TPC@50 Present: LArTPCs at Fermilab

November 20, 2024

Bonnie Fleming

CPAD 2024

Coordinating Panel for Advanced Detectors Workshop (CPAD 2024)

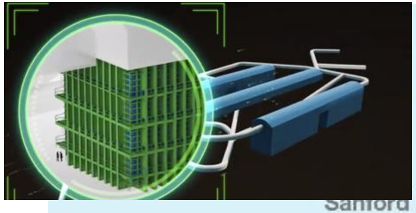
Perspective on the TPCs impact on the neutrino program

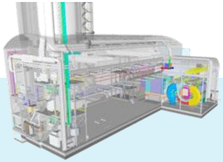
- Current program → LArTPCs for neutrino physics
  - Some history! How did we get here and how did things evolve along the way
  - DUNE and SBN underway now

My own perspective from neutrino physics at Fermilab

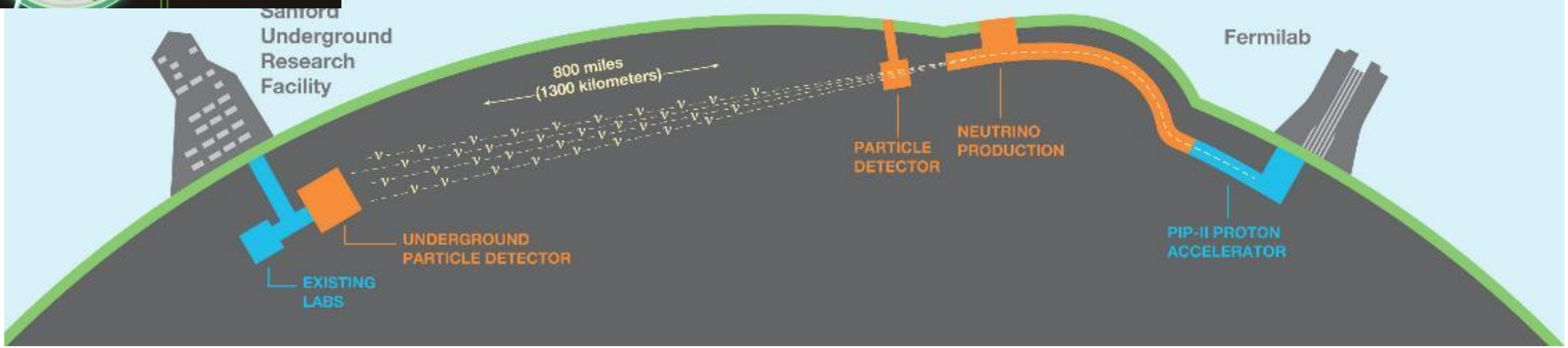
Apologies for omissions!

"Best in Class" neutrino experiment driven by LBNF and PIP-II





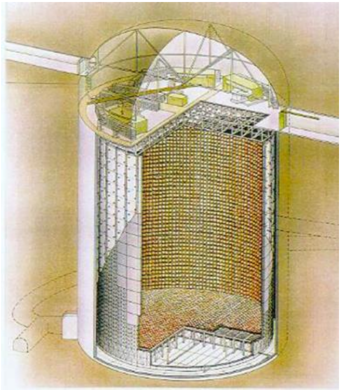
ND Lar detector



- **Origin of matter.** Investigate leptonic CP violation. Are neutrinos the reason the universe is made of matter?
- **Neutron star and black hole formation.** Ability to observe neutrinos from supernovae events and perhaps watch formation of black holes in real time.
- **Unification of forces.** Investigate nucleon decay, advance unified theory of energy and matter.

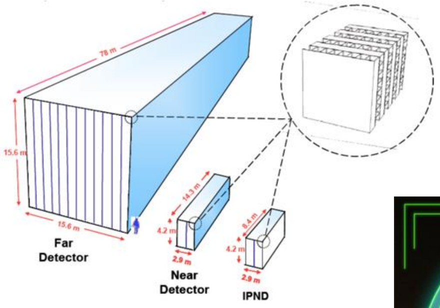
The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States" – DOE

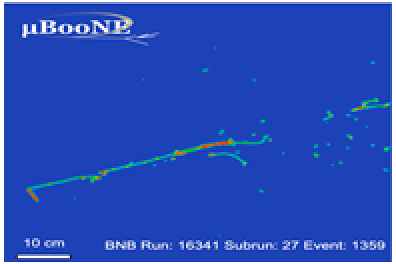
Evolving technological landscape: precision massive LArTPCs

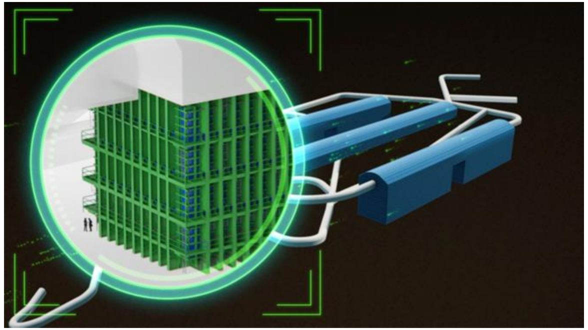


Precision detectors → massive detectors

→ **massive precision detectors!**







New technologies can be transformative

LArTPC: Liquid Argon Time Projection Chamber

- **LAr** as total absorption calorimeter
  - High statistics, abundant and cheap
  - ionization and scintillation light
  - Pioneering paper lays out electrode geometry and signal processing in a liquid argon ionization chamber

NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

W. J. WILLIS†

Department of Physics, Yale University, New Haven, Connecticut 06520, U.S.A.

and

V. RADEKA

Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

Received 14 May 1974

1974

- **TPC** as 4π charged particle detector
  - 3D reconstruction with fully active volume

The Time-Projection Chamber
- A new 4π detector for charged particles

David R. Nygren

Lawrence Berkeley Laboratory
Berkeley, California 97420

1976

- **LAr+TPC** to obtain fine-grained 3D tracking with local dE/dx information and fully active target medium

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

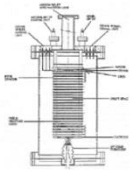
C. Rubbia

1977

Fermilab

Carlo Rubbia proposes LAr detectors for neutrino physics and starts an R&D program towards ICARUS (1977)

Test Stands →

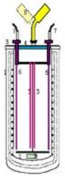


24 cm drift wires chamber

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

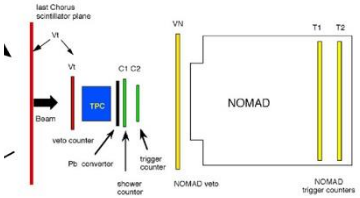
3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



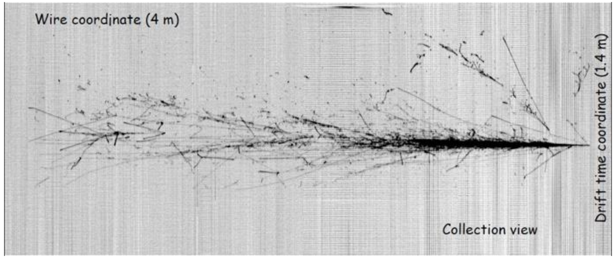
T600: 600 ton LarTPC
In Gran Sasso National Lab
~17 GeV CNGS beam

Seeing neutrino Interactions →



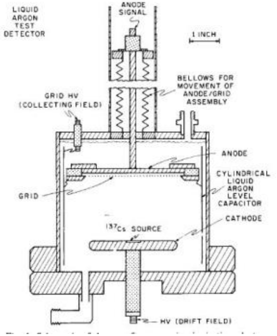
50 litres prototype
1.4 m drift chamber

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.



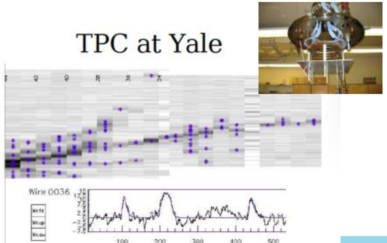
Neutrino interaction in ICARUS from CNGS beam

Efforts in the US →



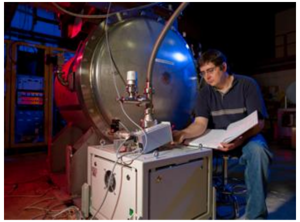
Herb Chen's
Four channel
Test stand
1978

TPC at Yale



First tracks in US, April 2007

FNAL Material Teststand, 2008



ArgoNeuT
(2009 - 2010)
ν-Ar Cross Sections

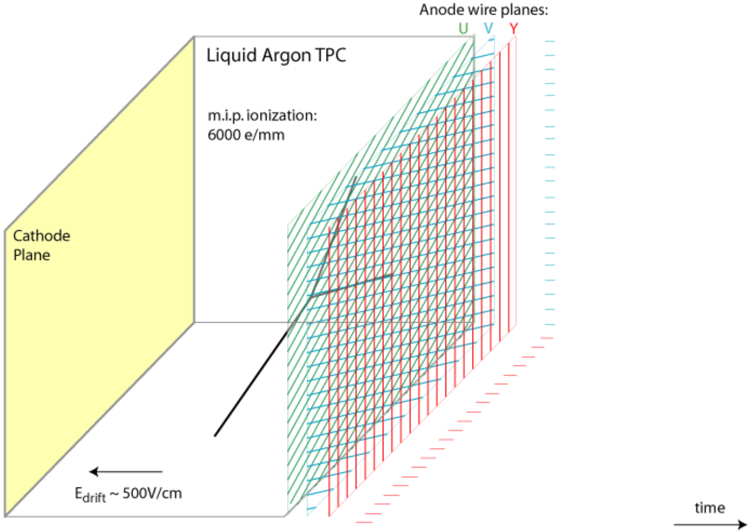
Liquid Argon Time Projection Chambers

- Passing charged particles ionize Argon
- Electric fields drift electrons meters to wire chamber planes
- Induction/Collection planes image charge, record dE/dx

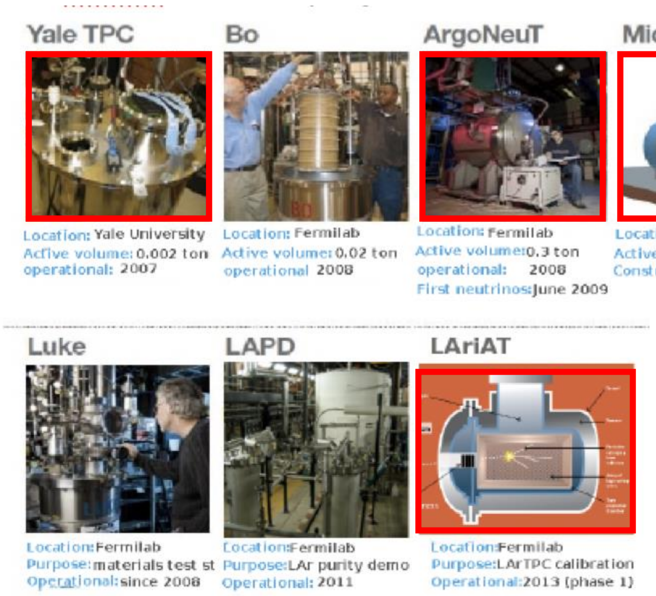
<- 500 V/cm

Early on: Asking: CAN these work at scale

- *Cold, low noise electronics, multiplexed signals*
- *Ultrapure Argon*
  - *What materials are OK*
  - *Achievable in large vessels without evacuation*
- *High voltage implementation*
- *Stable, long term operation*
- *Fully automated reconstruction*



The US LArTPC program



Don't look too closely at dates!

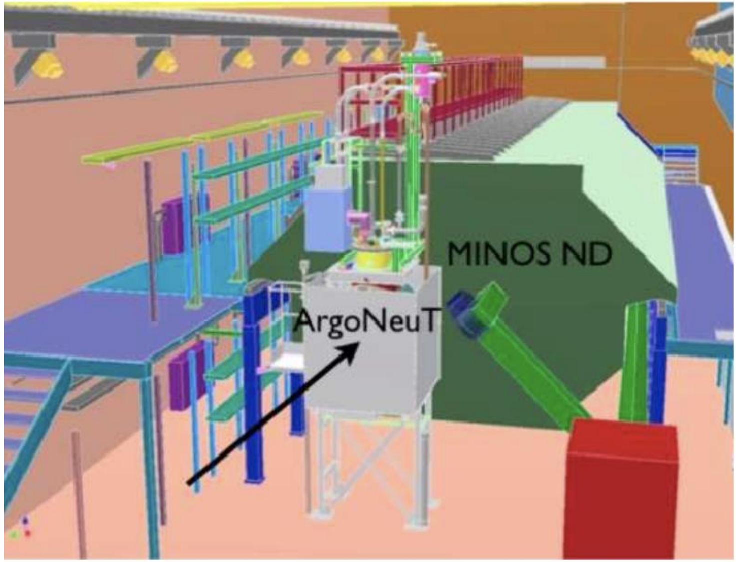
Some things came just after this:

- ICARUS at FNAL as SBN far detector
- 35 ton
- ProtoDUNEs!

- US program grew significantly → Technology decision for DUNE in 2012 to use LArTPCs for DUNE
- At some point we went from CAN these detectors work to how can we optimize them

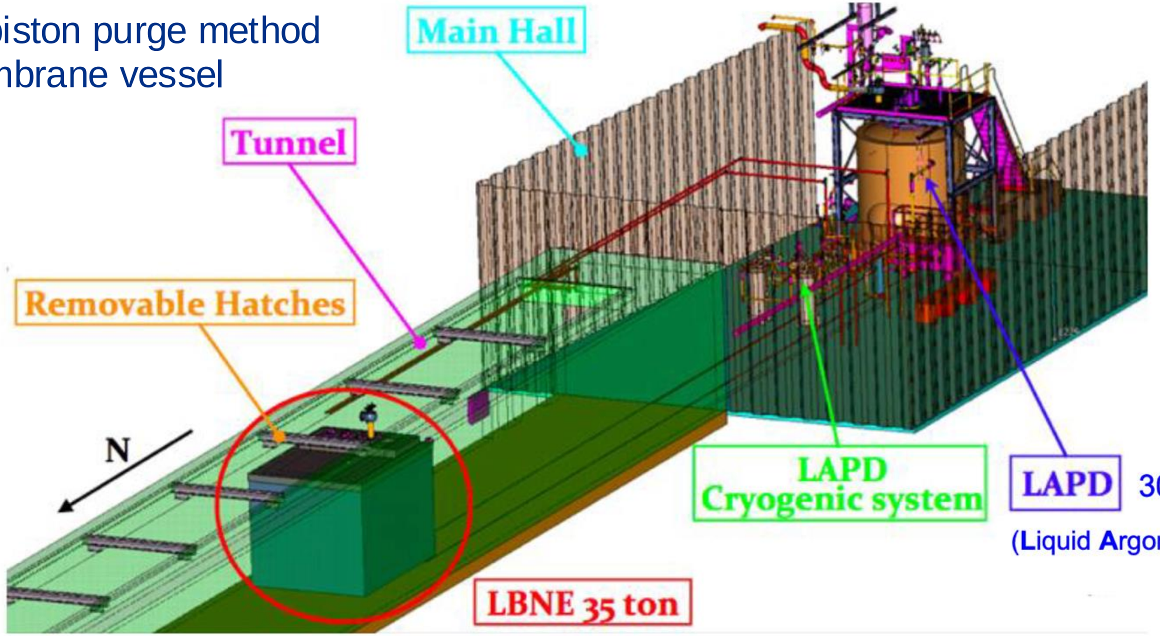
A first FNAL test: ArgoNeuT

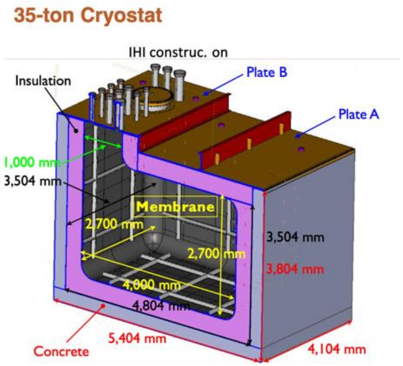
- Intended as an R&D test to see neutrino interactions
- Ran in NuMI beam for 6 months from 2008-2009
- Still publishing neutrino cross section papers
- Detector hardware later repurposed for LArIAT



LAPD and 35 ton

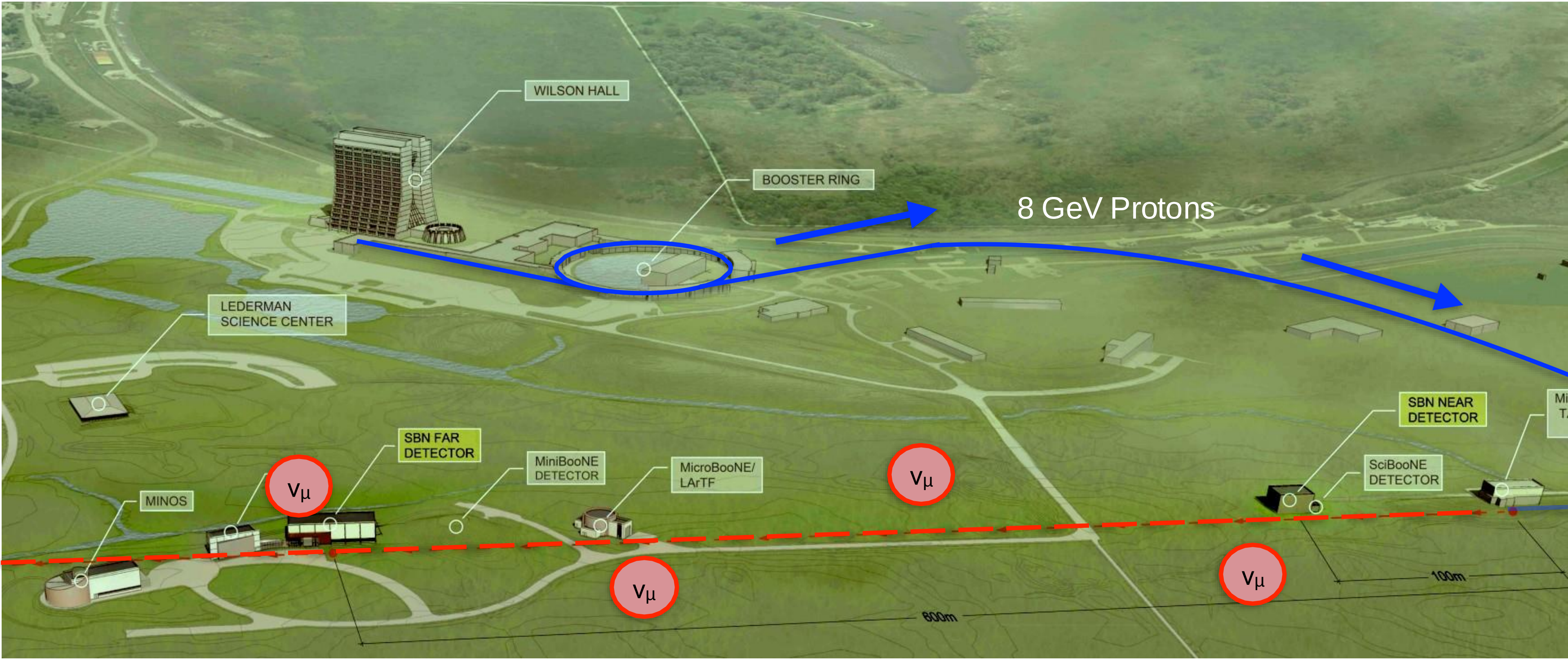
- LAr purity from piston purge method
- Achieved in membrane vessel





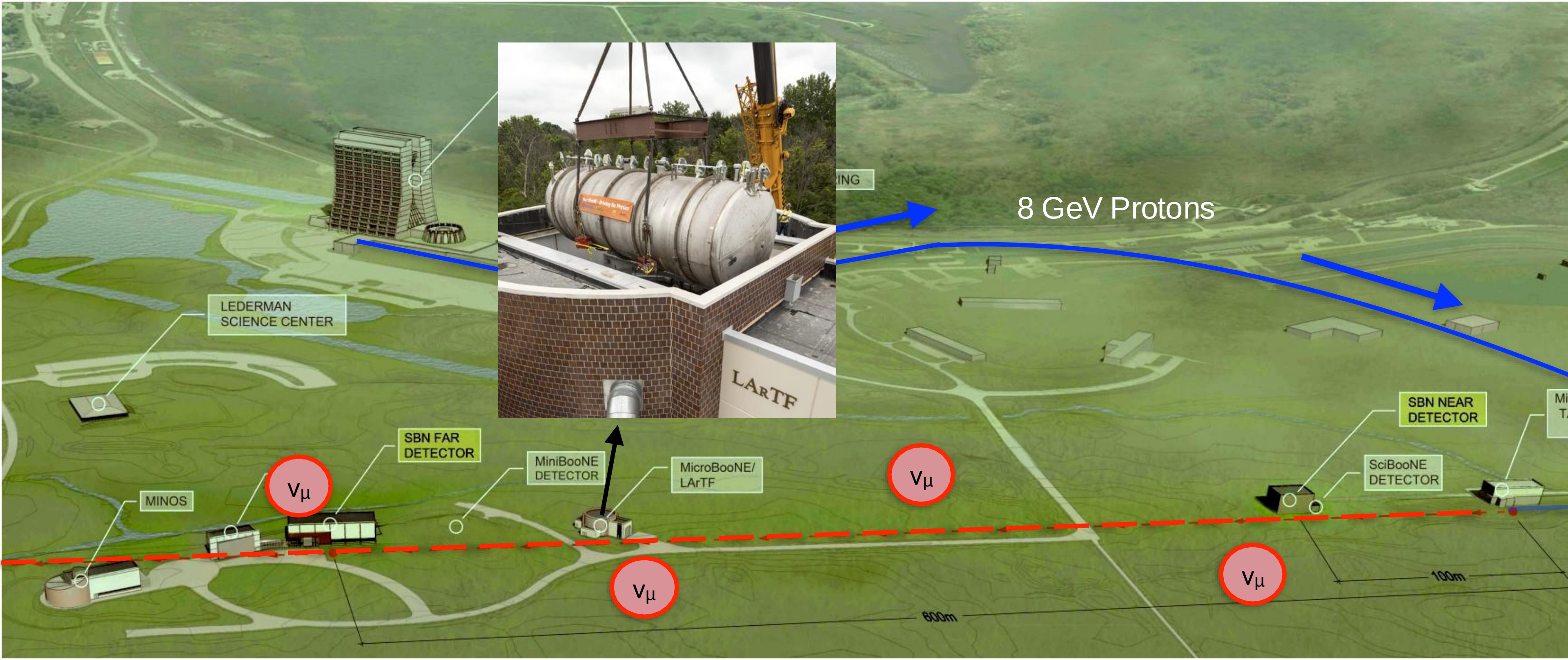
- The original purpose of the 35-ton cryostat was to demonstrate that liquid argon purity at the level required for TPC operation could be obtained in a non-evacuated, membrane cryostat (successfully demonstrated in early 2014)

The Booster Neutrino Beam Line at Fermilab



The Booster Neutrino Beam Line at Fermilab

MicroBooNE: part R&D part physics experiment



Success in building and running the experiment: it works!

June 2012

- Start of TPC construction

December 2014

- Detector installation complete: charge and light detection

June 2015

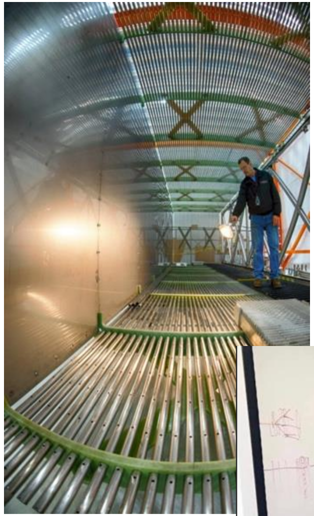
- Fill detector with liquid argon

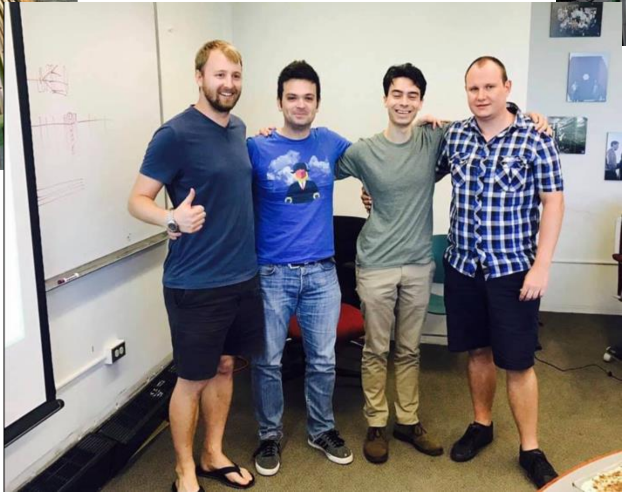
August 2015

- Turn on detector

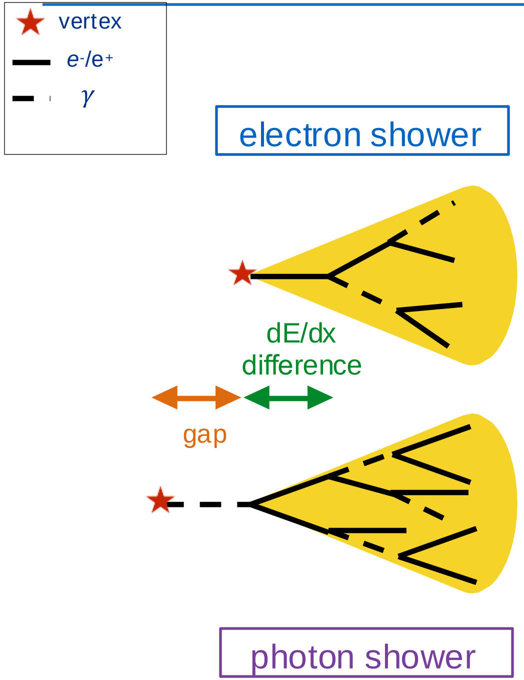
October 2015

- Start neutrino beam data-taking

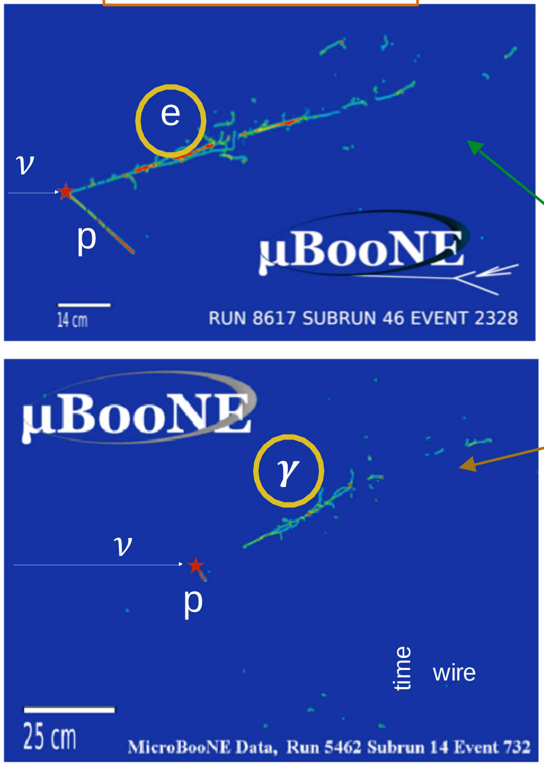


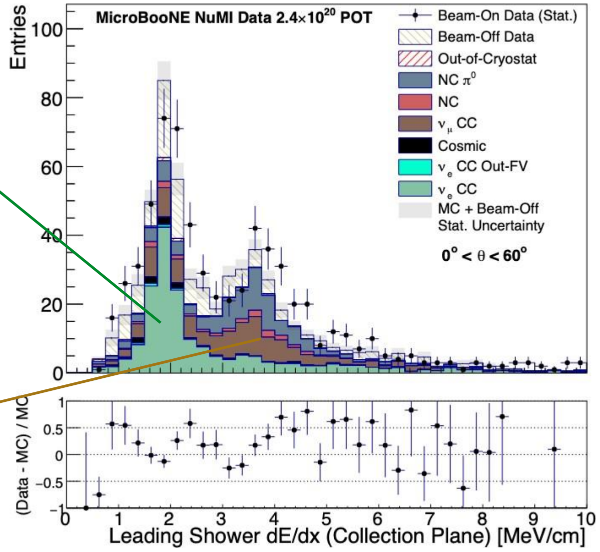


Reconstructing Data →. Distinguishing electrons from photons



topology information

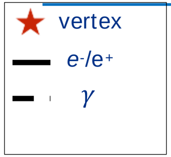




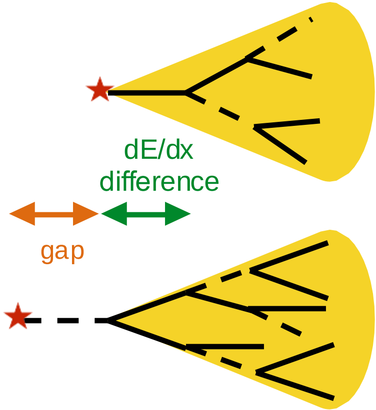
ionization dE/dx

MicroBooNE uses the excellent properties and resolution of its LArTPC to select both eLEE and γLEE signals with high purity

Identify final state hadronic activity

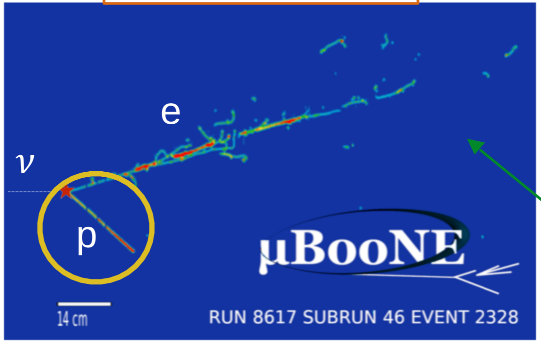


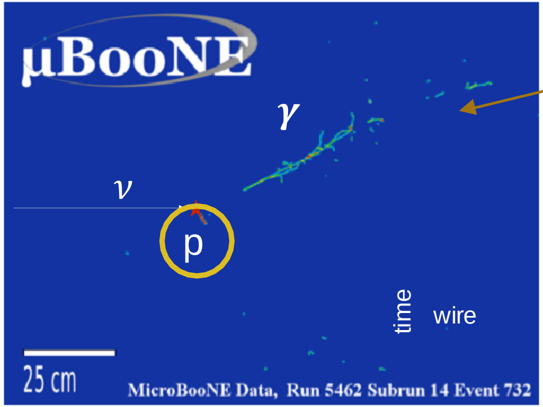
electron shower

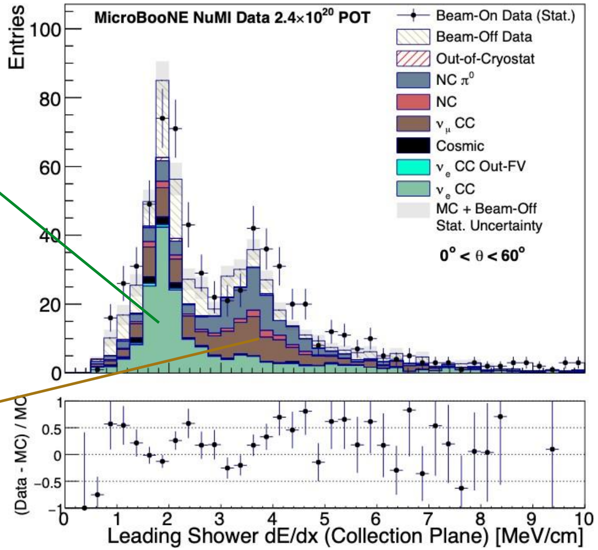


photon shower

topology information



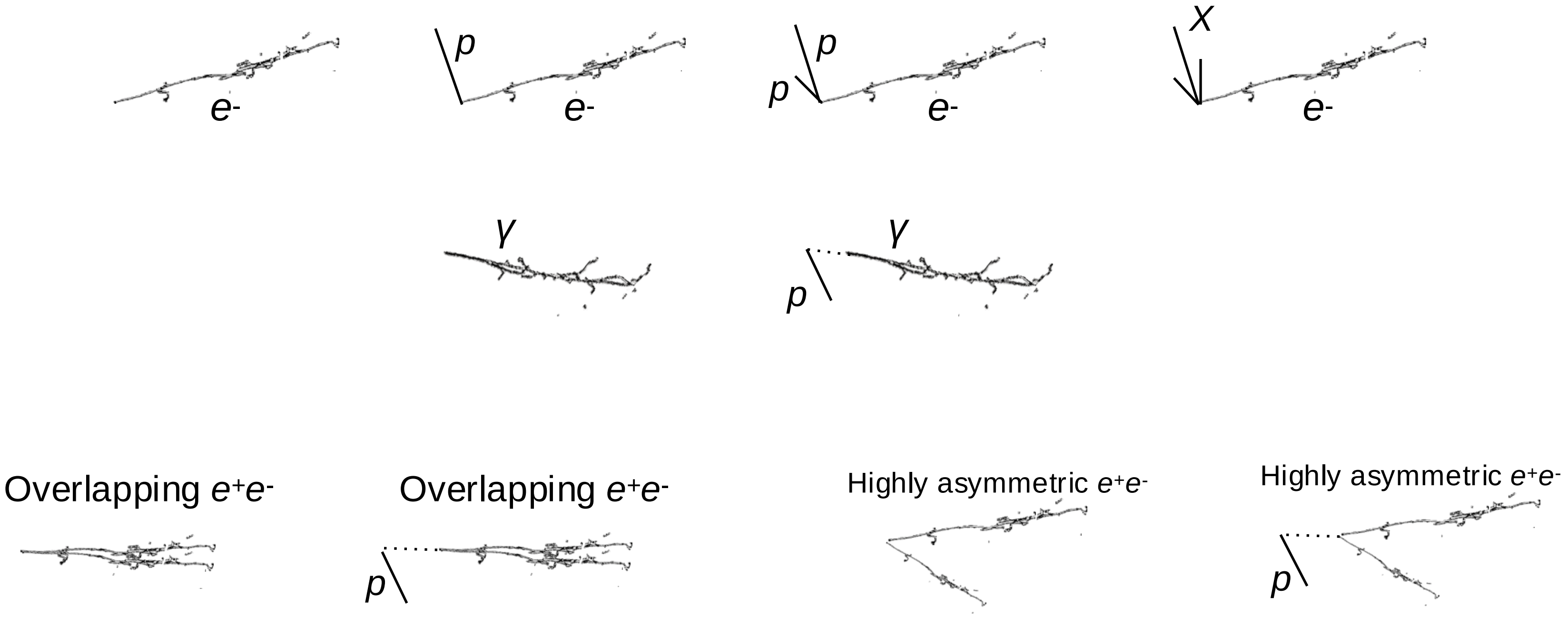




ionization dE/dx

What and how many hadrons are produced?

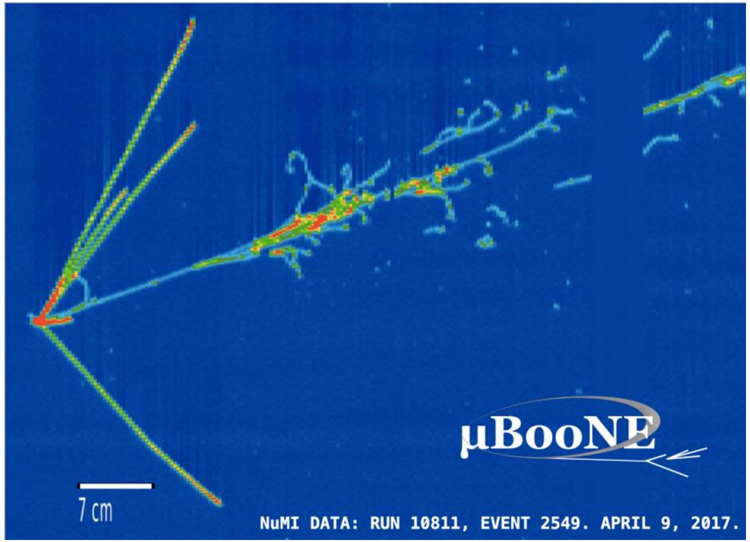
Landscape of Possible MicroBooNE LEE Final State Topologies



Paradigm shift in physics measurements given the level of details and calorimetry recorded

1e/1γ — MiniBooNE signal

1γ | 1e — MicroBooNE proposal



MicroBooNE First Results and Beyond

First series of results (1/2 the MicroBooNE data set)

1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma0p$	$1\gamma1p$	$1\gamma X$

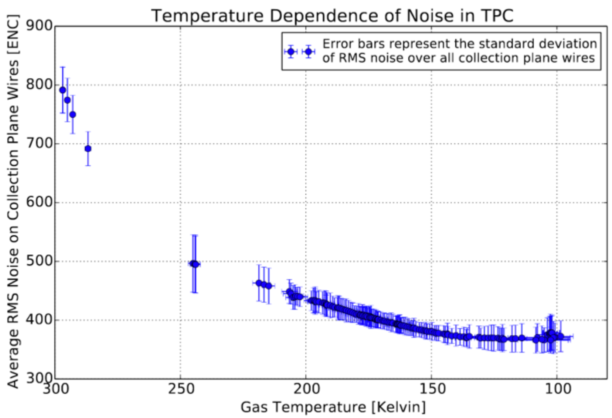
Fermilab

R&D successes passed on to SBN/DUNE

Successful implementation of:

- Development, implementation and long term running of **Cold, low noise electronics**
- Excellent (near perfect) Purity ~x6 better than design
- Precision laser calibration system
- Stable, long term running

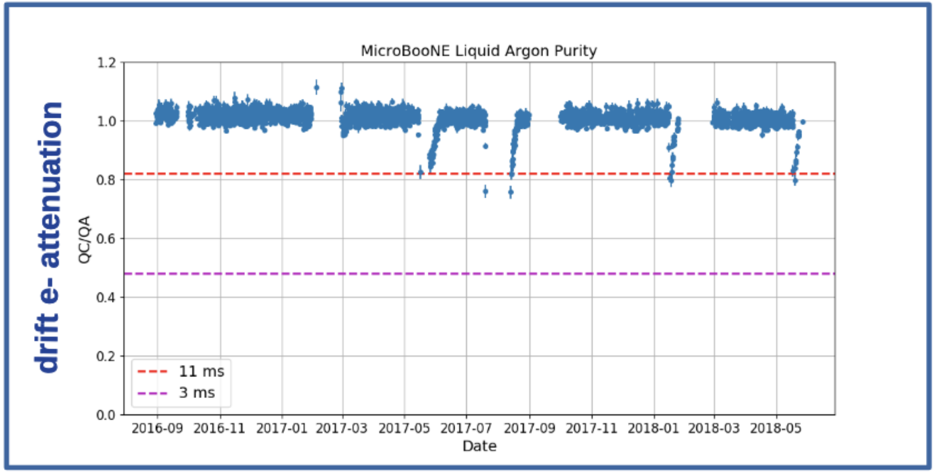
→ (500k interactions over 5 years)



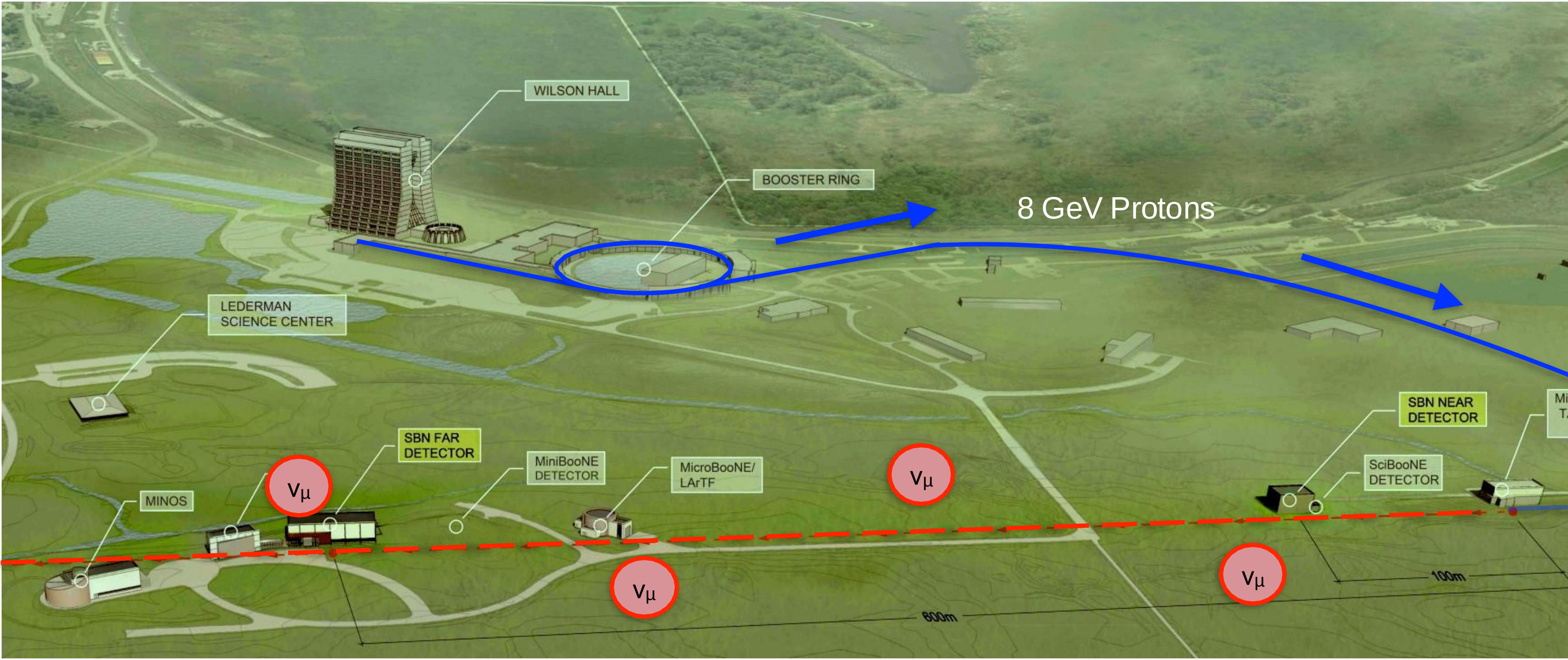
Significant challenges

- Ran at 60% of design HV through data taking
- HV feedthrough challenge mid-run
- 10% of wires in TPC – connected

(97% of TPC covered by 2 wire planes)



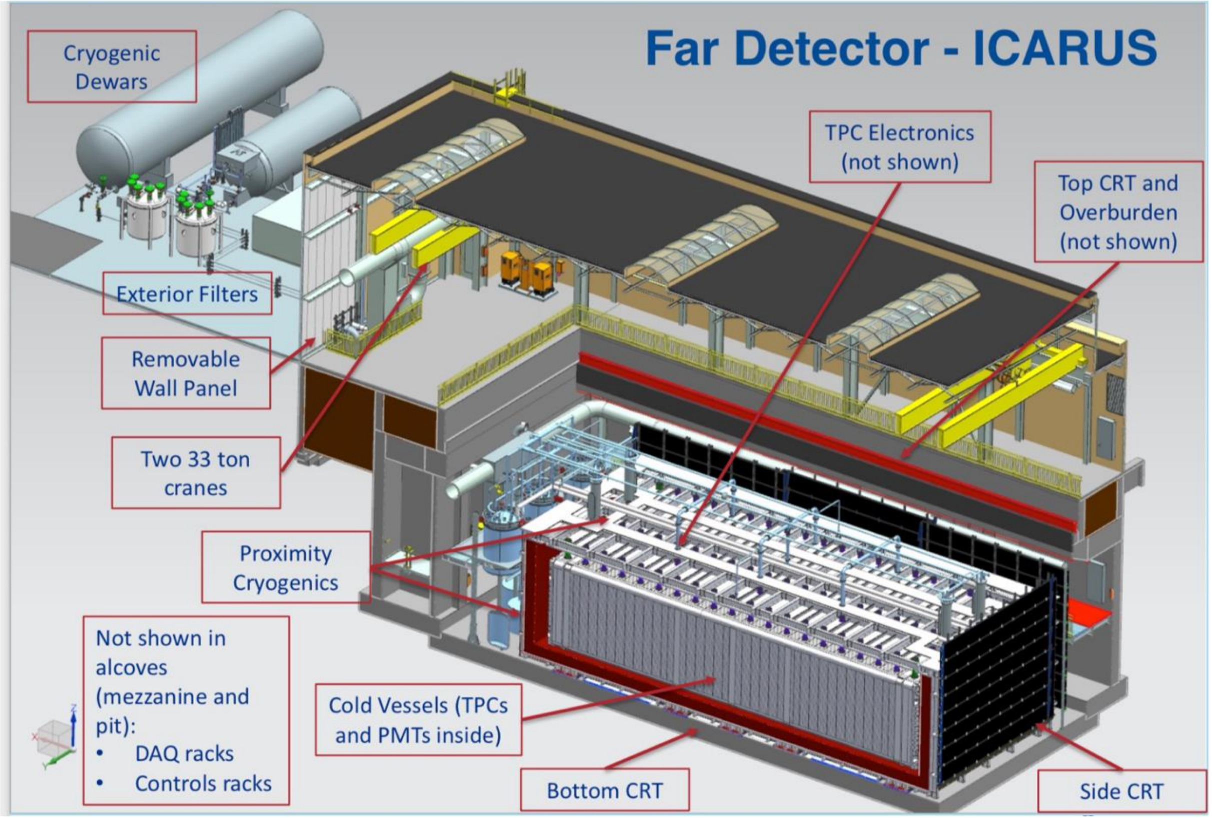
The Booster Neutrino Beam Line at Fermilab



The Short-Baseline Neutrino (SBN) Program at Fermilab

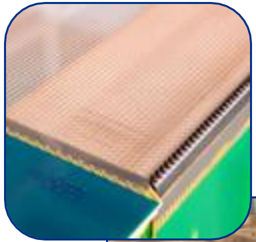
Example sterile neutrino oscillation probability over the SBN baseline (near the peak neutrino energy)

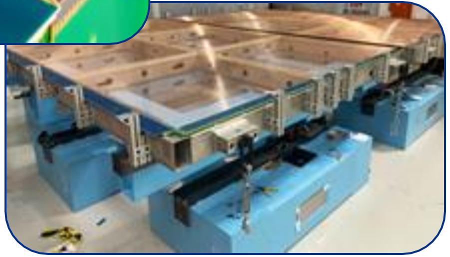
Far Detector: ICARUS



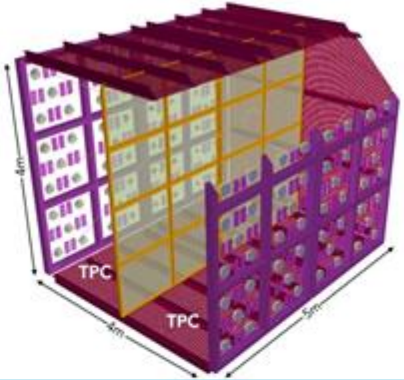
Near Detector SBND
Time Projection Chamber (TPC)

- **Two TPC regions that share a central HV cathode**
  - 5m (L) x 4m (H) anode planes (4 APAs)
  - 2m drift
  - Cathode HV = -100 kV
- **3 wire planes**
  - 1 collection (vertical), 2 induction (±60°)
  - 3 mm wire and interplane spacing
- **TPC cold electronics**
  - shaping, amplification, and digitization in cold
  - 11,264 wires read out by 88 FEMBs





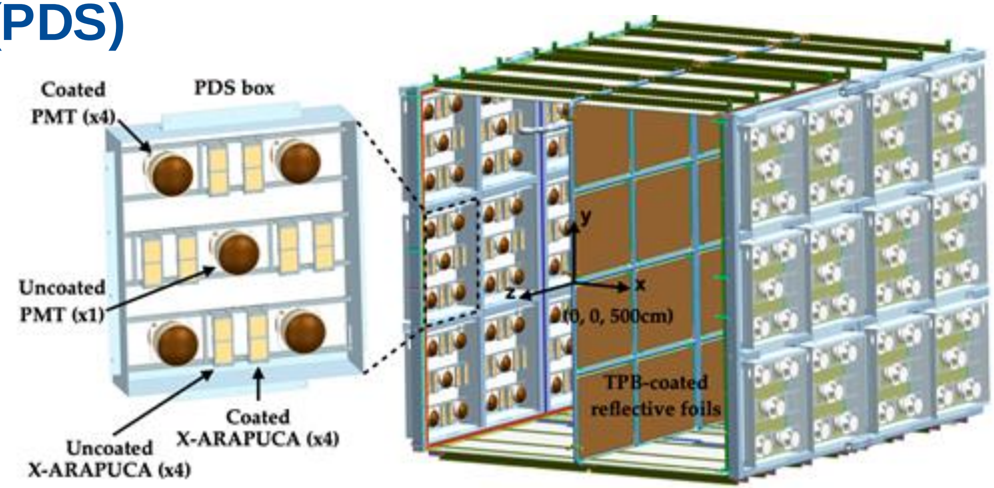
Construction of precision wire readout planes for the Short-Baseline Near Detector (SBND)
arXiv:2002.08424 *2020 JINST 15 P06033*



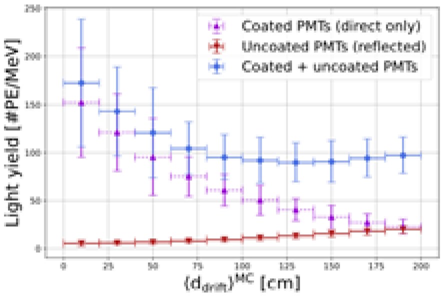
From D. Schmitz, SBND co-spokesperson

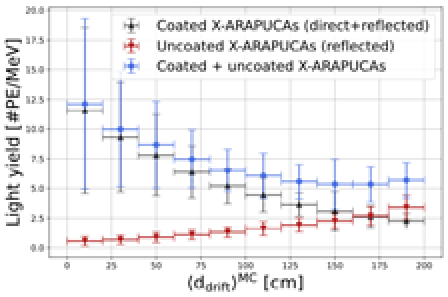
Photon Detection Systems (PDS)

- **120 PMTs** - Hamamatsu R5912-mod 8”
- **192 X-ARAPUCA** devices
- Reflective foil panels coated with wavelength shifter embedded into the cathode plane
- Light-yield **≥100 pe/MeV**



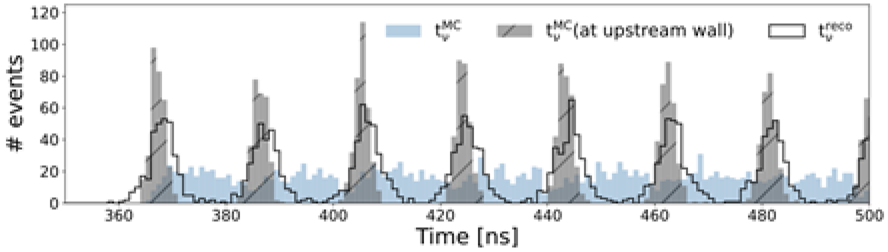
Light yields





Event timing

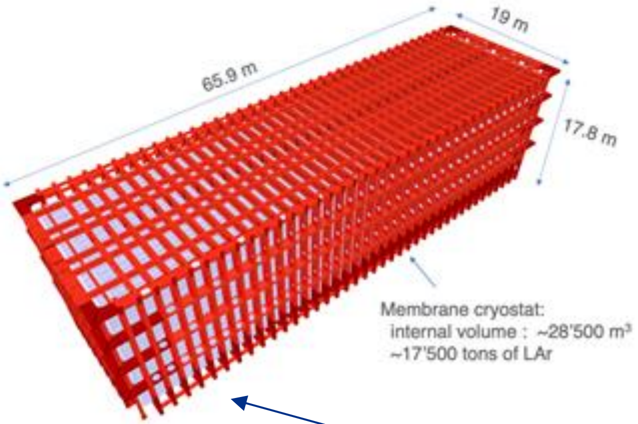
Scintillation Light in SBND: Simulation, Reconstruction, and Expected Performance of the Photon Detection System arXiv:2406.07514 *(accepted for publication at EPJC)*



From D. Schmitz, SBND co-spokesperson

Cryostat and Cryogenics

- SBND cryostat and cryogenics a very successful collaboration between CERN and FNAL engineers and physicists.



Fermilab's Short-Baseline Near Detector, effectively a miniature version of what will go in the South Dakota cavern. Mustafa Hussain for The New York Times

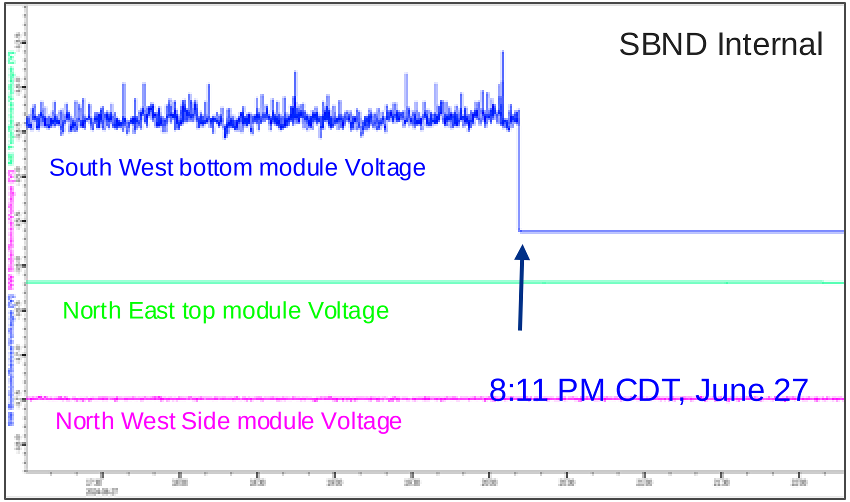
New York Times DUNE article, Aug 30, 2024

From D. Schmitz, SBND co-spokesperson

SBND Commissioning : TPC High Voltage

- SBND initially turn on of HV in March 2024
- Significant instabilities prevented ramp beyond ~30kV
- Worked for several months investigating unstable connection causing instability
    - Used light and charge monitoring, developed new techniques
- On June 24th, the detector activation procedure was (re)initiated, with the TPC cathode HV ramped up in 5kV steps, while carefully monitoring the rate of the current spikes occurring down the problematic field cage's path to ground.
    - Discharge rate linearly increased with HV in the O(~Hz) range. Amplitude of impacts was not seen to increase.
- At 8:11 PM CDT on June 27th, with the cathode at -35 kV, the current flow to ground down the problematic field cage path suddenly became stable.
- Reached 100kV (nominal) and began physics run on July 4th. Stable running since then

Voltage measurements on the field cage modules [3/16 displayed]



First Candidate Neutrino Events!

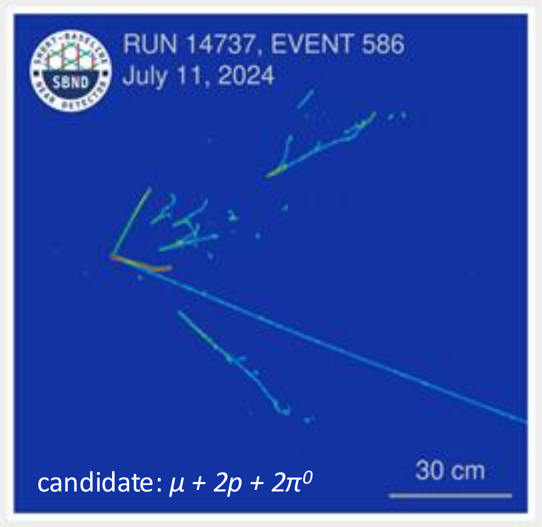
collection plane, zoomed

Time tick

Wire #

collection plane, zoomed

Time tick

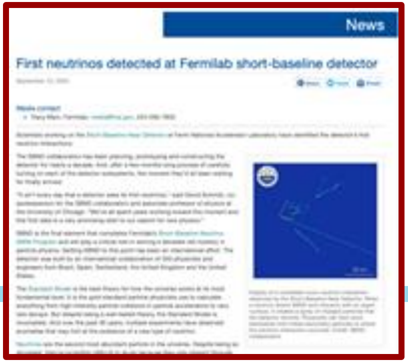


Wire #

collection plane, zoomed

Time tick

Wire #



News

First neutrinos detected at Fermilab short-baseline detector

Fermilab issued a press release about first neutrinos in SBND this week on Tuesday.

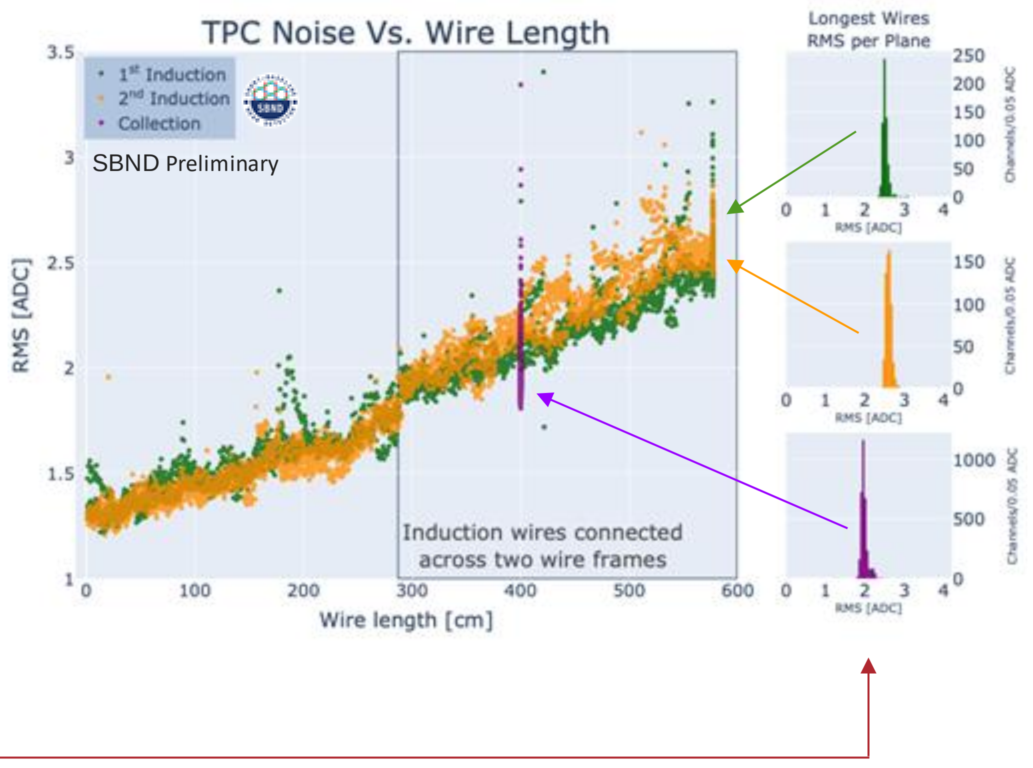
https://news.fnal.gov/2024/09/first-neutrinos-detected-at-fermilab-short-baseline-detector/

From D. Schmitz, SBND co-spokesperson

Fermilab

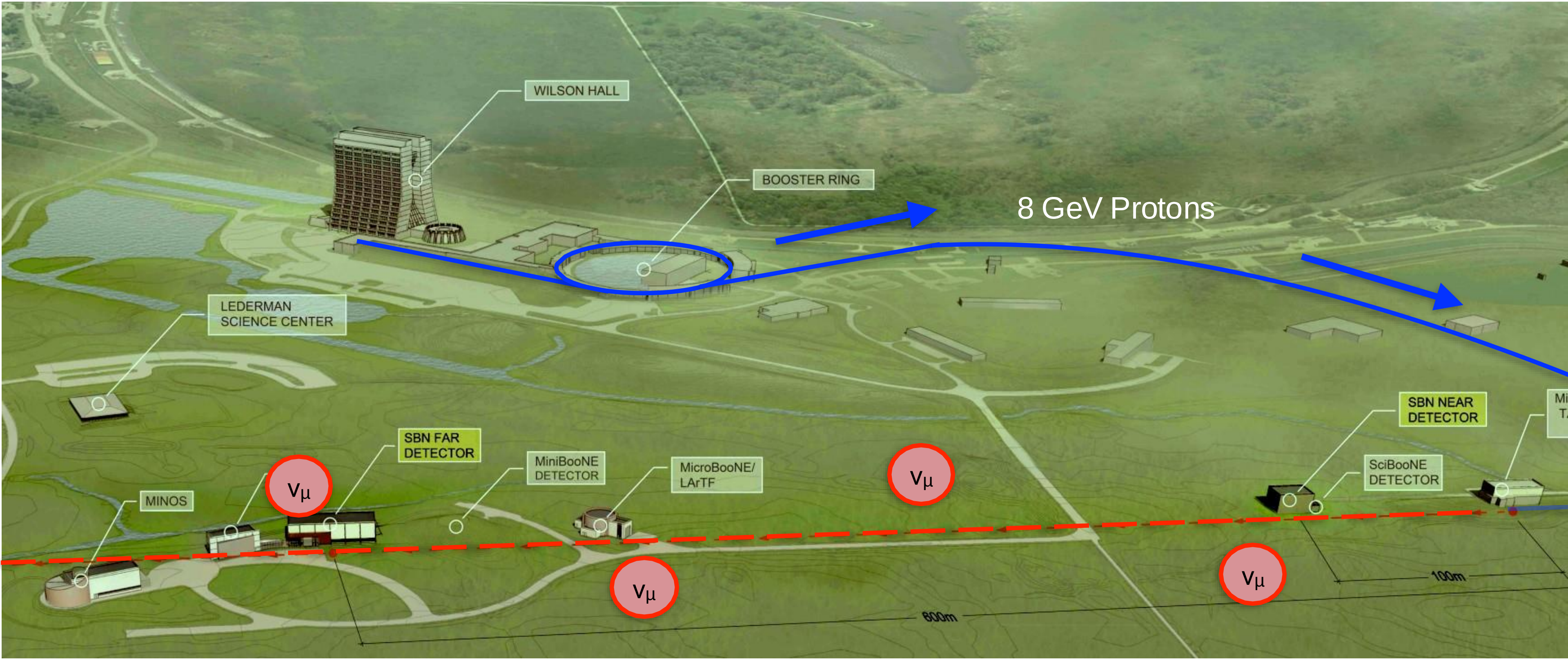
TPC Performance: Electronics Noise

- SBND cold electronics are an evolution from MicroBooNE and ProtoDUNE-SP, same front-end amplifier and FPGA as ProtoDUNE-SP, but SBND using a COTS ADC.
- Low noise grounding strategy began with the design of the SBND detector building. Grounding monitored continuously throughout installation and commissioning.
- Irreducible intrinsic noise is set by pre-amplifier and wire capacitance: **4m wire ⟺ 380e/1.9 ADC counts noise**

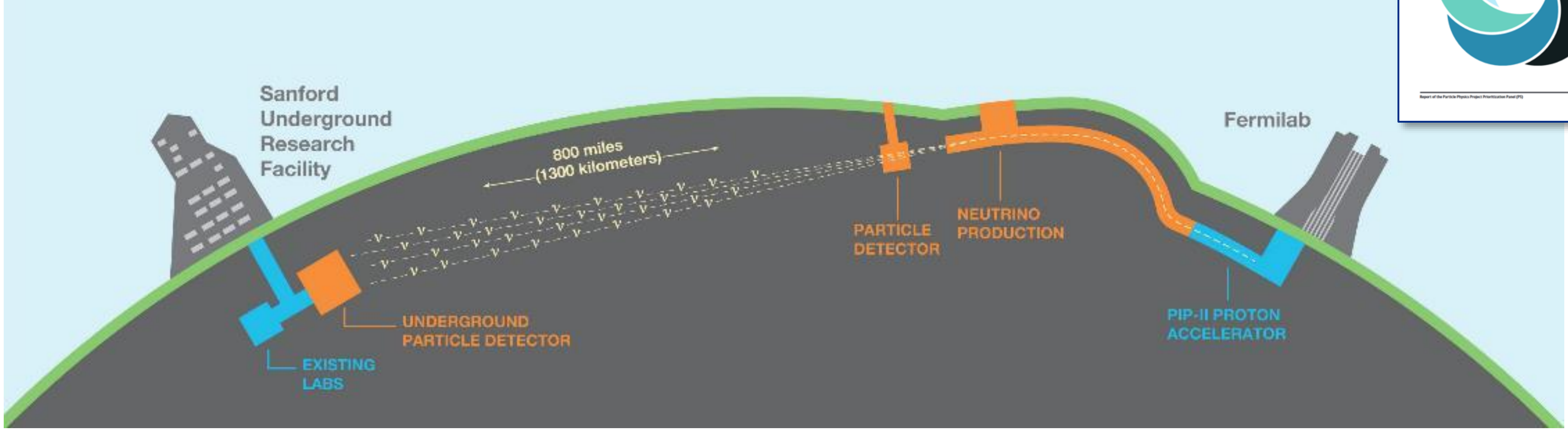


From D. Schmitz, SBND co-spokesperson

SBND and ICARUS about to start taking data for FY25 run



"Best in Class" neutrino experiment driven by LBNF and PIP-II



- **Origin of matter.** Investigate leptonic CP violation. Are neutrinos the reason the universe is made of matter?
- **Neutron star and black hole formation.** Ability to observe neutrinos from supernovae events and perhaps watch formation of black holes in real time.
- **Unification of forces.** Investigate nucleon decay, advance unified theory of energy and matter.

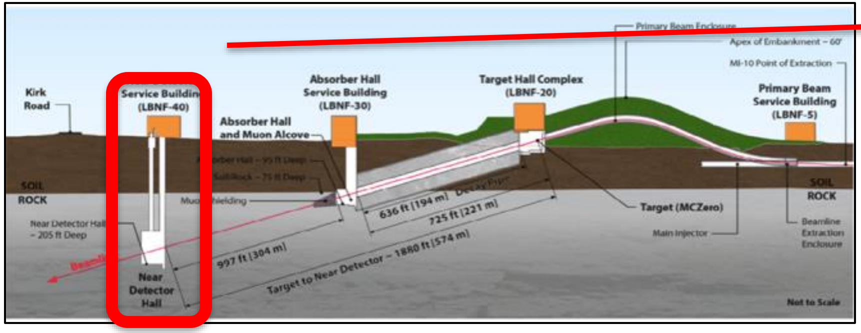
The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States" – DOE

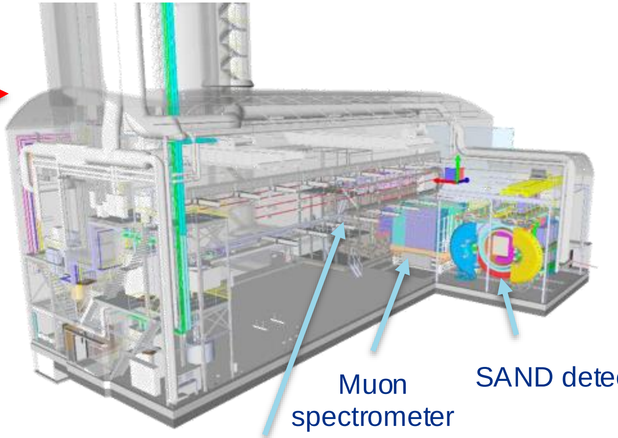
DUNE collaboration

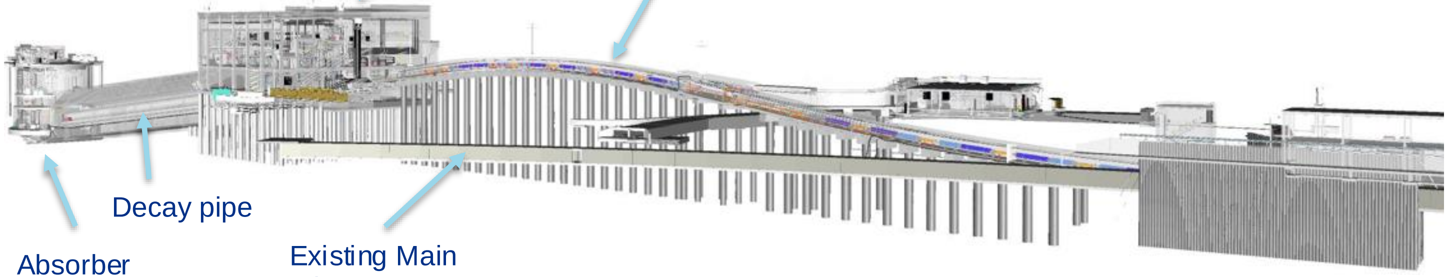
DUNE coll. Meet at FNAL, May. 2022

Over 1,400 scientists, from more than 200 Institutions, ≥ 37 countries plus CERN

Near Site Conventional Facilities



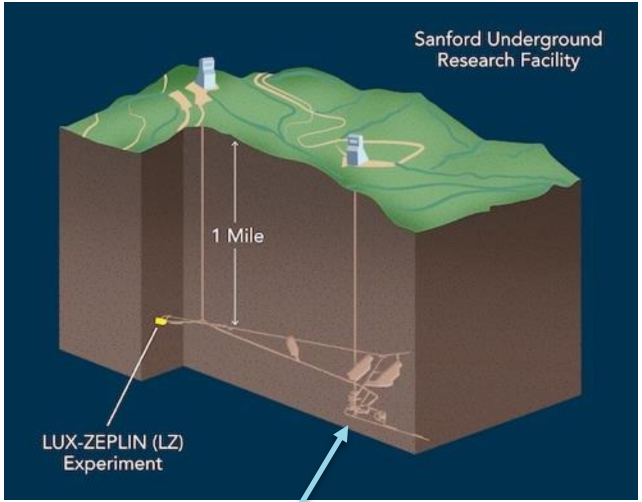


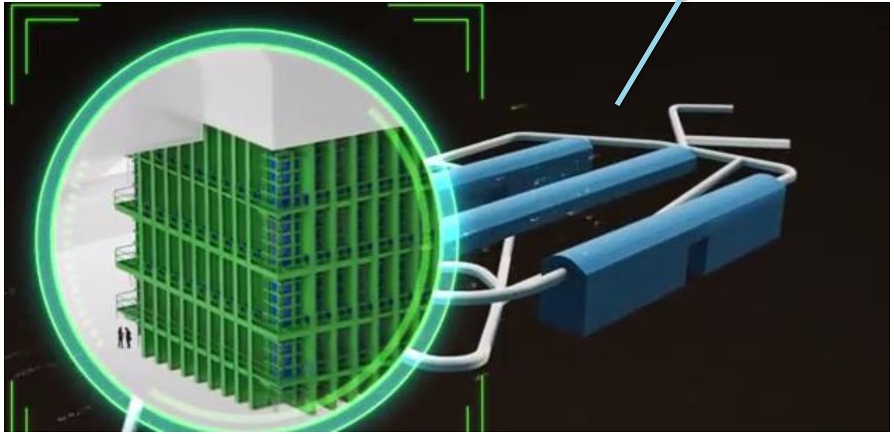


Fermilab

Far site: SURF

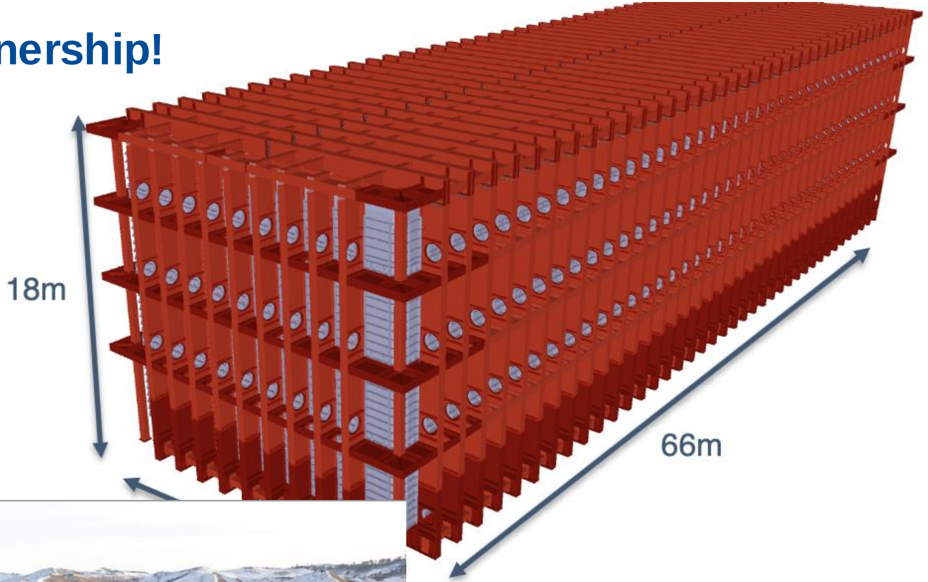
- Deepest laboratory in the US: 1.5 km underground
- Three main caverns: 4 detectors halls in 2 caverns and 1 support cavern (cryogenics and services)
- Excavation is COMPLETE! *(875,000 tons of rock to be excavated)*
- FD first module installation second half of 2020’s



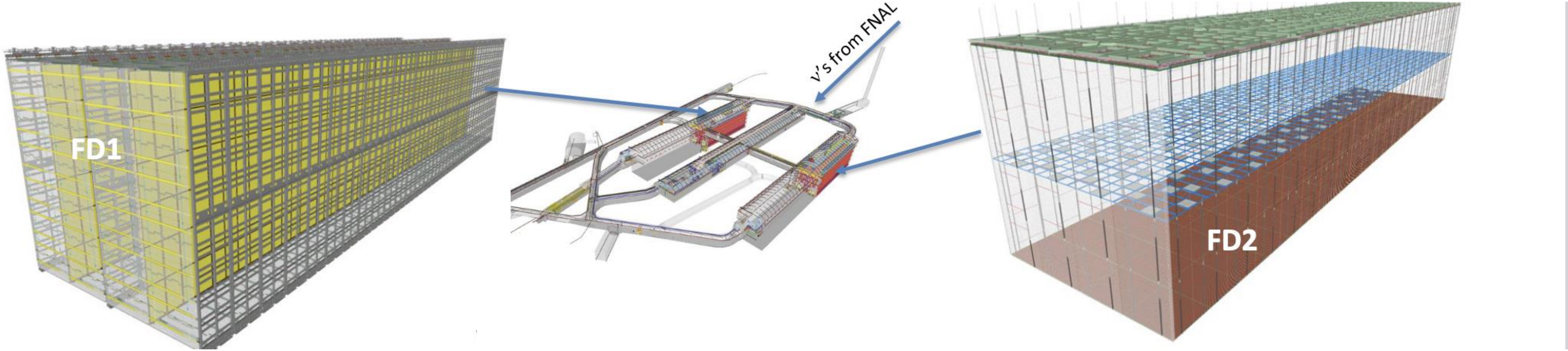


Far detector modules → International partnership!

CERN contributing the cryostats: constructed in Europe, shipped to South Dakota

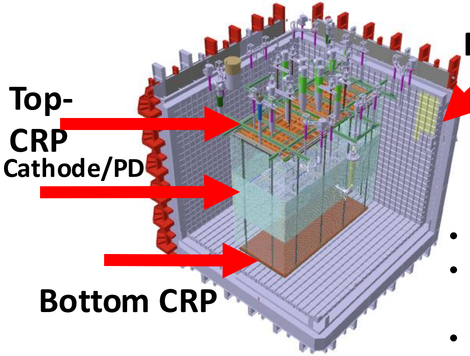


DUNE far detector modules



FD1: Horizontal drift with APA readout
FD2: Vertical drift with CRP readout

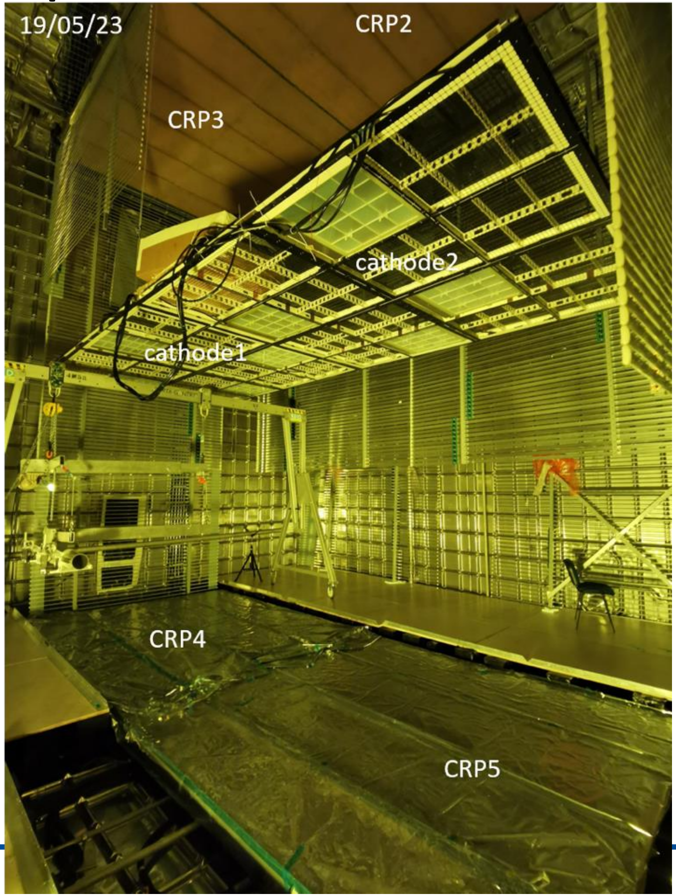
TPC completed June 9!



- 2 top CRP (#2-3)
- 2 cathodes (8 x-Arapuca)
- 2 bottom CRP (#4-5)
- 8 membrane x-Arapuca

Upgrade of cathode PDS electronics (based on Module-1 versions) completed July 2024

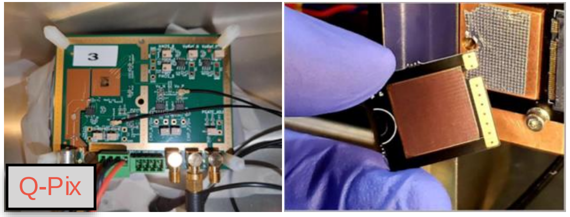
CRP3 & support fra

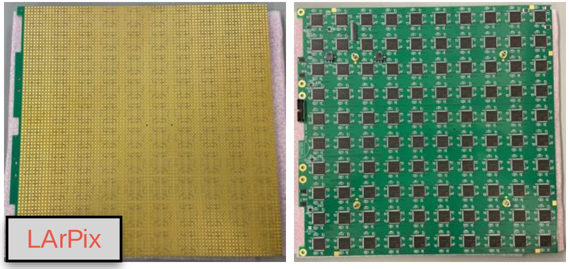


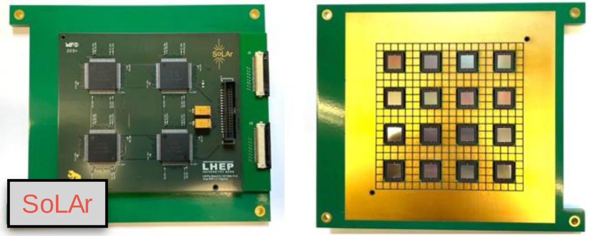
Looking ahead to DUNE Phase II

Optimized Charge and Photon Readouts for Phase II FD

3







Perspective on the TPCs impact on the neutrino program

- Recent trajectory for TPCs at FNAL began around 2002
- Just over 20 years of development so far (!)
- Transition we went from CAN we build these to HOW to optimize them
- Remarkable detectors already show paradigm shift in neutrino physics measurements