Search for ALPs at ICARUS AND LArTPC R&D

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INTENSE: Particle Physics Experiments at the Intensity Frontier

May, 2023

THE UNIVERSITY OF TEXAS AT ARLINGTON

Outline

1) Introduction
2) What Are Axion-Like Particles
3) Couplings
4) The SBN Program
5) Hardware Experience
6) Future Work and Conclusions

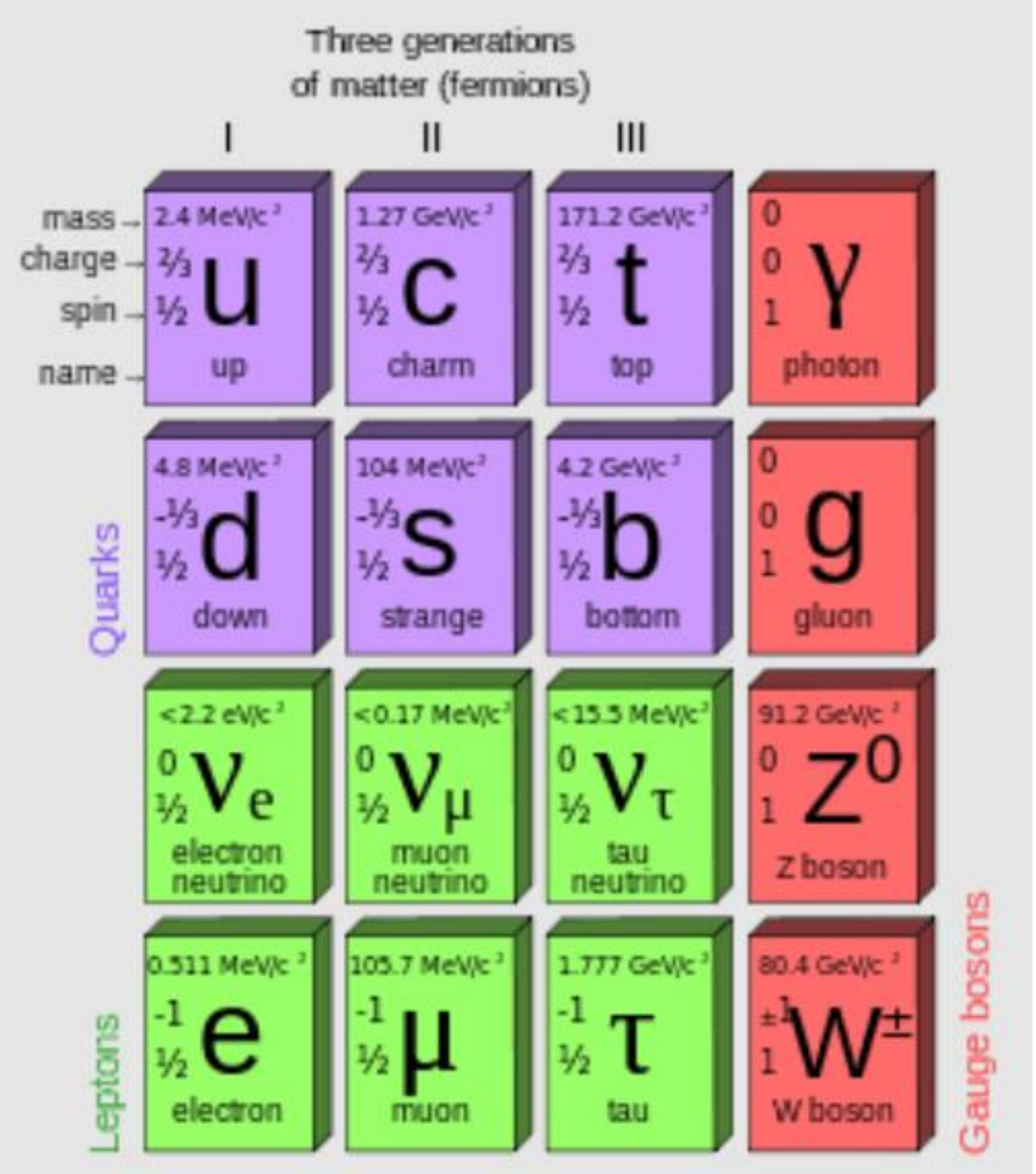
1) Introduction

Standard Model

- Physicists today have an *almost* complete model of the nature of particles in our universe.
- But, some fundamental questions remain…
  - Matter-antimatter symmetry
  - Neutrinos
  - Dark Matter

How do we try to answer them?

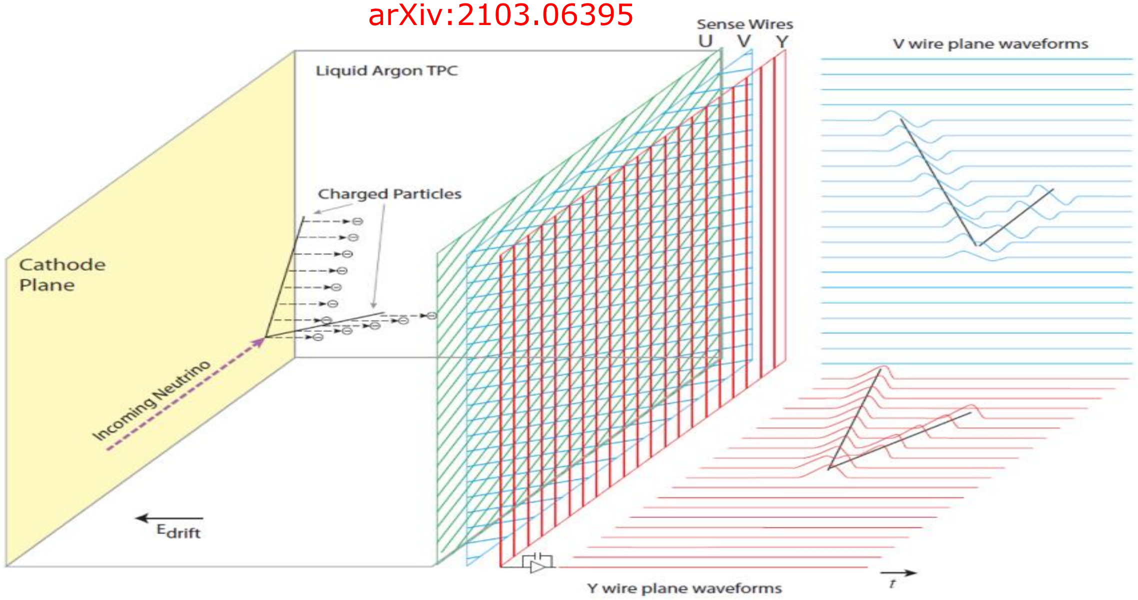
By building big expensive machines to probe the smallest parts of nature



arXiv:2103.06395

Liquid Argon Time Projection Chamber

- LArTPCs today are the forefront of particle physics technology.
- They allow us to study particles via their interactions with liquid argon.
- Could there exist particles not discovered yet?



Axions and Axion-Like Particles

- First proposed by Peccei and Quinn for the resolution of the strong CP problem.
- Good candidate for Dark Matter
- Potentially detectable due to their weak couplings to SM particles.
- The goal to find them is easier said than done!


Roberto Peccei and Helen Quinn

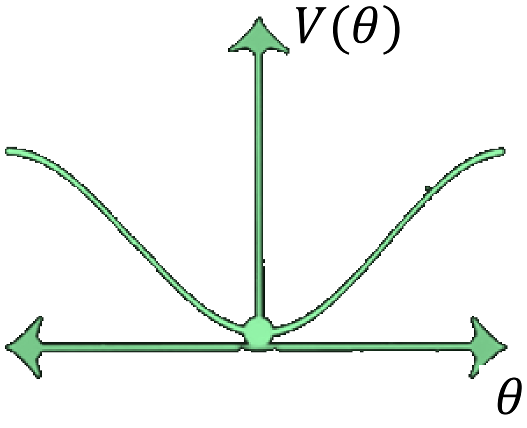
2) What Are Axion-Like Particles

Axions or axion-like particles (ALPs) are hypothetical pseudoscalar particles, which could help solve current physics problems like:

- **The Strong CP problem**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m e^{i\theta'\gamma_5})\psi.$$

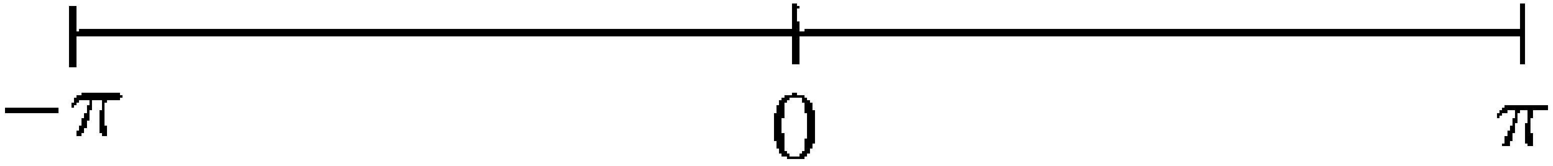
$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}_{\mathrm{INV}} + \theta\mathcal{L}_{\mathrm{VIO}}$$



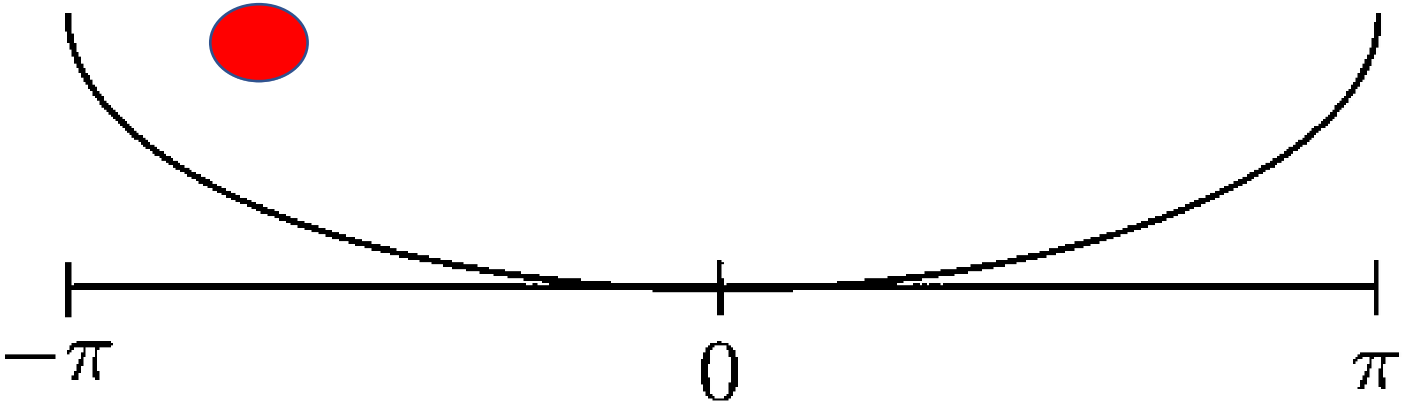
Axion field

$\theta(a)$

What is the value of this θ?



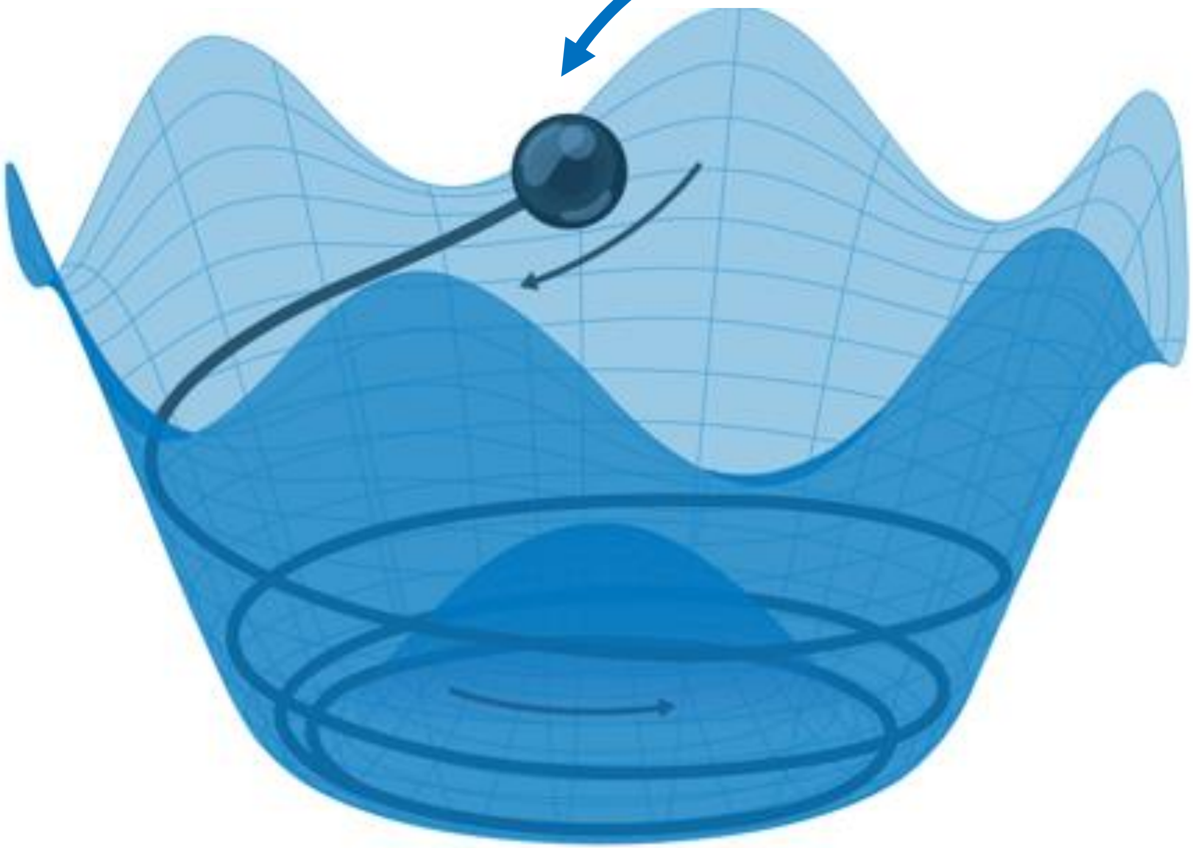
And of $\theta(a)$?



2) What Are Axion-Like Particles

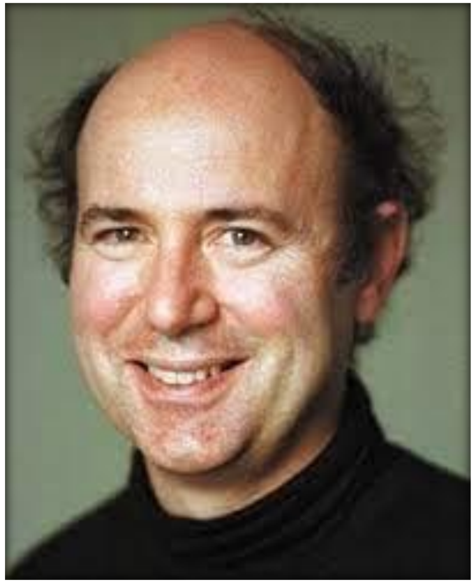
DM Candidate

Maximum energy state



The Axion Field at the Big Bang

arXiv:1910.02080



Frank Wilczek

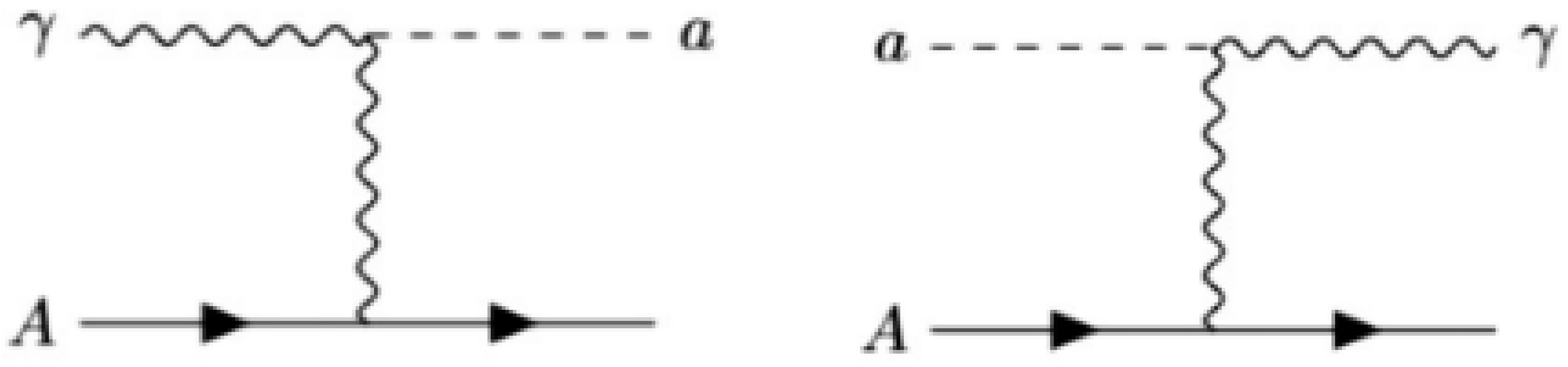
Steven Weinberg

3) Couplings

Axions couple to various SM particles, however, we are primarily concerned with ALP coupling to photons, via the Lagrangian of the form $\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

ALP Primakoff Scattering

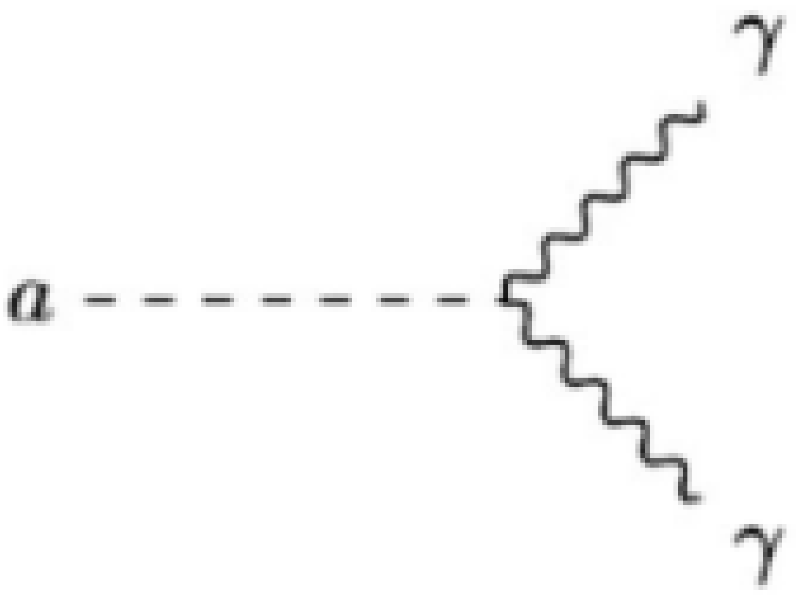
The Primakoff scattering process refers to either $a \rightarrow \gamma$ or $\gamma \rightarrow a$. Not to be confused with the same process involving an external strong EM field or plasma instead of the atomic electric field.



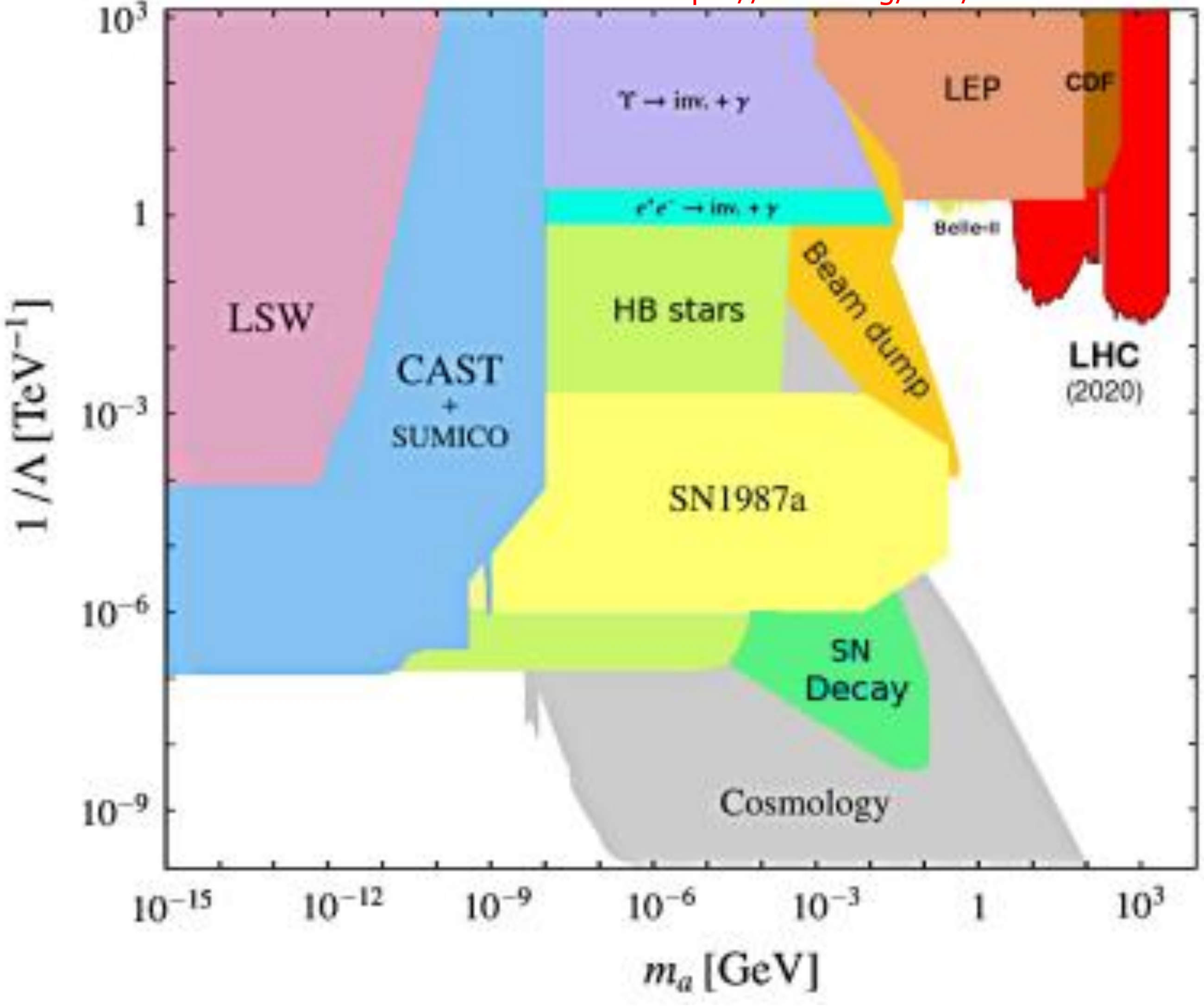
3) Couplings

ALP Decay

ALPs may decay into a 2 photons $a \to \gamma\gamma$ via the $g_{a\gamma}$ coupling constant and the decay width as $\Gamma = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$



https://arxiv.org/abs/2102.08971



The Short Baseline Neutrino Program

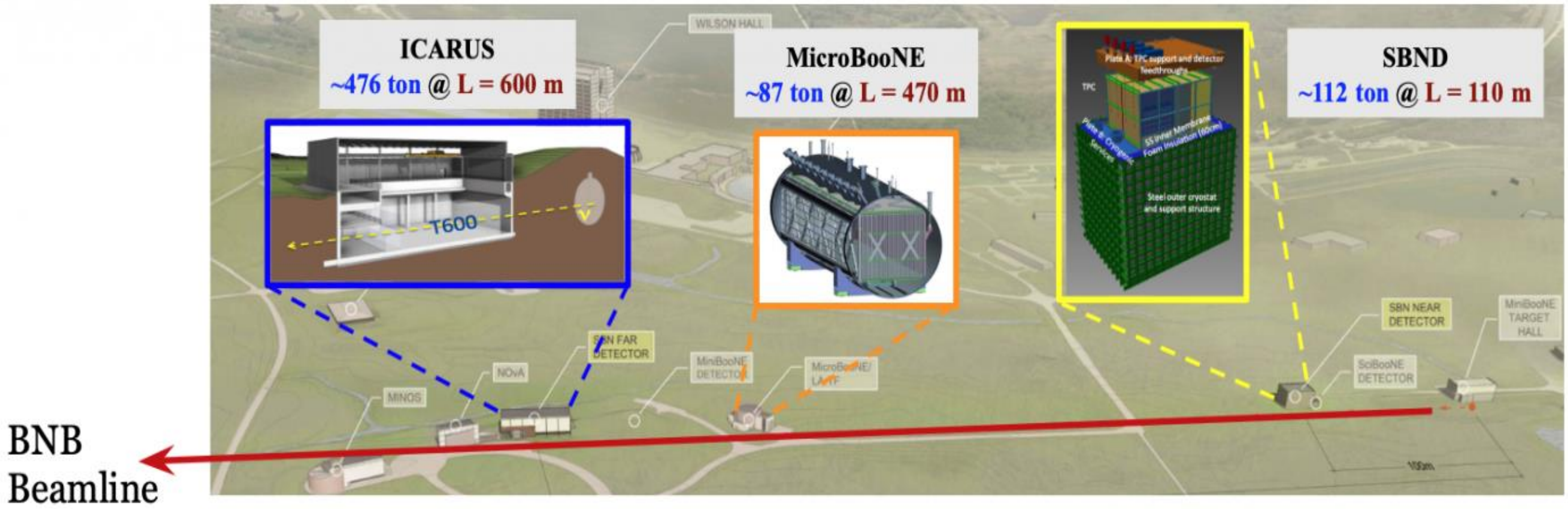
A quick summary – the SBN complex comprises the Booster Neutrino Beam (BNB) and:

i. Short-Baseline Near Detector (SBND)

ii. MicroBooNE

iii. Short-Baseline Far Detector (ICARUS)

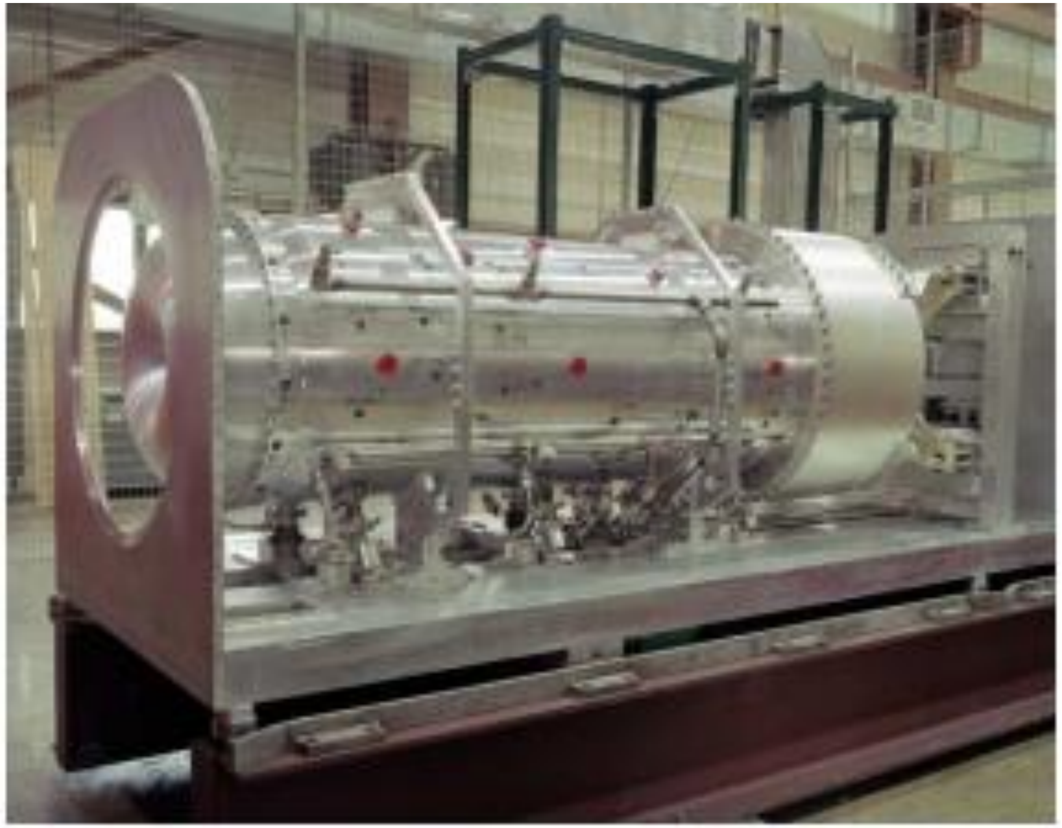
https://sites.slac.stanford.edu/neutrino/experiments/icarus



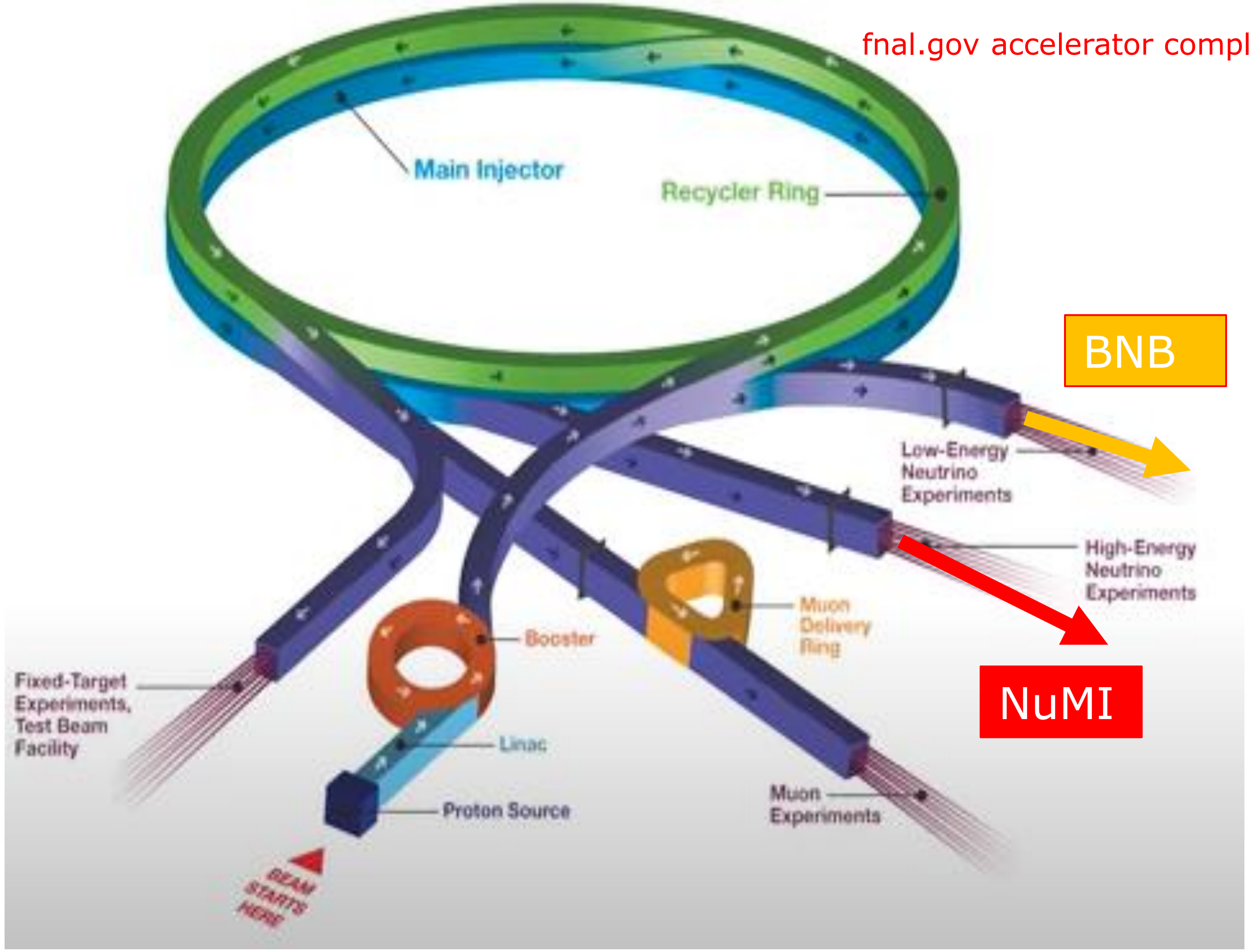
Booster Neutrino Beam (BNB)

- 8 GeV protons from the Fermilab Booster onto a Beryllium target
- Magnetic horn focuses mesons
- Meson decays with Fe beam dump.

Žarko Pavlović – Booster Neutrino Beam

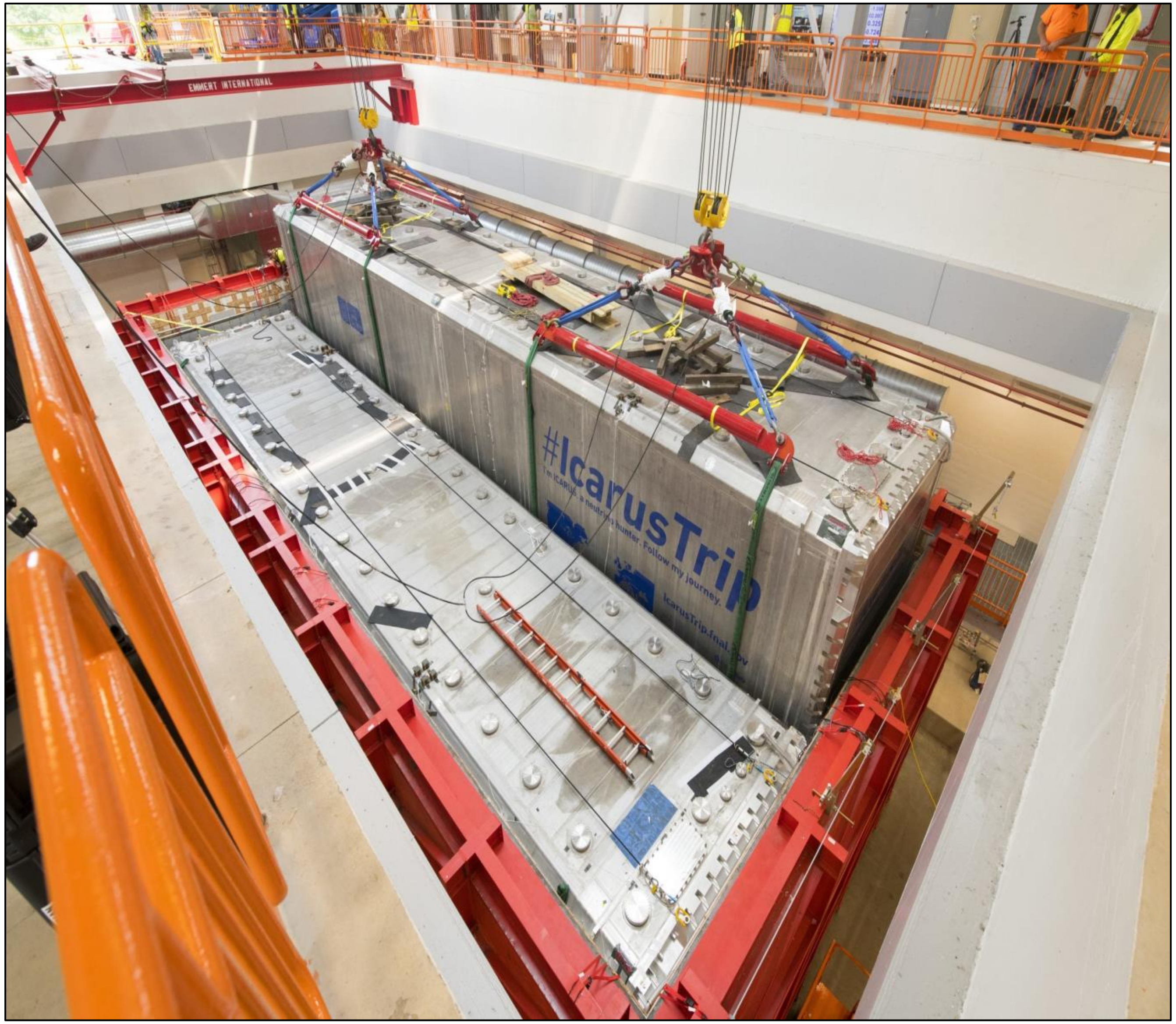


fnal.gov accelerator complex



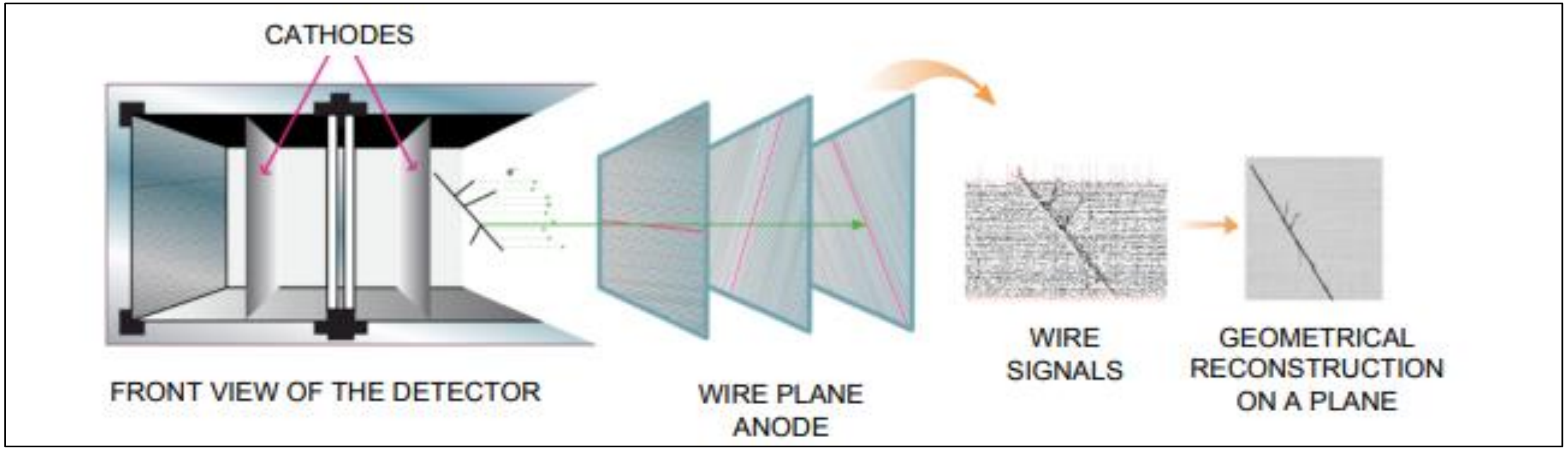
Imaging Cosmic And Rare Underground Signals (ICARUS)

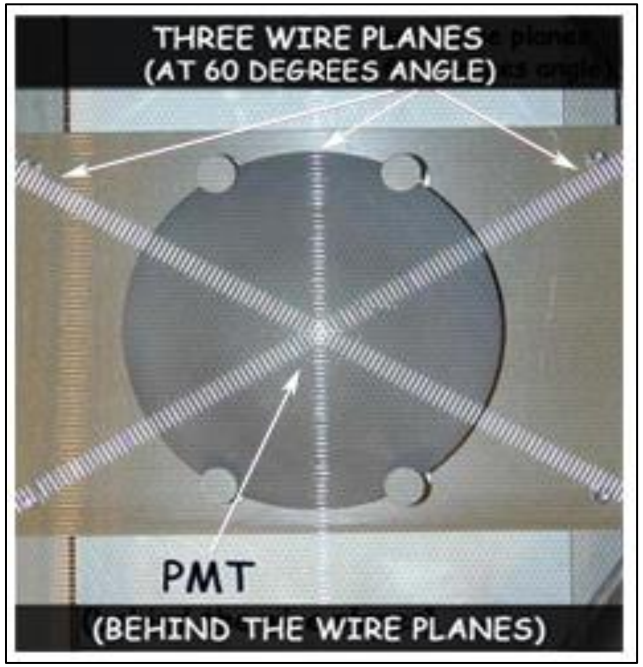
news.fnal.gov icarus installed

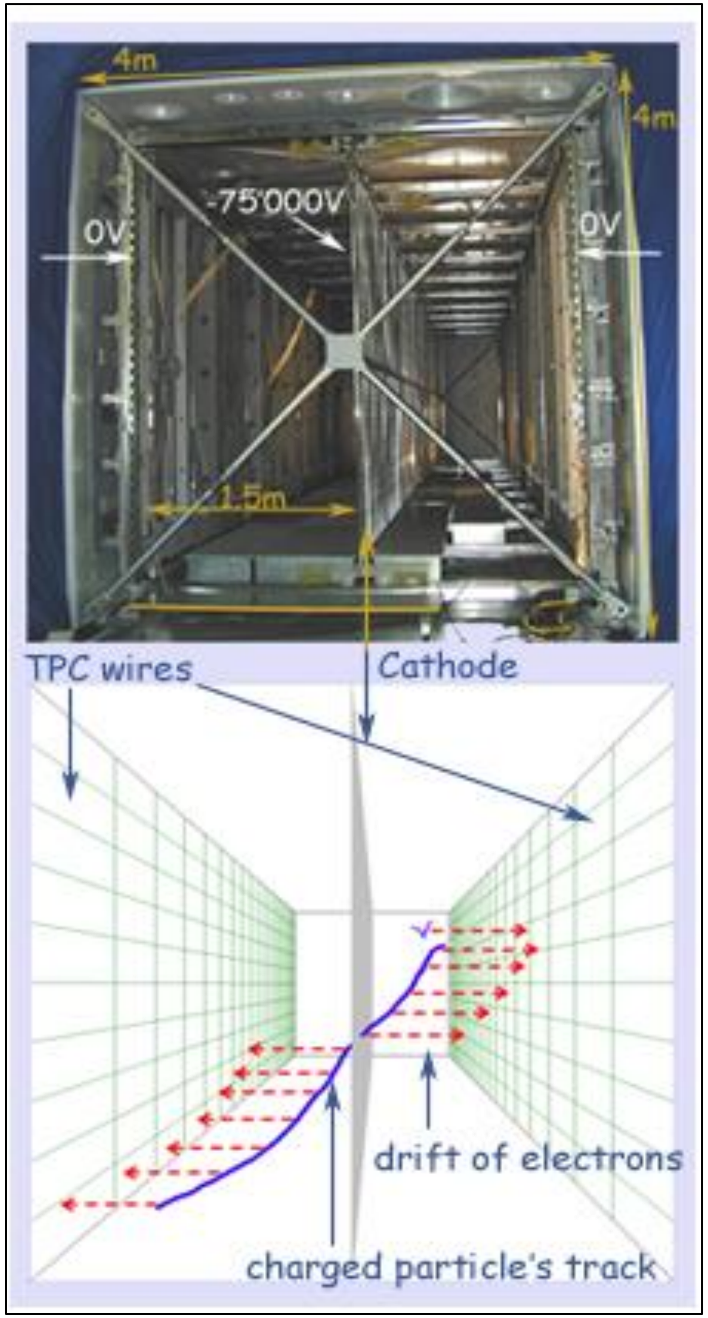


- Consists of two T300 modules that each have two LArTPCs.
- Each module is roughly 3.6 x 3.9 x 19.9 cubic meters with ≈ 476 tons active LAr.
- 500 V/cm Electric field gives a drift time of ~ 1*ms* over 1.5*m*.
- 3 wire planes with 400*ns* sampling rate and a total of ~ 54,000 channels.

Imaging Cosmic And Rare Underground Signals (ICARUS)



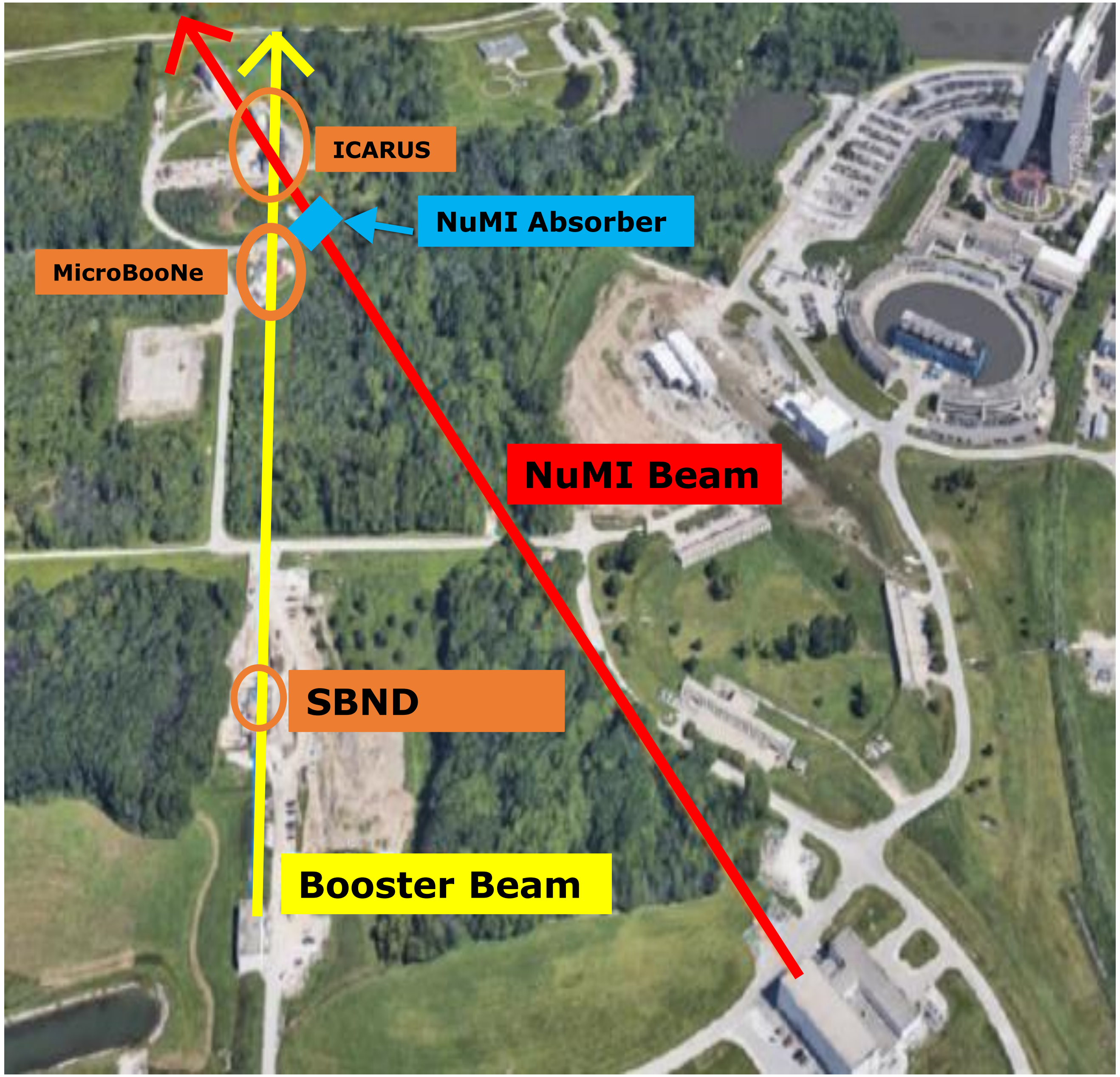




https://www.osti.gov/biblio/1867676/

Why ICARUS?

- Largest working LArTPC (before protoDUNE)
- Unique sensitivity to BNB *and* NuMI
- The NuMI beam line is fed by 120 GeV protons and is roughly **6° off-axis** and ~800*m* from ICARUS.
- DM/ALP indirect searches have experimental principles analogous to neutrino detection.



arXiv:2210.02462

ICARUS & ALPs

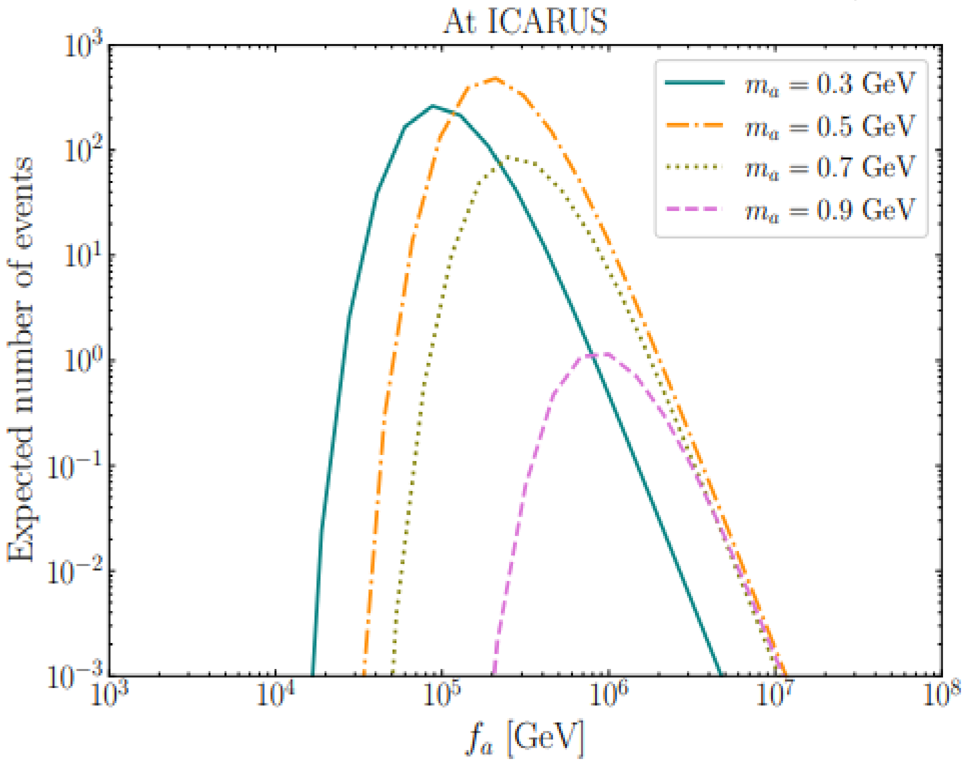
$$N_{\text{axions}} = N_{\text{POT}} \times \begin{cases} 0.82|\theta_{a\pi}|^2 + 0.072|\theta_{a\eta}|^2 + 0.0038|\theta_{a\eta'}|^2 & \textbf{\textit{for 8 GeV BNB}} \\ 2.9|\theta_{a\pi}|^2 + 0.33|\theta_{a\eta}|^2 + 0.034|\theta_{a\eta'}|^2 & \textbf{\textit{For 120 GeV NuMI}} \end{cases}$$

- Similar graph necessary for axion decays into the diphoton signature
- Explore dominant decay channels related to ALP masses

Experiment	E_p**(GeV)**	N_{POT}	$d(m)$	$L(m)$	$w \times h\ (m \times m)$
ICARUS $\begin{cases} \textbf{\textit{BNB}} \\ \textbf{\textit{NuMI}} \end{cases}$	8 120	6.6×10^{20} 2.5×10^{21}	600 790	19.9	$(3.9 \times 3.6) \times 2$

Detector Specifications for ICARUS

The expected number of events at ICARUS in which the axion decays into dimuons within the detector, as a function of the decay constant f_a



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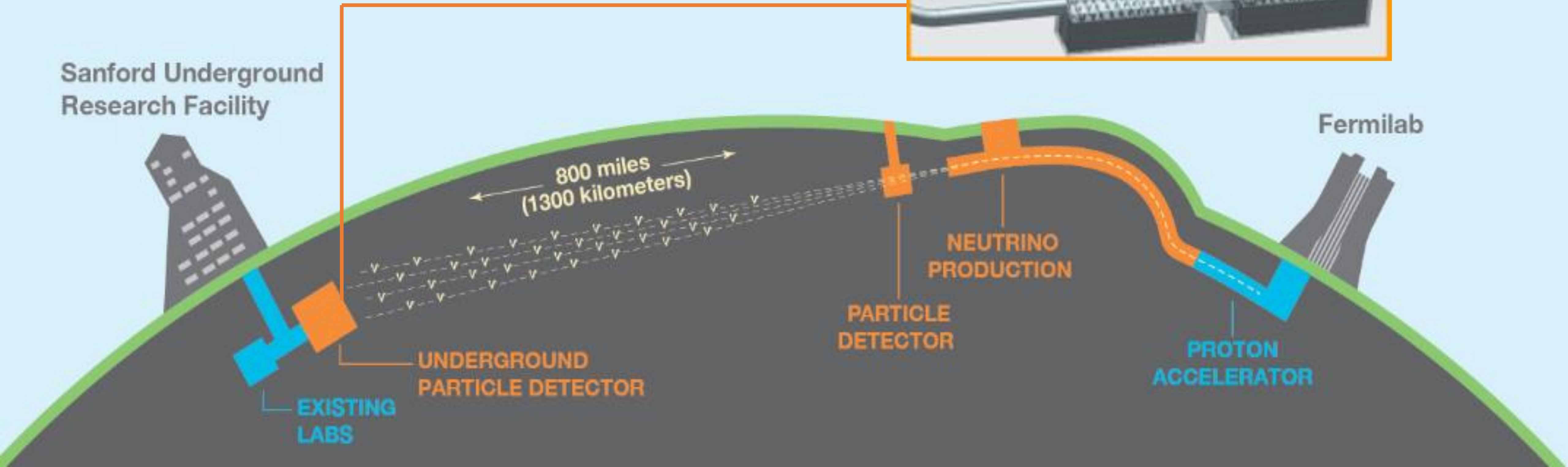
7) Hardware Experience - DUNE Summary

Deep Underground Neutrino Experiment or DUNE is an Liquid Argon (LAr) based international experiment for neutrino science, and it comprises of:

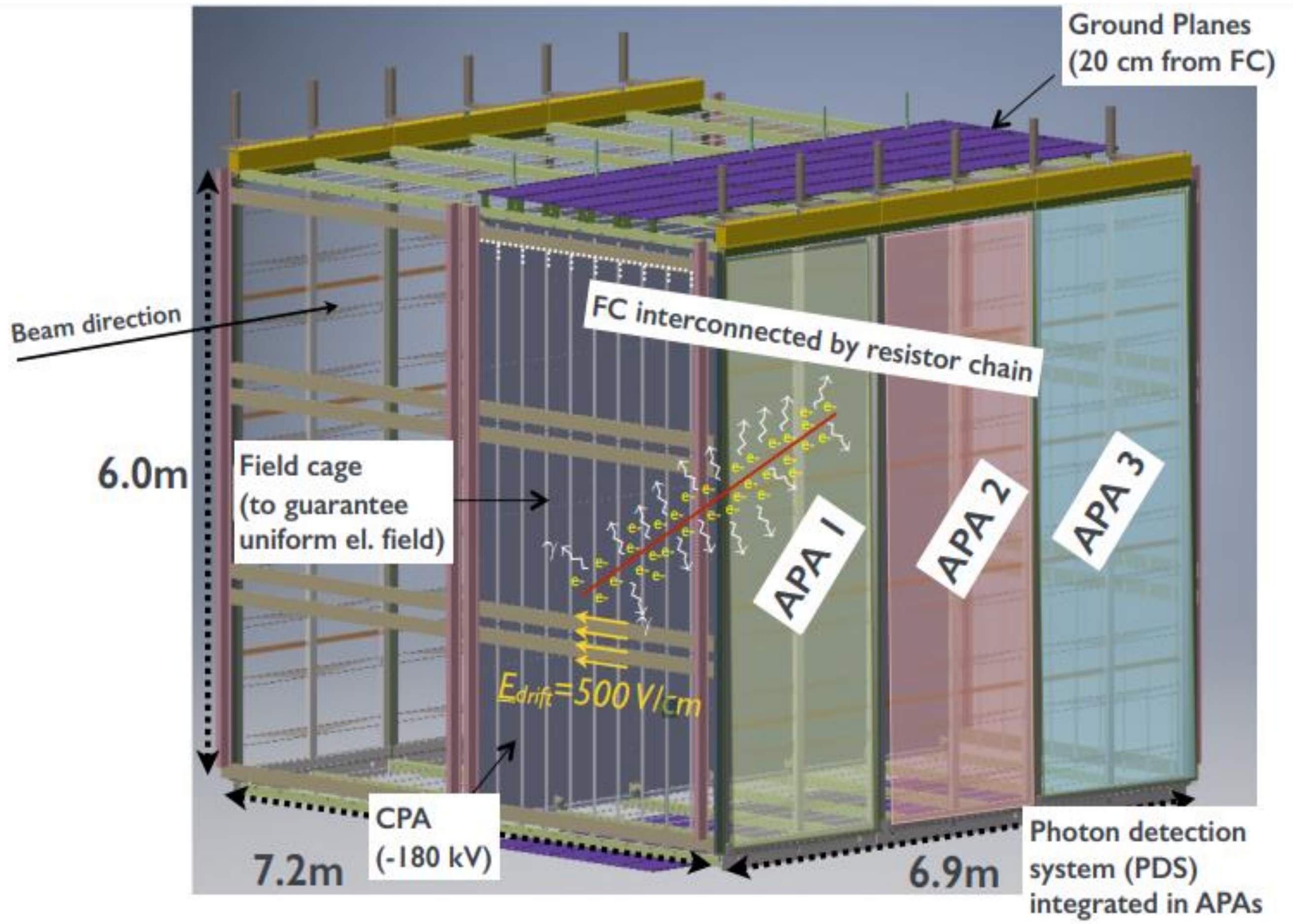
- A high intensity neutrino beam
- Near Detector
- Far Detector

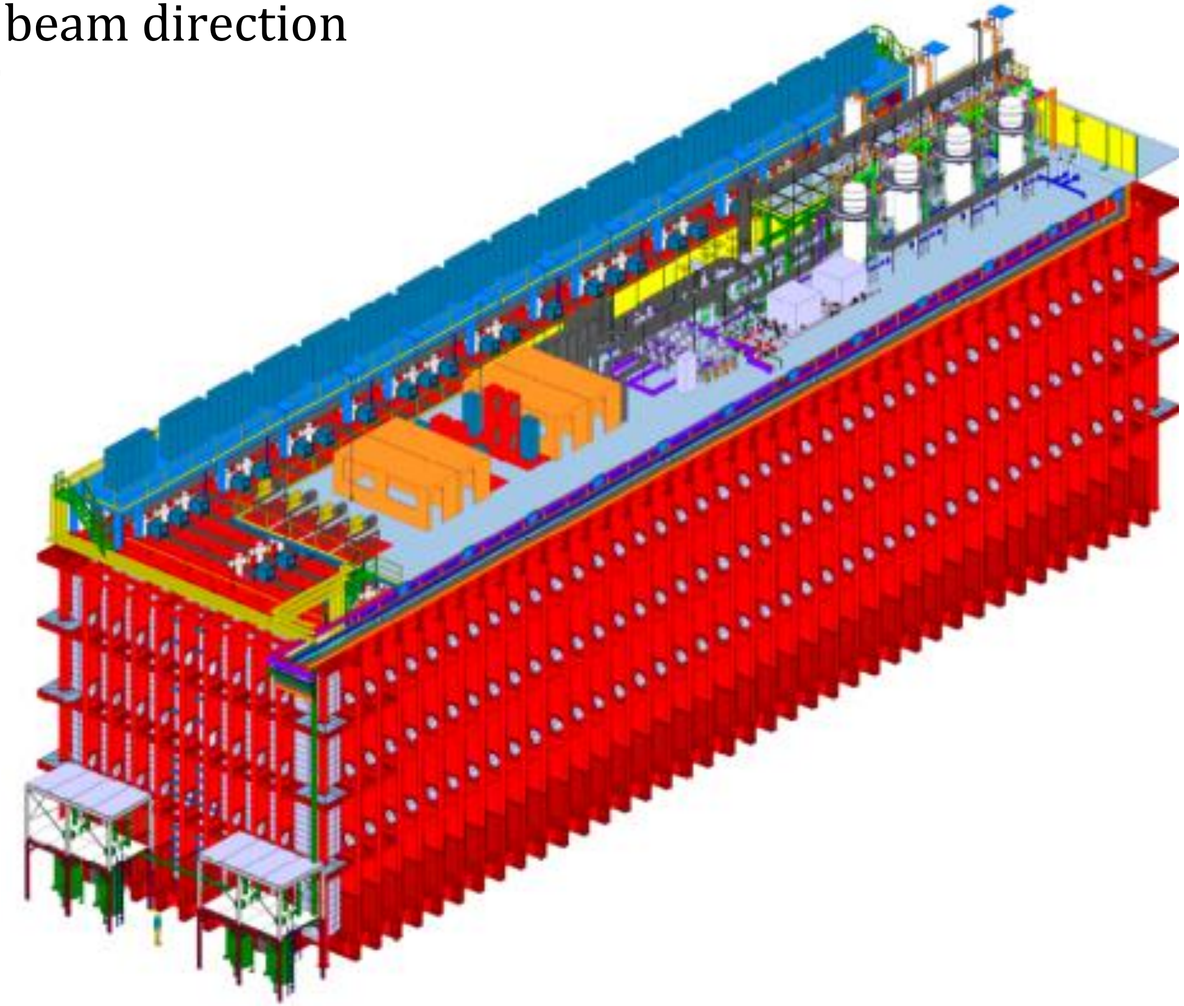
https://www.dunescience.org/



ProtoDUNE Single Phase – Horizontal Drift

- ProtoDUNE SP-HD has been constructed and successfully operated at the CERN Neutrino Platform
- Prototypes FD components at 1:1 scale with 1:20 in total LAr mass $\approx 750\ t$
- TPC is made of two vertical anode planes, one vertical cathode plane and a surrounding field cage. Dimensions are $7.2\ m$ drift $\times\ 6.1\ m$ high $\times\ 7\ m$ beam direction

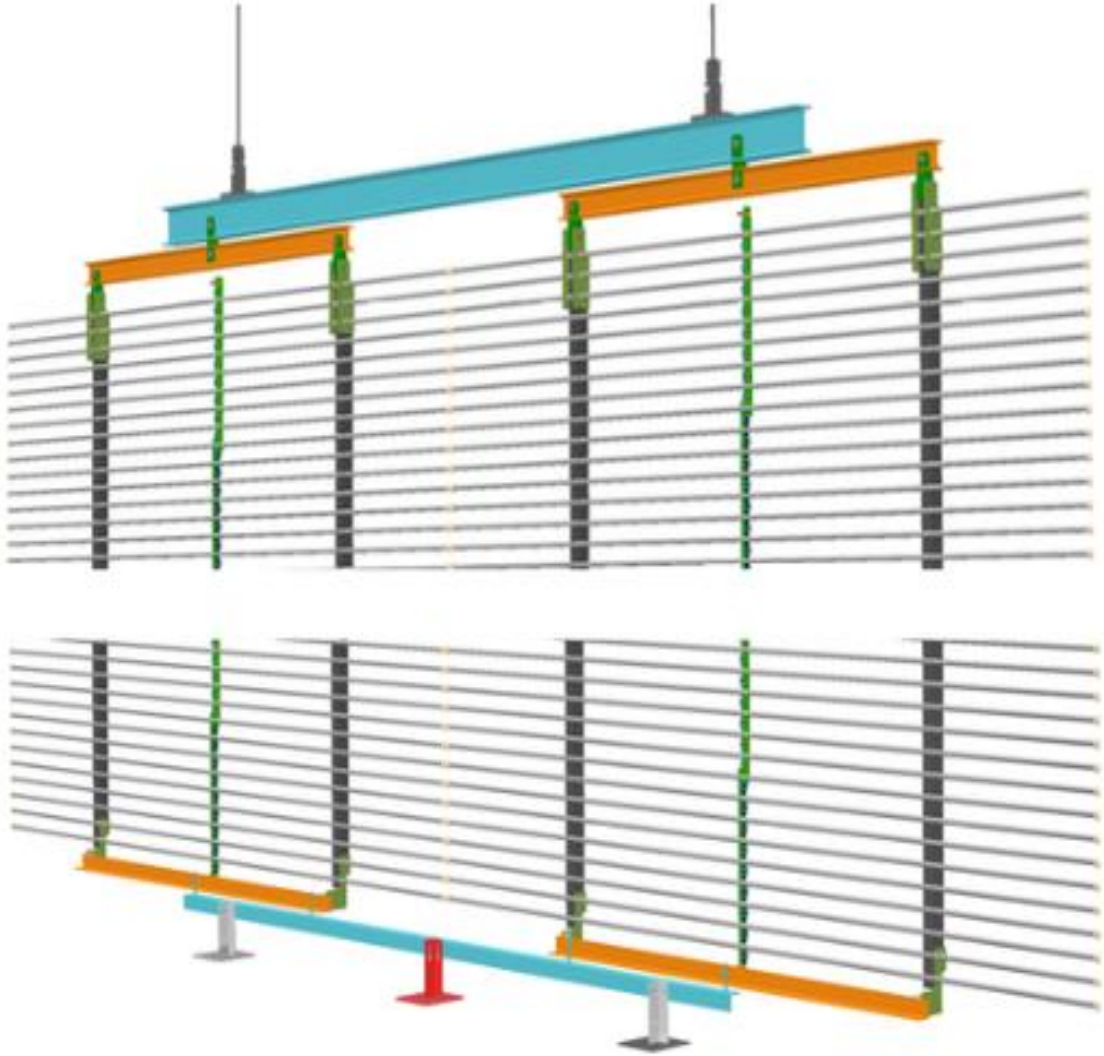




7) Hardware Experience - FD1 (SP-HD) And ProtoDUNE II

Ref: Dr. Jaehoon Yu

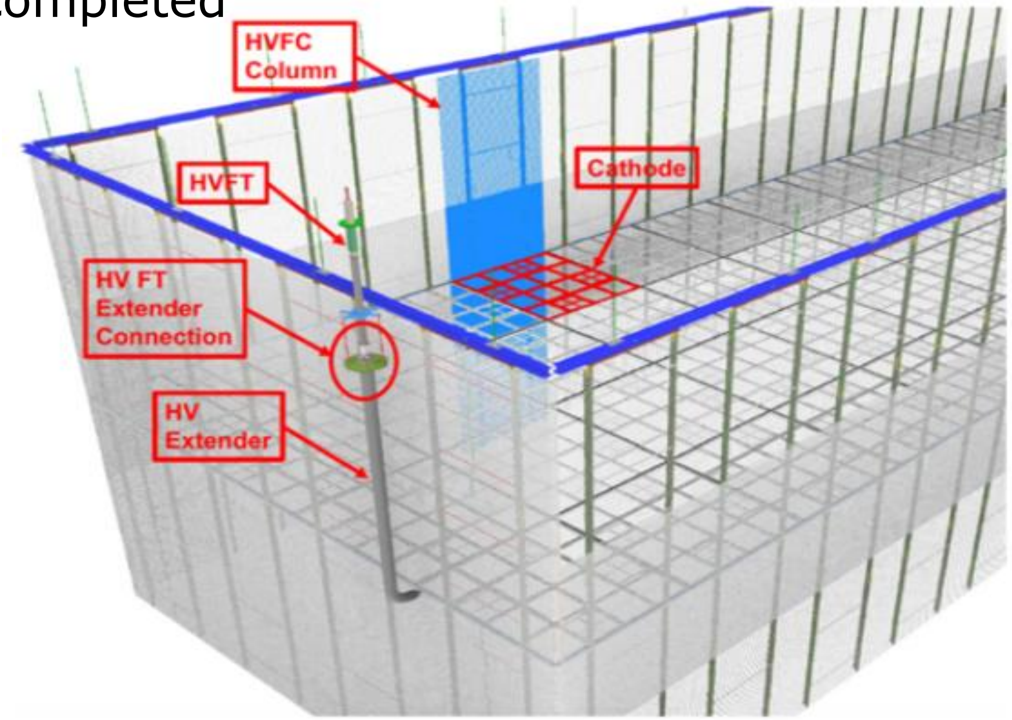
HD ProtoDUNE II field cage and the team who built the FC modules and installed them

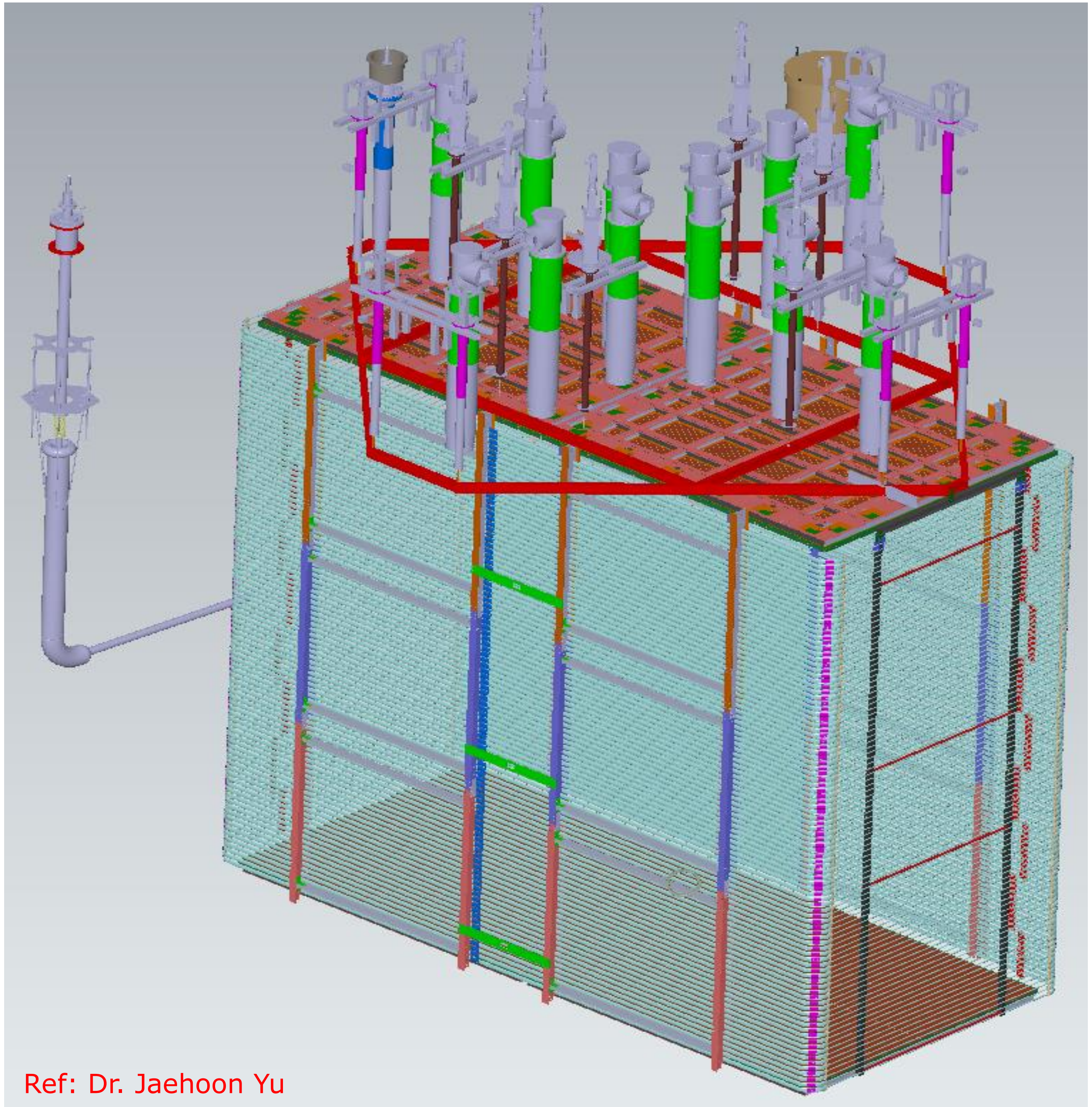


Field Cage Component

DUNE Single Phase – Vertical Drift

- Perforated Circuit Board (PCB) Anode and Charge Readout Planes (CRP) implemented with a total of 12 m vertical drift distance.
- ProtoDUNE SP-VD will begin construction 2023-2024. Small scale 50 liters LArTPC tests completed



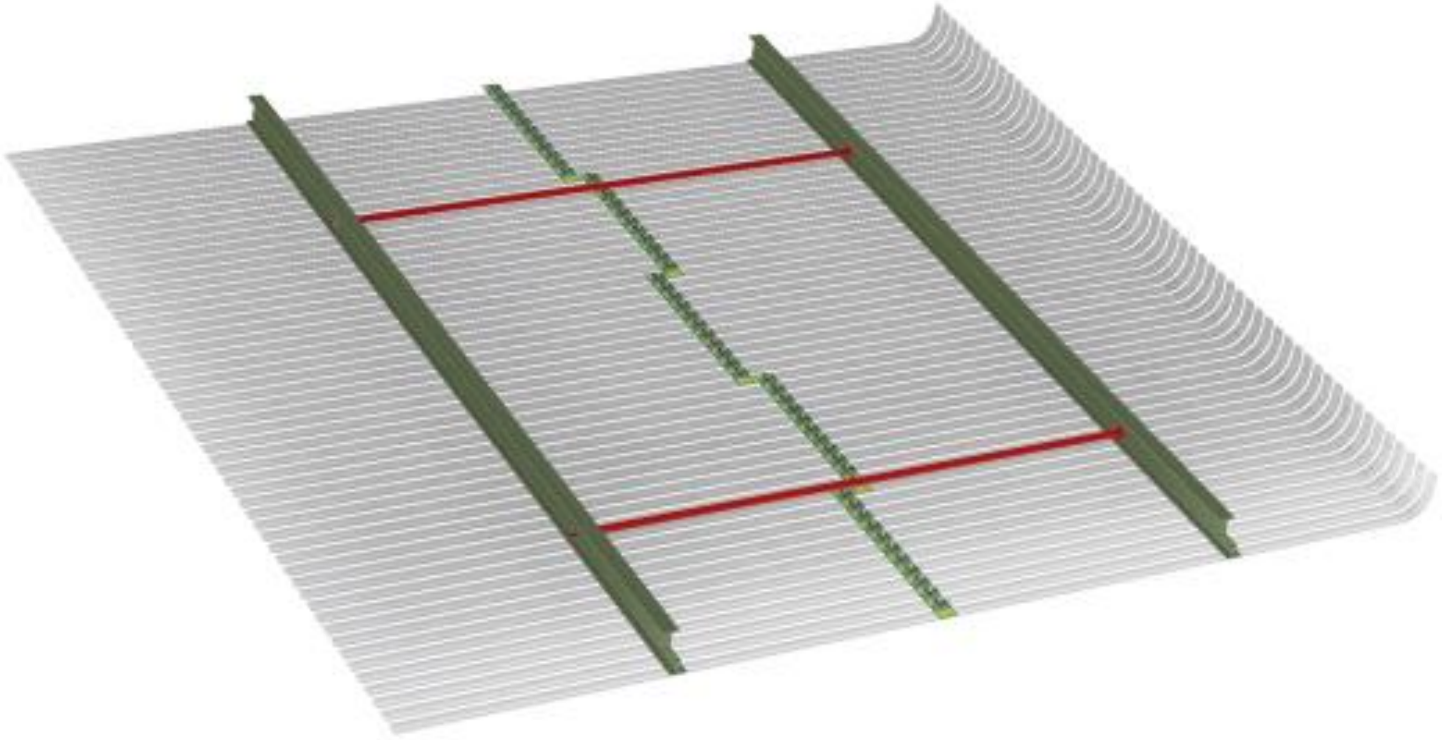


Ref: Dr. Jaehoon Yu

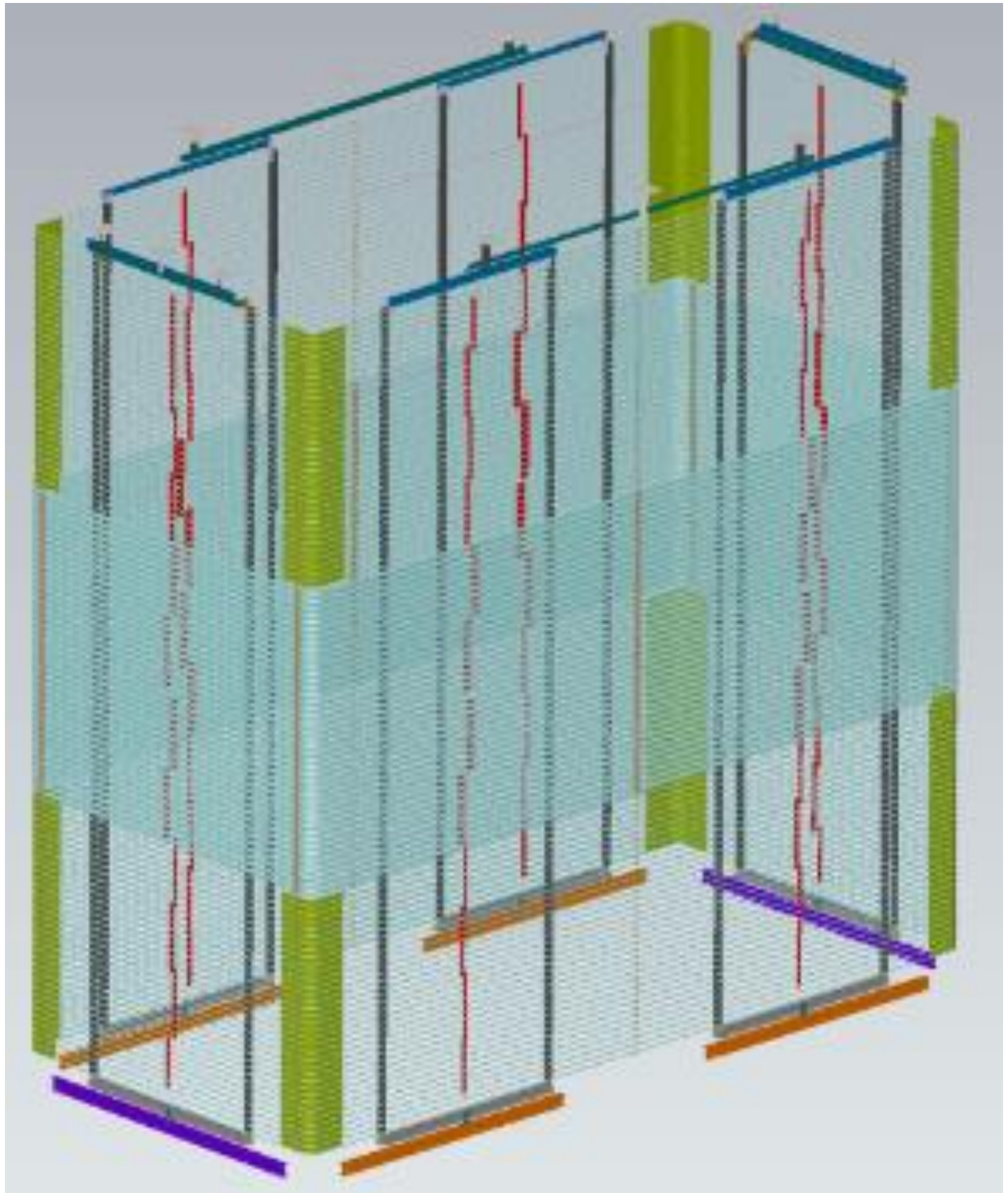
7) Hardware Experience: SP-VD Field Cage

Scope of Work

- FC surrounds the active volume and helps provide a uniform electric field
- Drift E field while integrating it with the HVS with at least 250 V/cm

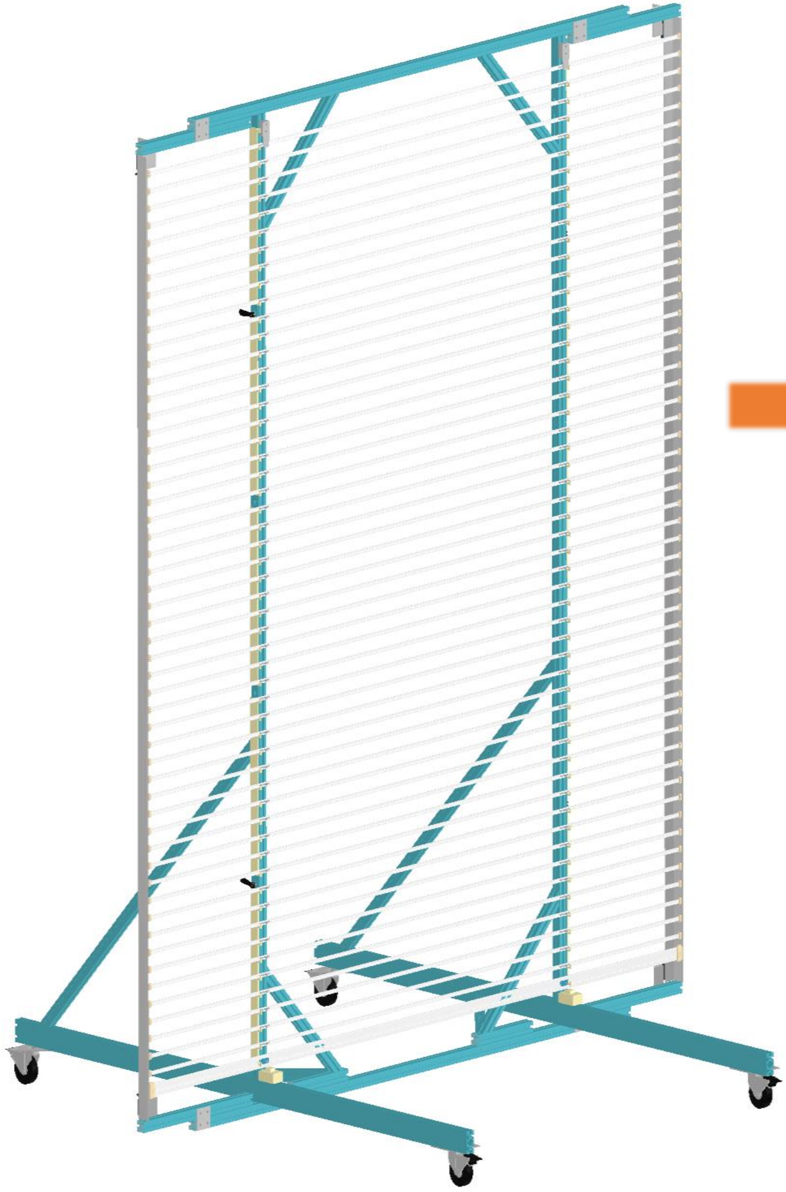


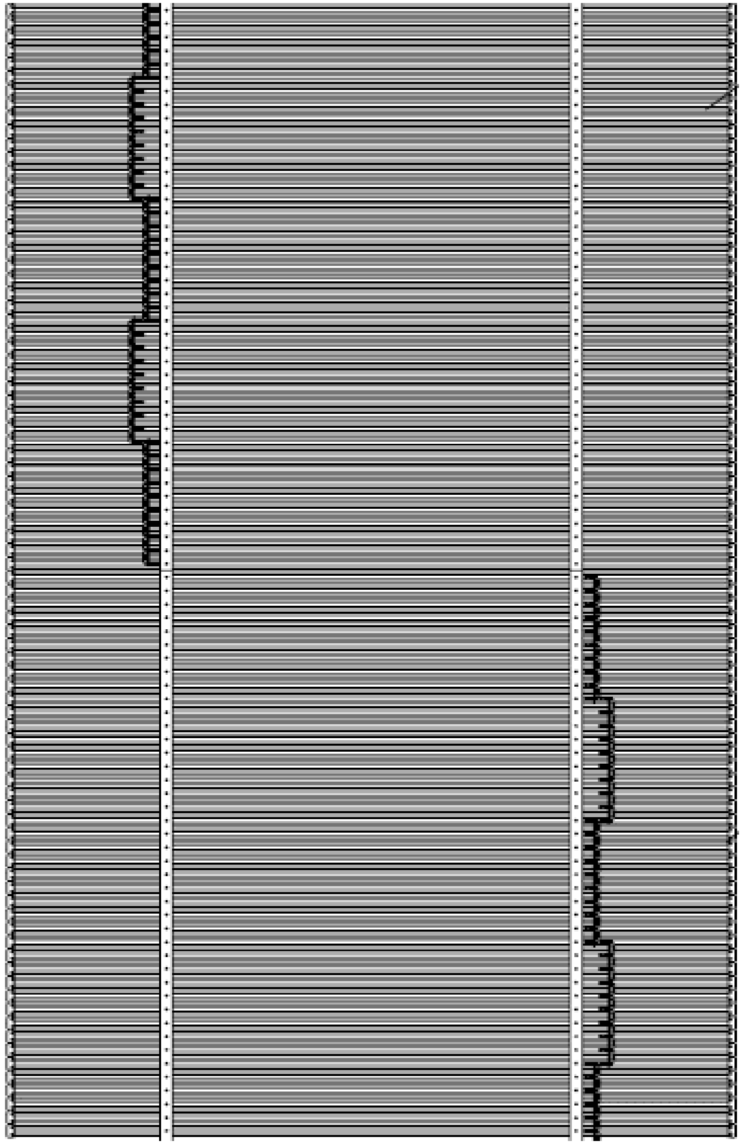
End wall field cage module with its profiles with a 90° bend on one side

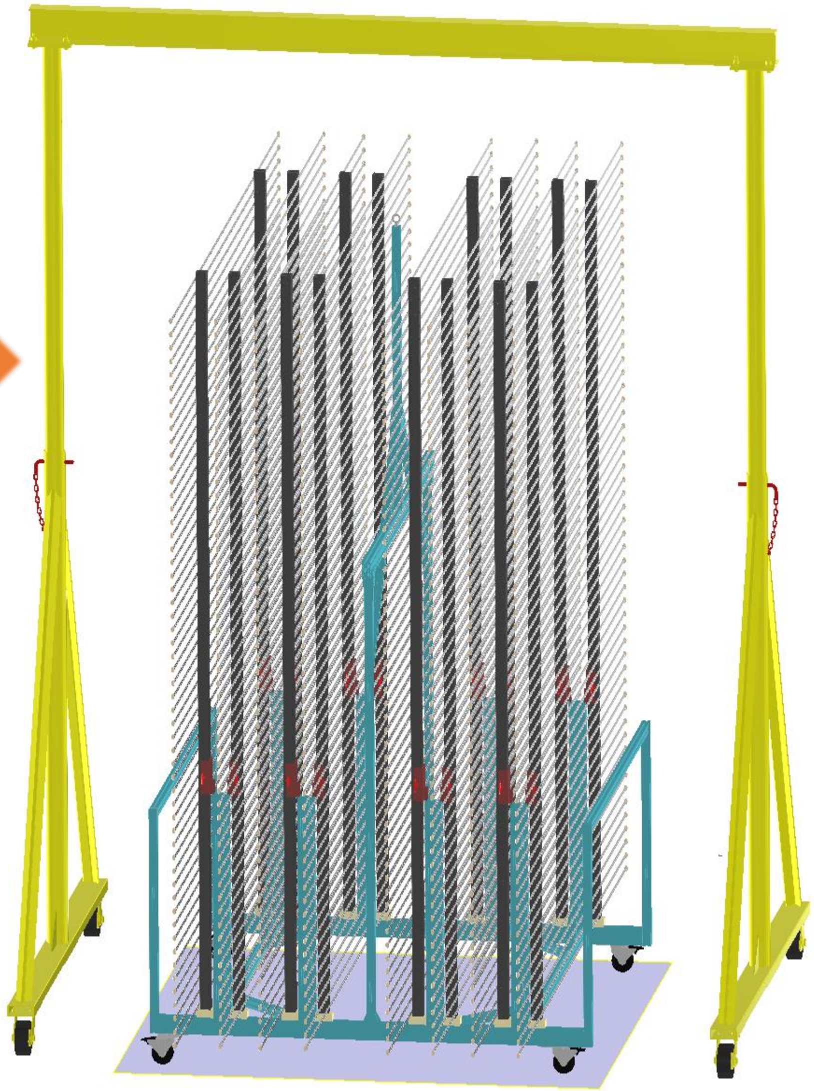


Vertical Drift Field Cage Model

7) Hardware Experience: Module Assembly

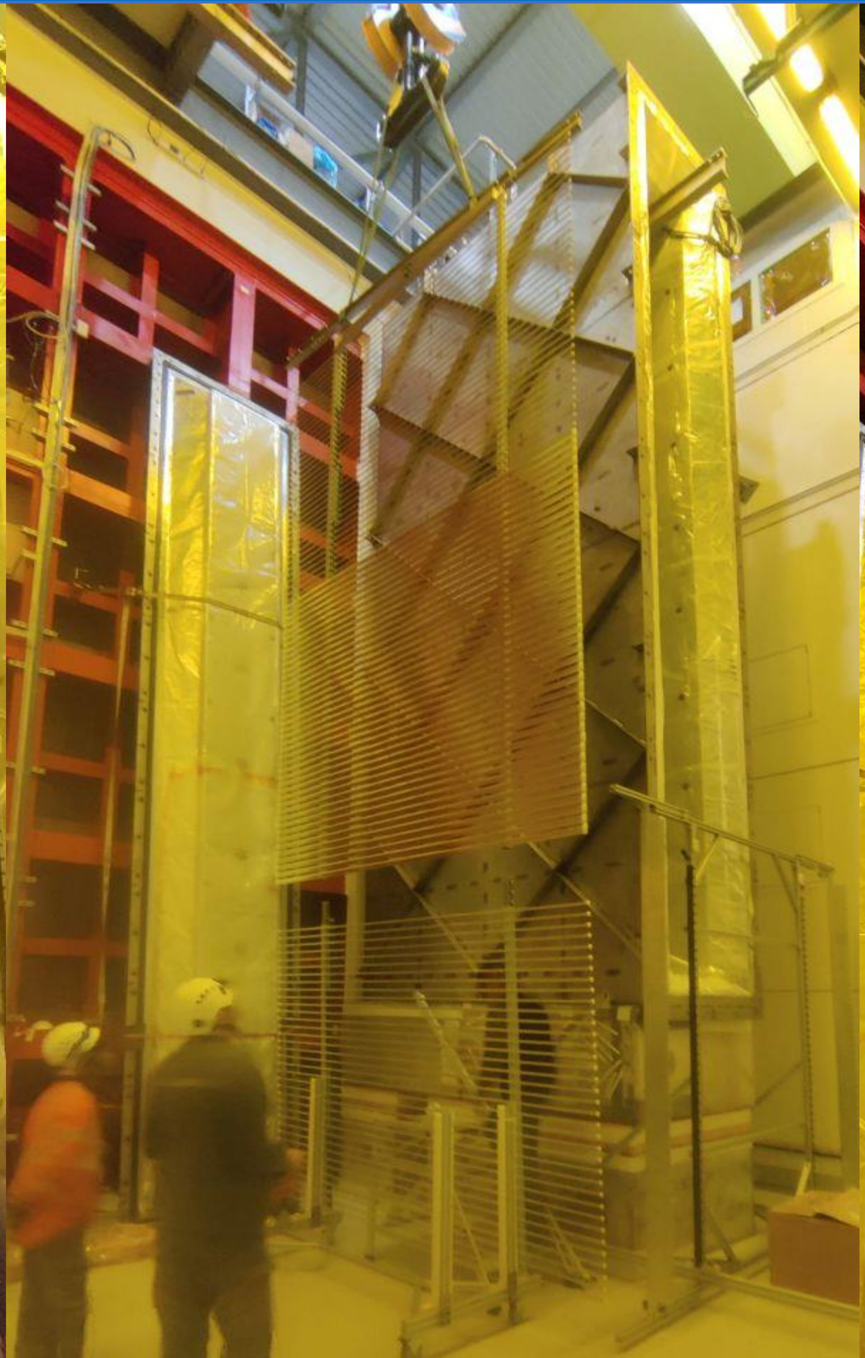


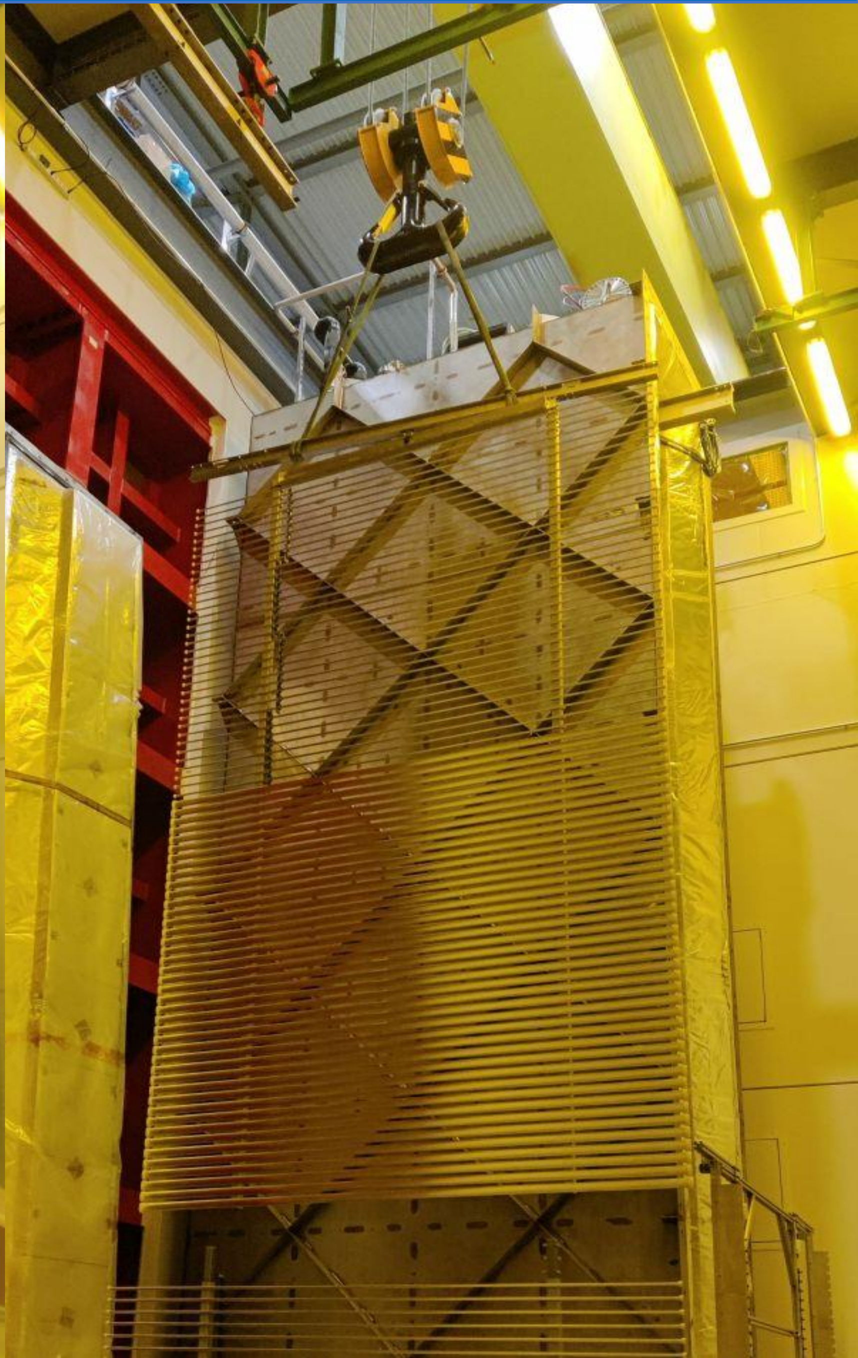




Left to right: Assembly station, completed module, storage cart

7) Hardware Experience: Installation





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1) Introduction

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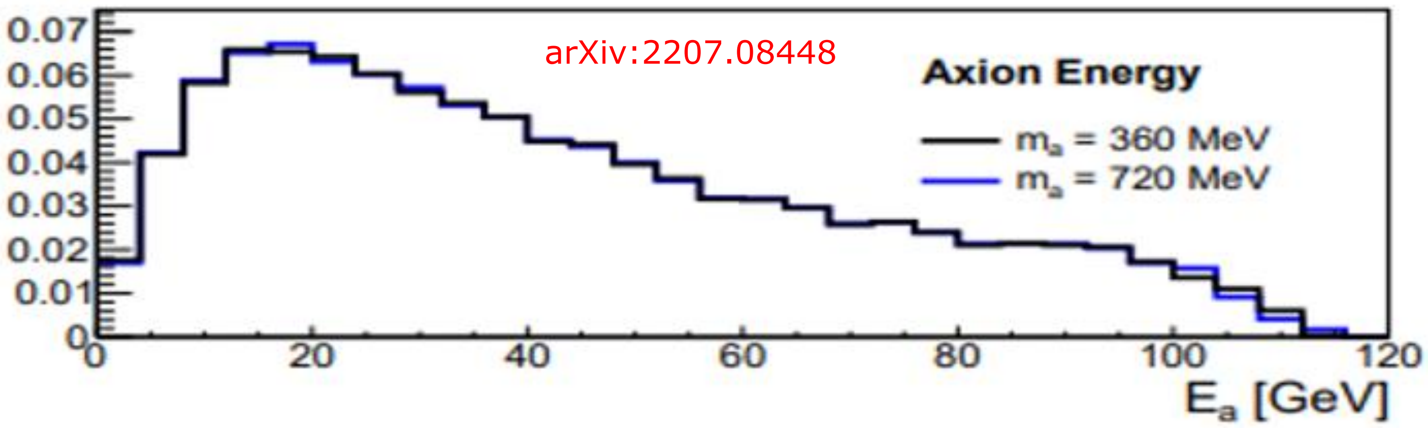
8) Future Work

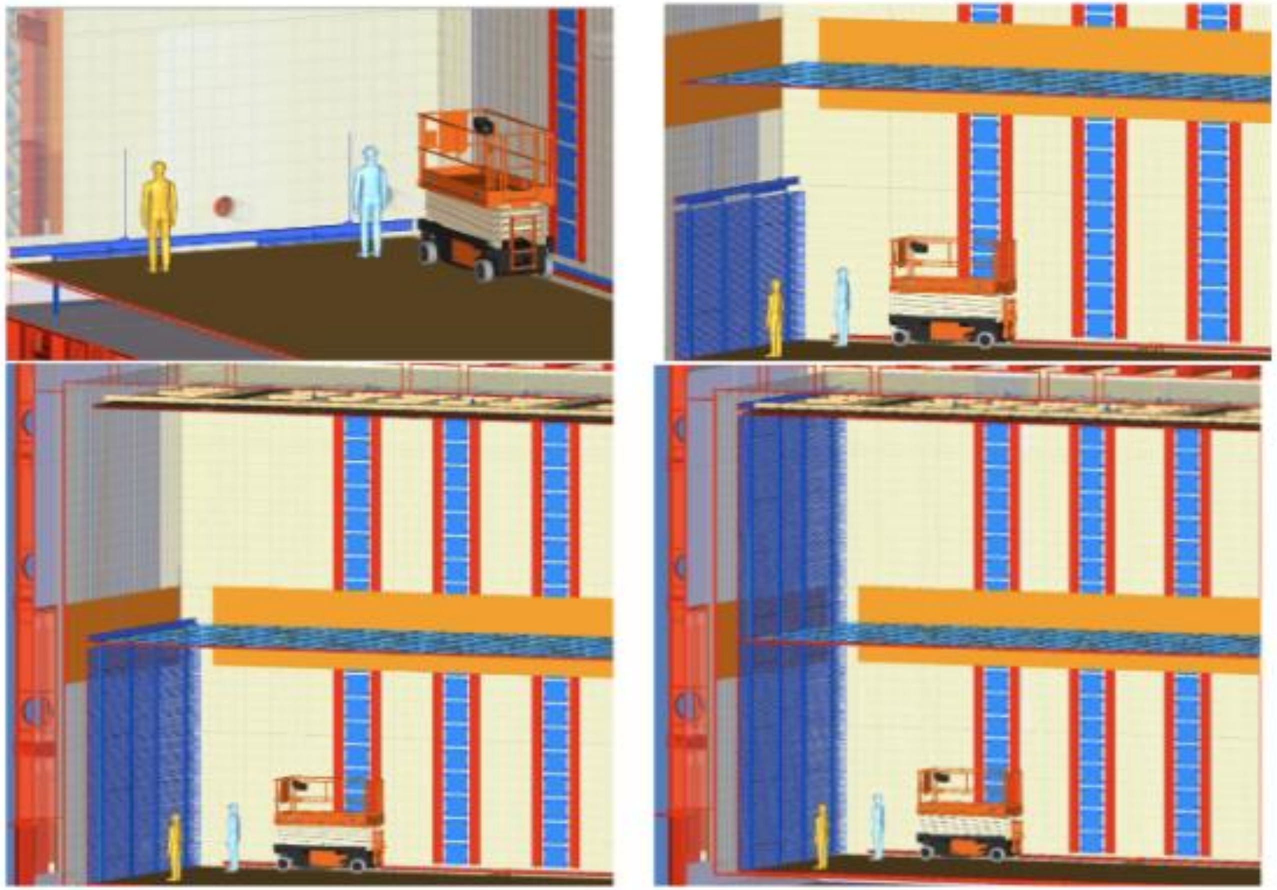
Spring 2023 - Summer 2023

- Set up all mechanics for ALP analysis
- Evaluate efficiency parameters of ICARUS
- Complete phenomenological study
- ProtoDUNE SP-VD module construction

Summer 2023 – Fall 2023

- Create axion energy, daughter particle opening angle, and energy plots for different m_a
- Completion of VD Module 0 construction and the start of the HD ProtoDUNE-II data taking

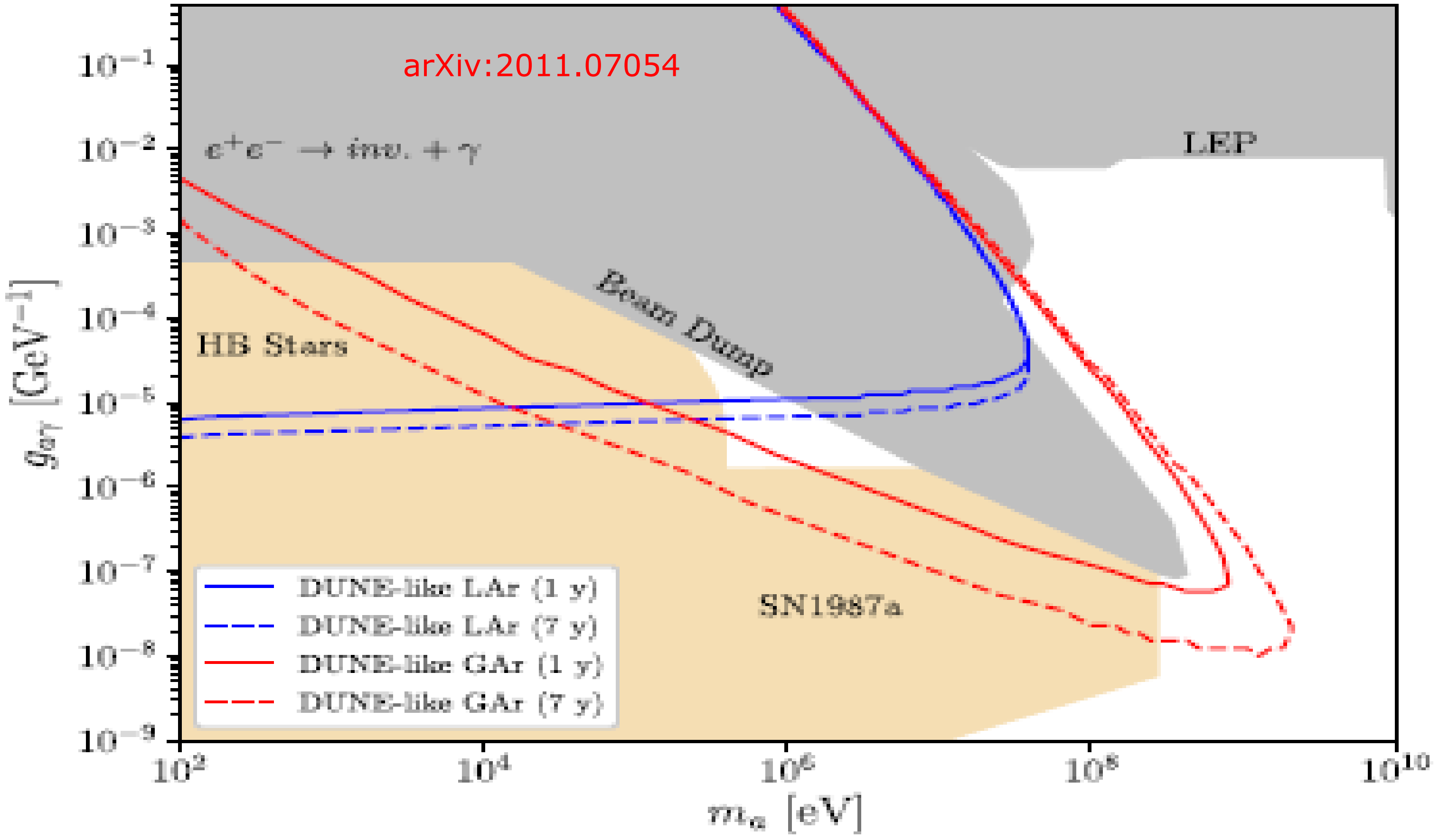




8) Future Work

Spring 2024 – Summer 2024

- Analyze real data of ICARUS runs and apply background cuts
- Develop new constraints on the axion model parameter space with 90% and 95% C.L. using ICARUS and the NuMI off-axis
- HD ProtoDUNE II data analysis and VD Module 0 data taking



Summer 2024 – Spring 2025

- Start writing dissertation with goal of publishing results of the data analysis.
- VD Module 0 data analysis and publication

8) Conclusion

The ICARUS detector can be very impactful for ALP searches

- QCD axion and other ALPs are well motivated extension of current physics theories.
- Great opportunities exist in the axion coupling to gauge bosons with a single or diphoton signature space.
- Identifying the ICARUS parameter space with its constraints is the key! Backgrounds are recognizable and possible to be significantly reduced.
- Data analysis processes already underway with goal of completing dissertation by the end of 2024

ProtoDUNE II and LArTPC R&D Work

- ProtoDUNE construction and data analysis at CERN will help with my hardware experience
- Great opportunity to learn hands-on about LArTPC technology
- Small contribution towards the next big thing in high energy physics - DUNE

9) References

1) The ICARUS Experiment. *https://icarus.sites.lngs.infn.it/index.php*

2) R. Acciarri *et al*. “A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam.” arXiv:1503.01520 [physics.ins-det]

3) Animesh Chatterjee. “Search for Low Mass Dark Matter at ICARUS Detector Using NuMI Beam”

4) Vedran Brdar, Bhaskar Dutta *et al*. “Axion-like Particles at Future Neutrino Experiments: Closing the "Cosmological Triangle.” arXiv:2011.07054 [hep-ph]

5) Andrzej Szelc. “How LArSoft Simulation Works.” *https://indico.hep.manchester.ac.uk/*

6) Tom Brooks. “Tutorial 2: Generating Events.” *https://indico.hep.manchester.ac.uk/*

7) B. Abi *et al.* “Volume I. Introduction to DUNE.: 2020 JINST 15 T08010

8) B. Abi *et al.* “Volume IV. The DUNE far detector single-phase technology.” 2020 JINST 15 T08010

Back Up Slides

Why Argon?

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Helium isn't very dense, requires very cold temps to stay liquid, and doesn't ionize well

Neon has poor electron mobility and requires very cold temps to stay liquid

Krypton is not very abundant (1 ppm in the atmosphere) nor does it produce as much scintillation light

Xenon is even less abundant (87 ppb in the atmosphere)

Ref: Dr. Jonathan Asaadi

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Argon is more dense than water and can be kept in the liquid phase easily

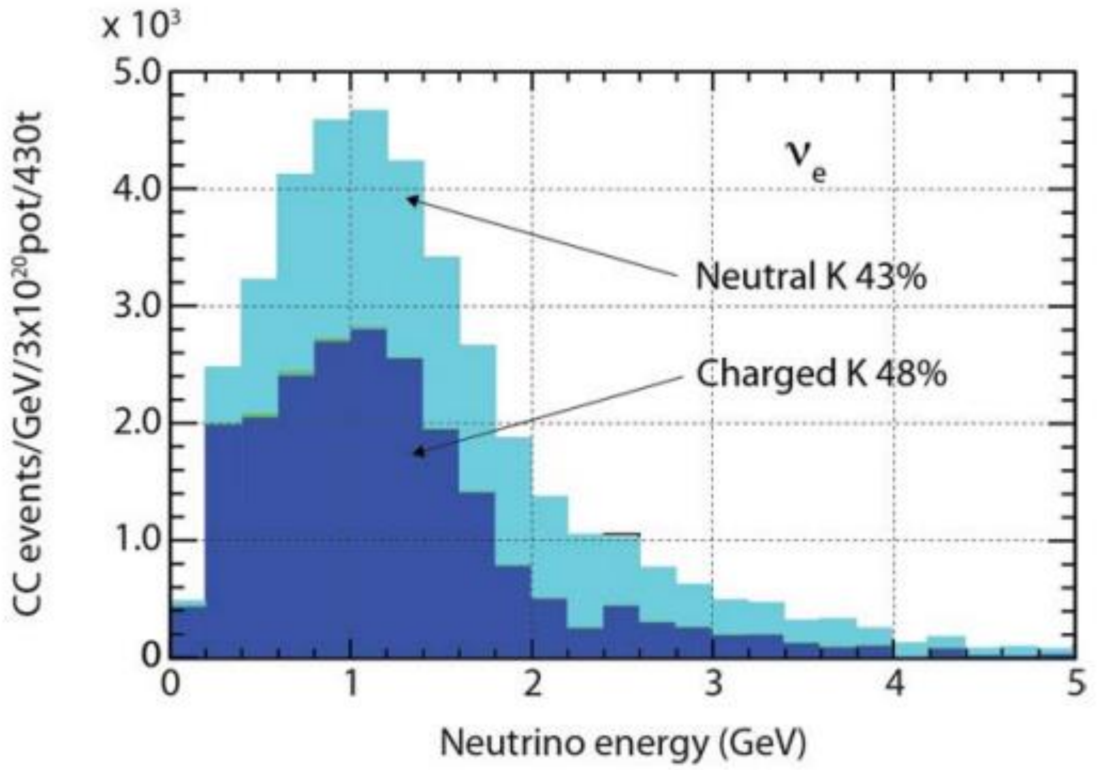
Argon is relatively abundant (3.5 ppm in the atmosphere...or about 1% of the earth's atmosphere) more than CO_2

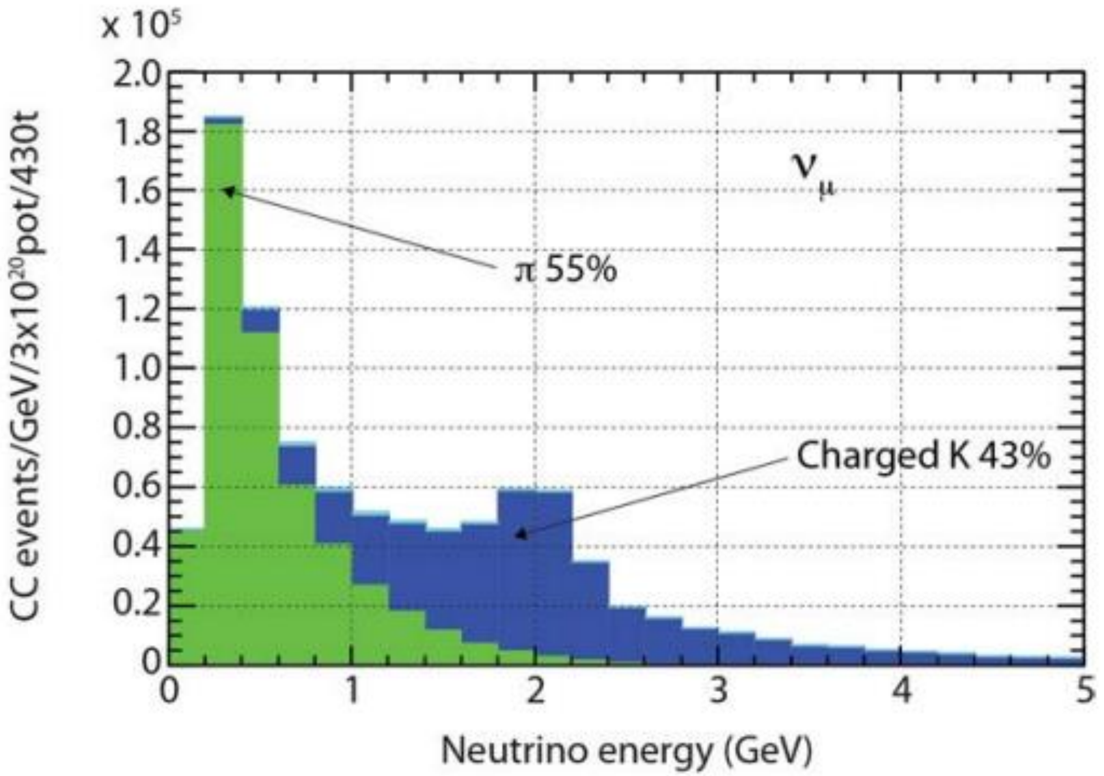
Argon ionizes easily (55,000 electrons / cm) and has a high electron mobility (it's greek name means slow)

Argon produces lots of scintillation light! (Added bonus...it is transparent to the light it produces)

Ref: Dr. Jonathan Asaadi

What neutrinos does ICARUS see from NuMI?





Neutrino rates in the T600 at the proposed "Far" location, ~105 mrad off-axis at ~880 m from the NuMI target for one year of exposure (~3 1020 pot). (Left) Electron neutrino spectrum originates essentially from kaon decay and presents a broad peak covering the 0.5-2 GeV energy range. (Right) Muon neutrino components: a very low energy peak coming from pion decay is present as well as a peak at about 2 GeV due to kaon decay are clearly present

arXiv:1312.7252

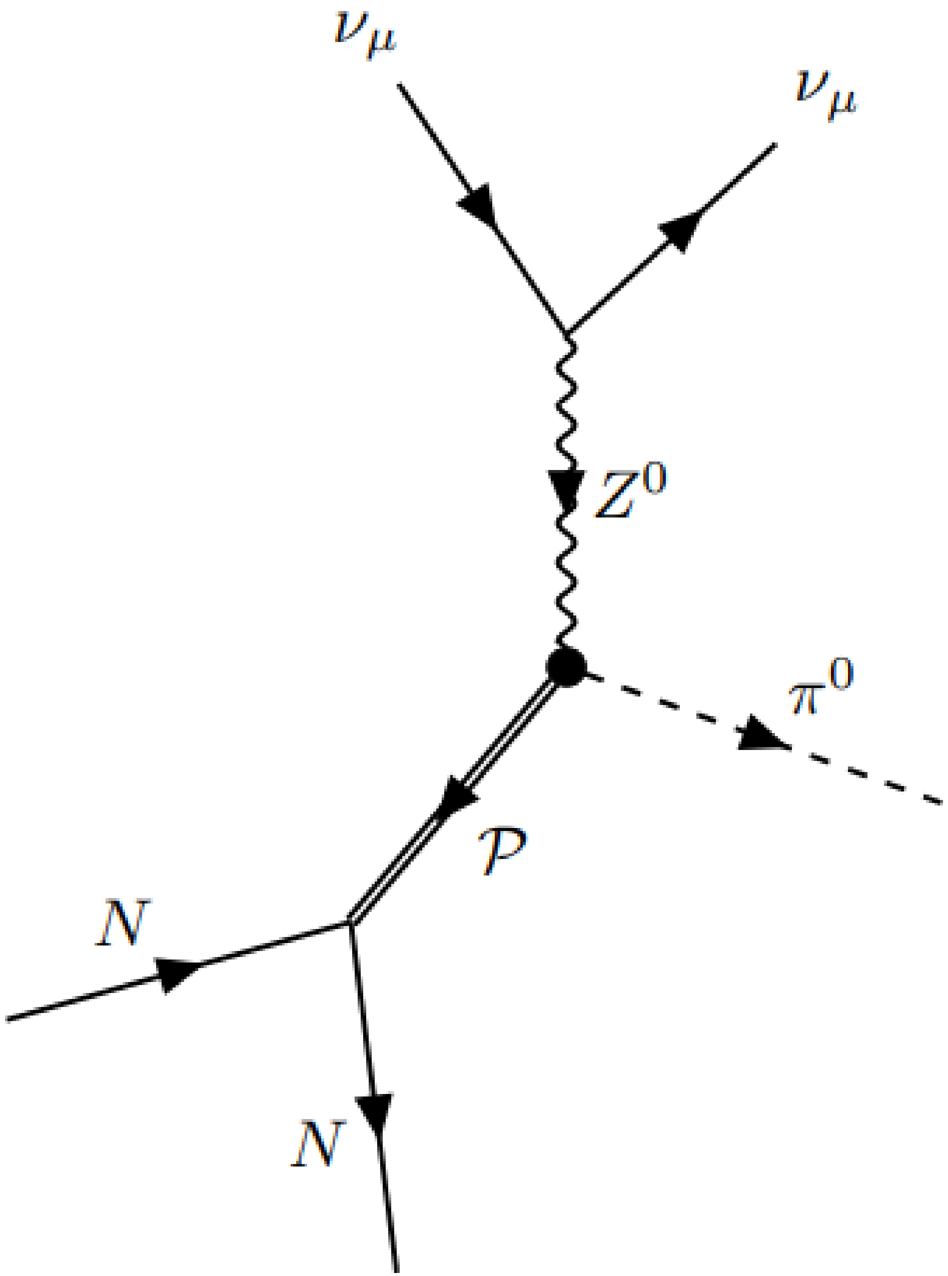
ICARUS and NuMI coordinates

Table 1 lists the positions in NuMI coordinates used in this note.

	x^N [cm]	y^N [cm]	z^N [cm]	θ [rad]	θ [°]
ICARUS origin $x^I = y^I = z^I = 0$	450.37	8015.39	79511.94	100.63	5.77
TPC center, $y^I =$ -23.45 cm	450.37	7991.98	79512.66	100.33	5.75
$x^I =$ −358.49 cm	120.19	7983.84	79373.28	100.26	5.74
$x^I =$ +358.49 cm	780.56	8000.12	79652.05	100.57	5.76
$y^I =$ −134.96 cm	450.37	7833.84	79521.90	98.36	5.64
$y^I =$ −55.75 cm	450.37	7912.91	79517.28	99.34	5.69
$y^I =$ +102.66 cm	450.37	8071.05	79508.04	101.32	5.81
$y^I =$ +181.86 cm	450.37	8150.12	79503.42	102.31	5.86
$z^I =$ −894.95 cm	798.94	7943.91	78689.78	101.12	5.79
$z^I =$ +894.95 cm	101.81	8040.05	80335.54	99.76	5.72

ICARUS origin with respect to NuMI origin in ICARUS coordinates is (31512.04, 177 3364.49, 73363.25) [cm]. The majority of NuMI neutrinos reaching ICARUS originate from the very beginning of NuMI beam line and angular dispersion is very small, thus this vector provides a good approximation of the angle at which NuMI neutrinos enter the ICARUS detector.

D. Cherdack, A. Aduszkiewicz, A. Wood, “Prediction of NuMI electron and muon neutrino 2 flux in ICARUS.” *https://sbn-docdb.fnal.gov/*



NC pion production – Coherent Scattering

COH: The characteristic of neutral current coherent scattering with one single π^0 final state is a single, forward-going π^0, with no other pions or nucleons or vertex activity . *P* is the so-called pomeron (or pomeron-like particle). Simply put, *P* should carry the quantum number of vacuum and a small momentum transfer.

http://hdl.handle.net/10057/15475

NC pion production – Resonant Scattering

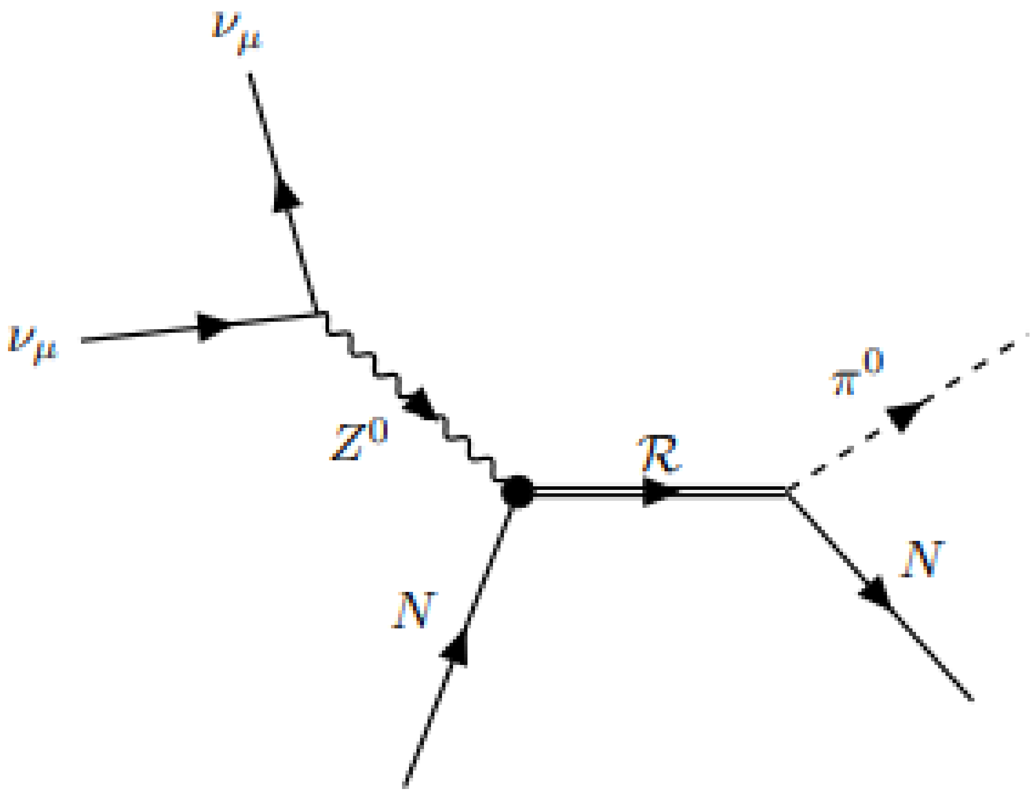


Figure 19: RES

In scattering off of free nucleons, there are seven possible resonant single pion reaction channels (seven each for neutrino and antineutrino scattering), three charged current (CC):

$$\nu_\mu p \to \nu_\mu p\pi^0, \ \bar{\nu}_\mu p \to \bar{\nu}_\mu p\pi^0$$

$$\nu_\mu p \to \mu^- p\pi^+, \ \bar{\nu}_\mu p \to \mu^+ p\pi^-$$

$$\nu_\mu p \to \nu_\mu n\pi^+, \ \bar{\nu}_\mu n \to \bar{\nu}_\mu n\pi^0$$

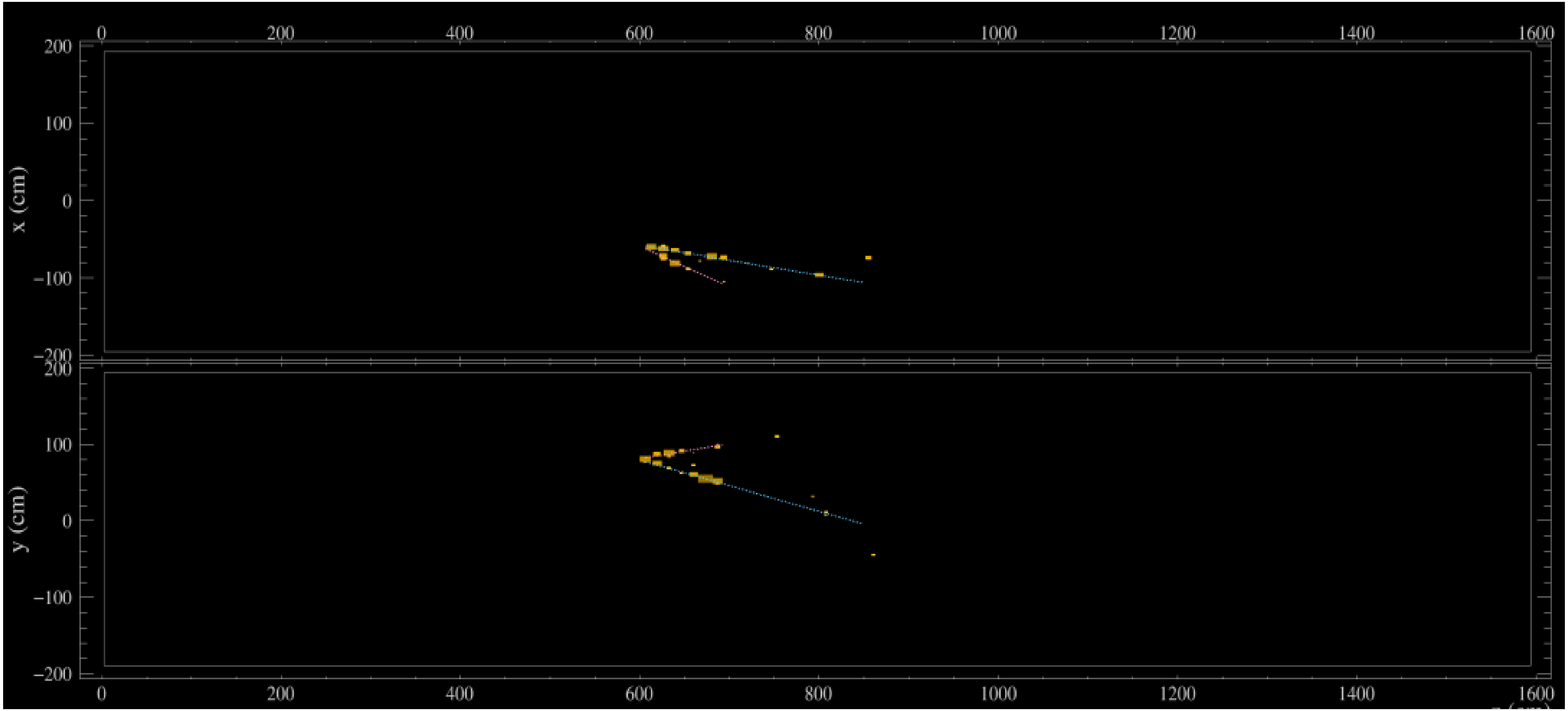
$$\nu_\mu n \to \mu^- p\pi^0, \ \bar{\nu}_\mu p \to \mu^+ n\pi^0$$

$$\nu_\mu n \to \nu_\mu n\pi^0, \ \bar{\nu}_\mu n \to \nu_\mu n\pi^0$$

$$\nu_\mu p \to \mu^- p\pi^+, \ \bar{\nu}_\mu p \to \mu^+ p\pi^-$$

$$\nu_\mu n \to \nu_\mu p\pi^-, \ \bar{\nu}_\mu n \to \bar{\nu}_\mu p\pi^-$$

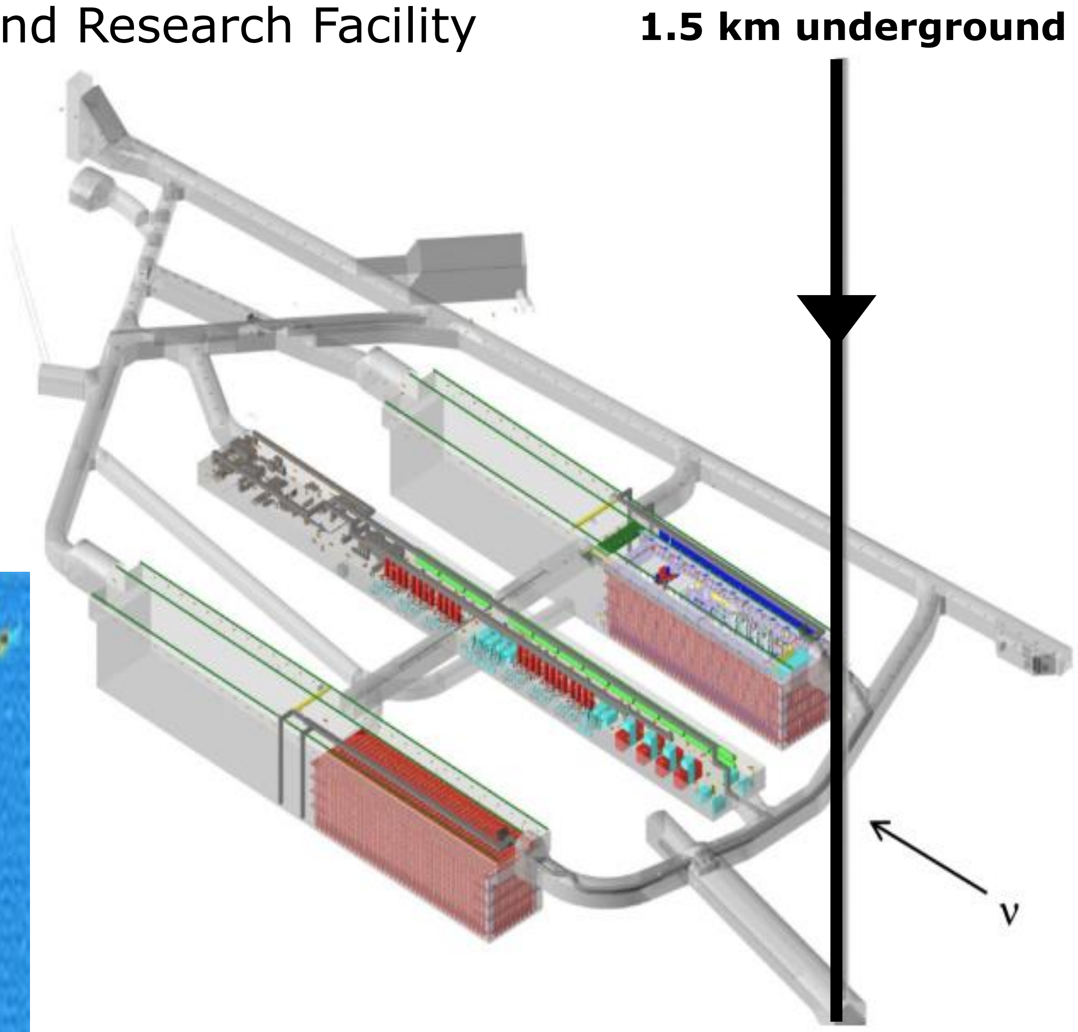
http://hdl.handle.net/10057/15475

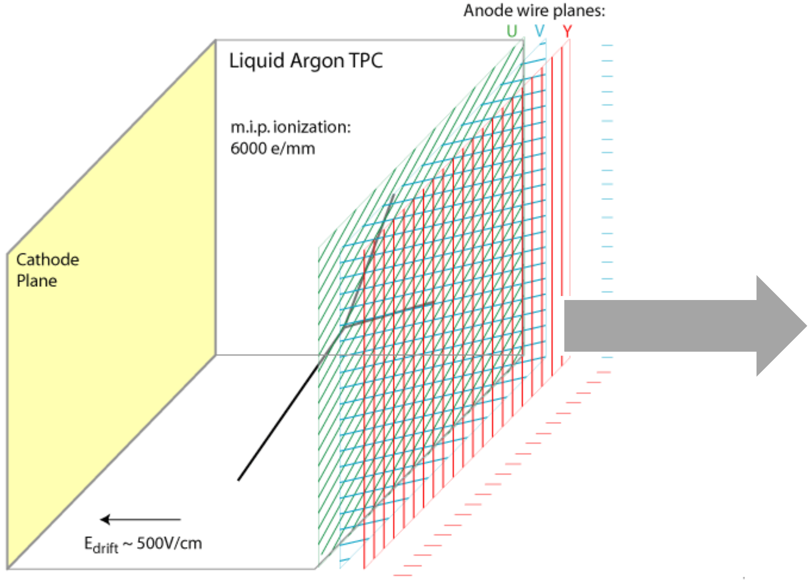


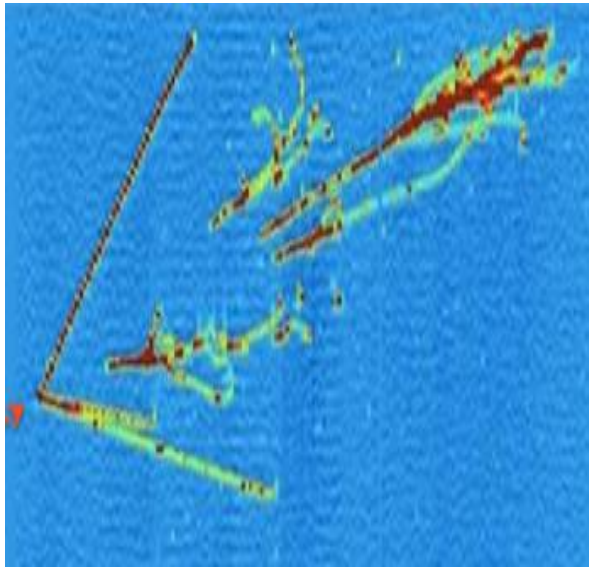
Machine Learning: Identifying $\pi^0 \rightarrow \gamma\gamma$ events using Prong Level Convolutional Visual Networks (CVN). http://hdl.handle.net/10057/15475

Far Detectors

- 4 LArTPCs, 800 miles away, at the Sanford Underground Research Facility
- Total 70 kt with fiducial volume of LAr of 40 kt
- Two types – Horizontal Drift (HD) and Vertical Drift (VD)
- Two prototypes present at CERN – ProtoDUNE HD and ProtoDUNE VD

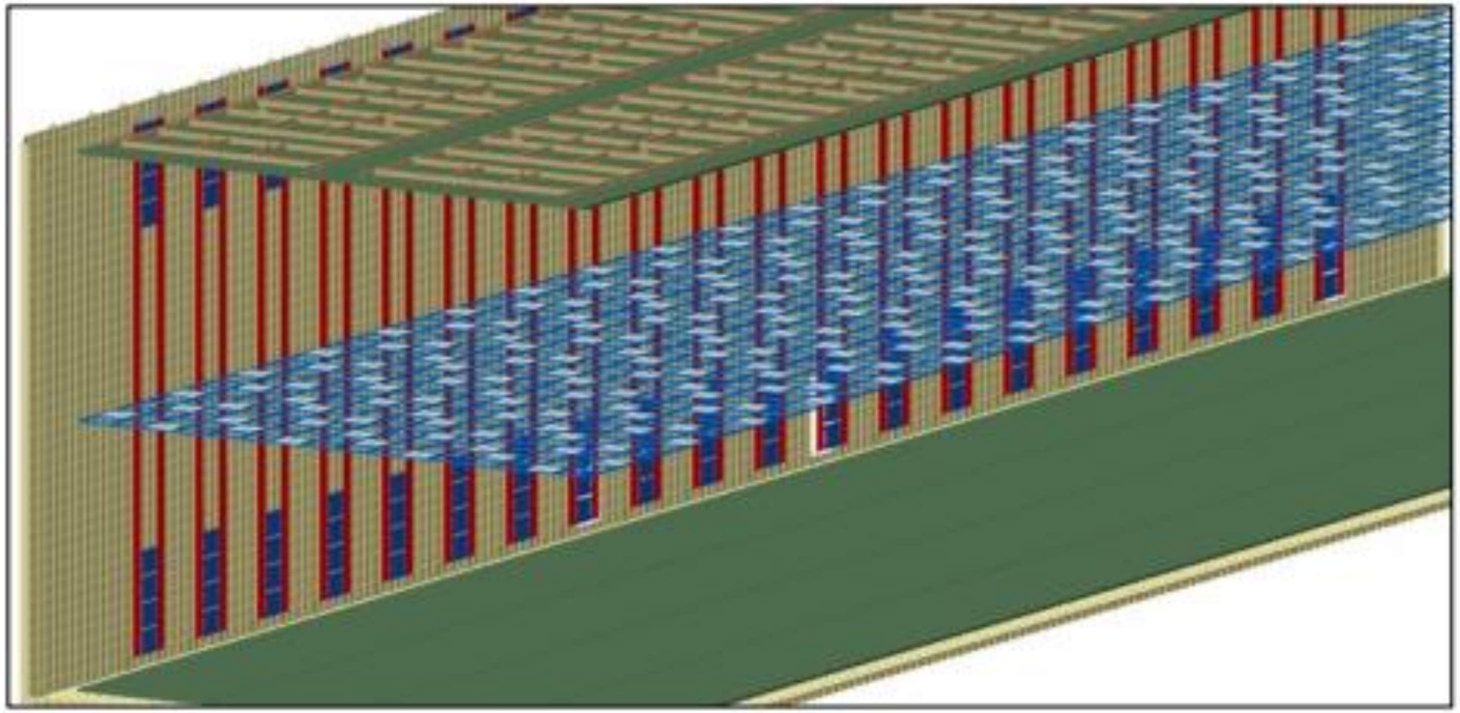


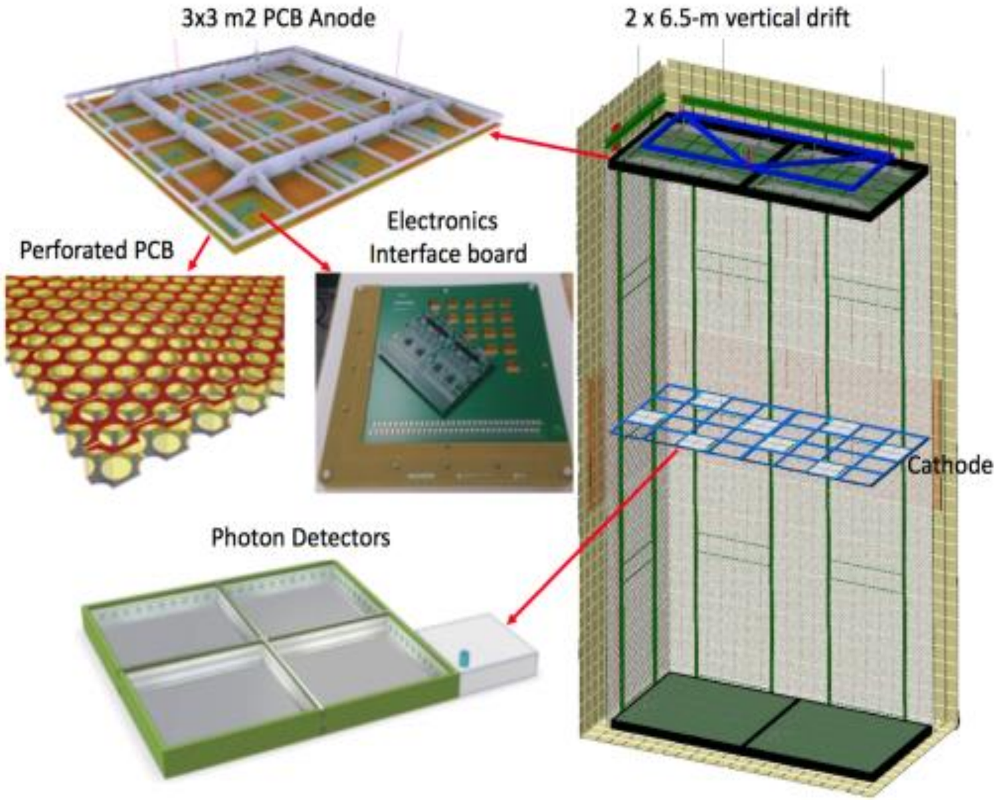




ProtoDUNE Single Phase – Horizontal Drift

Far Detector #2 (Vertical Drift)





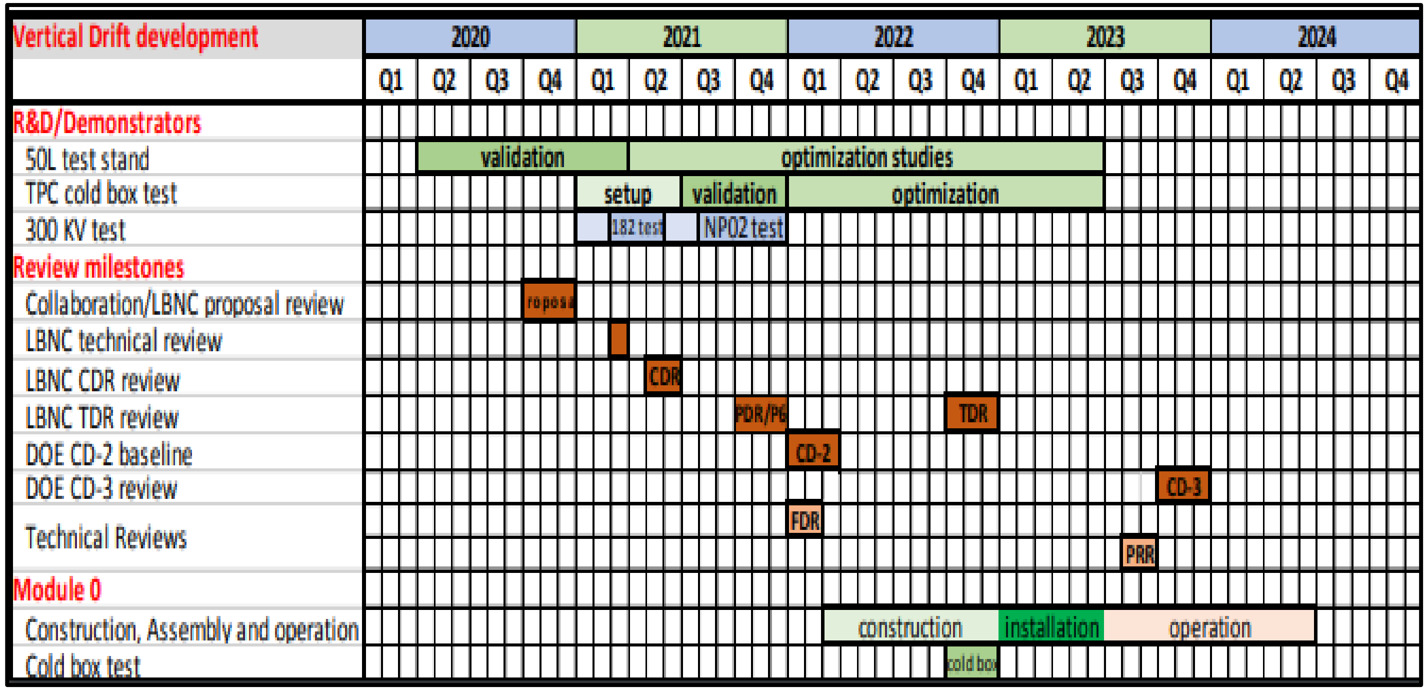
- 320 X-ARAPUCA 60 x 60 cm^2 on cathode, analog readout
- 320 X-ARAPUCA 60 x 60 cm^2 on cryostat membrane, ~3 m from cathode
  - Enhanced field cage transparency -> 70%

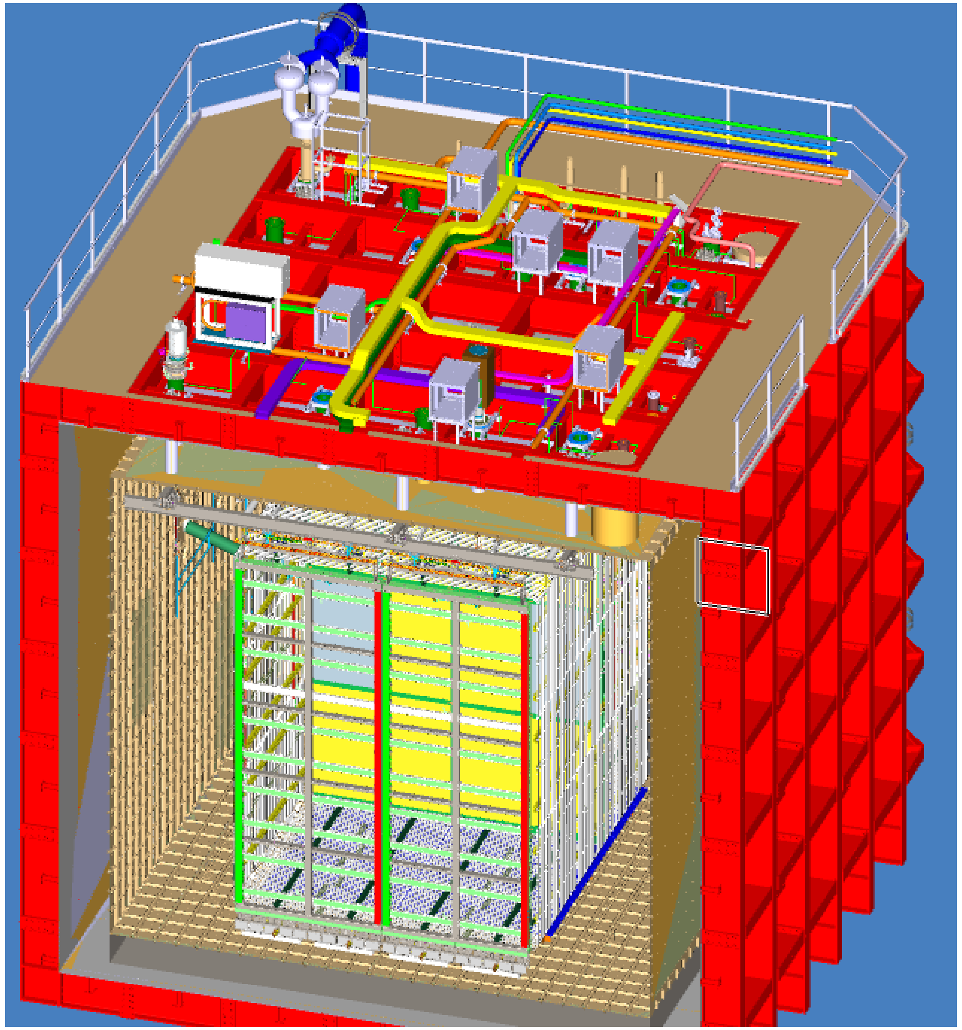
Based on X-ARAPUCA – “4π” reference design

SiPM and electronics partially on Cathode: @ 300 kV

Module 0

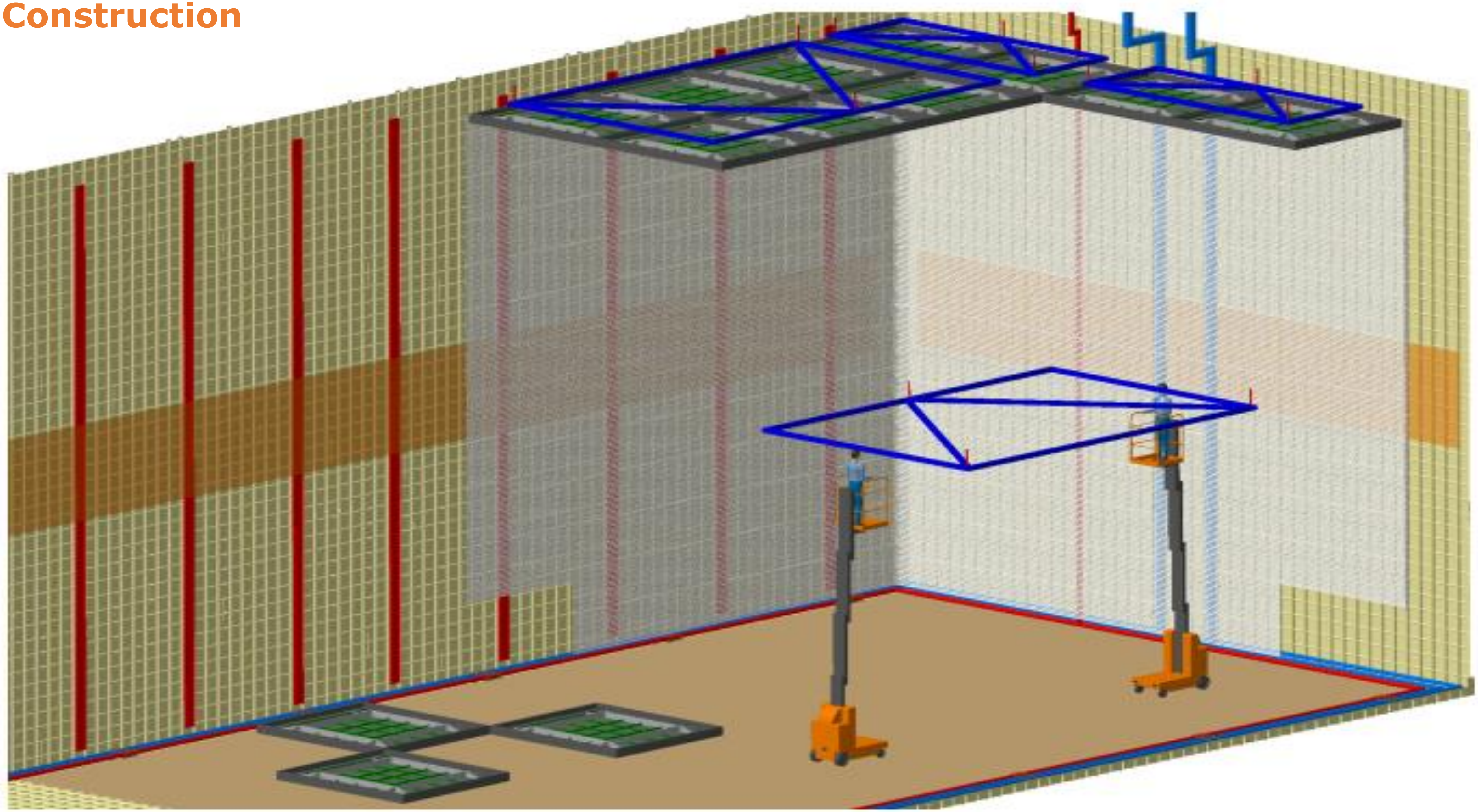
- Full characterization of DUNE FDs with upgraded components, electronics, subsystems, etc.
- Increased data and beam statistics (reconstruction, particle ID, calibration)
- ProtoDUNE Phase I HD was decommissioned for observations, redesign and is ready for improved reinstallation for Phase II. 4 APAs instead of 6 with electronics on the bottom (APA’s will be flipped)





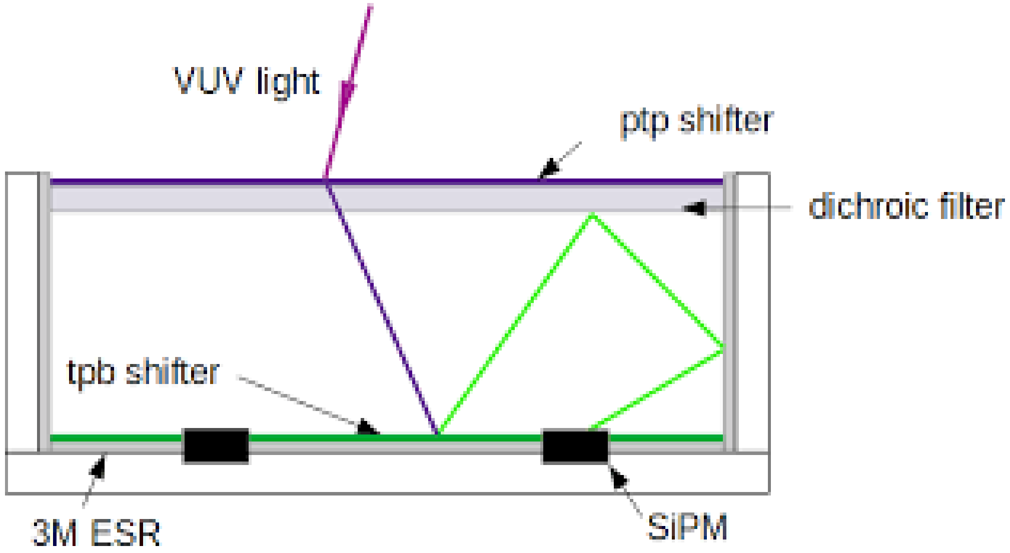
Scheme of the Vertical Drift module-0 detector in the ProtoDUNE-VD NP02 cryostat.

VD Construction



ProtoDUNE Single Phase – Vertical Drift

Charge Readout Planes (CRPs) from DP repurposed for VD. Perforated PCB anode, fully immersed in LAr. Photon Detection (PD) based on the new X-ARAPUCA technology



Stable High Voltage System with up-time at 300 kV greater than 99.5% during continuous operation.

Dual Phase vs Vertical Drift

- Removal of the extraction stage to the gas phase and the subsequent charge amplification stage eliminates need to bias the grid at high voltage and signal amplification.
- Ease of manufacturing, cheap and faster to develop.
- No risk of breaking wires of the APAs, simple support structure.