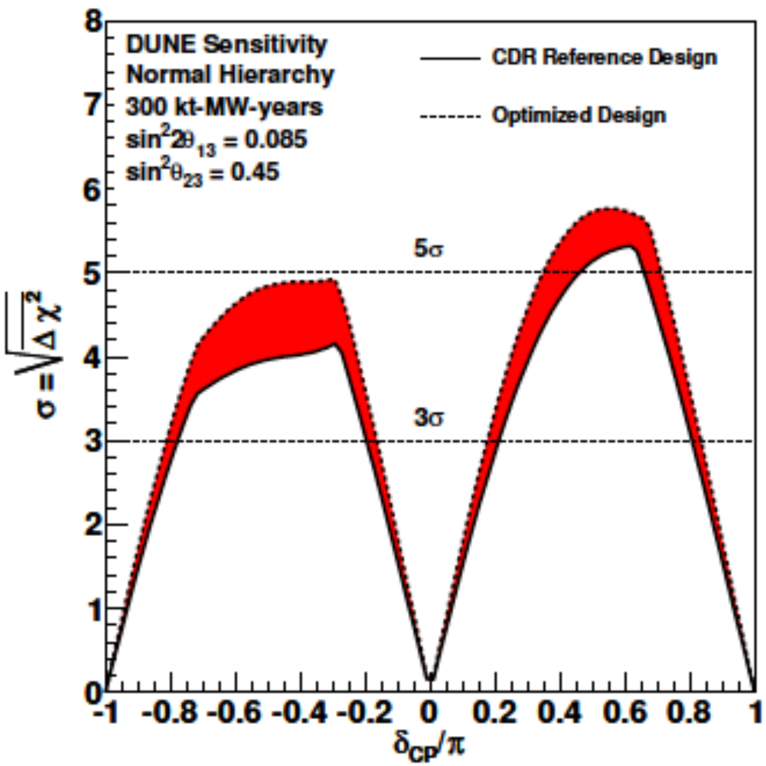
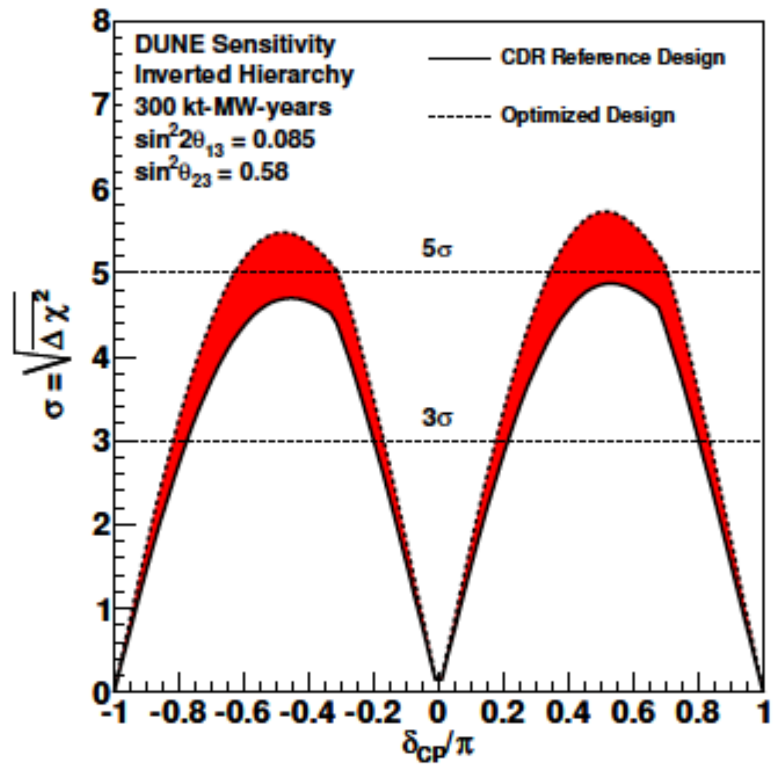
sensitivity – mass hierarchy



DUNE CDR "physics volume" arXiv:1512.06148v2

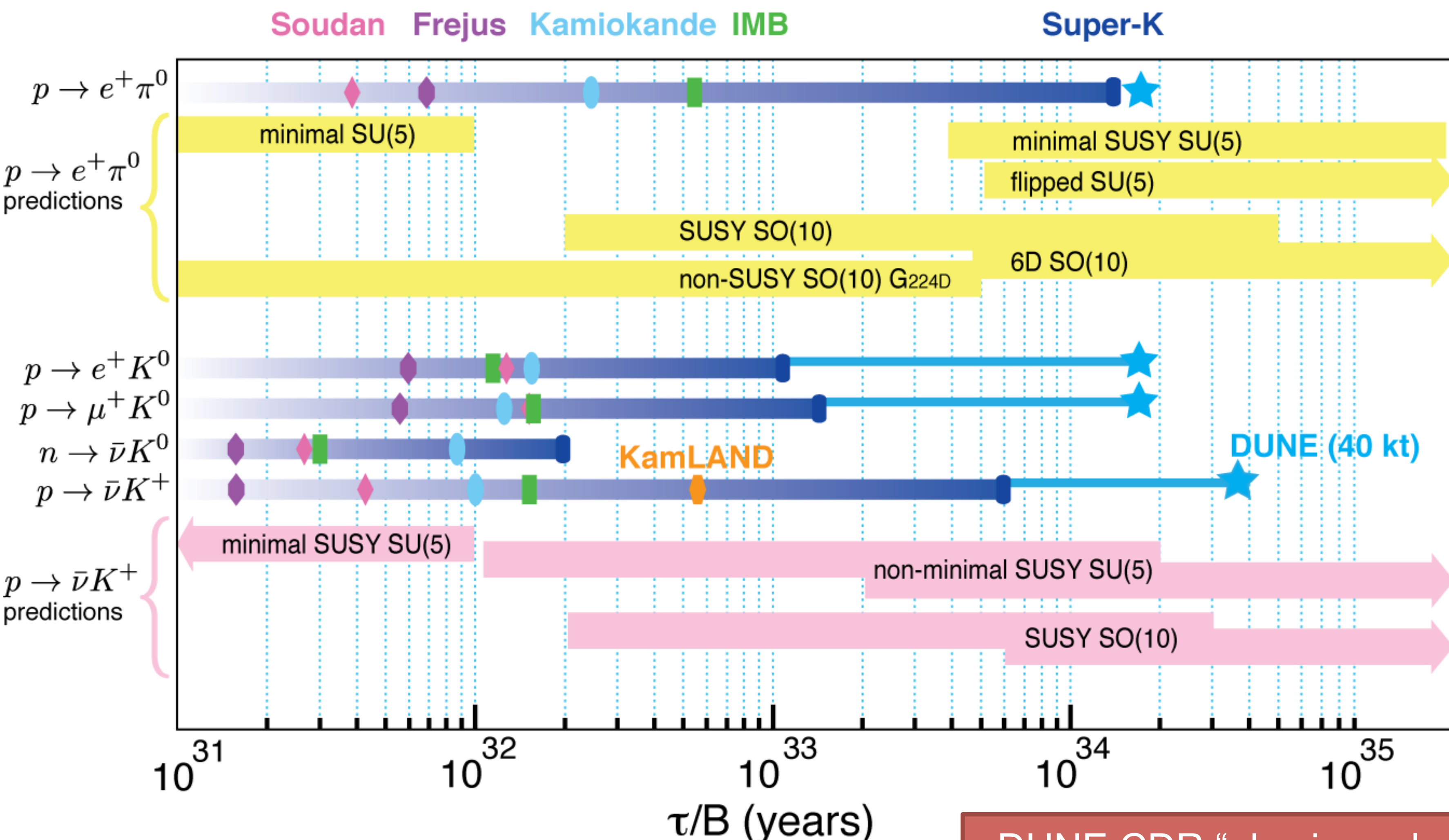
sensitivity - CPV





DUNE CDR "physics volume"
arXiv:1512.06148v2

sensitivity – proton decay



DUNE CDR “physics volume”
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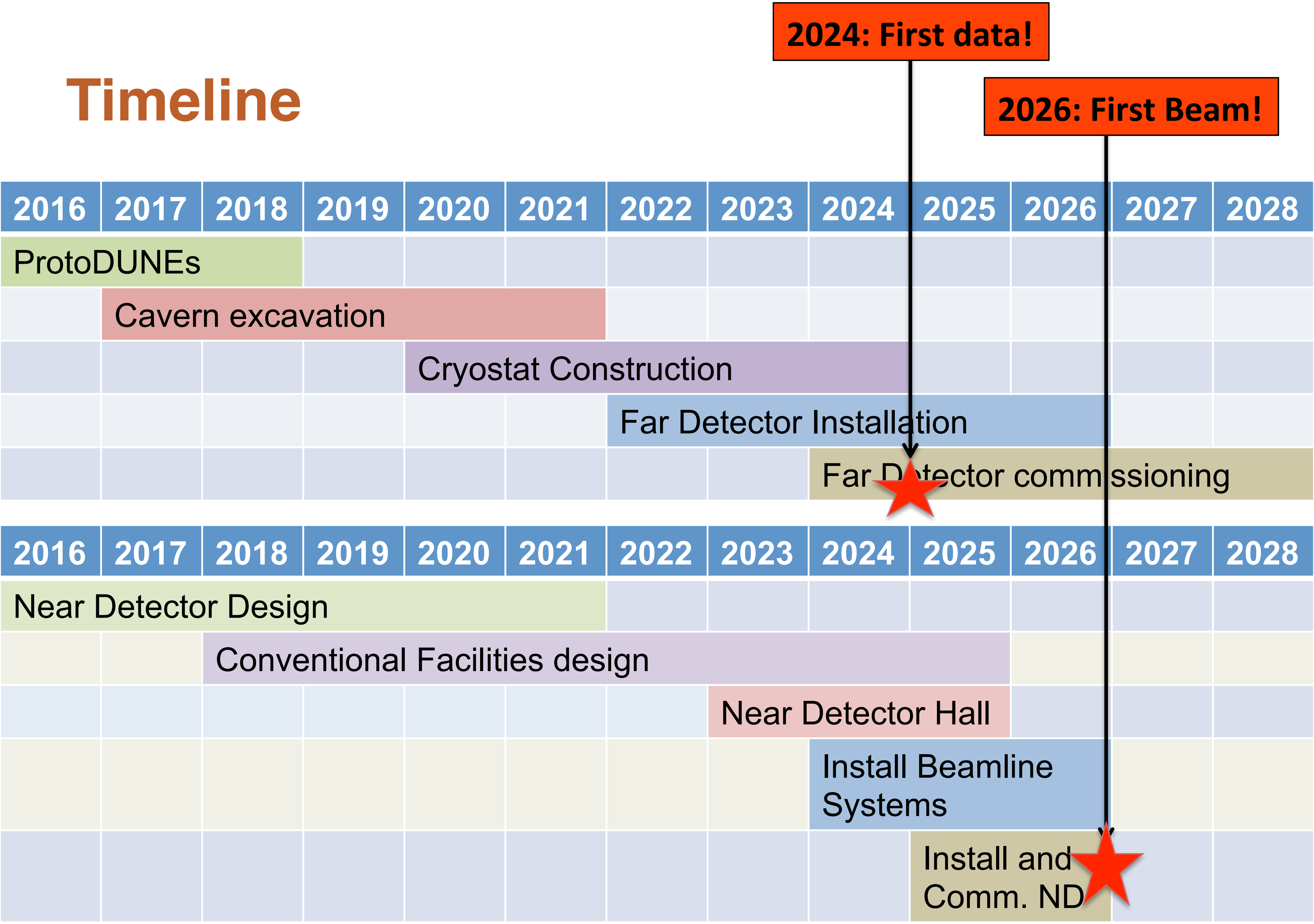
Timeline


2024: First data!
2026: First Beam!
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
ProtoDUNEs
Cavern excavation
Cryostat Construction
Far Detector Installation
Far Detector commissioning
Near Detector Design
Conventional Facilities design
Near Detector Hall
Install Beamline Systems
Install and Comm. ND

What’s happening now?

- Development of specific detector/beam components such as beamline target, light detection systems and cold readout electronics
- Small scale integrated far detector prototypes operating in 2016
- Optimization of beam/detector designs for the best physics sensitivities

Detailed near detector design, automatic reconstruction of neutrino interactions in far detector, optimize beam focusing system

What’s happening soon?

- CERN neutrino platform, complete with hadron test beam, is hosting two engineering prototypes for the far detector.
  - Component construction in 2016-17
  - Installation in 2017 and operation in 2018.

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- Development of specific detector/beam components such as beamline target, light detection systems and cold readout electronics
- Small scale integrated far det 6
- Optimization of beam/detecto sensitivities

Detailed near detector design, a interactions in far detector, optimize beam focusing system

Many critical projects await interested students, postdocs and faculty.

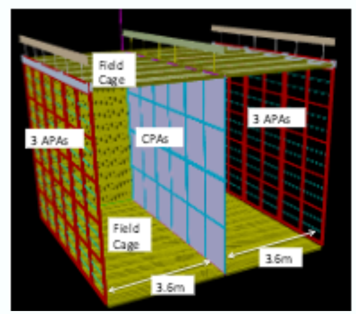
What's happening soon?

- CERN neutrino platform, complete with hadron test beam, is hosting two engineering prototypes for the far detector.
  - Component construction in 2016-17
  - Installation in 2017 and operation in 2018.

Detector Development and Prototyping

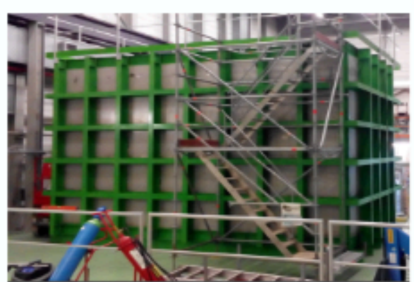
- Mitigation of risks associated with current detector designs
- Establishment of construction facilities required for full-scale production of detector components
- Early detection of potential issues with construction methods and detector performance
- Provides required calibration of detector response to particle interactions in test beam

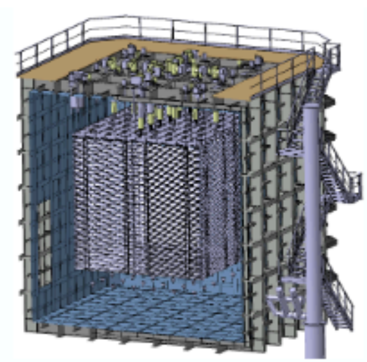
35ton @ FNAL



ProtoDUNEs @ CERN

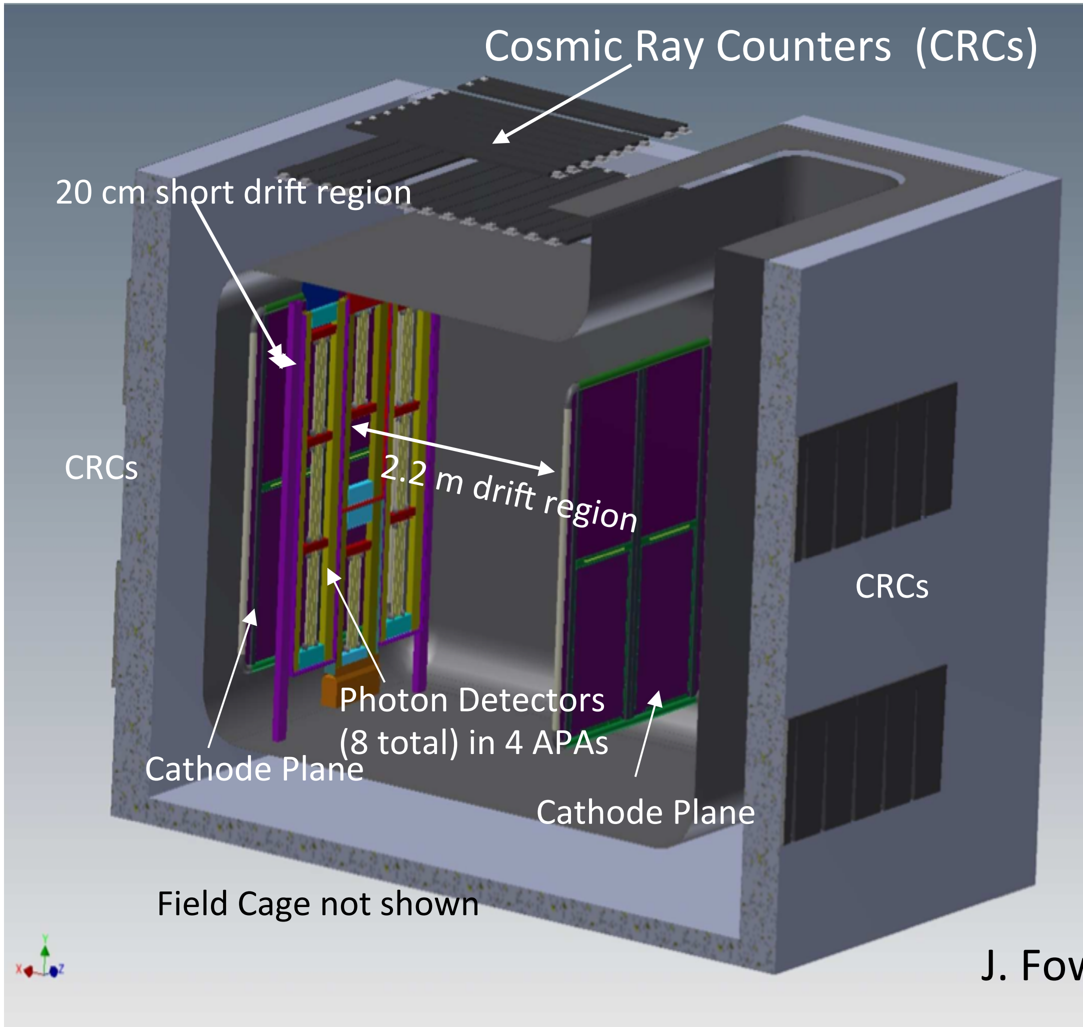
WA105 @ CERN





Novel aspects of the 35ton

- Membrane cryostat
- FR4 printed circuit board field cage
- Light-guide style photon detectors
- Wrapped wire planes
- Multiple drift volumes
- Cold electronics: FE ASIC + ADC ASIC
- Triggerless DAQ operation (continuous readout)



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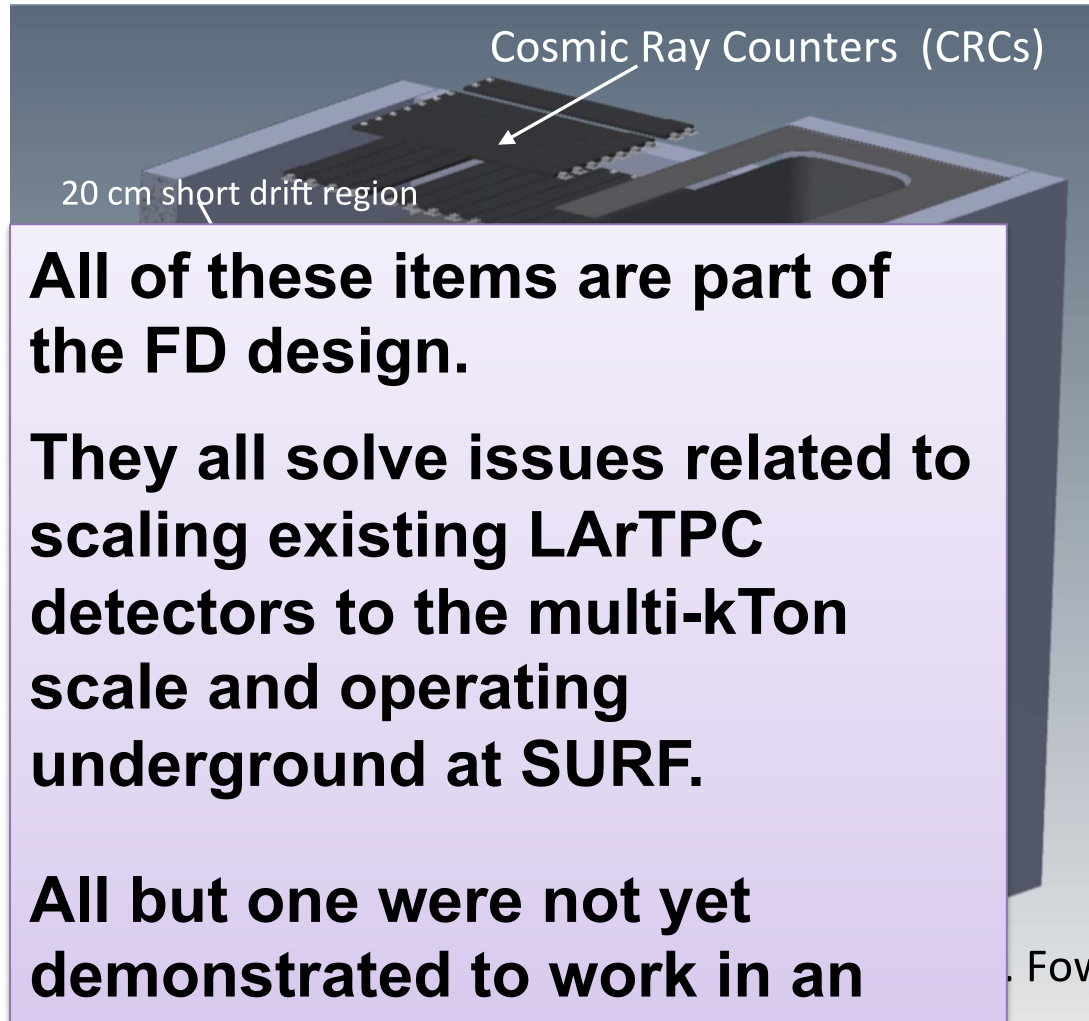


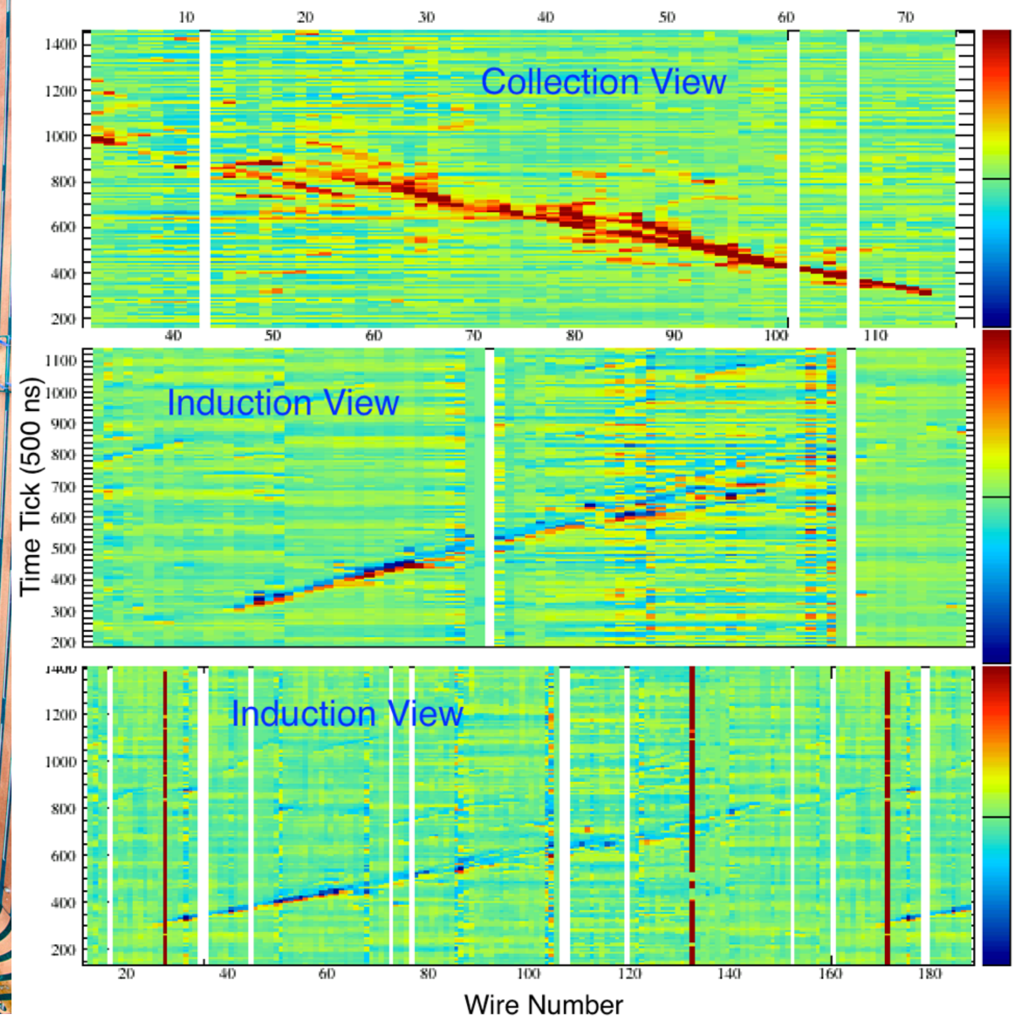
All of these items are part of the FD design.

They all solve issues related to scaling existing LArTPC detectors to the multi-kTon scale and operating underground at SURF.

All but one were not yet demonstrated to work in an integrated system in Dec 2015.

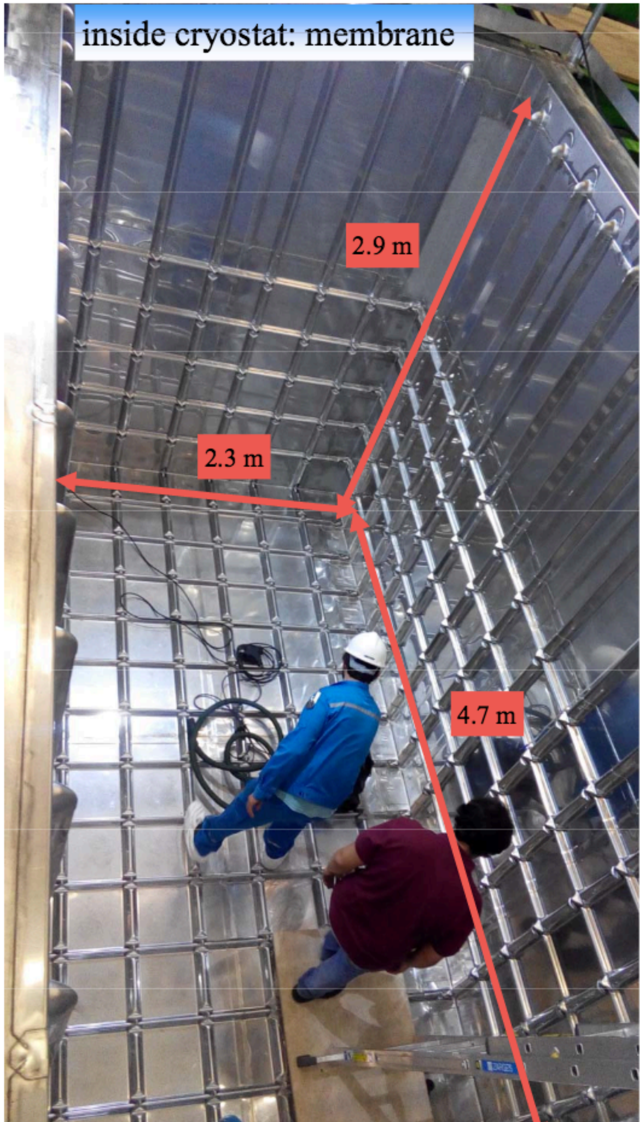
35ton Single Phase Prototype at FNAL

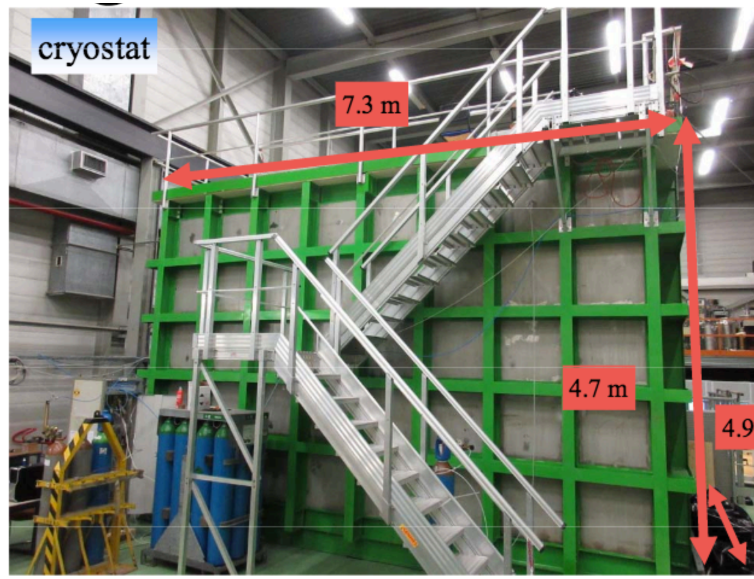
Spring 2016 Cosmic Ray Run

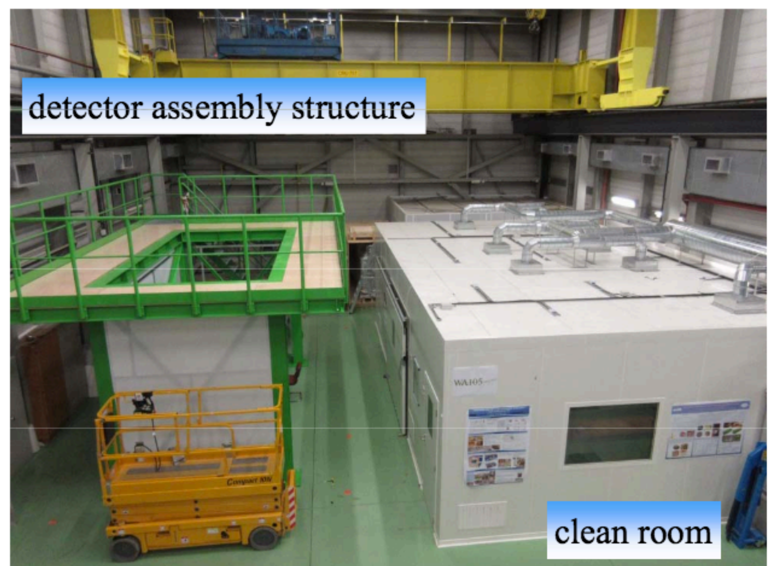


Fermilab DUNE

WA105 Dual Phase Prototype 1x1x3m at CERN

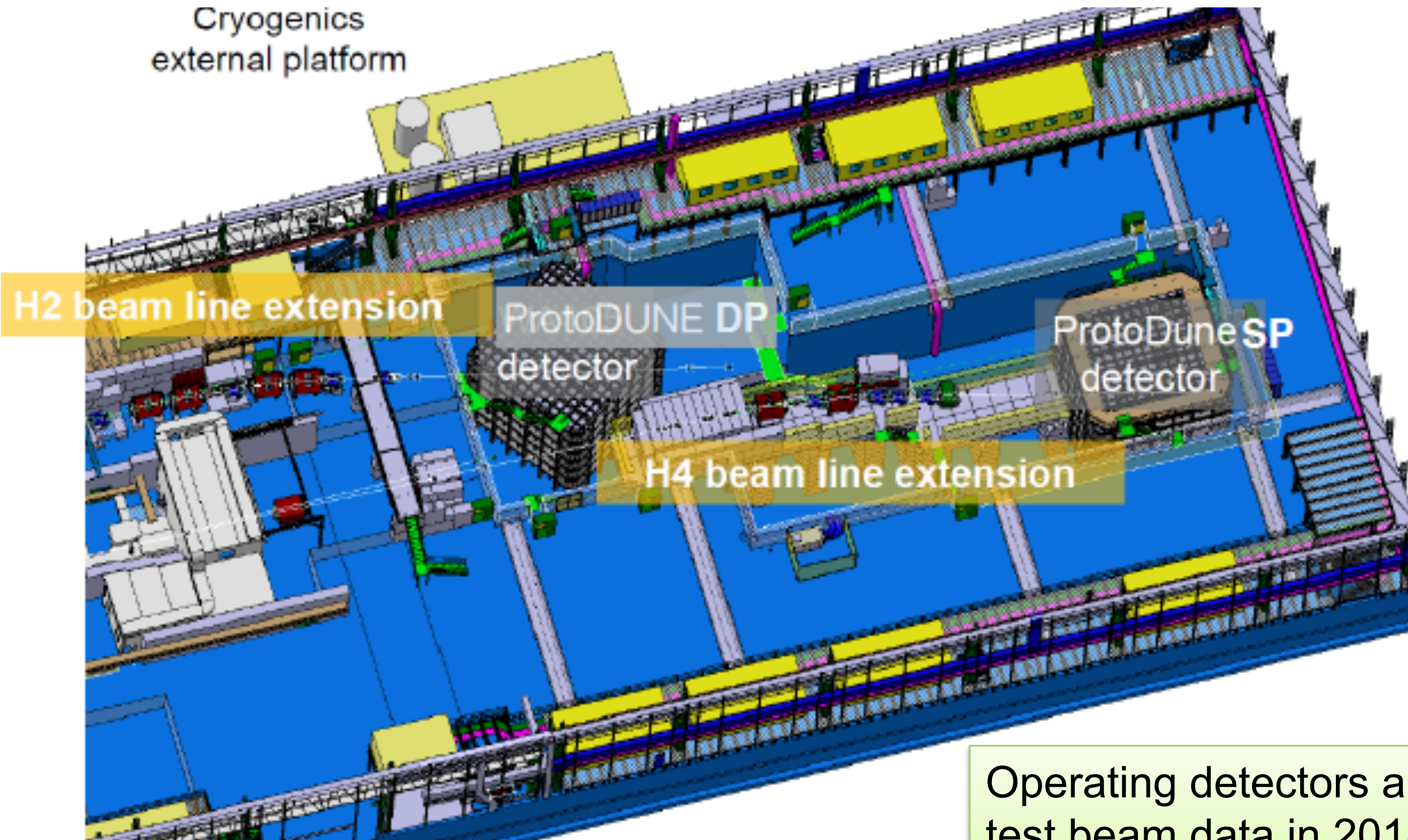






Cosmic Run planned Fall 2016

ProtoDUNEs at CERN Neutrino Platform



Operating detectors and test beam data in 2018!

Proposed measurement program for SP ProtoDUNE

Calibration of the detector in a test beam is highly desired

- EM shower energy resolution
- Electron/photon separation
- PID using dE/dx vs range
- Many more . . . .

Particle	Momenta (GeV/c)	Sample Size	Purpose
π^+	0.2, 0.3, 0.4, 0.5, 0.7, 1, 2, 3, 5, 7	10k	hadronic cal, π^0 content
π^-	0.2, 0.3, 0.4, 0.5, 0.7, 1	10k	hadronic cal, π^0 content
π^+	2	600k	π^o/γ sample
proton	0.7, 1, 2, 3	10k	response, PID
proton	1	1M	mis-ID, PD, recombination
e^+ or e^-	0.2, 0.3, 0.4, 0.5, 1, 2, 3, 5, 7	10k	e-γ separation/EM shower
μ^-	(0.2), 0.5, 1, 2	10k	E_μ, charge sign
μ^+	(0.2), 0.5, 1, 2	10k	E_μ, Michel el.,charge sign
μ^- or μ^+	3, 5, 7	5k	E_μ MCS
anti-proton	low-energy tune	(100)	anti-proton stars
K^+	1	(13k)	response, PID, PD
K^+	0.5, 0.7	(5k)	response, PID, PD
μ, e, proton	1 (vary angle $\times 5$)	10k	reconstruction

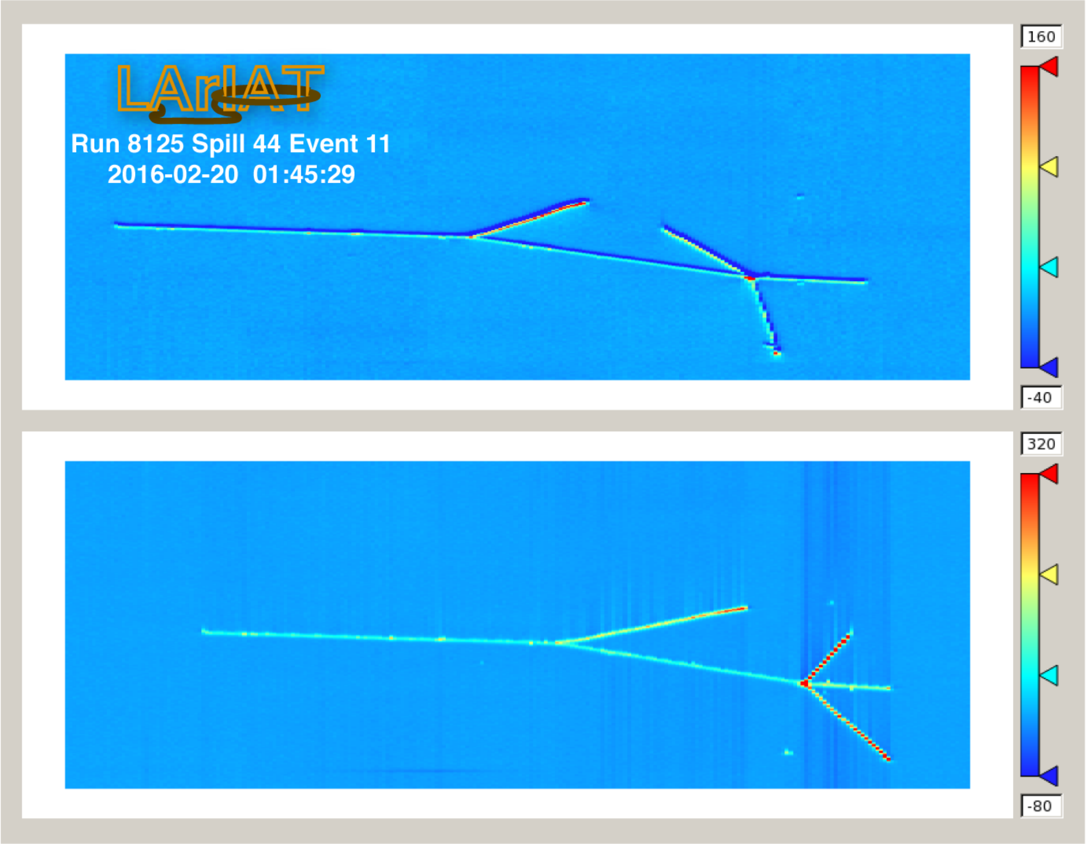
Summary

- The DUNE science program addresses fundamental questions in particle physics
  - Neutrino Oscillations: mass hierarchy and CP violation
  - Nucleon Decay
  - Supernova burst detection, neutrino astrophysics
- LBNF/DUNE will employ a 1.2 MW (and upgradable) neutrino beam, a fine-grained near detector at Fermilab and a modular 40kt LAr far detector at SURF.
- DUNE is a growing international collaboration that welcomes new members to help define, build and further improve the experimental program

Backup Slides

LArTPCs in Test Beams

Charged particle beams covering the energy range and particle species that will be seen in DUNE neutrino interactions



LArIAT@FNAL and the protoDUNEs@CERN address all of these goals

Detector Engineering goals

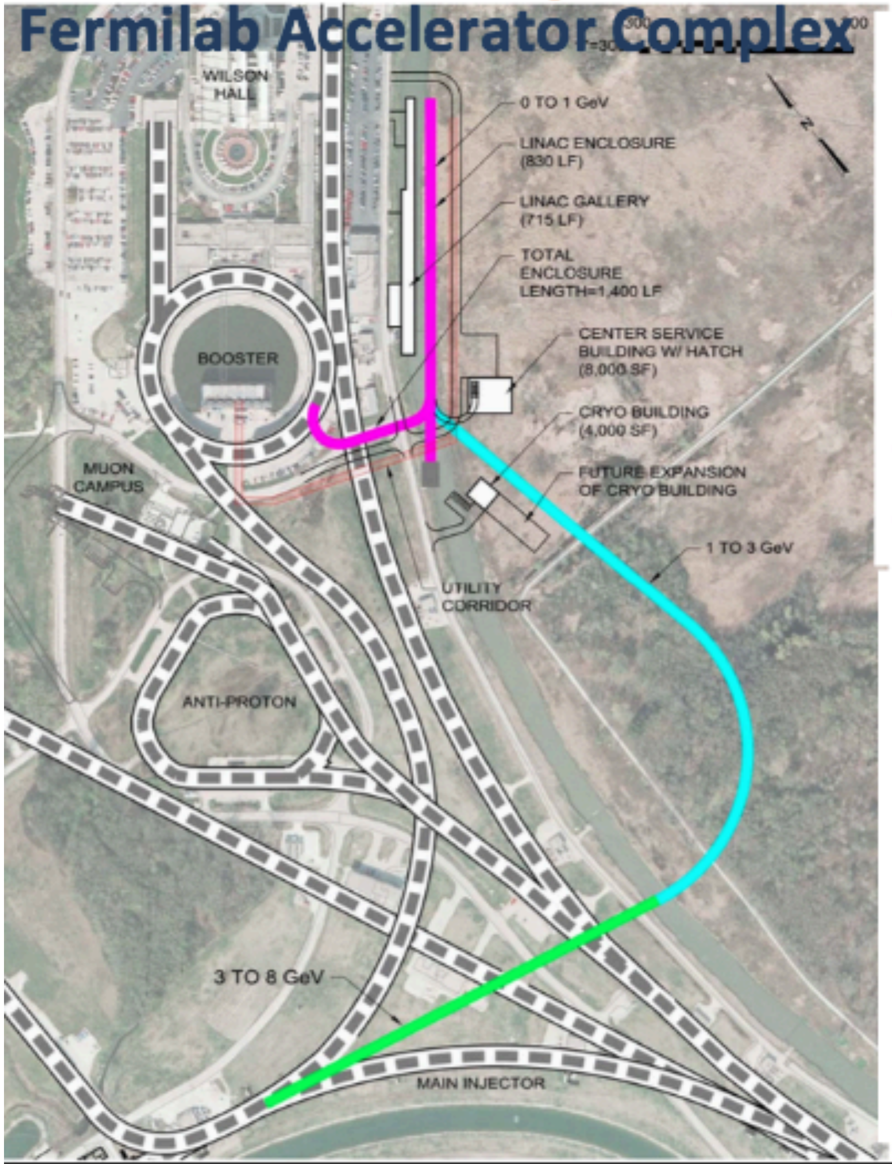
- Measure and benchmark detector performance
- Test installation procedures and operation

Physics Measurements

- Assess detector systematic uncertainties
- π-Ar and kaon-Ar interaction cross sections
- Geant4 validation and tuning
- Develop criteria for determining particle charge based on topology (decay vs. capture), without magnetic field
- Electron/photon shower ID

Jen Raaf, Fermilab

Proton Improvement Plan II and III



Upgrades to increase proton yield

PIP II : (ready by ~2025)

MI beam power → **1.2 MW**

- upgrade to superconducting (SC) 800 MeV linac
- Booster rep. rate: 15 → 20 Hz
- MI rep. cycle: 1.33 →1.2 s

PIP III : (> 2025)

MI beam power → **2.3 MW**

- Upgrade to 8 GeV SC linac

OR

- Upgrade to 2 GeV SC linac and
- Replace booster with 8 GeV rapid cycling synchrotron (RCS)

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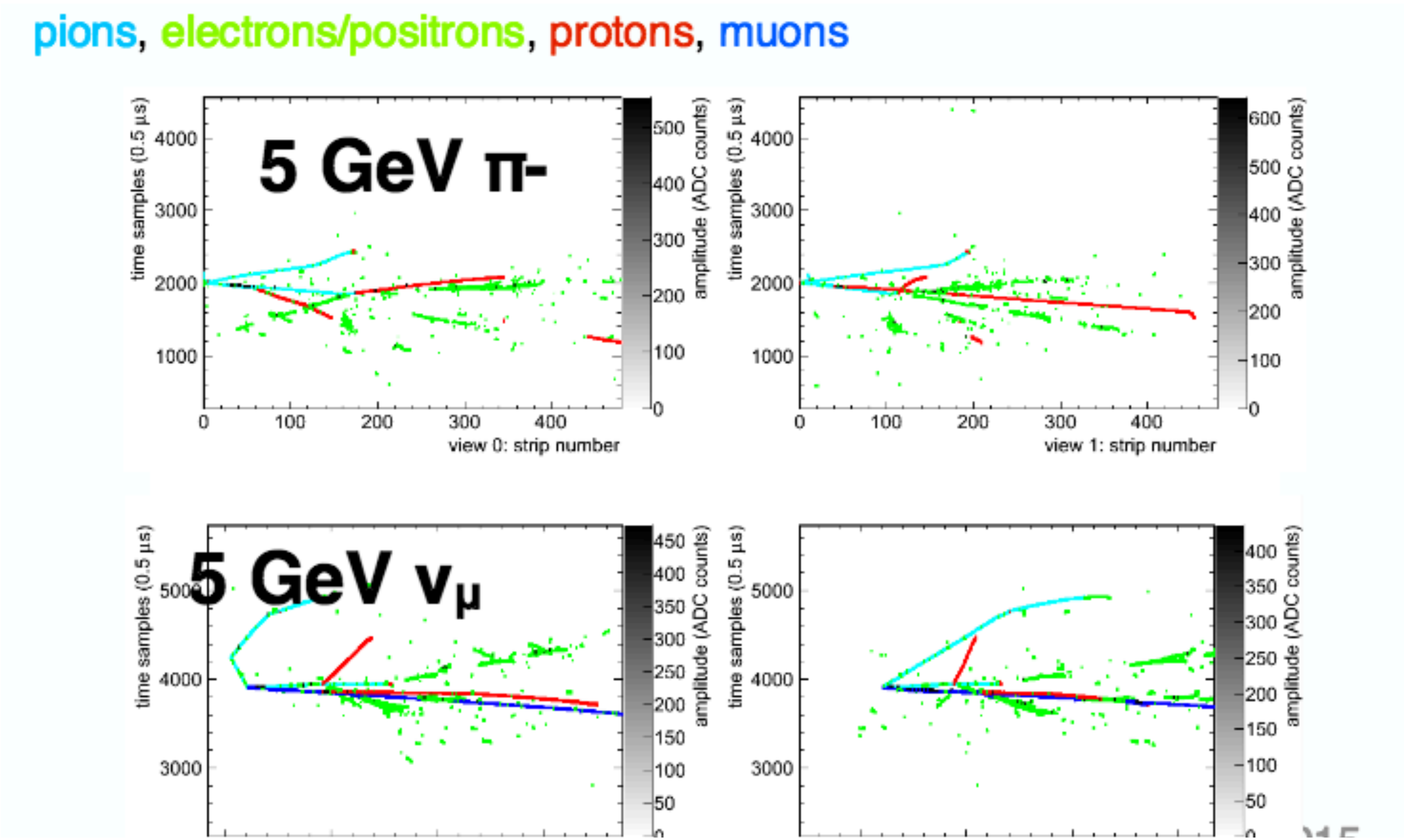
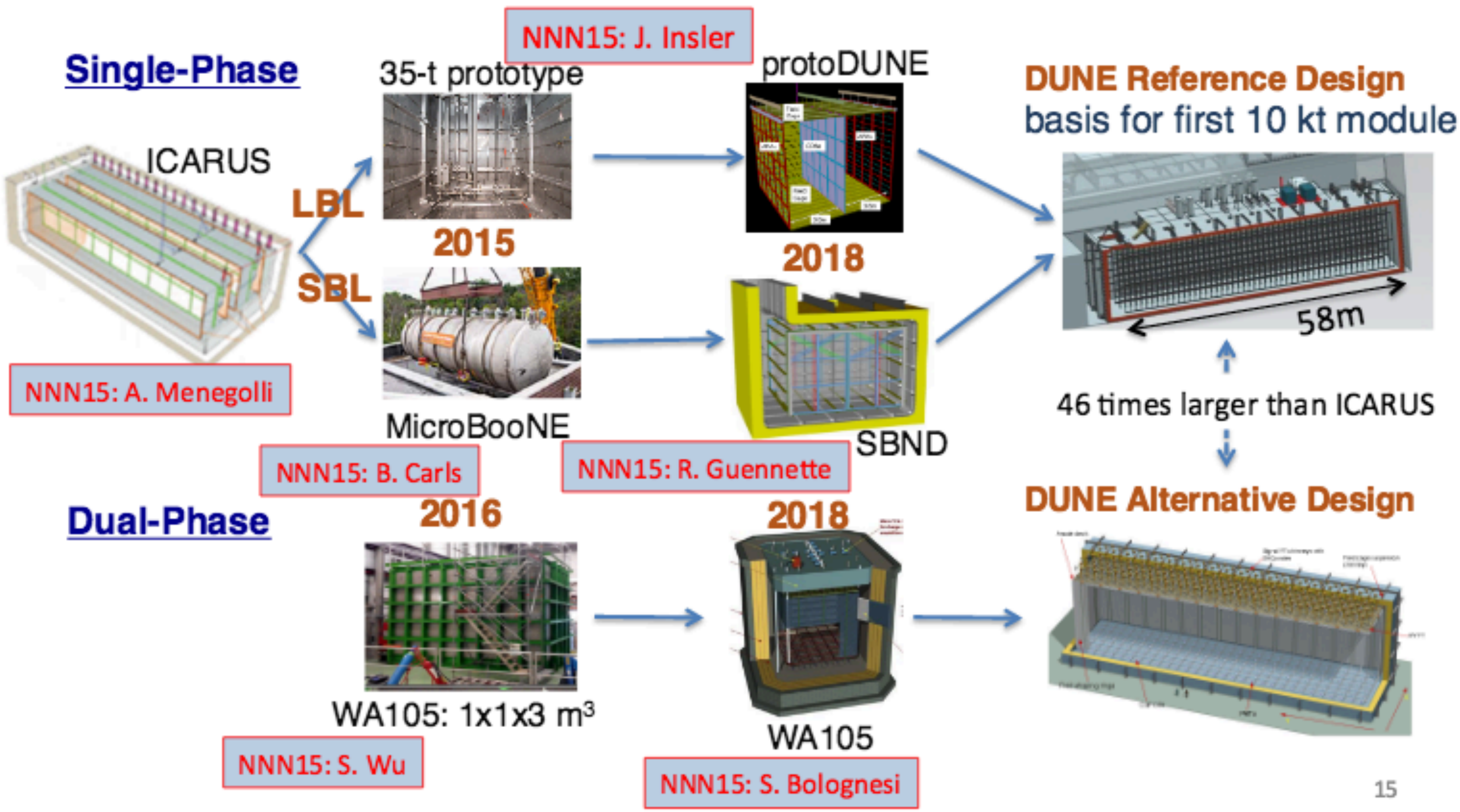
Simulated dual phase events

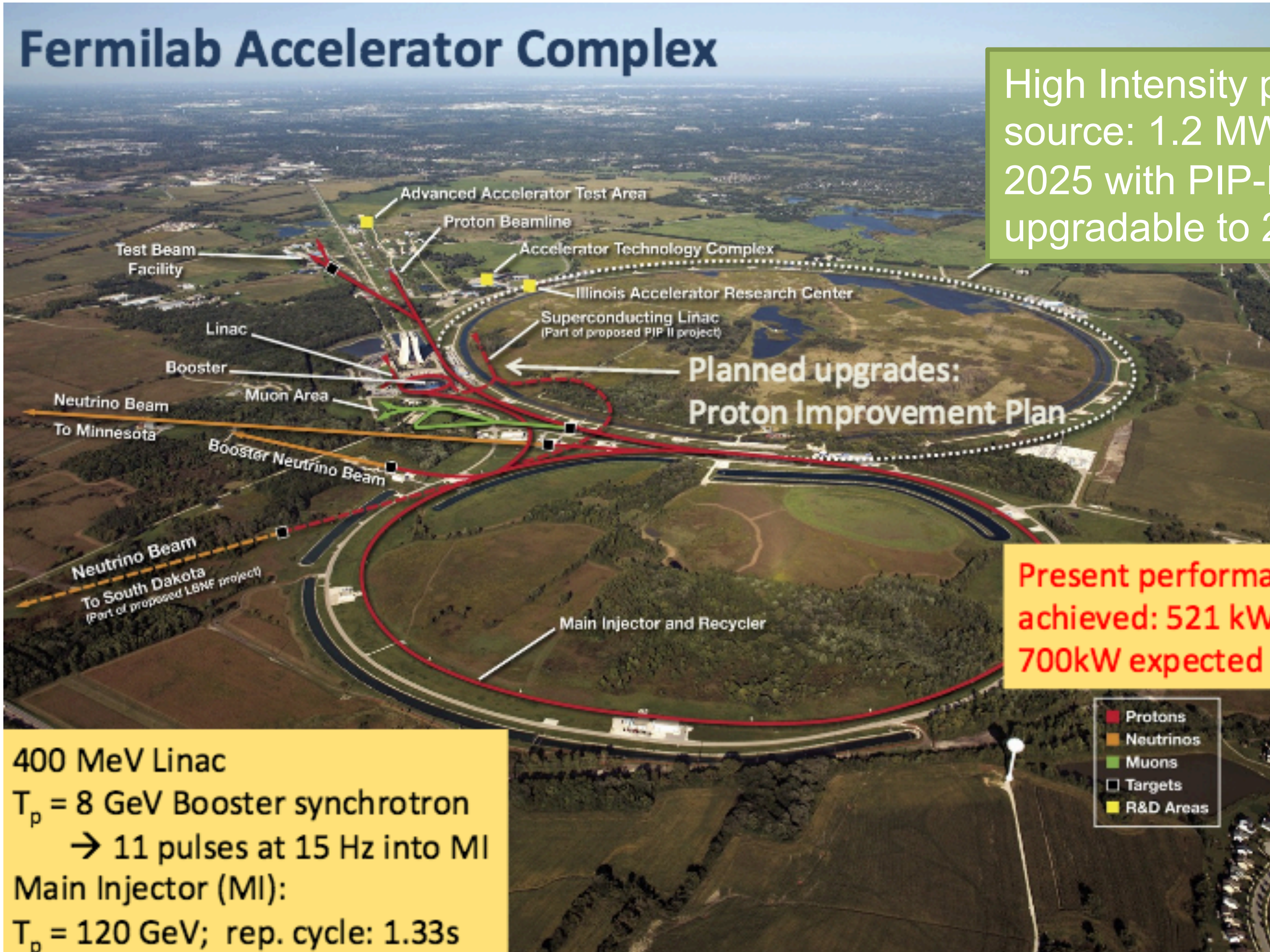


LArTPC Development Path

Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program



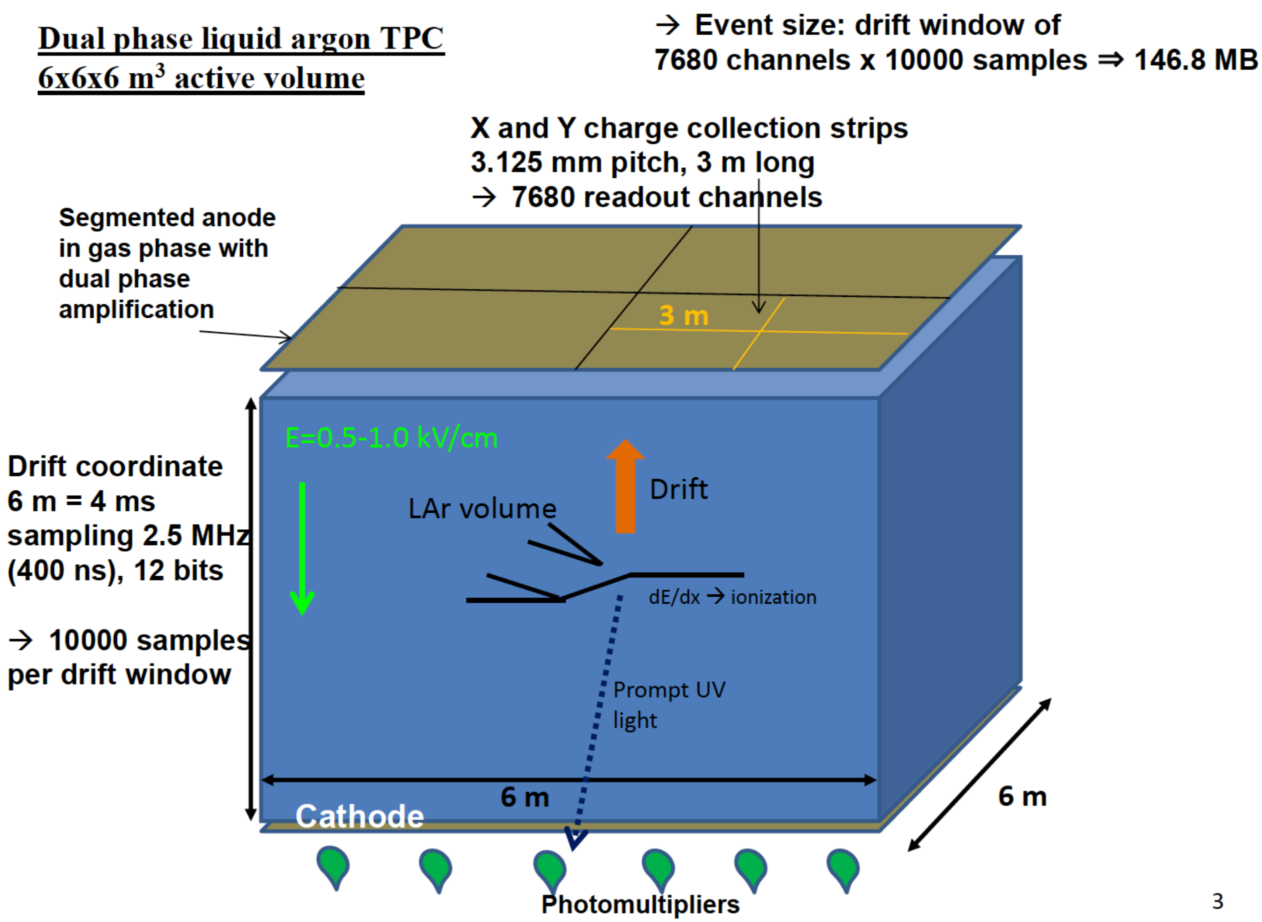
Long Baseline Neutrino Facility



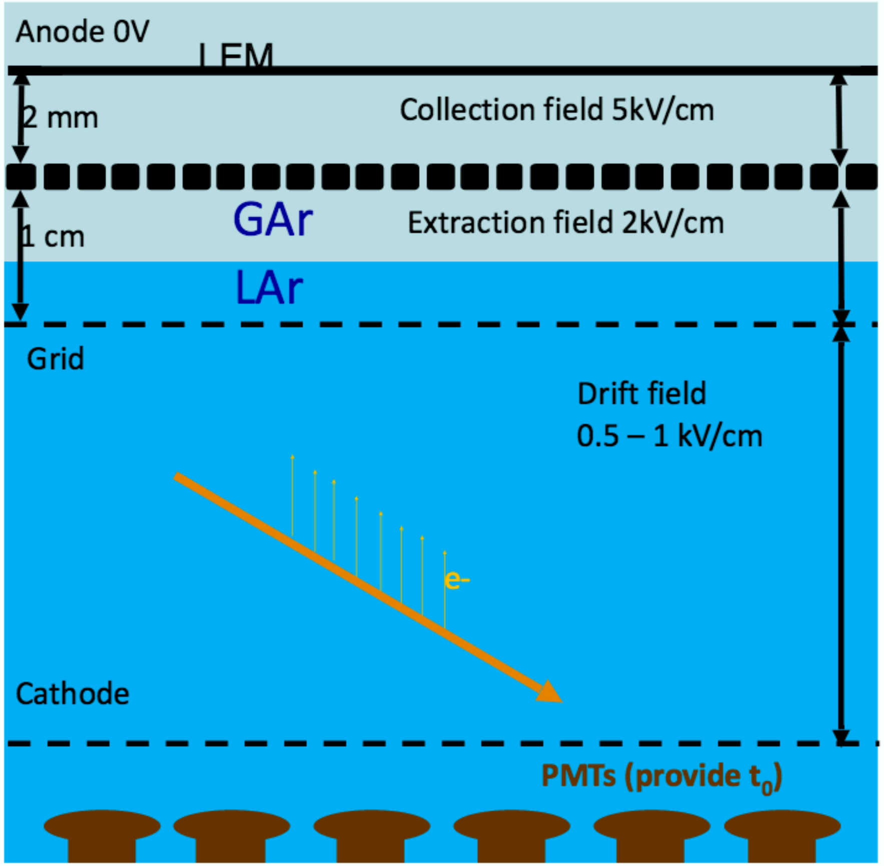
400 MeV Linac
T_p = 8 GeV Booster synchrotron
→ 11 pulses at 15 Hz into MI
Main Injector (MI):
T_p = 120 GeV; rep. cycle: 1.33s

High Intensity proton source: 1.2 MW in 2025 with PIP-II, upgradable to 2.3 MW

Dual Phase ProtoDUNE



Concept of double-phase LAr TPC (Not to scale)

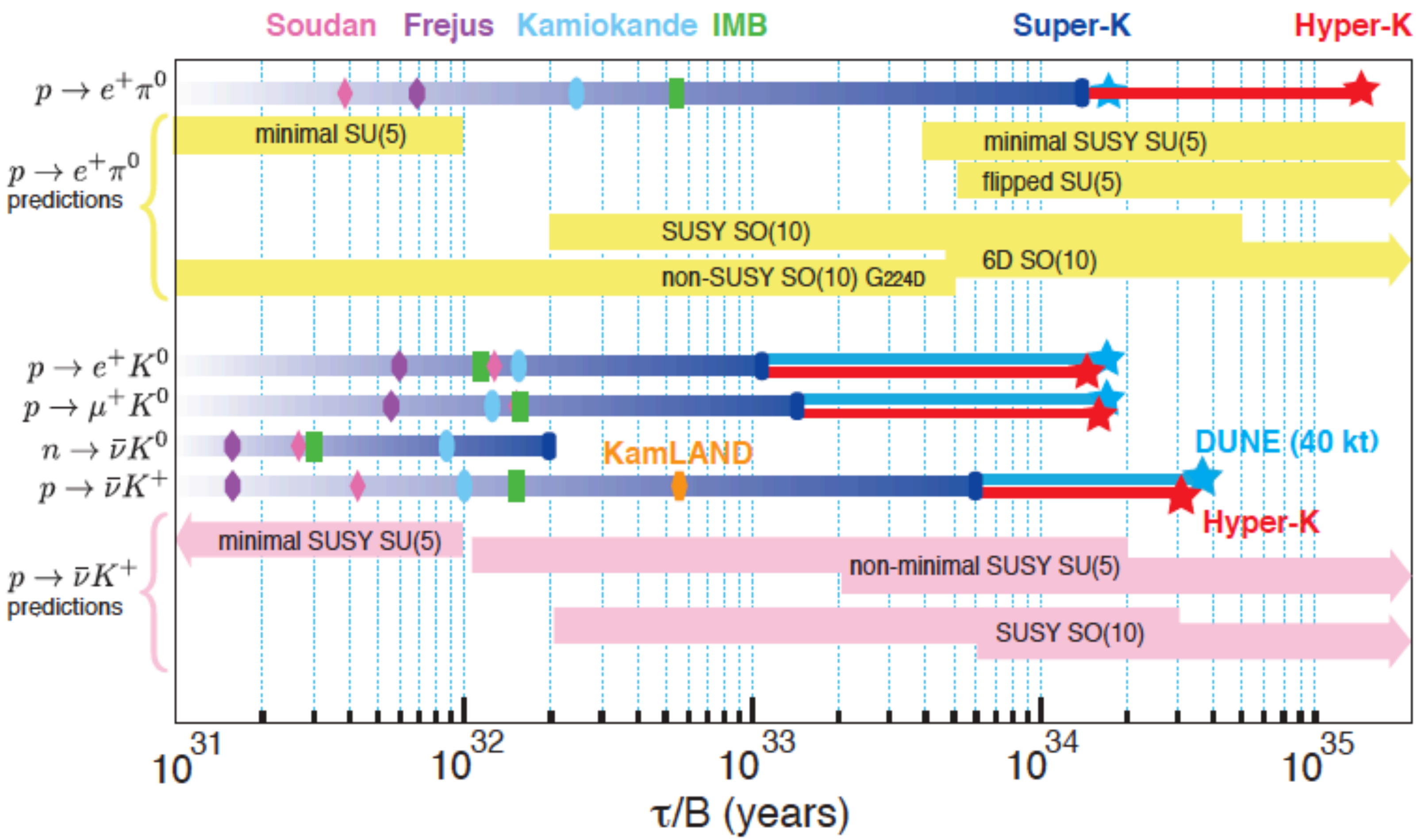


Large scale LAr TPC for LB neutrino oscillation physics, astrophysics, and nucleon decay search (GUT physics)

- Single cryo-tank based on industrial LNG solution to house O(10) kton of LAr mass
- Double-phase for charge readout with amplification:
  - **Long drift distances**
  - **Low energy detection thresholds**
  - **readouts with only collection views**
  - **maximise active LAr volume whilst minimising the number of channels.**

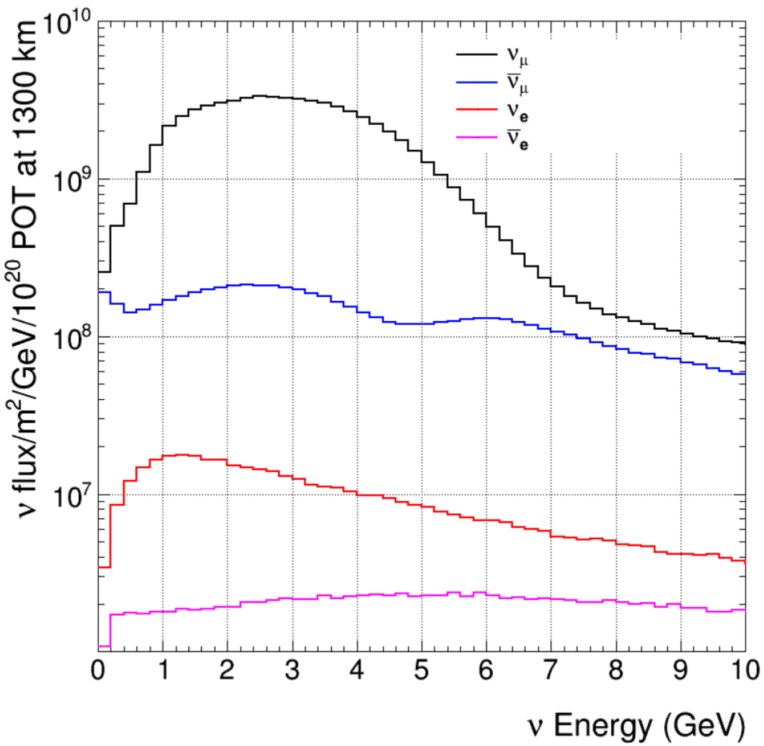
GLACIER concept. (A. Rubbia, Experiments for CP-violation: A giant liquid argon scintillation, Cherenkov and Charge imaging experiment? hep-ph/0402110.)

sensitivity – proton decay

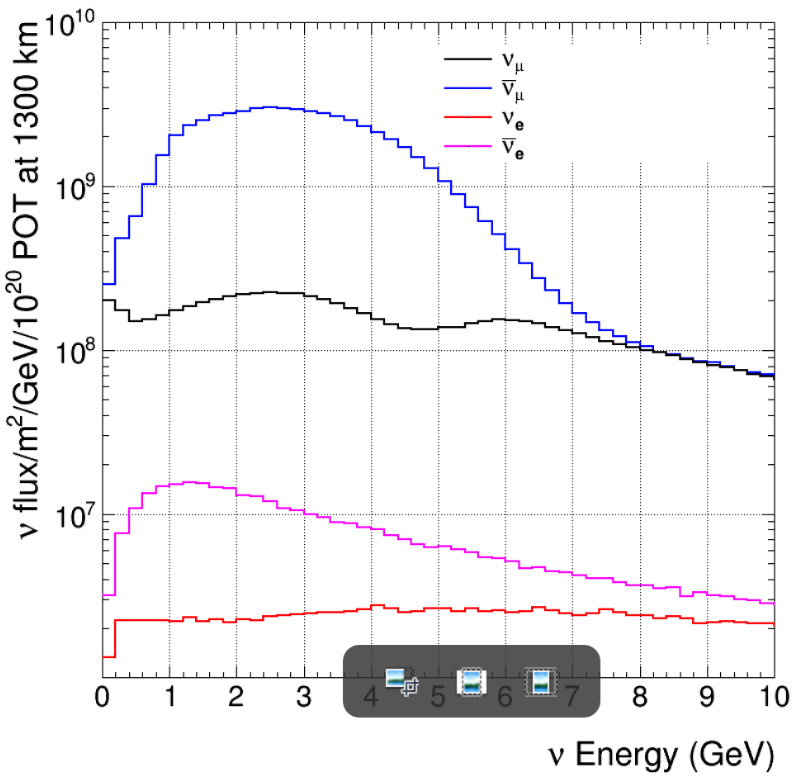


LBNF beam composition

Neutrino beam



Anti Neutrino beam



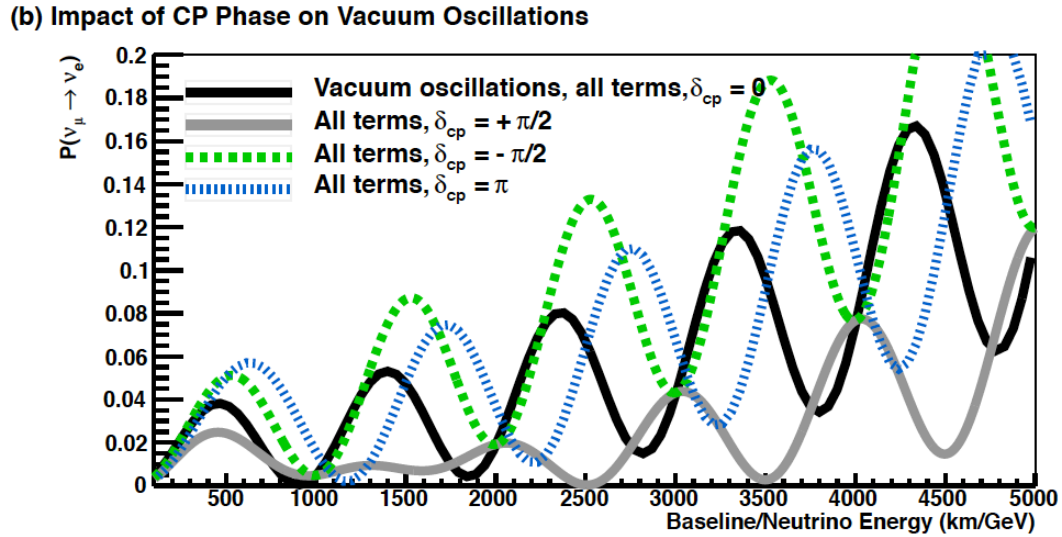
DUNE CDR – "LBNF volume" aiXrv: 1601.05823

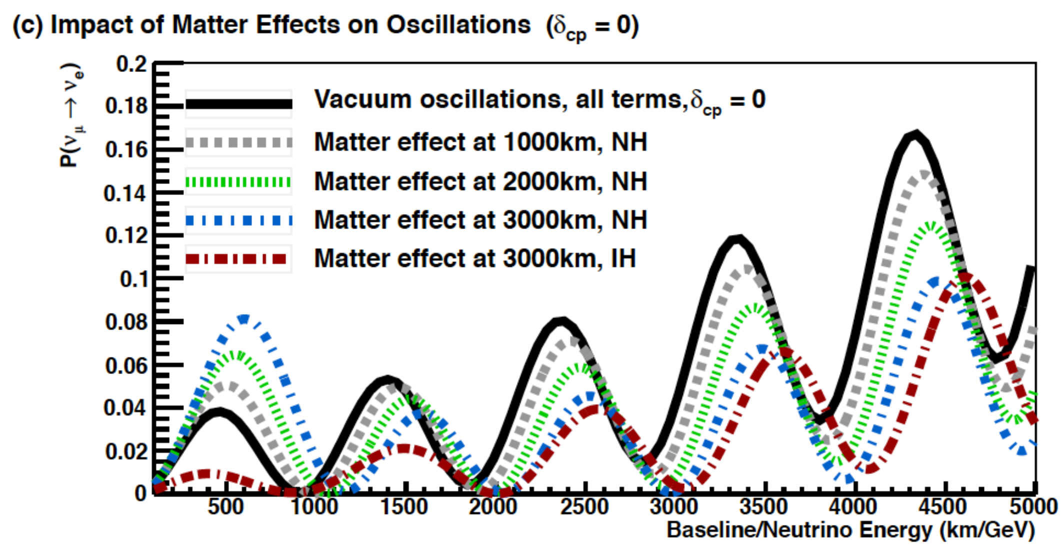
Disentangling MH and delta-CP

Phys Rev D91, 052015 (2015), figure 1

- Both MH and delta-CP change the height of the oscillation peak – degeneracy
- But each shifts the peak in L/E differently – use shape to disentangle

Plots are P(nu-mu -> nu-e) vs L/E.
Top is NH, different deltaCP values
Bottom is deltaCP=0 different L values





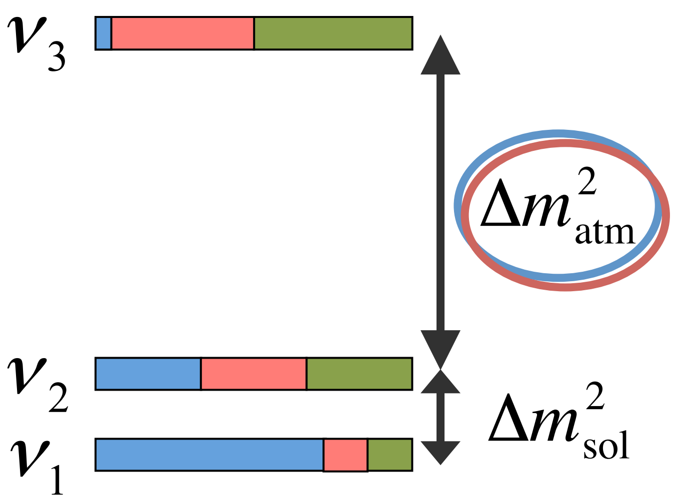
Oscillation Physics with Accelerator Long Baseline Beams

atmospheric / accelerator ν_μ — short baseline reactor / accelerator ν_e — solar / long baseline reactor

Flavor

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

Mass



ν_μ Disappearance:
θ_{23}, $|\Delta m^2_{\text{atm}}|$

$\nu_\mu \rightarrow \nu_e$ Appearance:
θ_{13}, δ_{CP}, MH