

# Neutrinos and the Universe

Zelimir Djurcic

Argonne National Laboratory

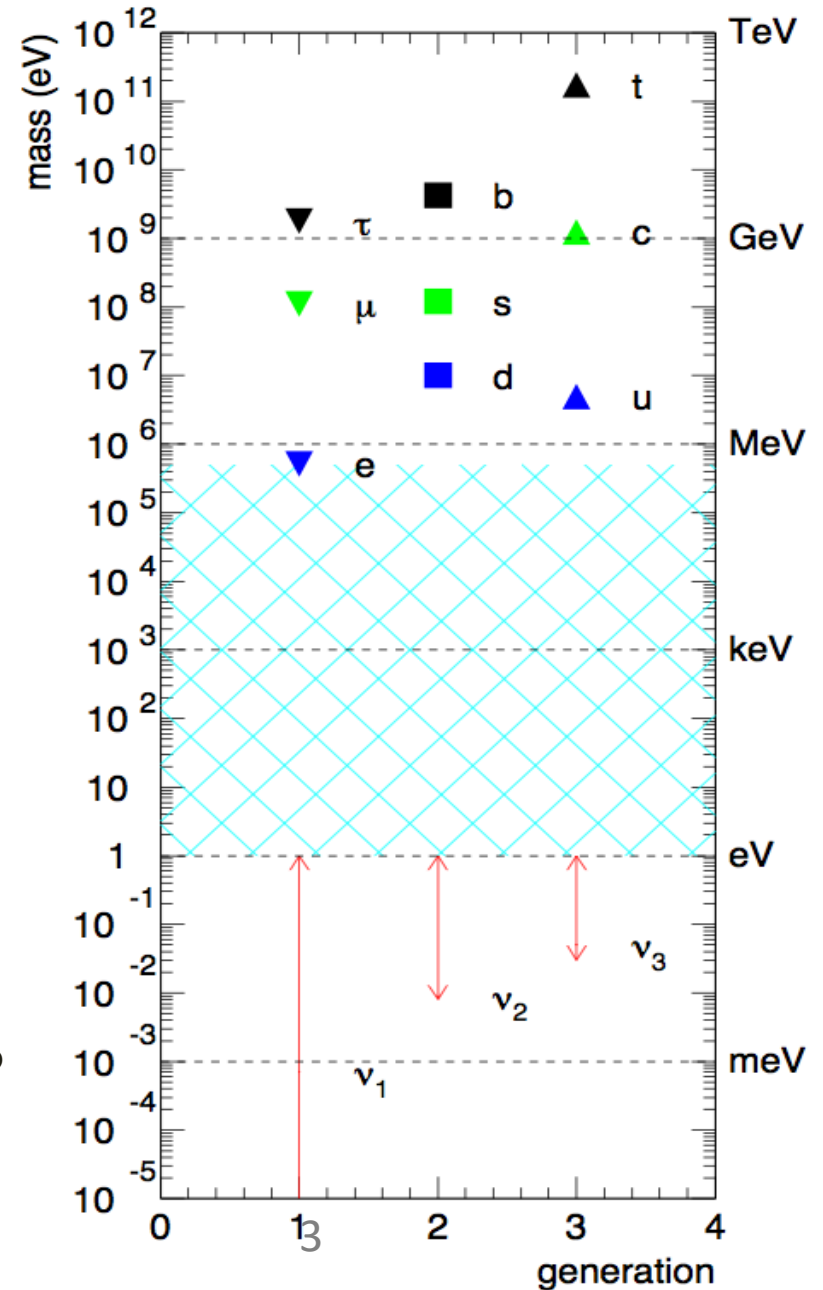
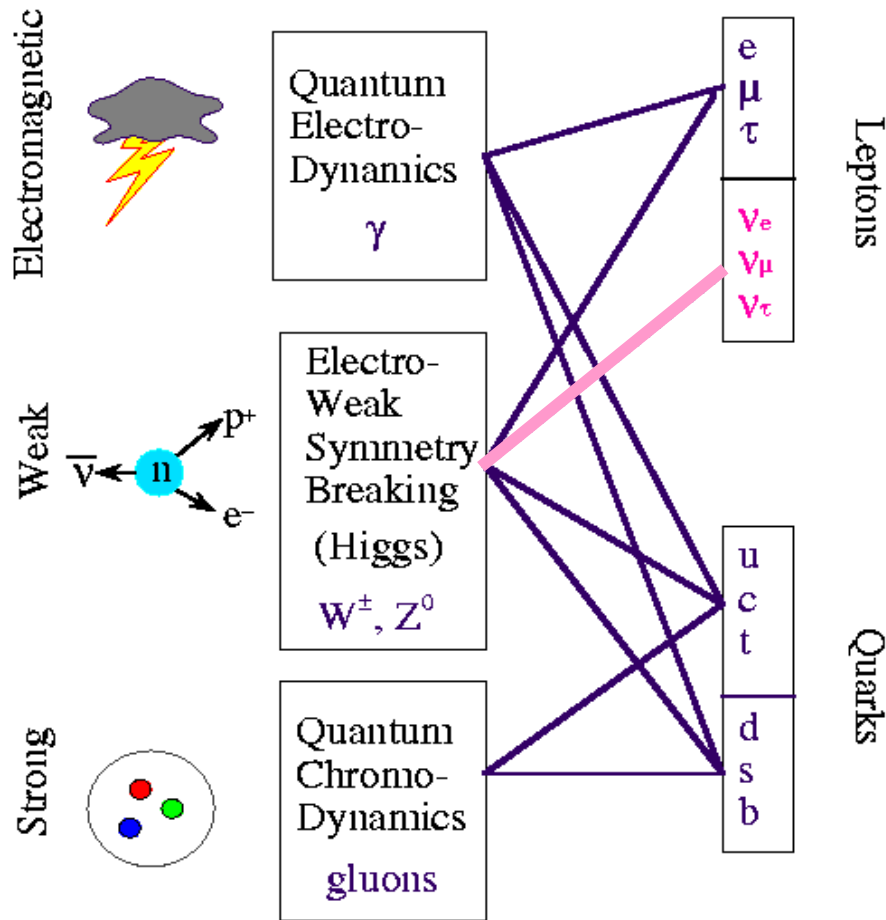
# Talk Summary

In this talk I will describe searches for differences between matter and anti-matter with neutrinos. More specifically, I will focus on neutrino CP-violation and neutrino mass. Today's discussion will cover some of the efforts we are putting together to probe these quantities. I will describe new experimental probes in areas of long-baseline and  $0\nu\beta\beta$  searches.

- Introduction
- Neutrino oscillation physics
  - Illustrated with Zelimir's former and current experiments
- CP-violation
- Majorana neutrino
- Neutrinoless double beta-decay
  - EXO
- Alternative ways to discover Majorana?
- Summary



# Standard Model of Particle Physics

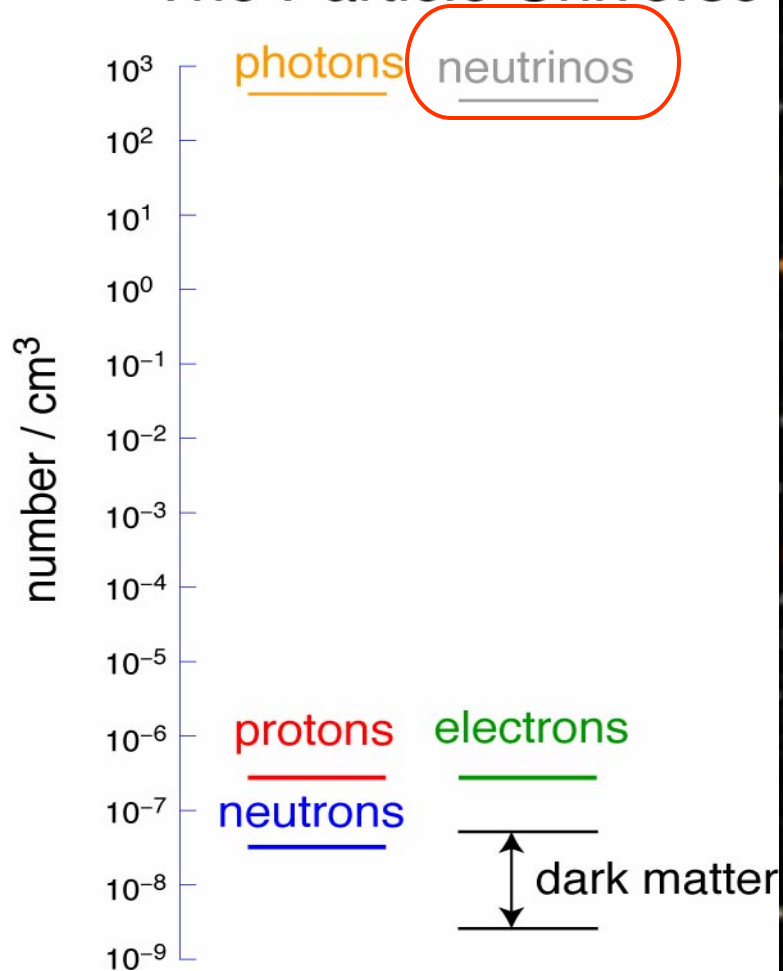


-Unlike the mass of a quark or charged lepton, neutrino mass is unlikely to be coming from a linear coupling between the particle and the Higgs boson field.



# Neutrinos Are Special

## The Particle Universe



- Neutrinos are the most abundant matter particles in the Universe after photons
  - 336 cosmic neutrinos/cm<sup>3</sup>
  - (comparable to 411 CMB photons/cm<sup>3</sup>)
- Neutrinos only interact through the “weak force” and gravity
- Neutrinos are very light
  - neutrino mass <  $10^{-6}$  electron mass
- Neutrinos play a crucial role for
  - energy production in the Sun
  - nucleo-synthesis: BBN, SN
  - generating the baryon asymmetry of the Universe => Matter

# Neutrino Sources

- Neutrinos come from “everywhere”

Nuclear Reactors



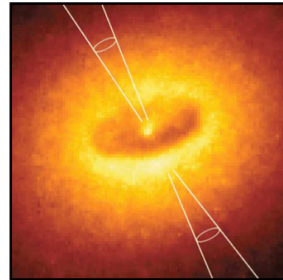
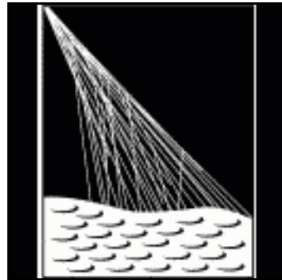
Sun

Particle Accelerators



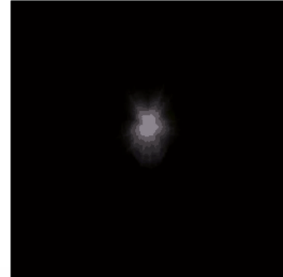
Supernovae  
(star collapse)

Earth's Atmosphere  
(Cosmic Rays)



Astrophysical Sources

Earth's Crust  
(Natural Radioactivity)

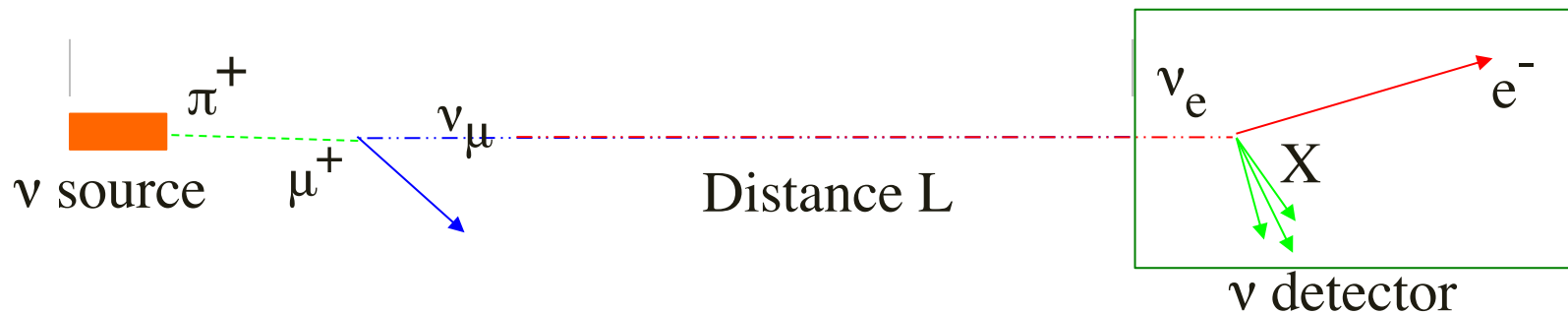


Big Bang  
( $330 \nu/\text{cm}^3$ )



# Neutrino Oscillation

- It has been observed that neutrinos change a flavor when travelling over a distance.

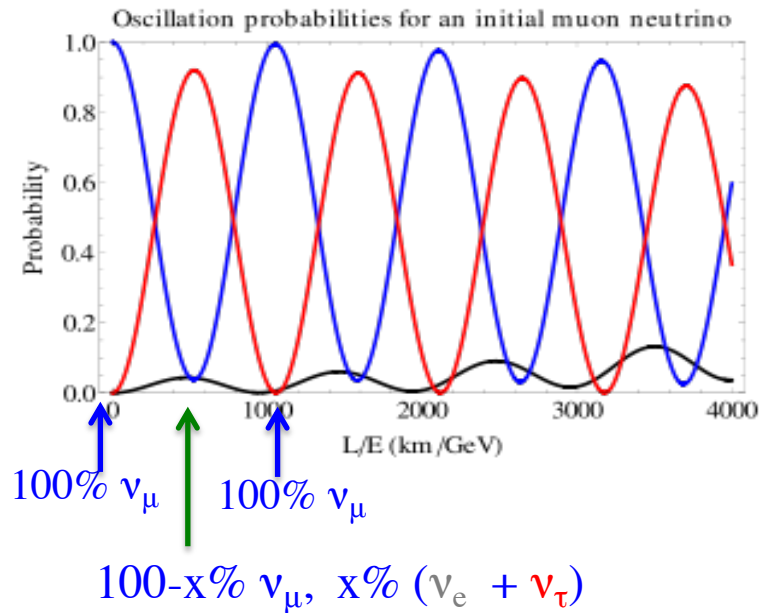


- Explained by neutrino mixing:
  - Neutrinos have (different) masses:  $m_1, m_2, m_3$ .
  - Mass states ( $\nu_1, \nu_2, \nu_3$ ) and flavor states ( $\nu_e, \nu_\mu, \nu_\tau$ ) (objects that participate in weak interaction) are not identical.
  - Such behavior may be explained by quantum mechanics, if the flavor states ( $\nu_e, \nu_\mu, \nu_\tau$ ) are a linear combinations of the mass states ( $\nu_1, \nu_2, \nu_3$ ).

$$|\nu_\alpha\rangle = \sum_{k=1}^n U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

# Neutrino Oscillation

- Spontaneous change of neutrino flavor is what we call a neutrino oscillation.



Example: Assume only two neutrinos  $\nu_1, \nu_2$  mix

$$|\nu_\mu(t)\rangle = -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle$$

$L$  is the distance from point of creation of neutrino beam to detection point

$\Delta m^2$  is the difference of squared mass of the two neutrino states

$$P_{\text{osc}} = \sin^2 2\theta \sin^2 1.27 \Delta m^2 [\text{eV}^2] \left[ \frac{L[\text{km}]}{E[\text{GeV}]} \right]$$

$\theta$  is the mixing angle

$E$  is the energy of the neutrino beam

-We know there are at least three neutrinos out there.

-With three known neutrinos the mixing of flavor and mass eigenstates is written in a form of so-called PMNS (Pontecorvo–Maki–Nakagawa–Sakata) matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



# Neutrino Oscillation

-PMNS (Pontecorvo–Maki–Nakagawa–Sakata) matrix:

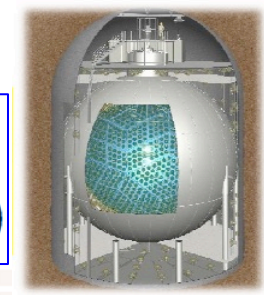
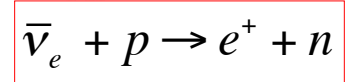
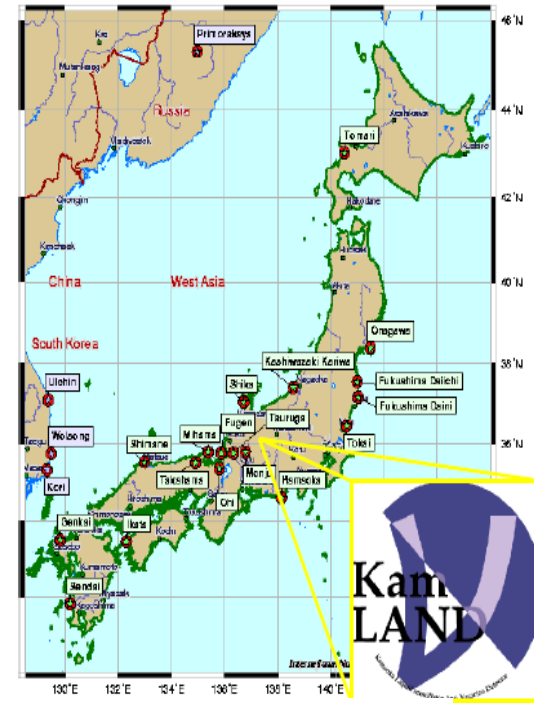
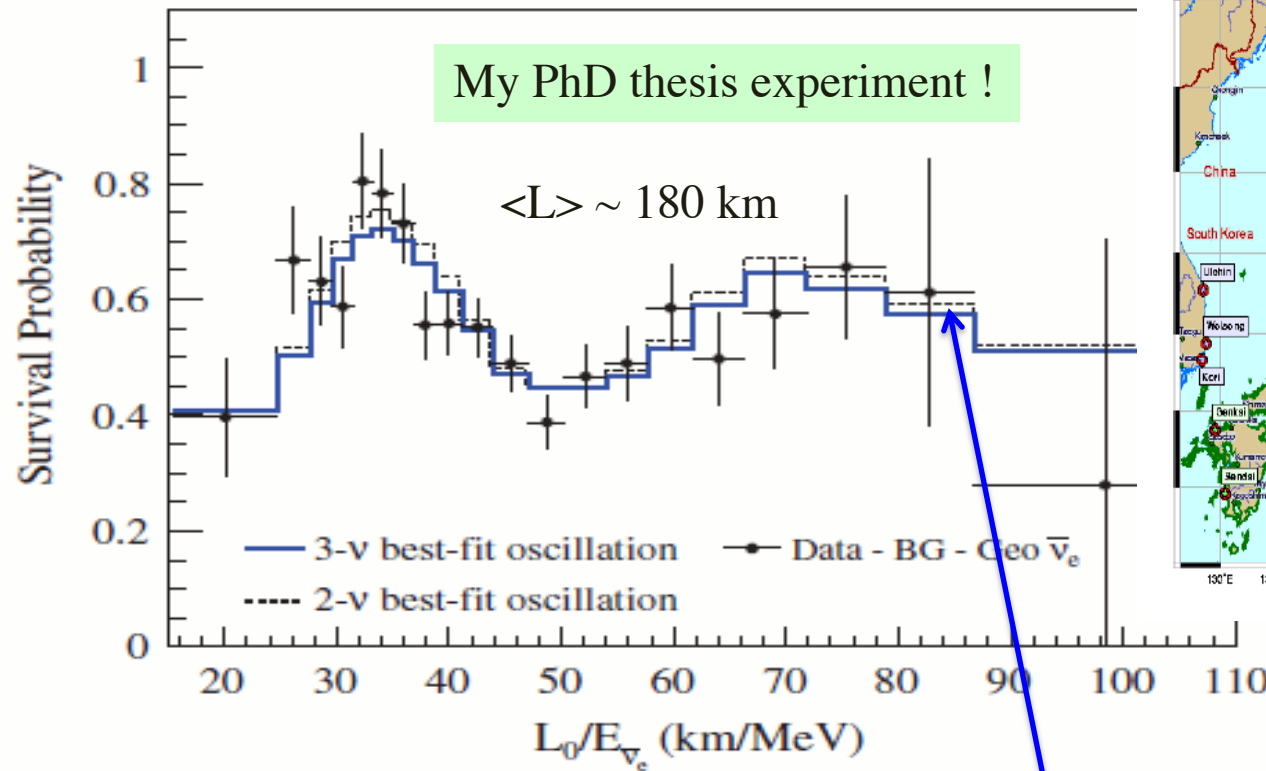
$$\begin{aligned}
 U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \\
 &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}
 \end{aligned}$$

- Mixing angles:  $c_{ij} = \cos \theta_{ij}$ ,  $s_{ij} = \sin \theta_{ij}$ , where  $i, j = 1, 2, 3$ .
- Dirac phase  $\delta_{CP}$  is non-zero only if neutrino oscillation violates CP-symmetry
  - we are putting a significant effort to determine if  $\sin\delta_{CP} \neq 0$ .
- Phases  $\alpha_1$  and  $\alpha_2$  are Majorana phases
  - physical meaning if neutrinos are Majorana particles.
  - additional source of CP-violation
  - if  $0\nu\beta\beta$  occurs, these phases influence its rate.
- If experiments show this  $3\times 3$  matrix to be non-unitary, a sterile neutrino or some other new physics is required.



# Example of Neutrino Experiment

- KamLAND experiment: reactor anti-neutrino disappearance experiment  
 -demonstrated neutrino mixing and provided the most-precise measurement of  $\Delta m_{21}^2$  up-to-date.



My PhD thesis  
 -radio-assay  
 -NAA  
 -oscillation  
 analysis

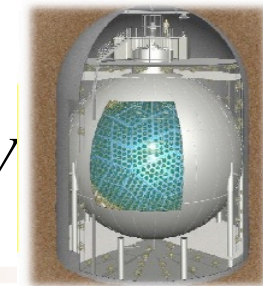
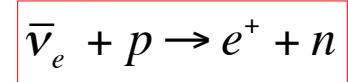
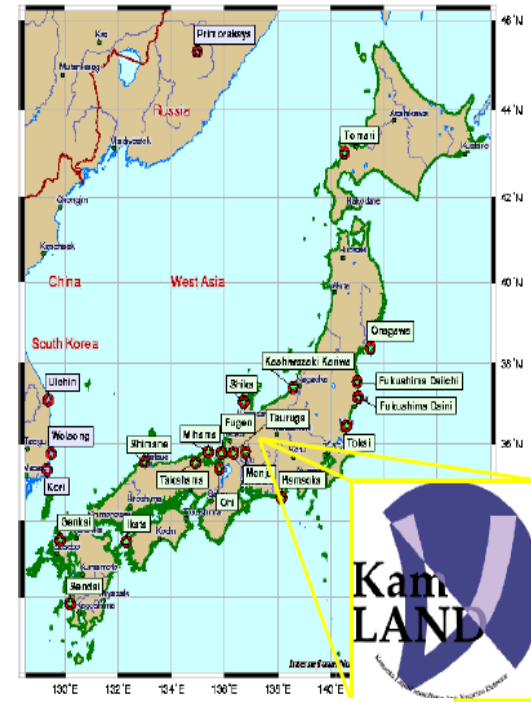
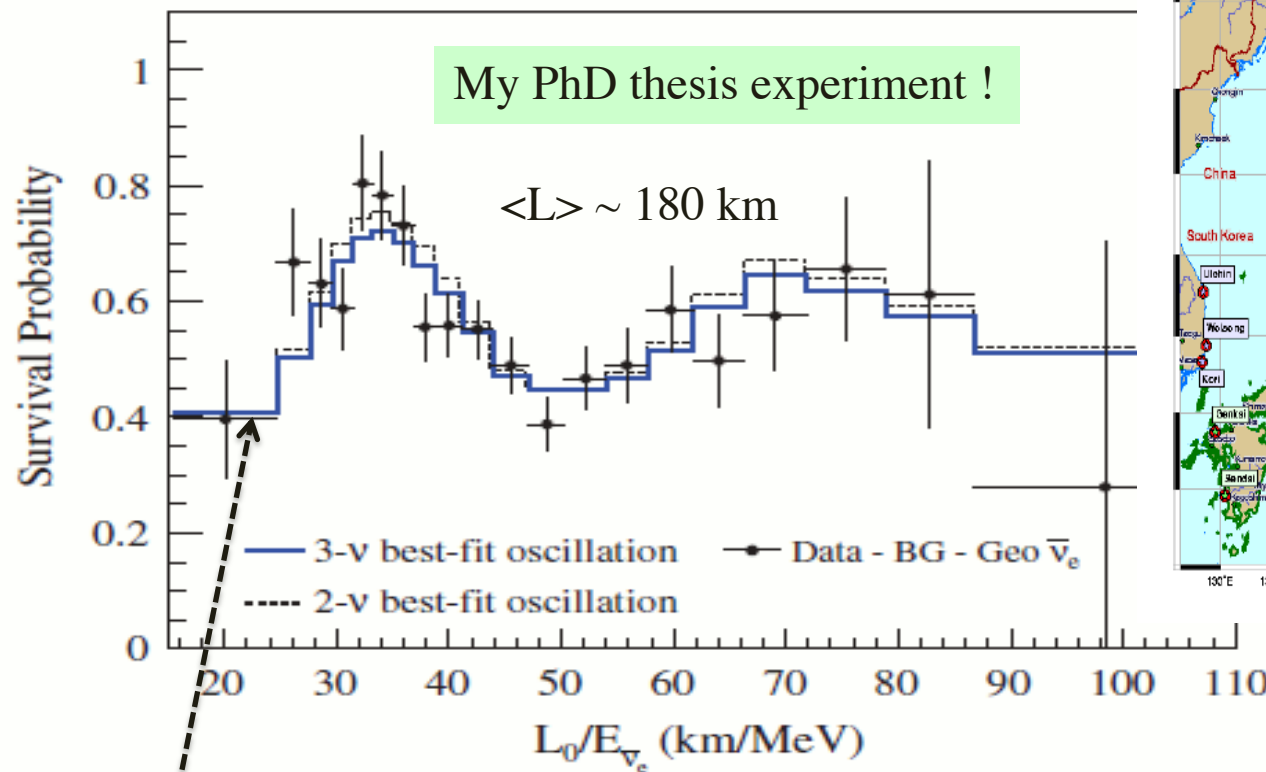
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

(becomes 2-v oscillation if  $\theta_{13} = 0!$ )



# Example of Neutrino Experiment

- KamLAND experiment: reactor anti-neutrino disappearance experiment  
 -demonstrated neutrino mixing and provided the most-precise measurement of  $\Delta m_{21}^2$  up-to-date.



My PhD thesis  
 -radio-assay  
 -NAA  
 -oscillation  
 analysis

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{21}^2 L[m] / E_\nu [MeV])$$

(if  $\theta_{13} = 0$ )



# What We Know

- Neutrinos were assumed to be massless particles until the discovery of the neutrino oscillation process.

- Neutrino Oscillation results

-Mass squared differences:

$$\Delta m_{21}^2 \approx 7.5 \times 10^{-5} \text{eV}^2$$

$$|\Delta m_{32}^2| \approx 2.5 \times 10^{-3} \text{eV}^2$$

-Mixing angles:

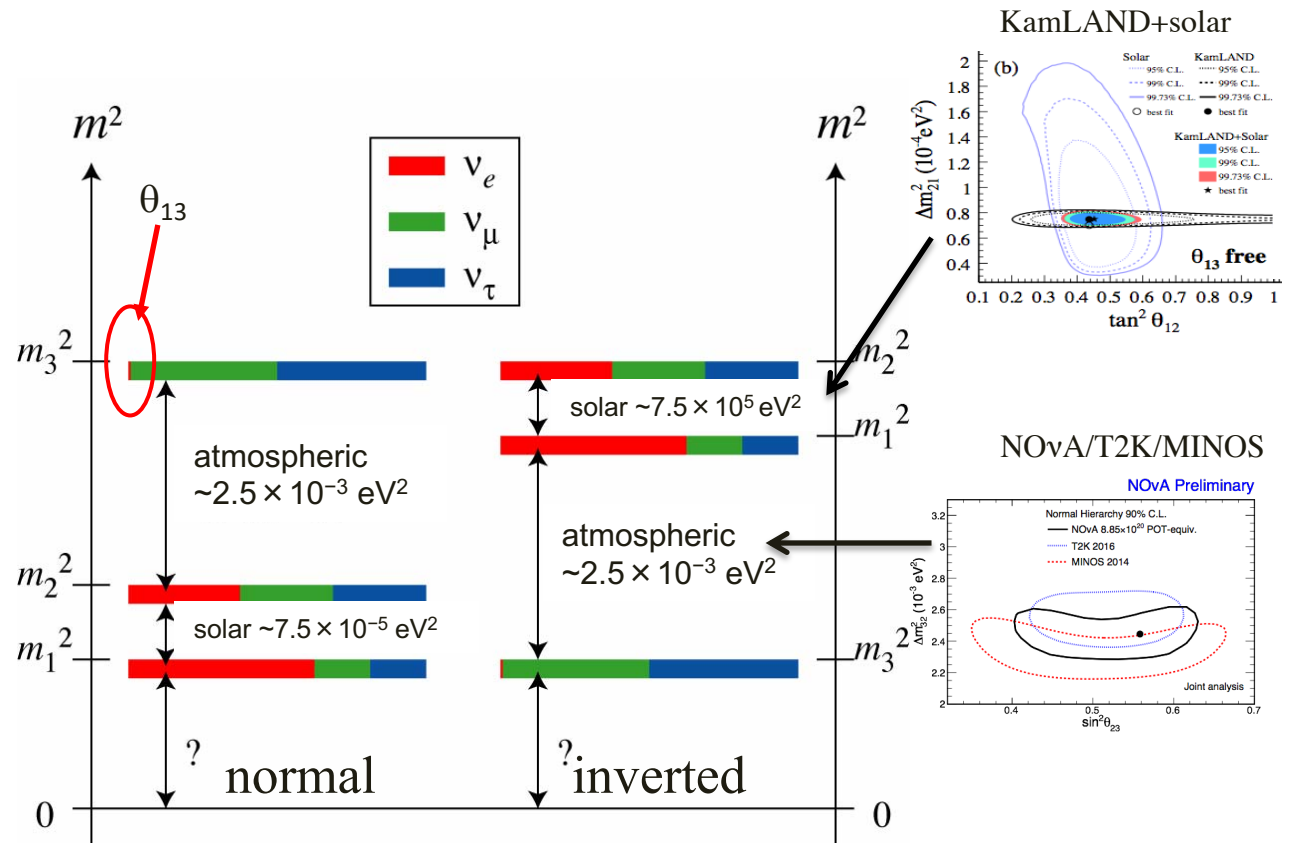
$$\sin^2 \theta_{12} \approx 0.31$$

$$\sin^2 \theta_{23} \approx 0.45 - 0.55$$

$$\sin^2 \theta_{13} \approx 0.02 \text{ (measured recently)}$$

-Absolute mass scale is unknown

=> need determine it in the future

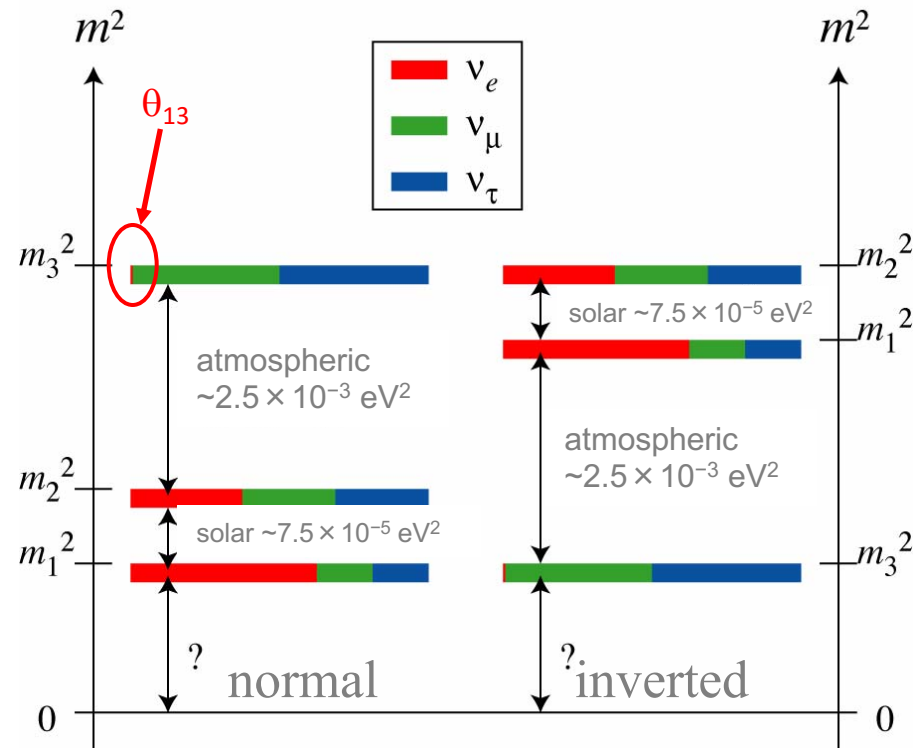


# Neutrino Oscillation Questions

Recently measured what is  $\nu_e$  component in the  $\nu_3$  mass eigenstate, i.e.  $\theta_{13}$ .

Missing information in 3x3 mixing scheme:

1. Is the  $\mu - \tau$  mixing maximal?  
-Only know  $\sin^2\theta_{23} \approx 0.45 - 0.55$
2. What is the mass hierarchy?  
-Normal or inverted?
3. Do neutrinos exhibit CP violation, i.e. is  $\delta_{CP} \neq 0$ ?



$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16s_{12}c_{12}s_{13}^2c_{13}^2s_{23}c_{23}\sin\delta\sin\left(\frac{\Delta m_{12}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{13}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

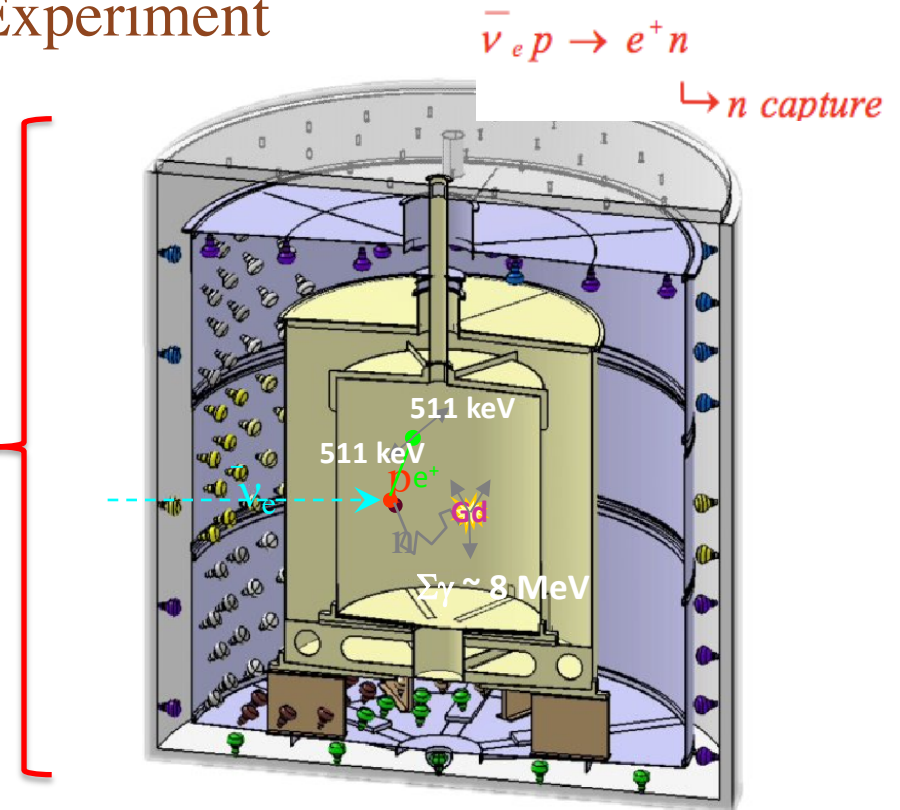
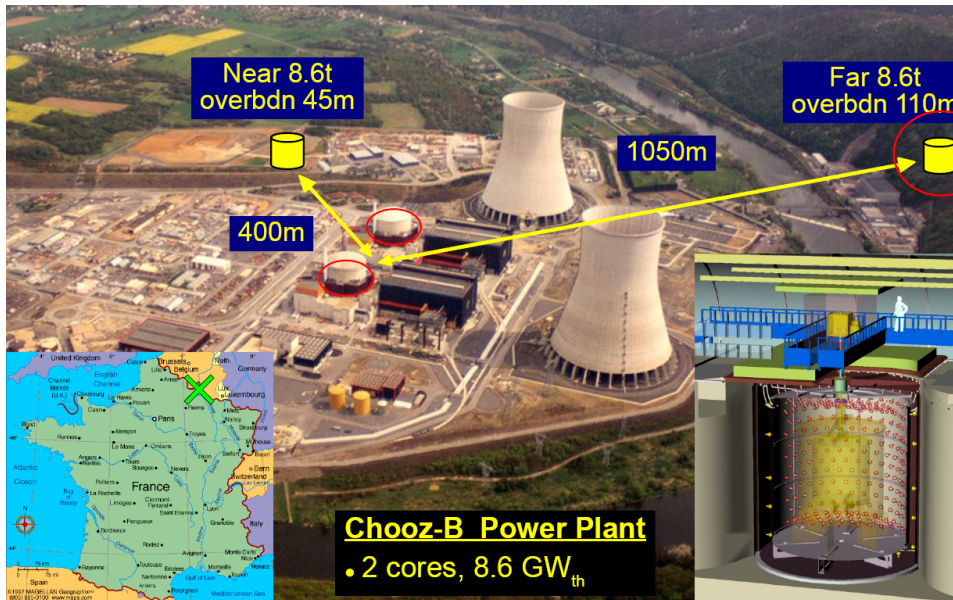
4. Why are quark and neutrino mixing matrices so different?

$$U_{MNSP} \sim \begin{pmatrix} \textit{Big} & \textit{Big} & \textit{Small} \\ \textit{Big} & \textit{Big} & \textit{Big} \\ \textit{Big} & \textit{Big} & \textit{Big} \end{pmatrix} \text{ vs. } V_{CKM} \sim \begin{pmatrix} 1 & \textit{Small} & \textit{Small} \\ \textit{Small} & 1 & \textit{Small} \\ \textit{Small} & \textit{Small} & 1 \end{pmatrix}$$

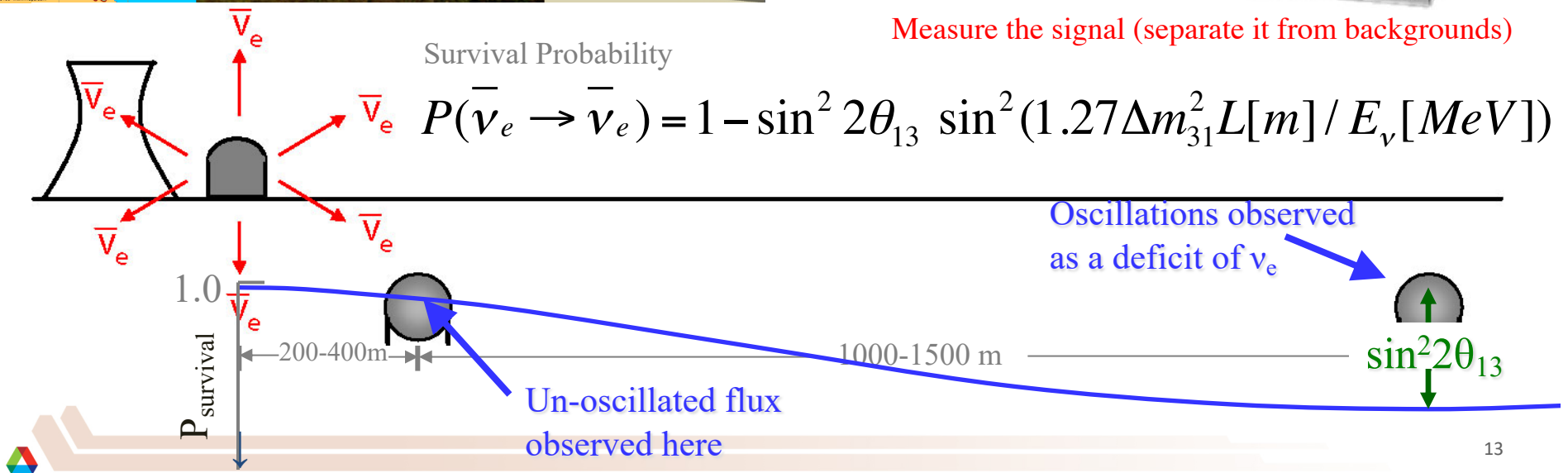


# Measurement of $\theta_{13}$ : Double Chooz Experiment

- Reactor anti-neutrino experiment designed to measure a small value of  $\theta_{13}$

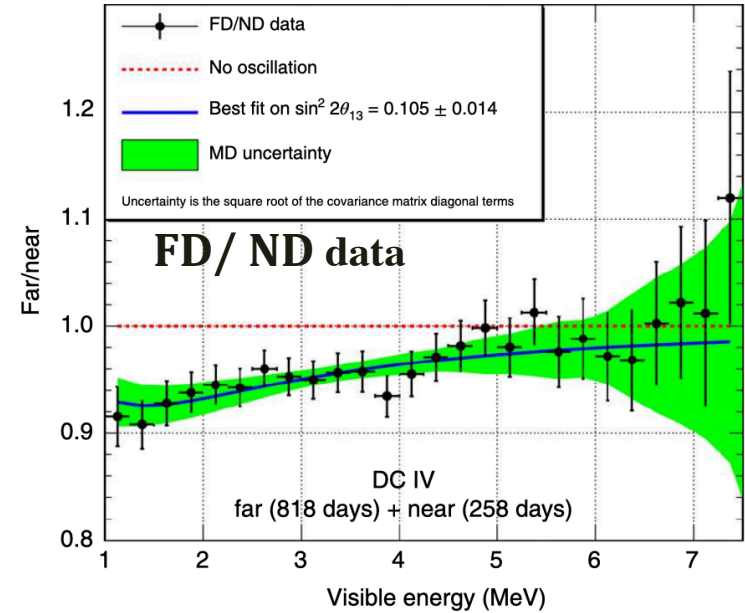
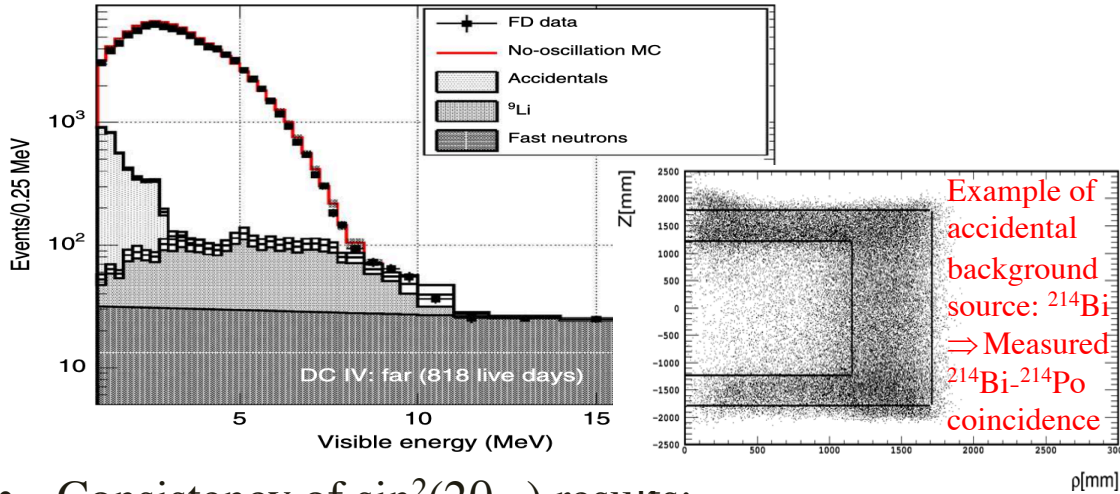


Measure the signal (separate it from backgrounds)

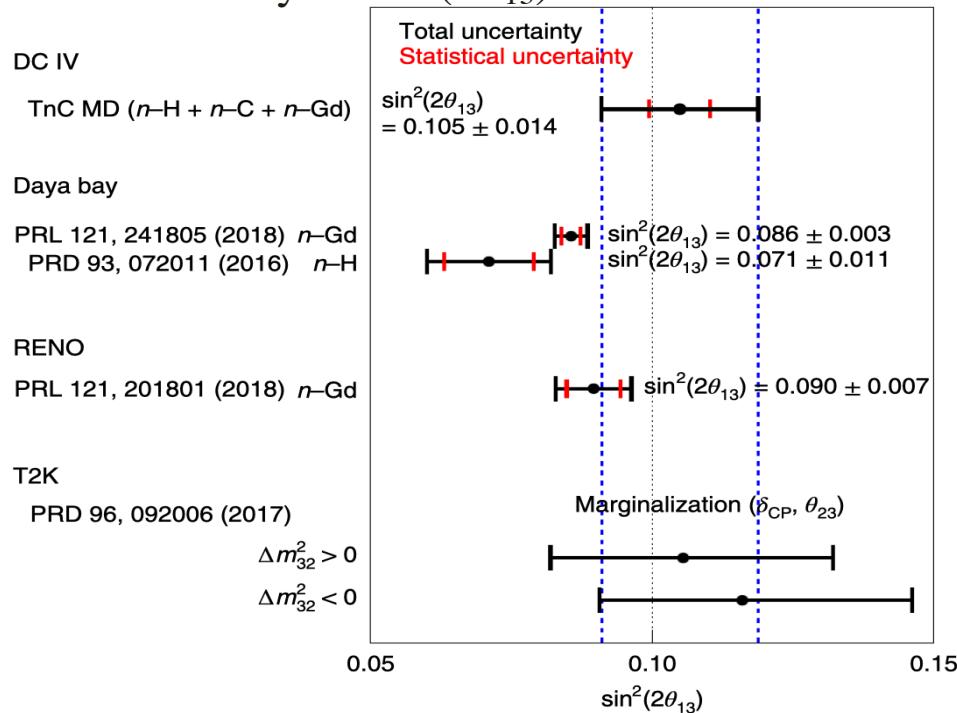


# Double Chooz Experiment (cont.)

- Measured FD  $\nu_e$  energy spectrum



- Consistency of  $\sin^2(2\theta_{13})$  results:



$\sin^2(2\theta_{13}) = 0.105 \pm 0.014$  (stat.+syst.)

(Published in Nature Physics 2020,  
<https://doi.org/10.1038/s41567-020-0831-y>)

Double Chooz notes:

- first non-zero value of  $\theta_{13}$  from reactor neutrino experiments in October 2011.
- PhD thesis by Guang Yang (ANL/IIT 2016):  
**“Measurement of  $\theta_{13}$  in the Double Chooz Experiment”**, PhD thesis advisor: Z. Djurcic
- More precise measurements from Daya Bay (China) and RENO (Korea).

# Neutrino Oscillations at Long-Baseline

- $\nu_\mu$  Disappearance Probability

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i}$$

$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i}$$

- $\nu_e$  Appearance Probability

See for example: Nunokawa, Parke, Valle, "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$+ \cos \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos \Delta_{32} \left( \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \right) \left( \frac{\sin(aL)}{aL} \Delta_{21} \right)$$

$$- \sin \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin \Delta_{32} \left( \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \right) \left( \frac{\sin(aL)}{aL} \Delta_{21} \right)$$

$$+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2,$$

$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\nu$$

CP-violation parameter  $\delta_{CP}$   
 Mass hierarchy (sign of  $\Delta m_{31}^2$ )  
 } Need measure this!

Size of  $\sin^2 \theta_{23}$  Use the results of accelerator muon neutrino oscillation measurement

Mixing angle  $\theta_{13}$  Take the value from reactor electron anti-neutrino oscillation experiments

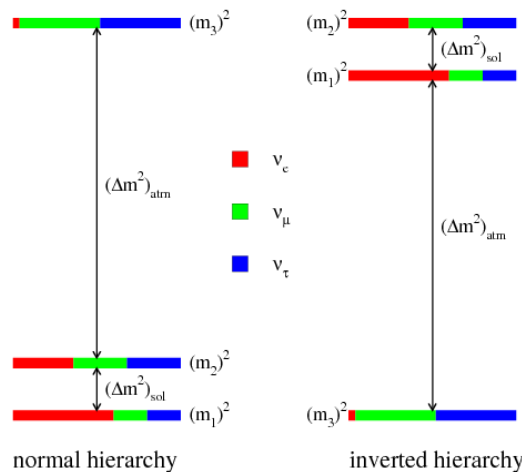
$$a = G_F N_e / \sqrt{2} \cong \frac{1}{3500 km}$$

aL = 0.08 for L = 295 km (T2K)  
 aL = 0.23 for L = 810 km (NOvA)  
 aL = 0.37 for L = 1300 km (DUNE)



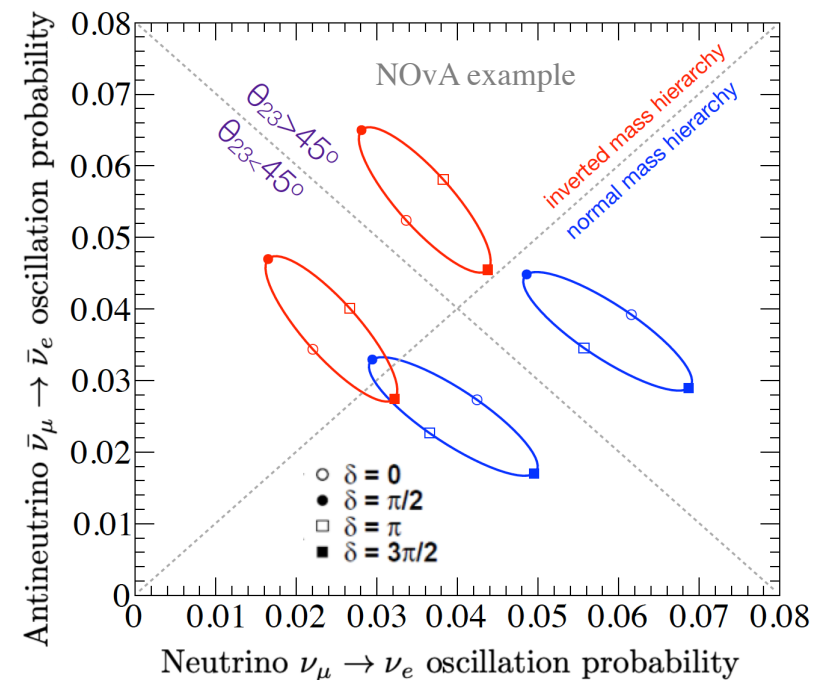
# Neutrino Oscillations at Long-Baseline

- Measure the oscillation probabilities of
  - a) appearance channels:  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - b) disappearance channels:  $\nu_\mu \rightarrow \nu_\mu$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
- Precision measurements of  $\theta_{13}, \Delta m^2_{32}, \theta_{23}$
- Determine the neutrino mass hierarchy
- Measure the CP violation parameter  $\delta$



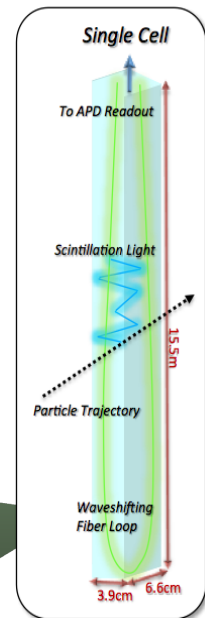
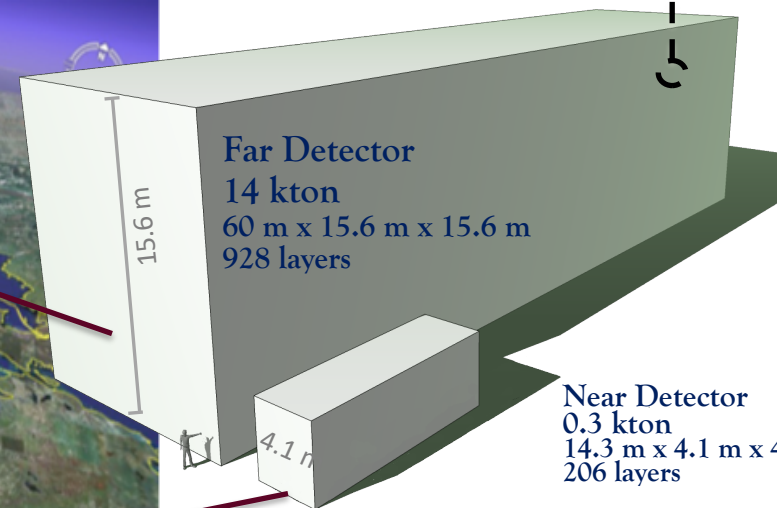
- Additional Physics Goals:
    - Neutrino cross-sections and interaction physics
    - Sterile Neutrinos
    - Supernovae, nucleon decay and additional physics
- searches enabled by capable neutrino detectors

$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$  ?



# NOvA Experiment

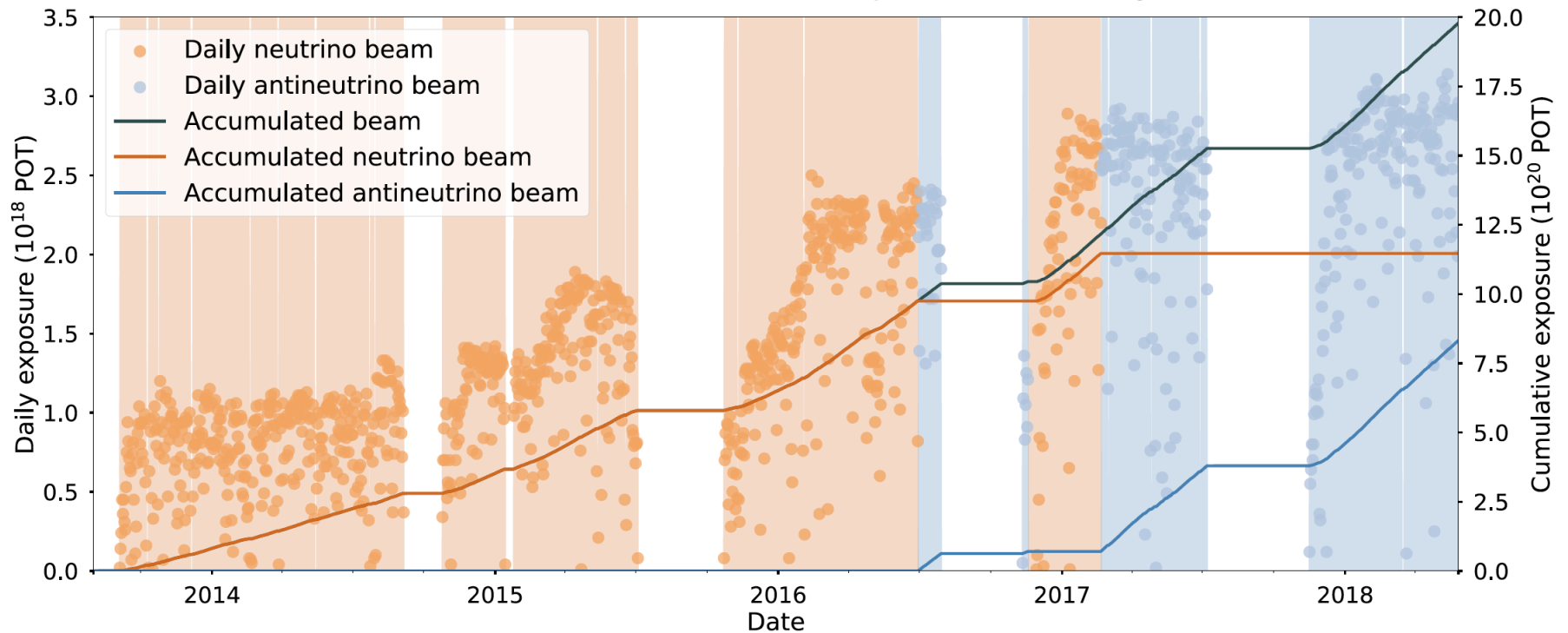
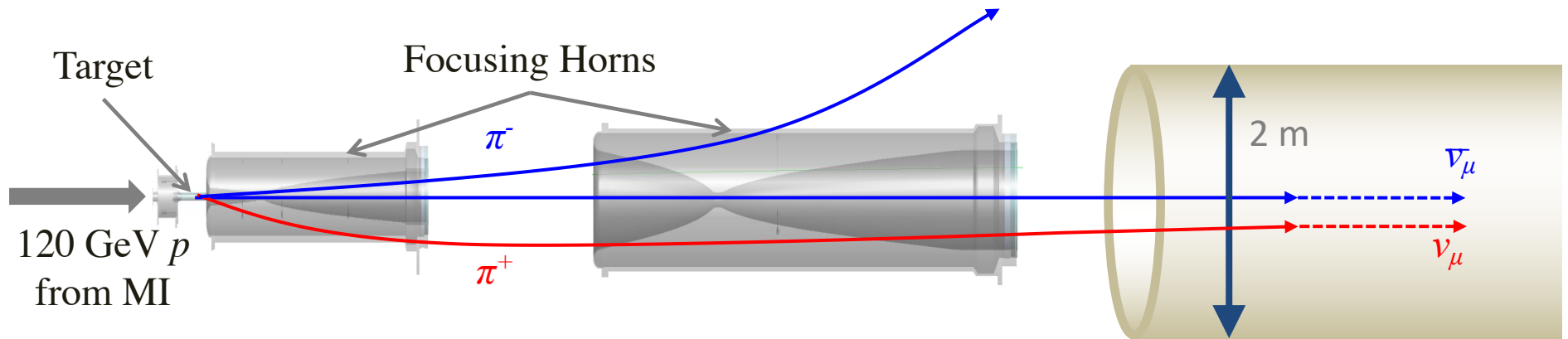
- The long-baseline off-axis neutrino oscillation experiment with functionally identical Near and Far Detectors
- Data taking with complete detectors started in November 2014
- Low-Z tracking calorimeters; detectors are 14 mrad off-axis.



- High power NuMI beam
  - upgraded for NOvA to take the power 350 – 750 kW
  - this result:  $8.85 \times 10^{20}$  POT neutrino mode,  $12.33 \times 10^{20}$  POT antineutrino mode, 732 kW peak intensity.



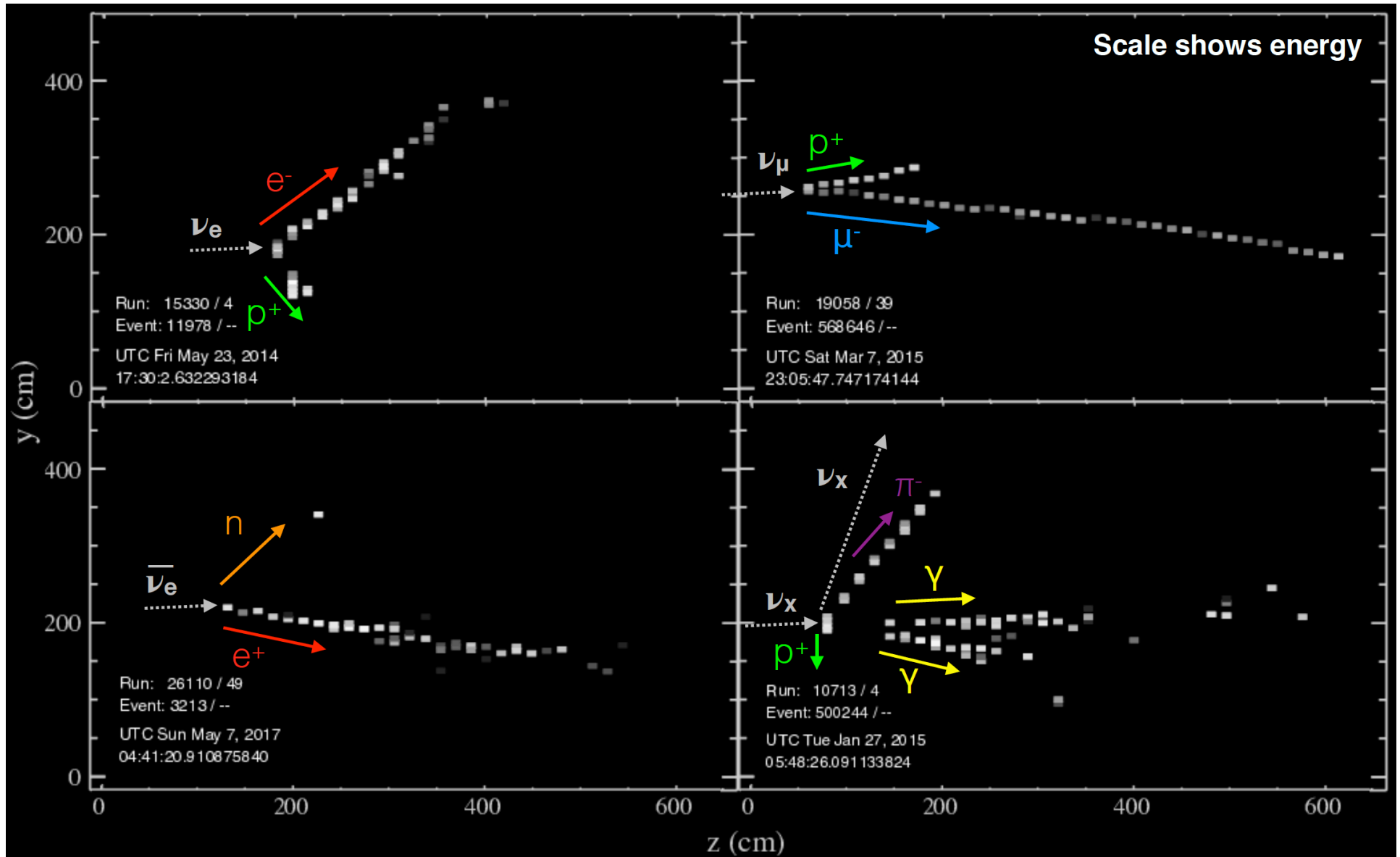
# NOvA Off-axis Neutrino Beam



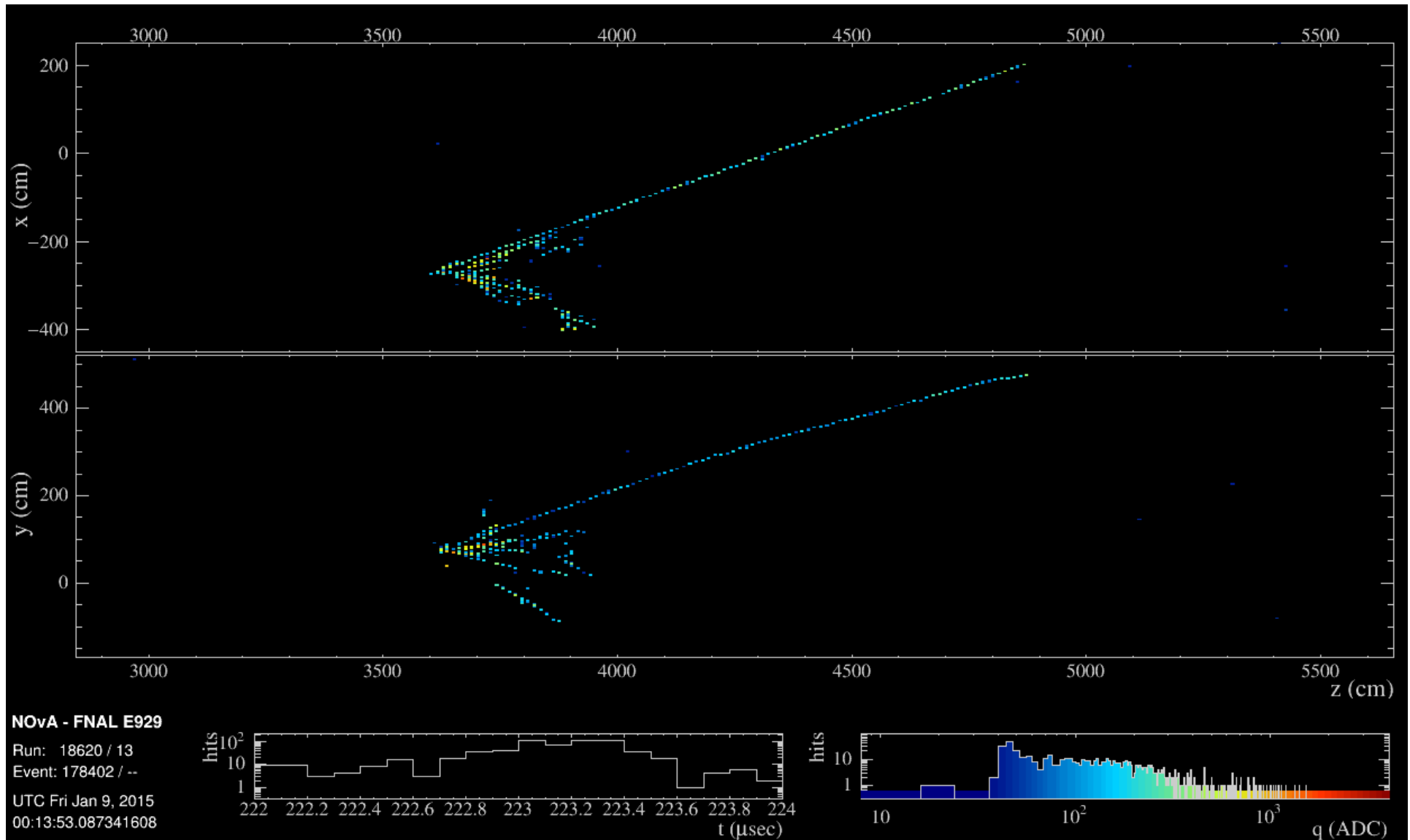
- $8.9 \times 10^{20}$  protons-on-target (POT) in neutrino beam configuration.
- $6.9 \times 10^{20}$  POT of antineutrino beam, June 2016 to February 2019.



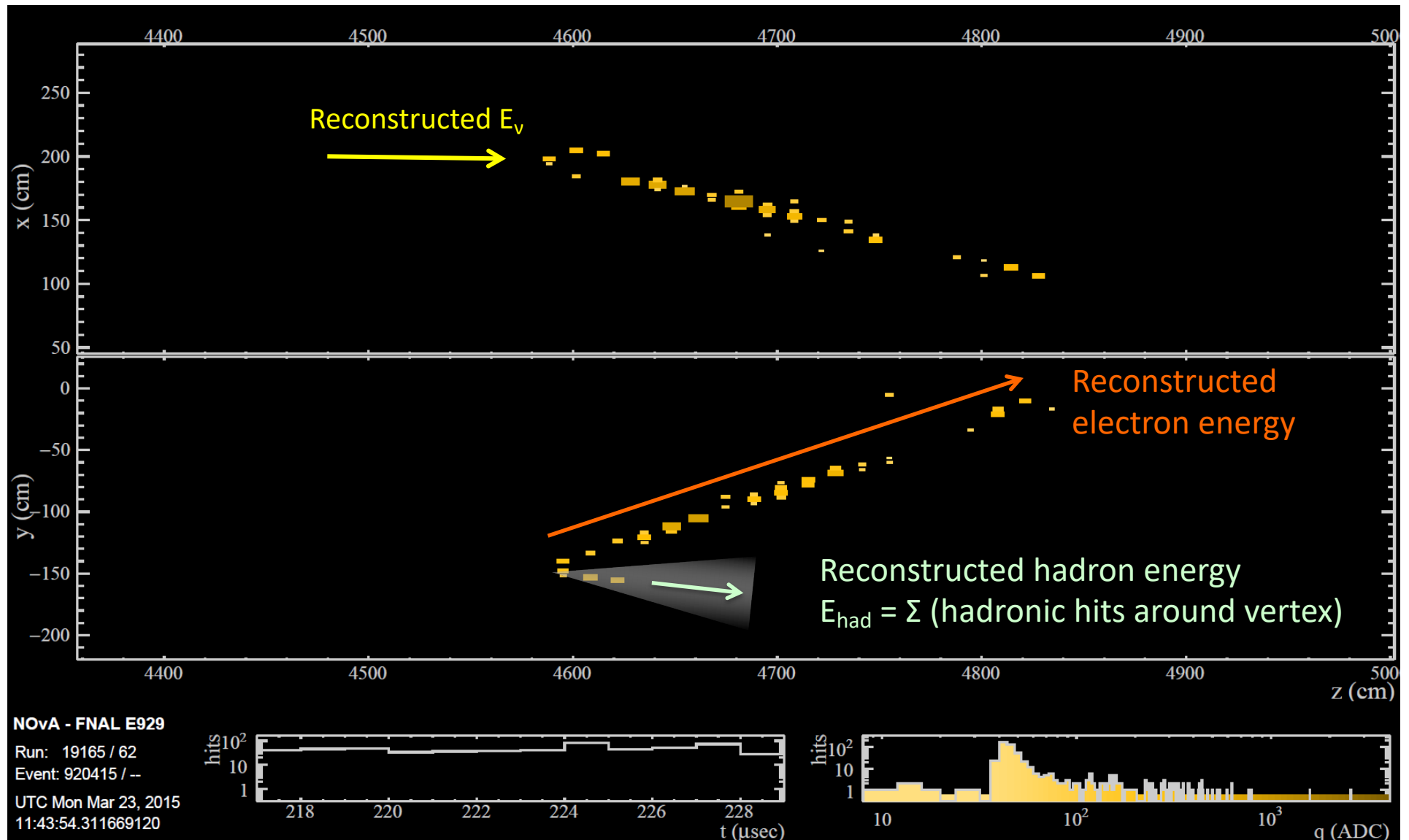
# NOvA Event Topologies



# Neutrino Interaction in the NOvA Far Detector

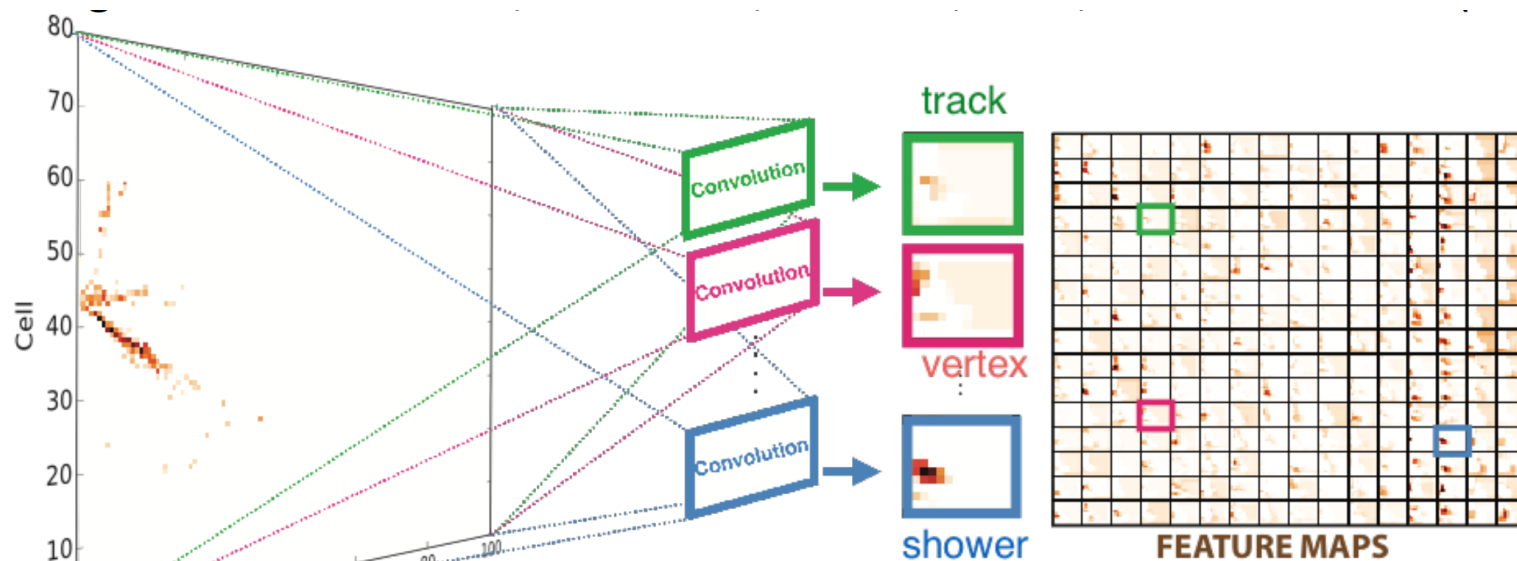


# NOvA Far Detector $\nu_e$ CC Candidate

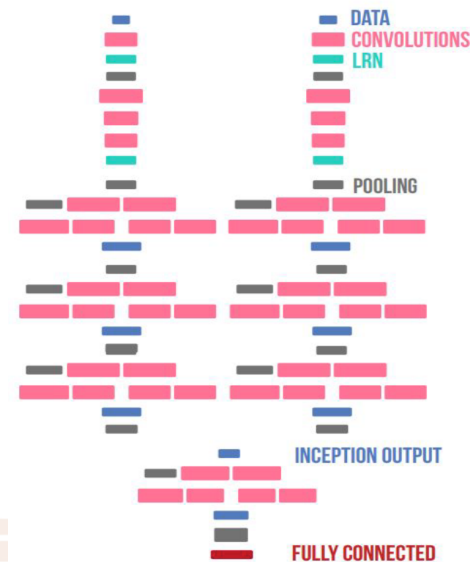


# Deep-learning particle classification

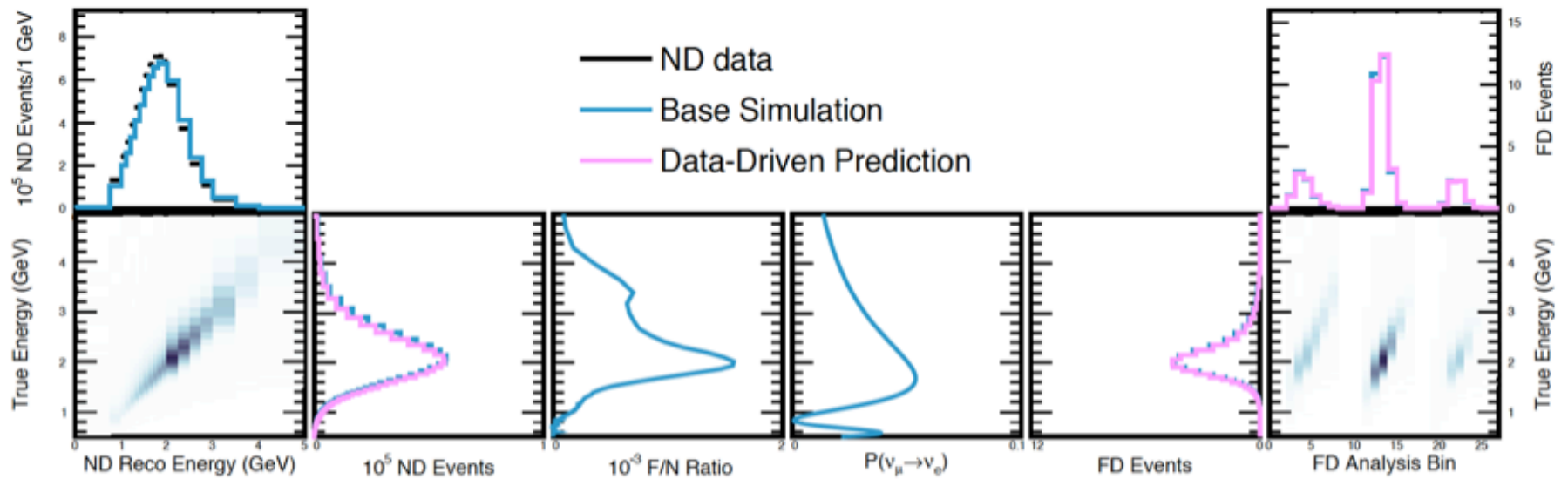
- Event classification with a convolutional visual network (CVN) initially based on GoogLeNet



- CVN employs a Deep Convolutional Network in the "image recognition" style.
- The network is trained on two dimensional views of the event's calibrated hits.
- Information of each view is combined in the final layers of the network.
- We also train the network separately on a neutrino and antineutrino beam samples.



# NOvA Oscillation Search with Near and Far Detectors



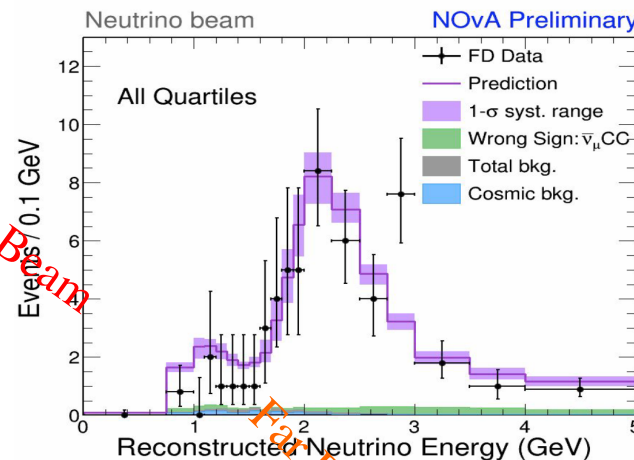
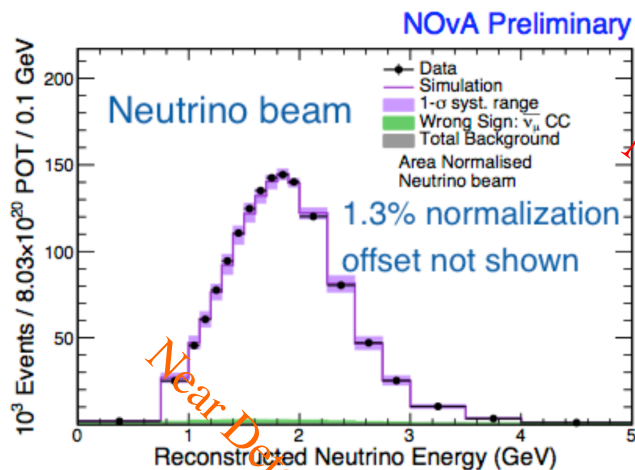
- Sample un-oscillated neutrino beam at Near Detector
  - compare observed and simulated near detector interaction spectrum
  - with data-driven methods tweak simulated Near Detector spectrum
- Propagate Near Detector spectrum to predict oscillated spectrum at Far Detector
  - compare oscillated spectrum to far Detector Data
  - extract oscillation parameters
- Technique allows us to reduce key systematic uncertainties:
  - neutrino flux
  - neutrino interaction cross-section models

PhD thesis by Shiqi Yu (ANL/IIT 2020)

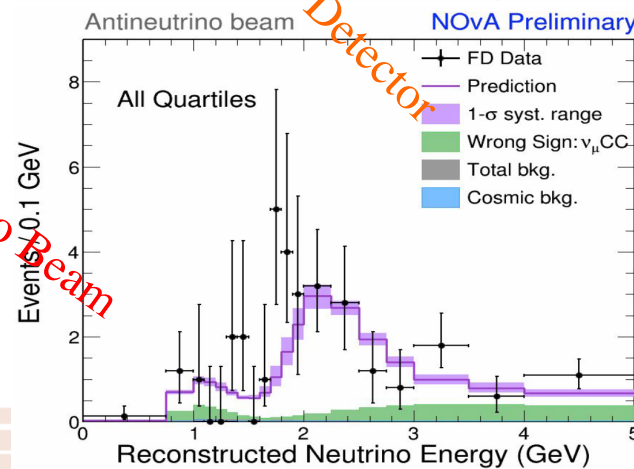
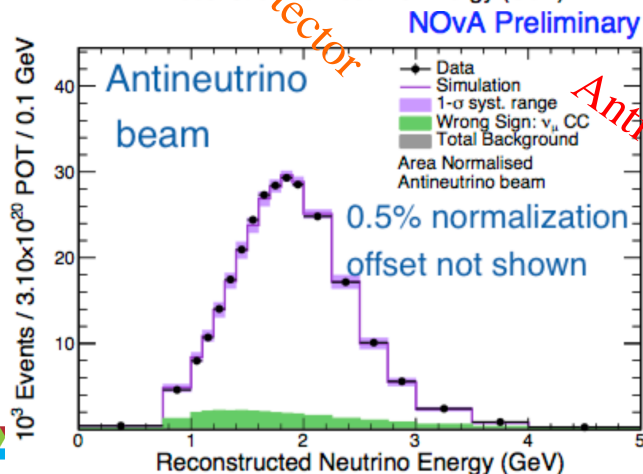


# NOvA $\nu_\mu$ and $\bar{\nu}_\mu$ Disappearance

- Identify contained  $\nu_\mu$  CC events in both Near and Far Detectors
  - Basic quality and selection cuts
  - CVN particle ID cut
  - Boosted decision tree (BDT) for cosmic rejection
  - Split into four samples by hadronic energy fraction
- Measure Energy  $E_\nu = E_\mu + E_{\text{had}}$
- Extract oscillation information from differences between the Far and Near energy spectra



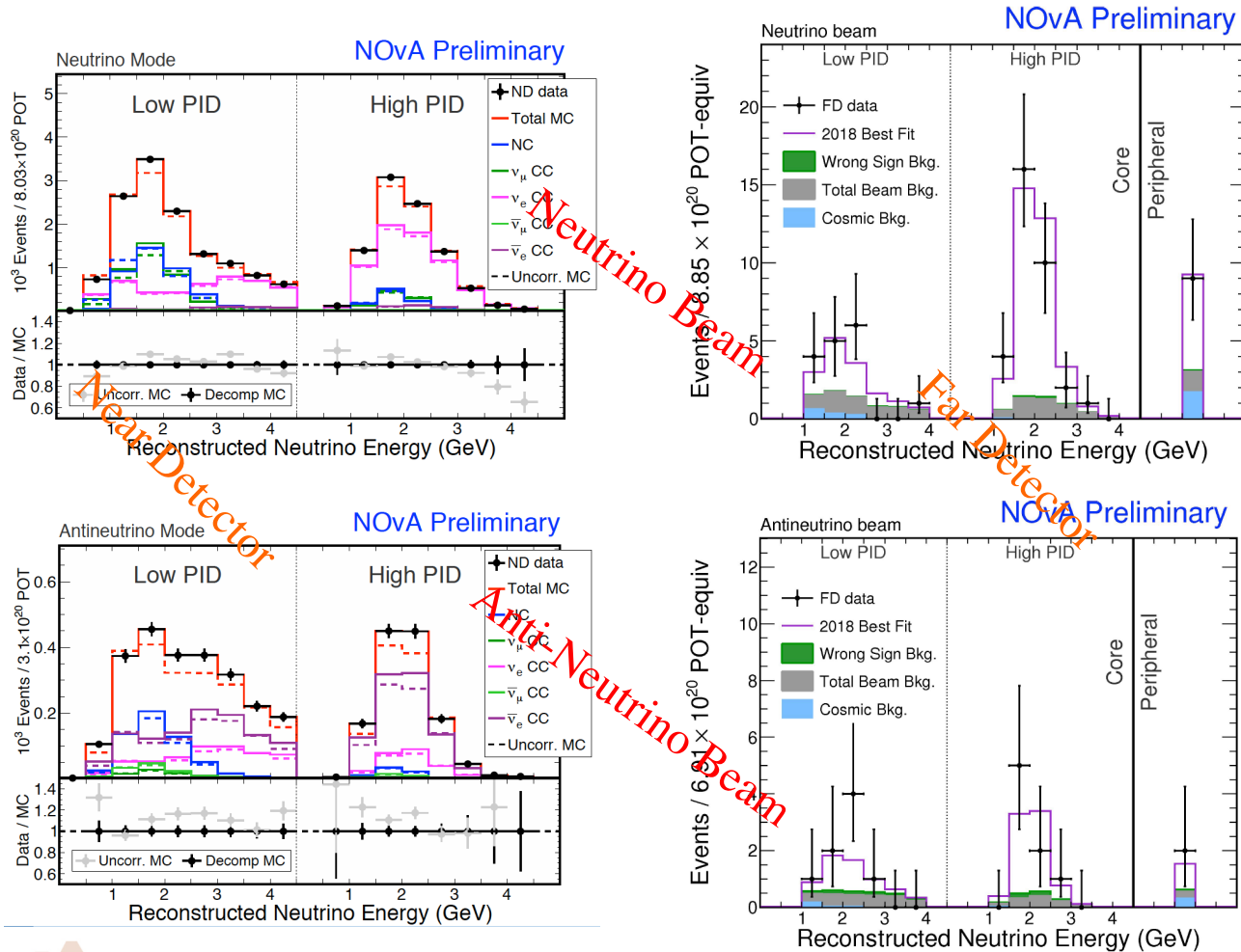
- Neutrino Beam
  - Expected  $730^{+38}_{-49}$  events without oscillations
  - Observed 130  $\nu_\mu$  candidate events



- Anti-neutrino Beam
  - Expected  $266^{+12}_{-14}$  events without oscillations
  - Observed 65  $\bar{\nu}_\mu$  candidate events

# NOvA $\nu_e$ and $\bar{\nu}_e$ Appearance

- Apply Basic selection and quality cuts.
- CVN particle ID cut, split into two samples.
- Peripheral sample selects events that fail basic selection but are pure electron-like events
- Near detector data used to constrain backgrounds and form prediction for Far Detector



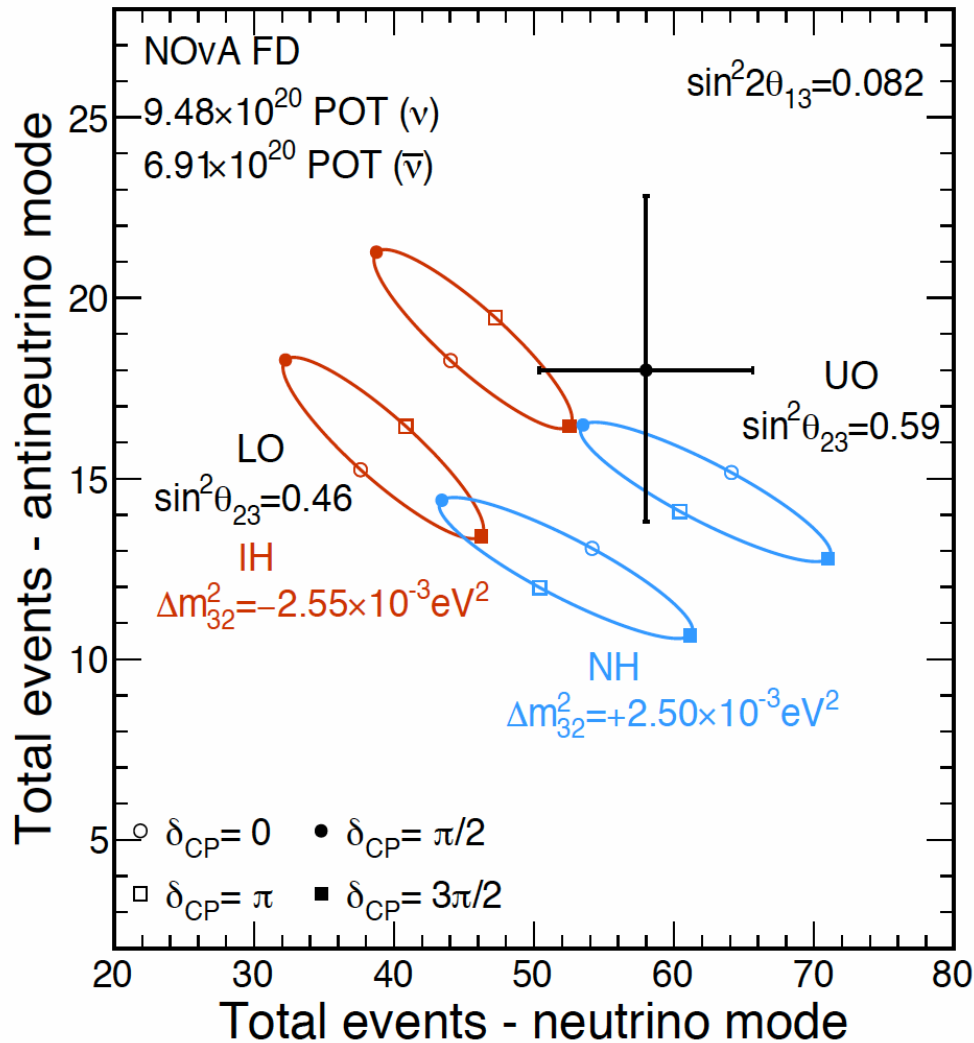
<b>Total Observed</b>	<b>58</b>
Total Prediction	59.0
Wrong-sign	0.7
Beam Bkgd.	11.1
Cosmic Bkgd.	3.3
<b>Total Bkgd.</b>	<b>15.1</b>

<b>Total Observed</b>	<b>18</b>
Total Prediction	15.9
Wrong-sign	1.1
Beam Bkgd.	3.5
Cosmic Bkgd.	0.7
<b>Total Bkgd.</b>	<b>5.3</b>



> 4 $\sigma$  evidence of electron anti-neutrino appearance

# NOvA $\nu_e$ and $\bar{\nu}_e$ Appearance



- Slight preference for the upper octant and normal hierarchy with observed neutrino and antineutrino events
- More sophisticated joint fit allows us to probe oscillation parameters

# NOvA joint fit results

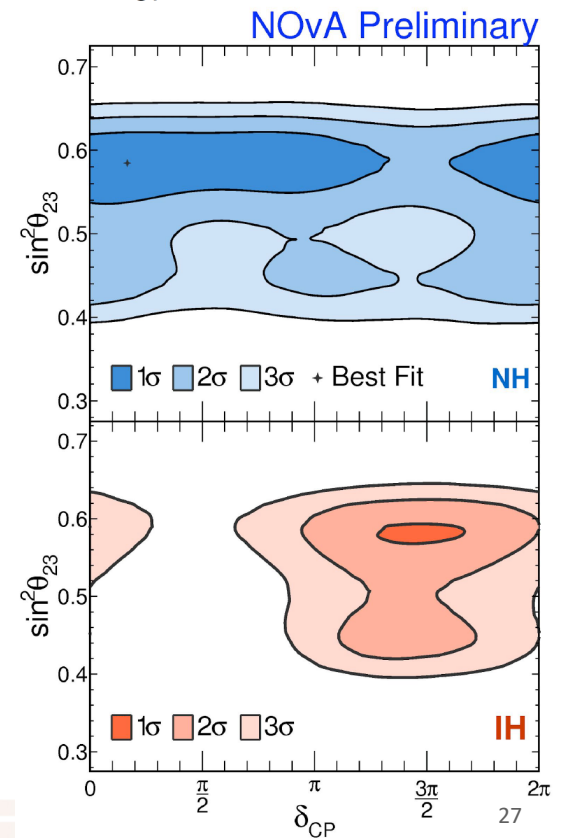
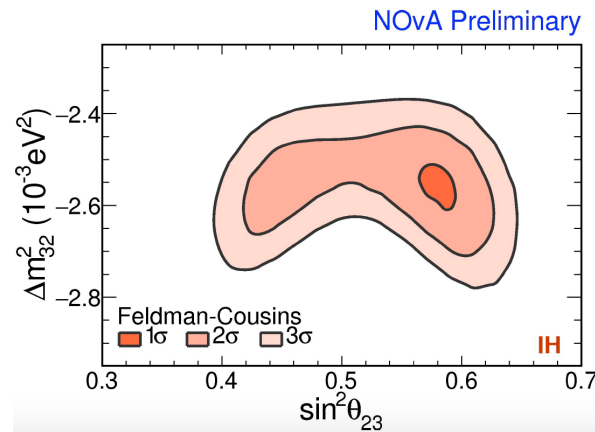
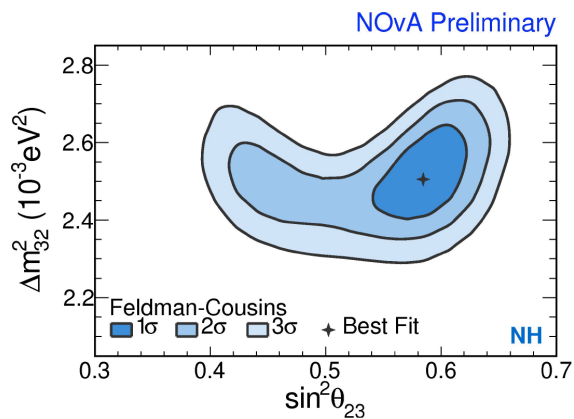
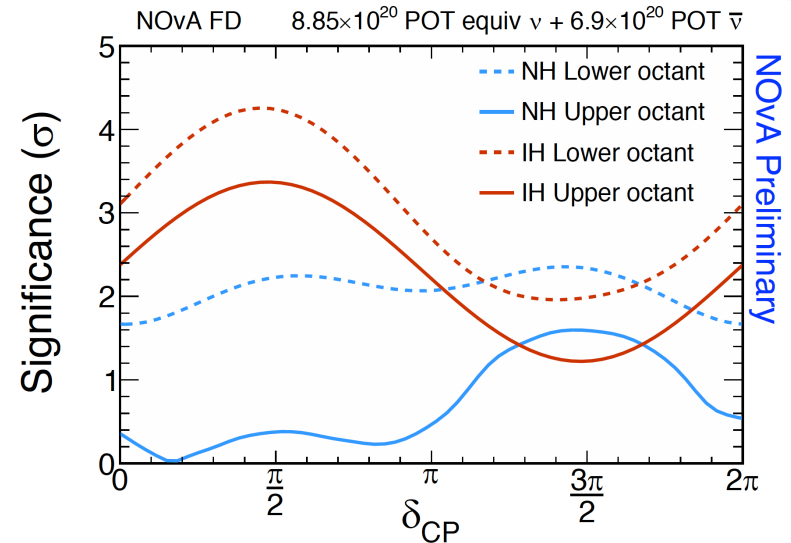
- Slight preference for NH, upper octant  $\theta_{23}$
- Prefer non-maximal  $\theta_{23}$  at  $1.8\sigma$
- Favor  $\theta_{23}$  upper octant at a similar level
- For IH, exclude  $\delta = \pi/2$  at  $> 3\sigma$

➤ Best fit values:

$$\delta_{CP} = 0.17\pi$$

$$\sin^2 \theta_{23} = 0.58 \pm 0.03$$

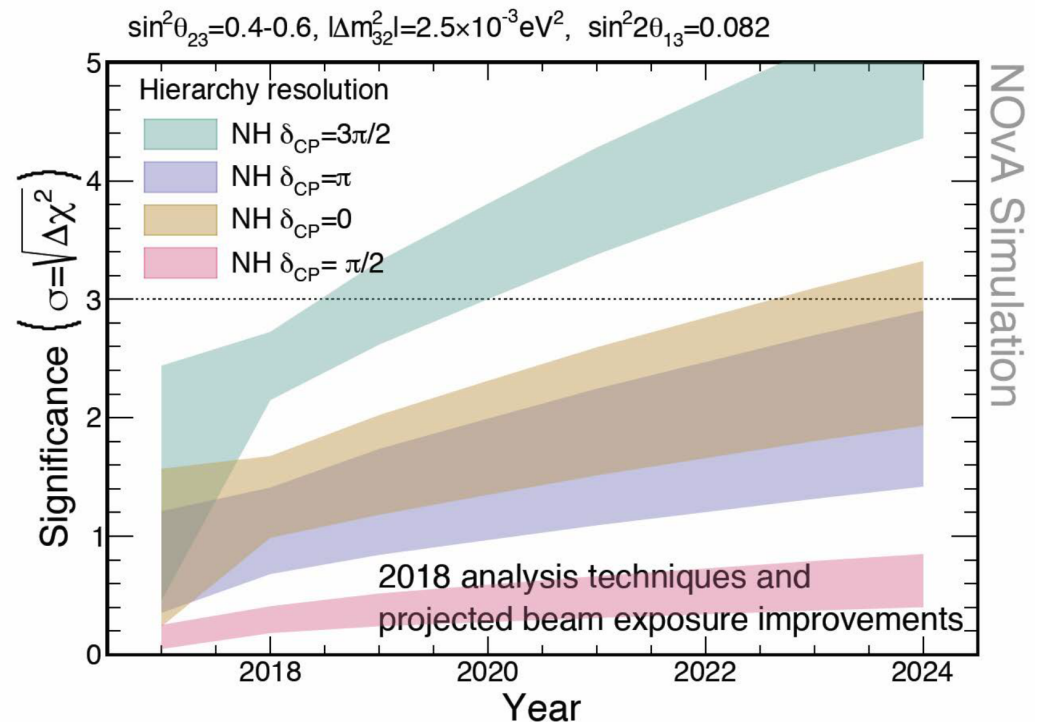
$$\Delta m^2 = 2.51_{-0.08}^{+0.12} \times 10^{-3} \text{ eV}^2$$



# NOvA Summary

- NOvA Presented first analysis with joint-fit of neutrino and anti-neutrino beam
- Observed  $> 4\sigma$  evidence of electron anti-neutrino appearance
- There is a slight preference for NH at  $1.8\sigma$  and exclude IH at  $> 3\sigma$  around  $\delta_{CP} = \pi/2$
- Rejected maximal mixing at  $1.8\sigma$  and the lower octant at a similar level

- Future NOvA sensitivities
  - NOvA run plan is to continue in anti-neutrino mode until spring 2019, then run 50% neutrino mode, 50% anti-neutrino mode to 2024
  - Run through 2024 with incremental upgrades to beam intensity to 1 MW



- With those NOvA will have up to  $5\sigma$  sensitivity to the mass hierarchy and up to  $2\sigma$  sensitivity to CP violation (if current best-fit)
  - important to compare NOvA with T2K (points to  $\delta_{CP} \sim 1.5\pi$  region)



# Deep Underground Neutrino Experiment (DUNE)



## Major features of the DUNE experiment are:

- *A high-intensity wide-band neutrino beam originating at FNAL*
  - 1.2 MW proton beam upgradable to 2.4 MW
- *A highly capable near detector to measure the neutrino flux / interactions*
- *A 40 kt fiducial mass liquid argon far detector*
  - Located 1300 km baseline at SURF's 1.5 km underground level (2300 mwe)
  - Staged construction of four ~10 kt detector modules. First module to be installed starting in 2024.

# Deep Underground Neutrino Experiment (DUNE)



## Major features of the DUNE experiment are:

- A high-intensity wide-band neutrino beam originating at Fermilab
  - 1.2 MW proton beam upgradable to 2.4 MW
- A highly capable near detector to measure the neutrino flux / interactions
- A 40 kt fiducial mass liquid argon far detector
  - Located 1300 km baseline at SURF's 1.5 km underground level (2300 mwe)
  - Staged construction of four ~10 kt detector modules. First module to be installed starting in 2024.

# DUNE Science Goals

- Primary focus of the DUNE science program is on fundamental open questions in particle physics and astro-particle physics:

## 1) Neutrino Oscillation Physics

- CPV in the leptonic sector

“Our best bet for explaining why there is matter in the universe”

- Mass Hierarchy

- Precision Oscillation Physics & testing the 3-flavor paradigm

## 2) Nucleon Decay

- Predicted in beyond the Standard Model theories [but not yet seen]

e.g. the SUSY-favored mode,  $p \rightarrow K^+ \bar{\nu}$

## 3) Supernova burst physics & astrophysics

- Galactic core collapse supernova, sensitivity to  $\nu_e$

Time information on neutron star or even black-hole formation

Any would be a major discovery

- Extended DUNE Science Program

- Other LBL oscillation physics with BSM sensitivity

- Oscillation physics with atmospheric neutrinos

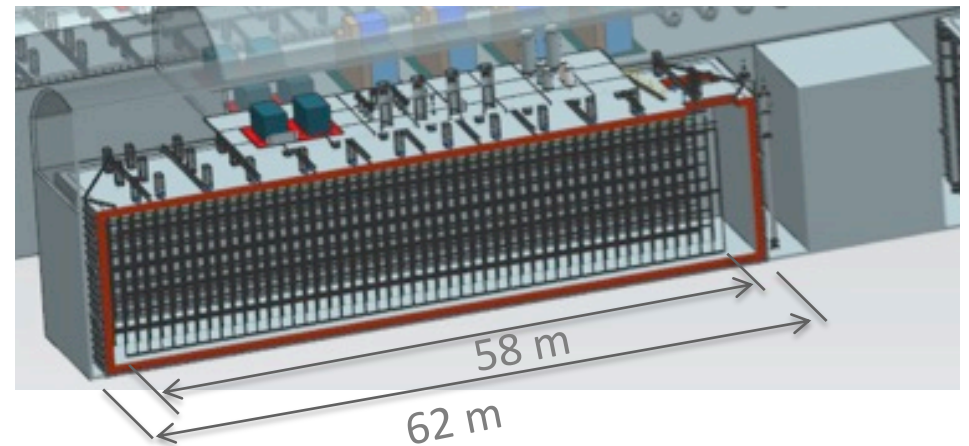
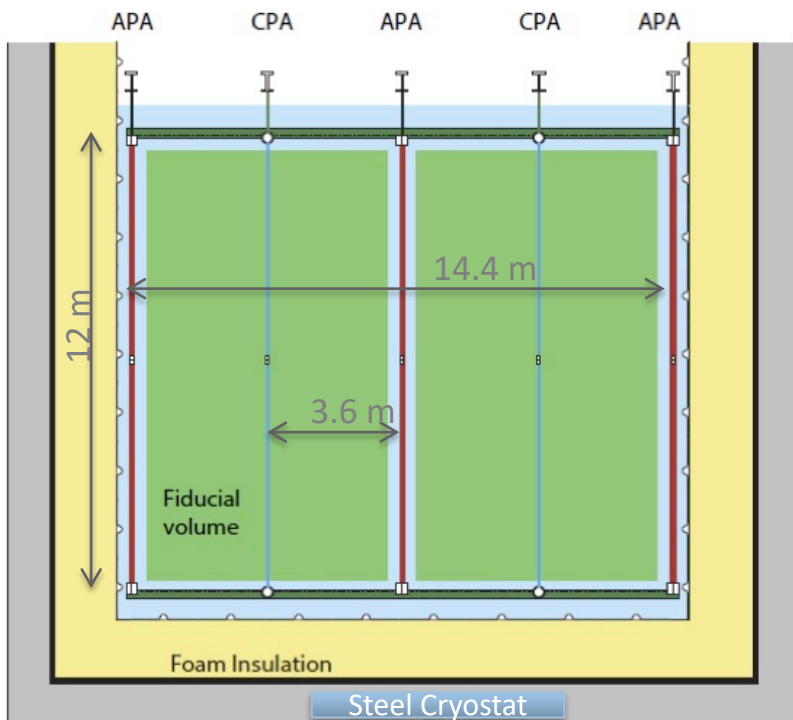
- Neutrino Physics in Near Detector

- Search for signatures of Dark Matter and other Rare Searches



# DUNE Far Detector

- Four 10-kt (fiducial) liquid argon TPC modules
  - *Liquid Argon Time projection chamber with both charge and optical readout*
- Single and dual-phase detector designs (1<sup>st</sup> module will be single phase)
- Integrated photon detection (need wavelength shifting to visible)
- Modules will not be identical

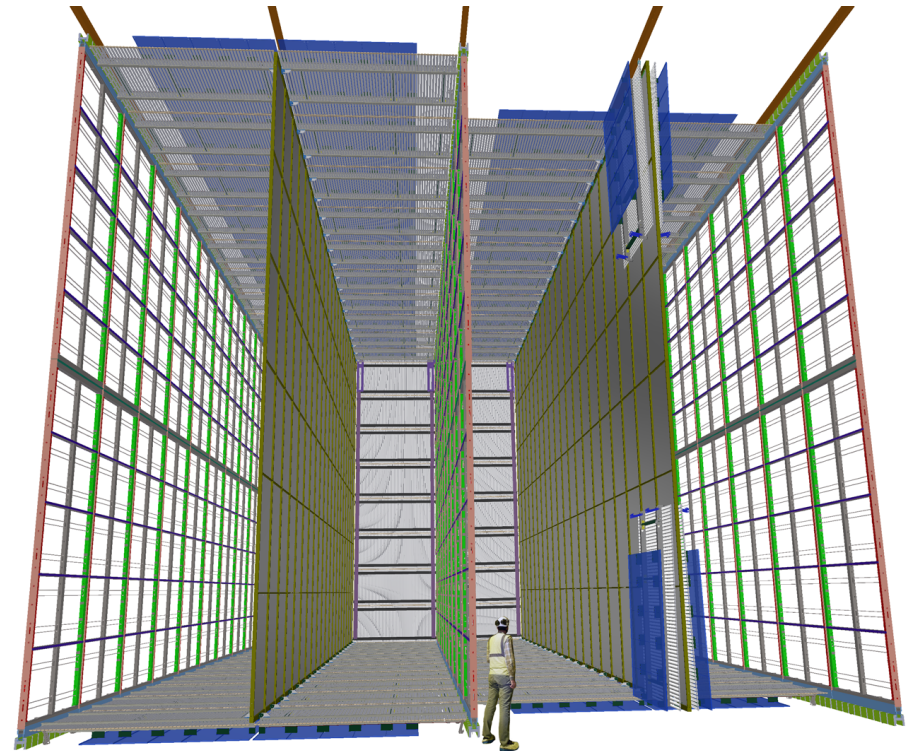
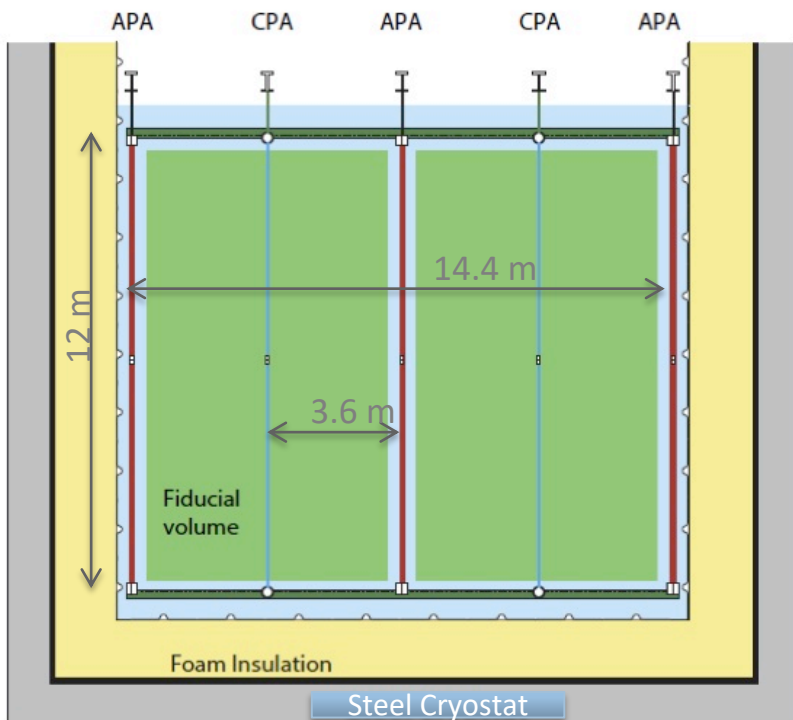


- 17.1/13.8/11.6 Total/Active/Fiducial mass
- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  - 3.6 m drift length

Single-phase: charge drifts  
to wire planes (APAs)

# DUNE Far Detector

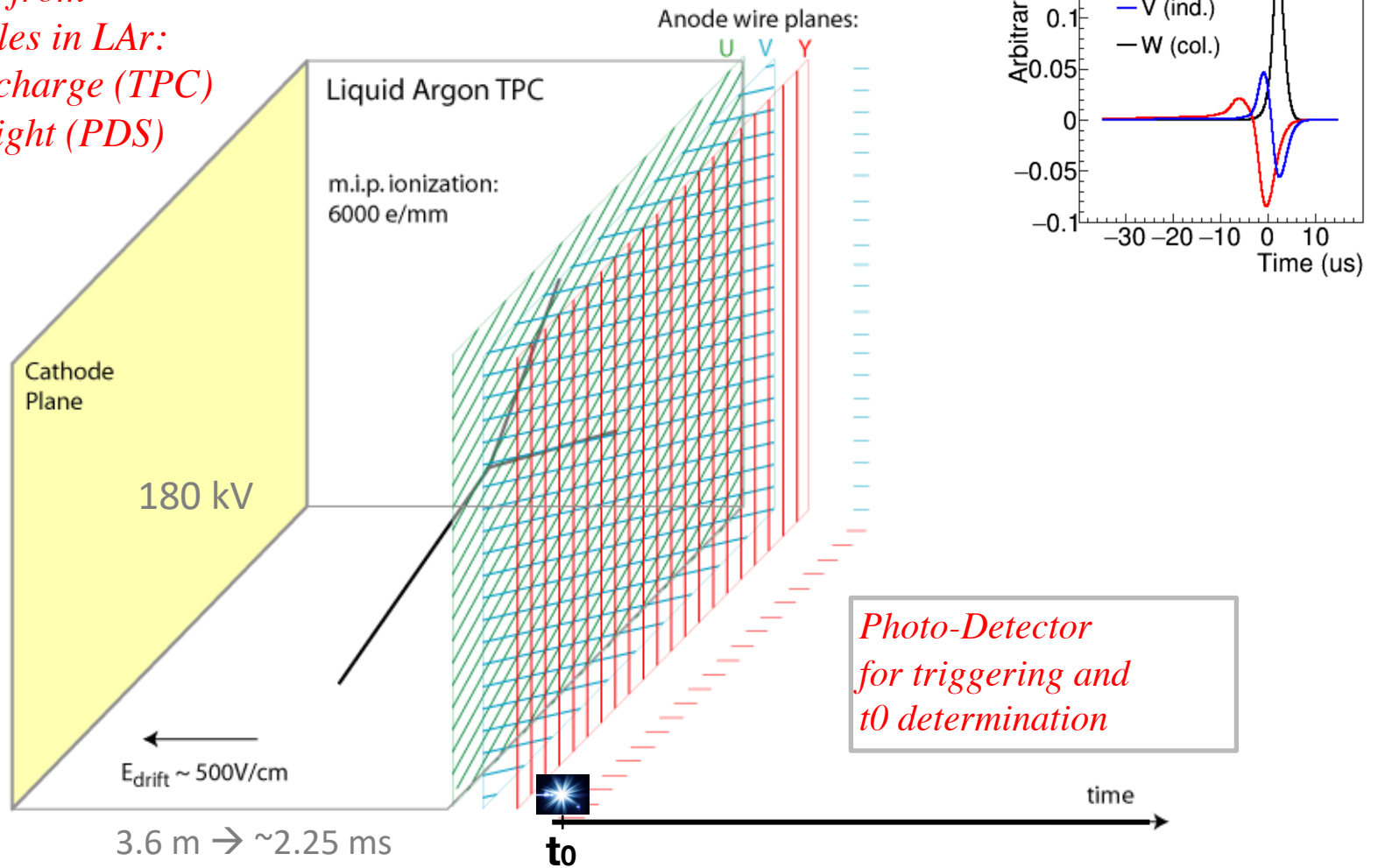
- Four 10-kt (fiducial) liquid argon TPC modules
  - *Liquid Argon Time projection chamber with both charge and optical readout*
- Single and dual-phase detector designs (1<sup>st</sup> module will be single phase)
- Integrated photon detection (need wavelength shifting to visible)
- Modules will not be identical



Single-phase: charge drifts  
to wire planes (APAs)

# DUNE Far Detector: SINGLE Phase Concept

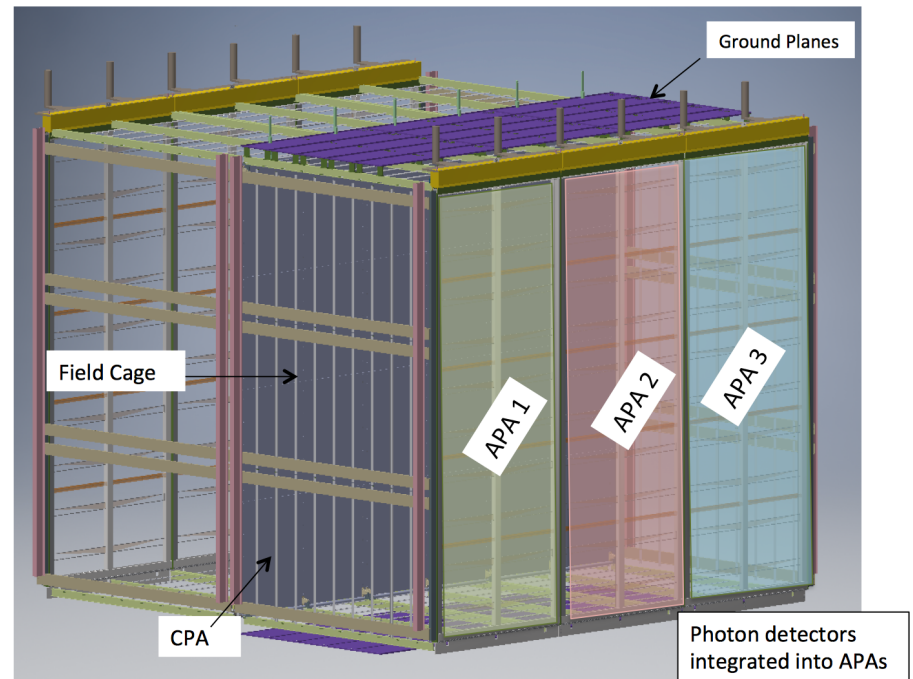
- *Energy release from charged particles in LAr:*
  - free electron charge (TPC)
  - scintillation light (PDS)



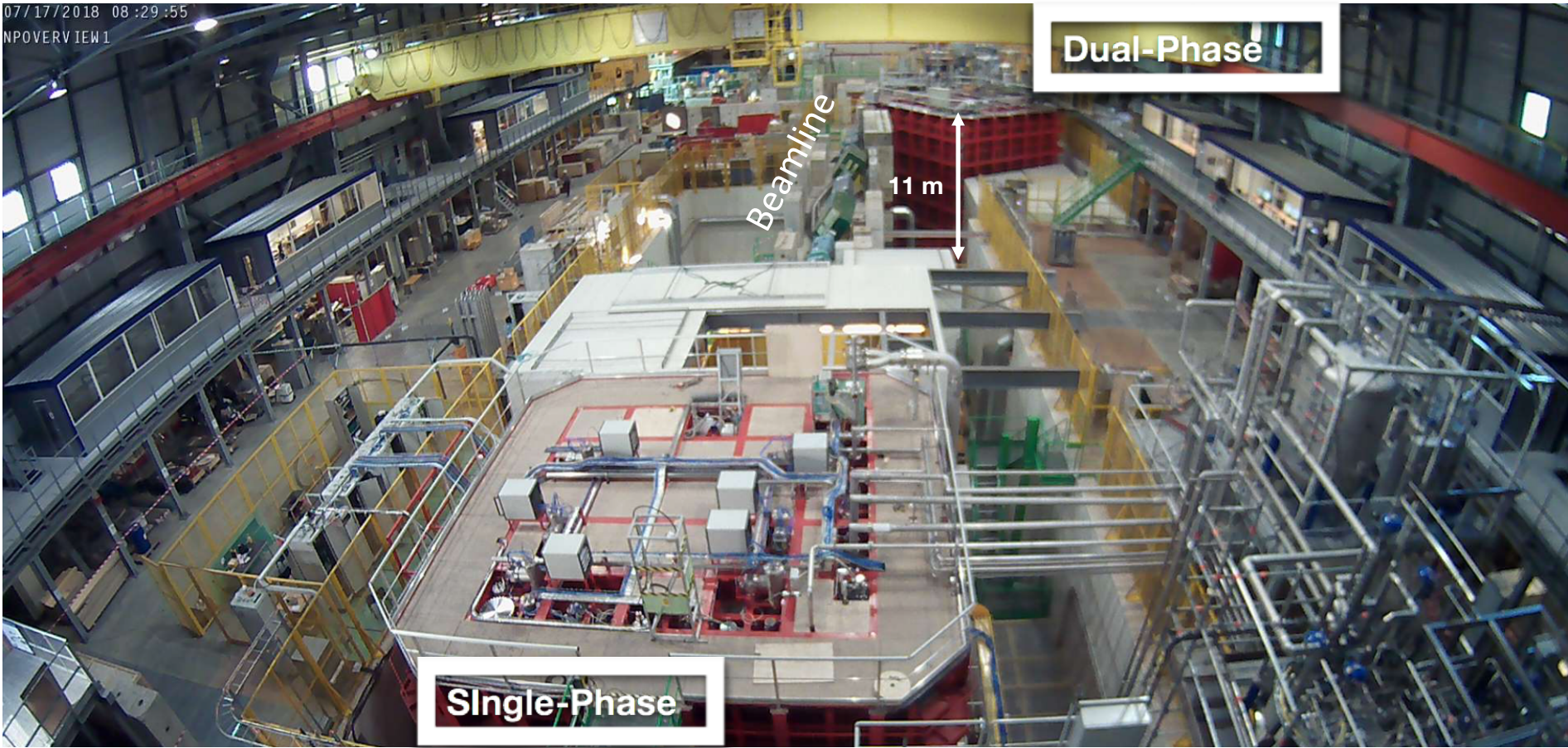
- DUNE detector development is underway through R&D and with a large-scale prototyping
  - The overarching goal is to demonstrate that the DUNE Far Detector meets the scientific requirements and technical specifications to measure neutrino CP violation.
  - Near Detector effort is underway.

- LArTPC located in the EHN1 Hall @ CERN: 760 tons of liquid argon
  - Provides a full drift length of future DUNE SP Far Detector
- Main Detector Elements include:
  - Time Projection Chamber (TPC)
  - Front-end electronics
  - Photon Detector System
  - Comic-Ray Tagger (CRT)
- ProtoDUNE-SP Goals:
  - Prototype the production and installation for SP DUNE Far Detector.
  - Validate detector performance with cosmic-rays; calibrate with different test-beam particle
    - Demonstrate photon-detector concept

## ProtoDUNE-SP TPC

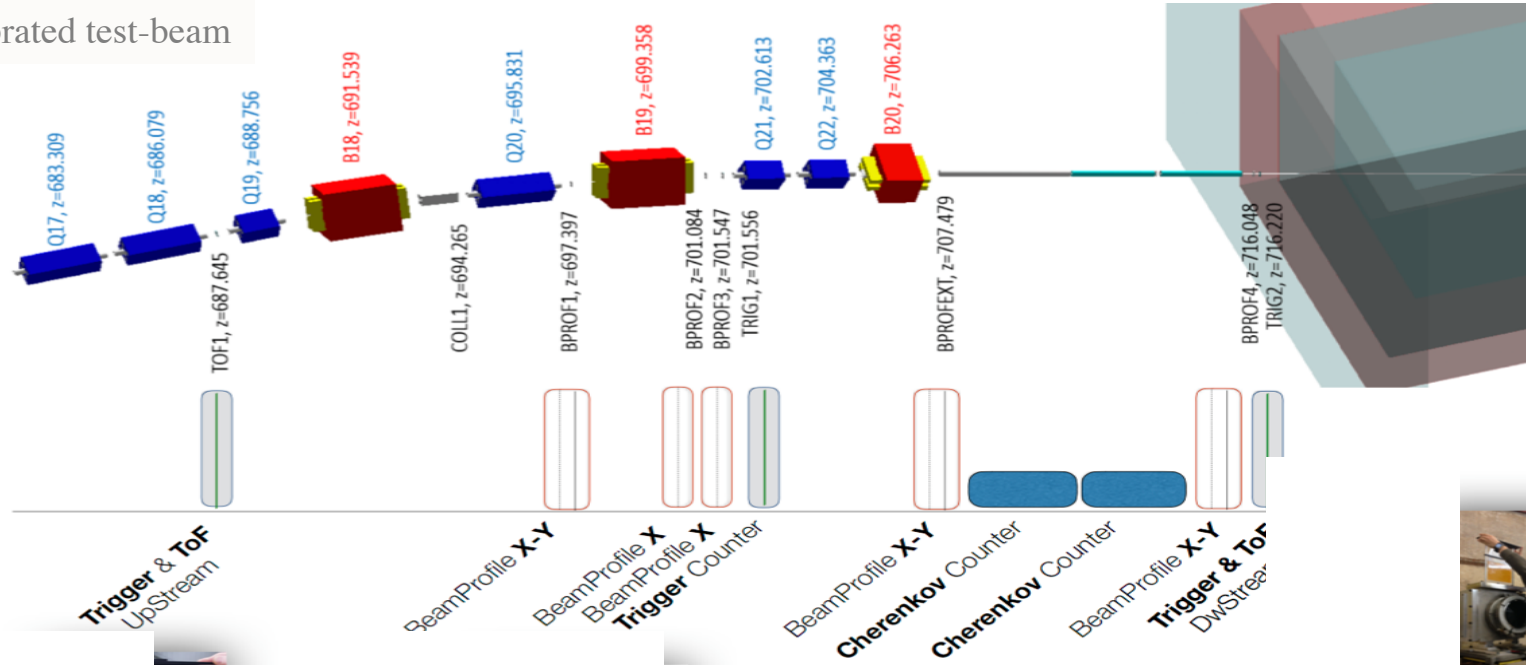


# CERN North Area



# ProtoDUNE Terst-Beam

Fully calibrated test-beam



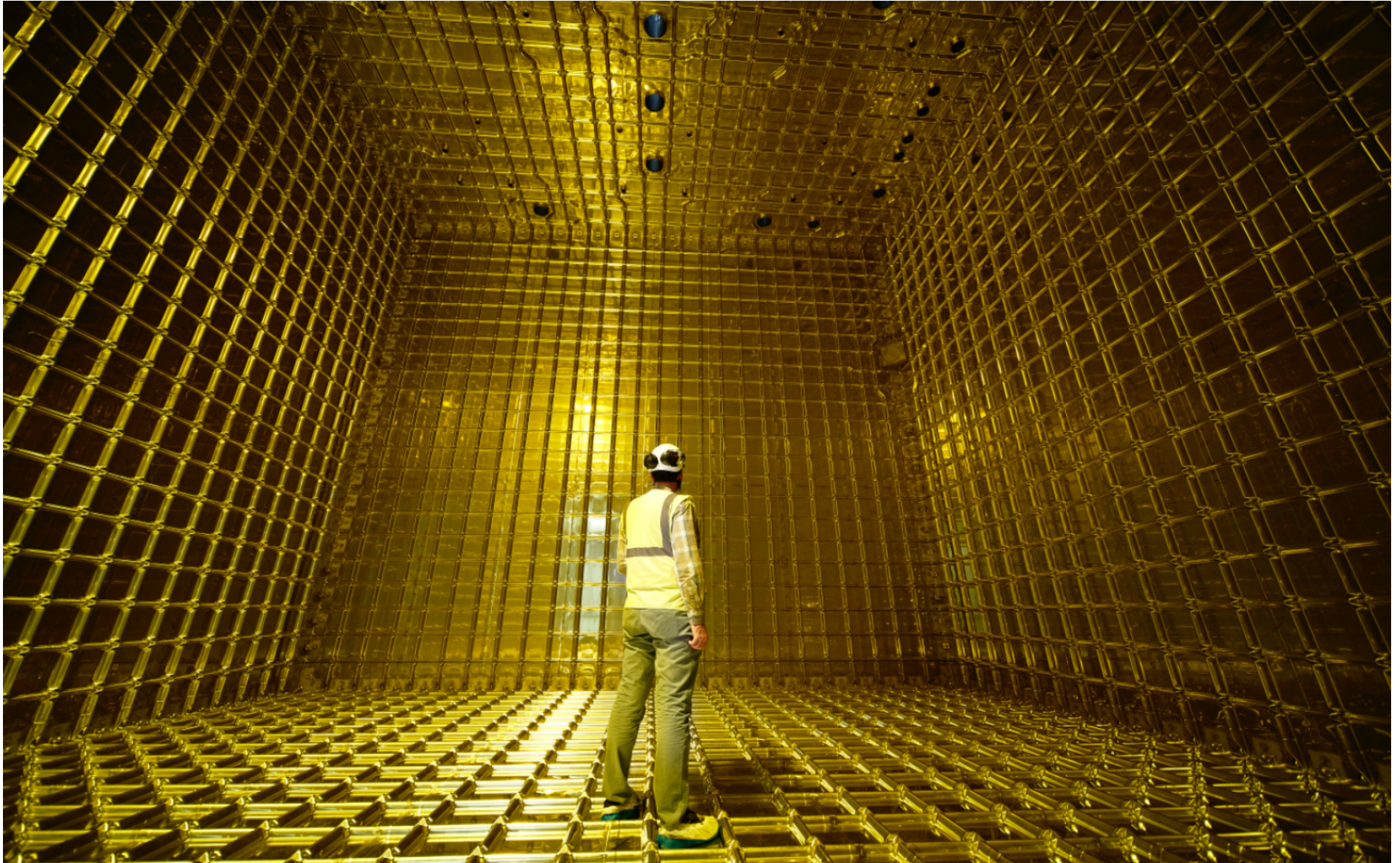
Collected >4M beam triggers Sep 21- Nov 11, 2018

Momentum	Total Triggers	Expected Pi trig.	Expected Proton trig.	Expected Electr. trig.	Expected Kaon trig.
0.3 GeV/c	269K	0	0	242K	0
0.5 GeV/c	340K	1.5K	1.5K	296K	0
1 GeV/c	1089K	382K	420K	262K	0
2 GeV/c	728K	333K	128K	173K	5K
3 GeV/c	568K	284K	107K	113K	15K
6 GeV/c	702K	394K	70K	197K	28K
7 GeV/c	477K	299K	51K	98K	24K
All momenta	4175K	1694K	779K	1384K	73K



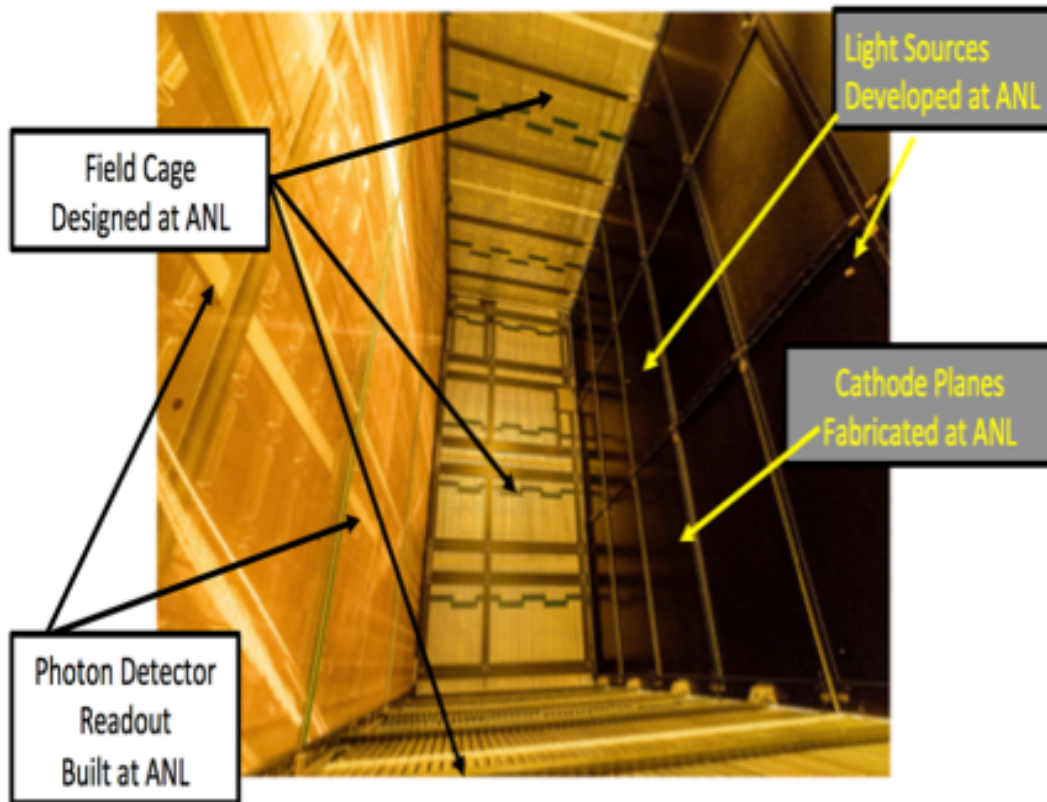
# Empty Cryostat

- ProtoDUNE - Single Phase

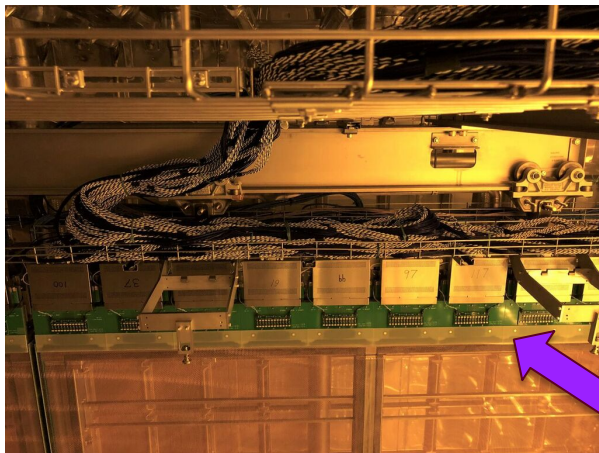


# Contribution to ProtoDUNE-SP

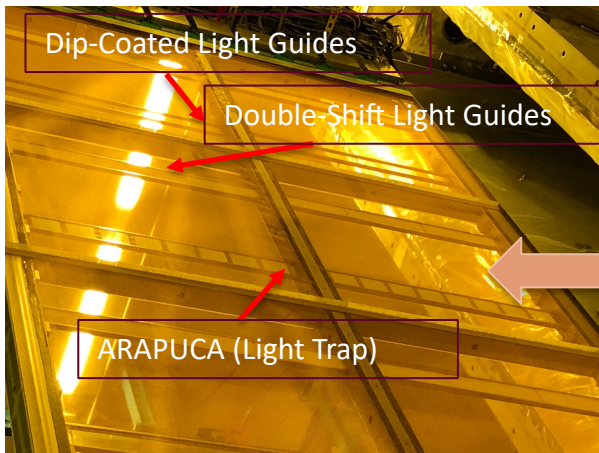
- This is what my team built for the ProtoDUNE
- Argonne fully engaged with Fermilab and other Labs/Universities in the realization of the ProtoDUNE-SP prototype experiment for DUNE.



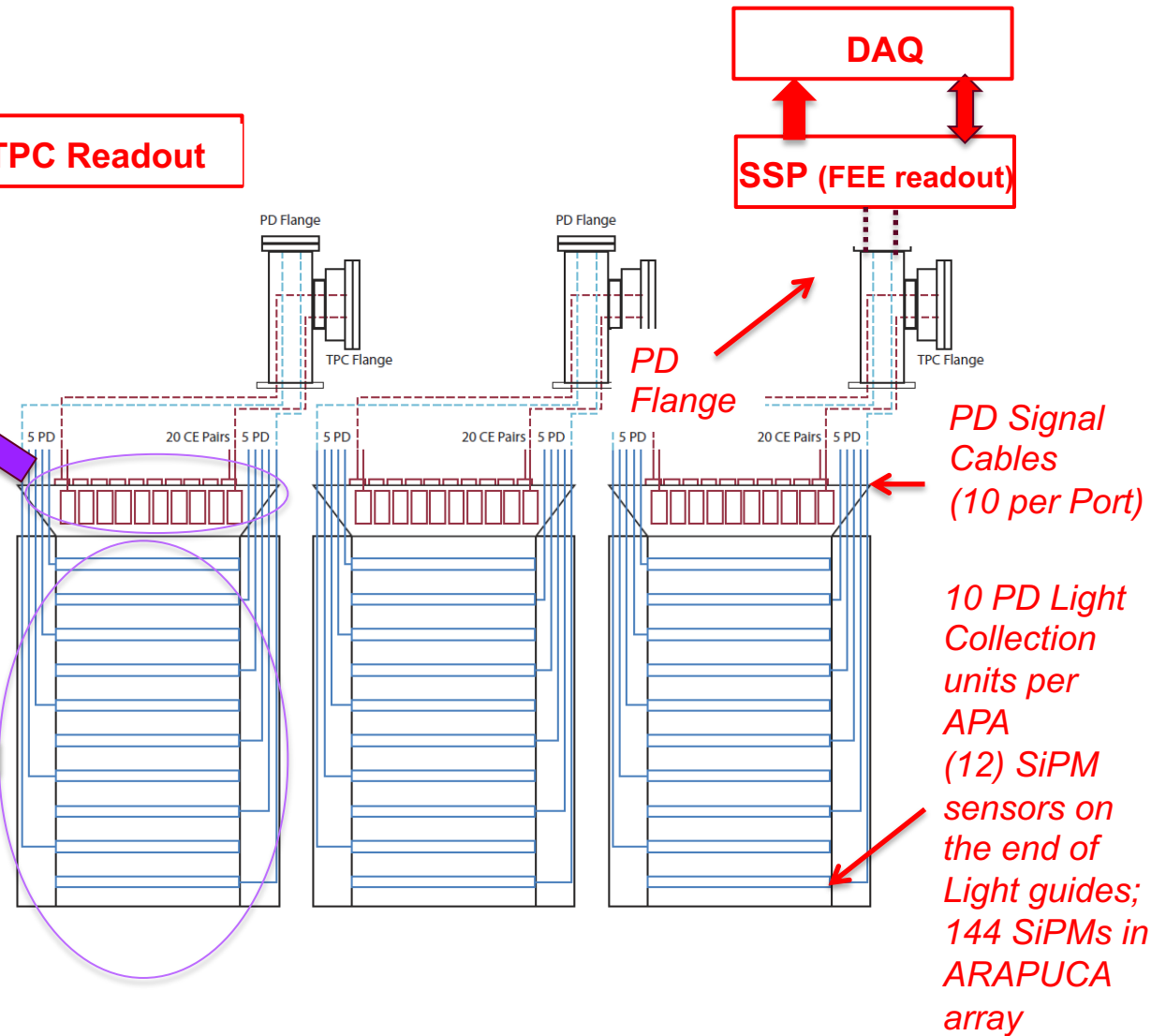
# ProtoDUNE-SP Main Detector Elements



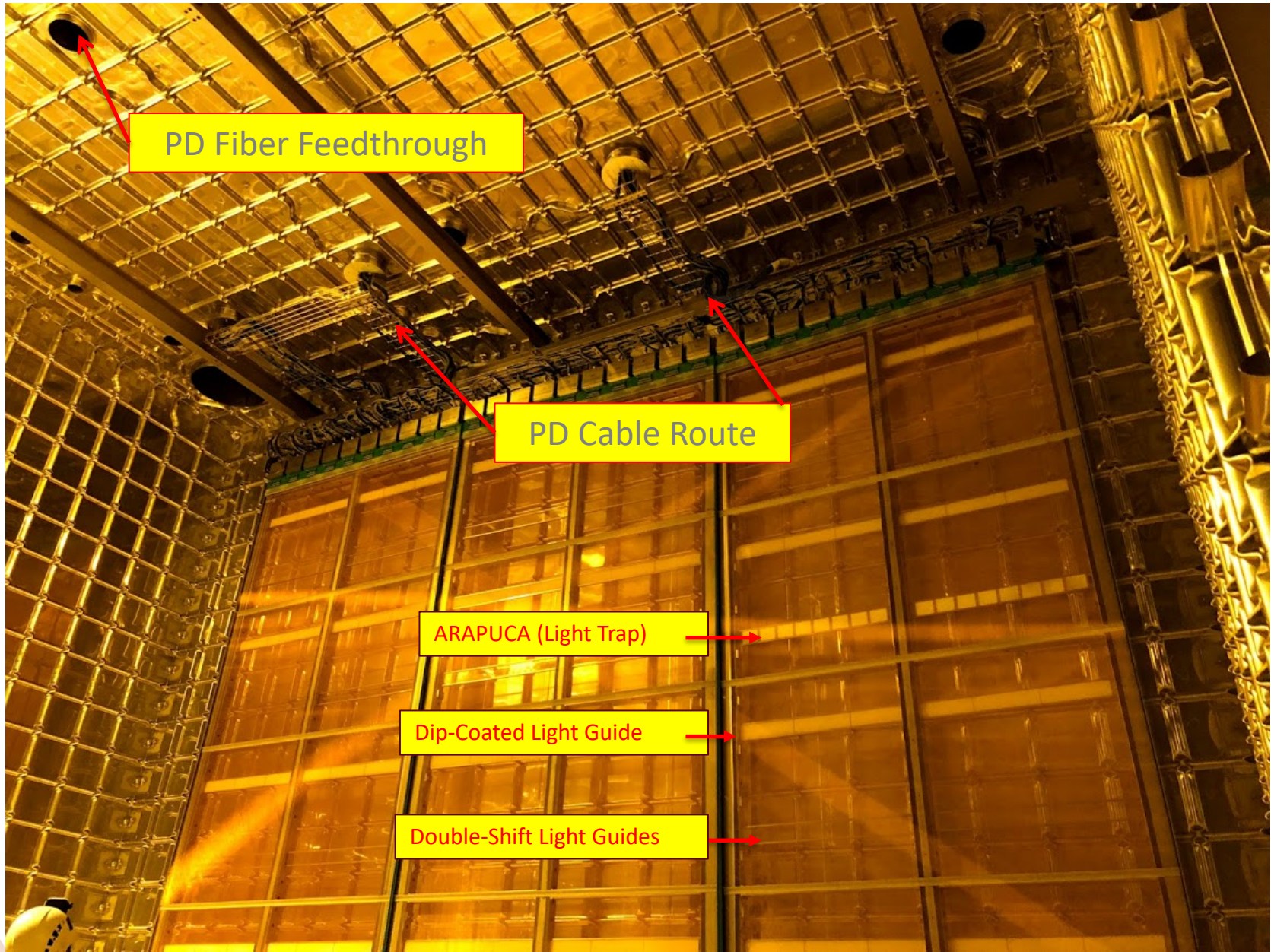
**TPC Readout**



58 light guide and 2 ARAPUCA photon collectors

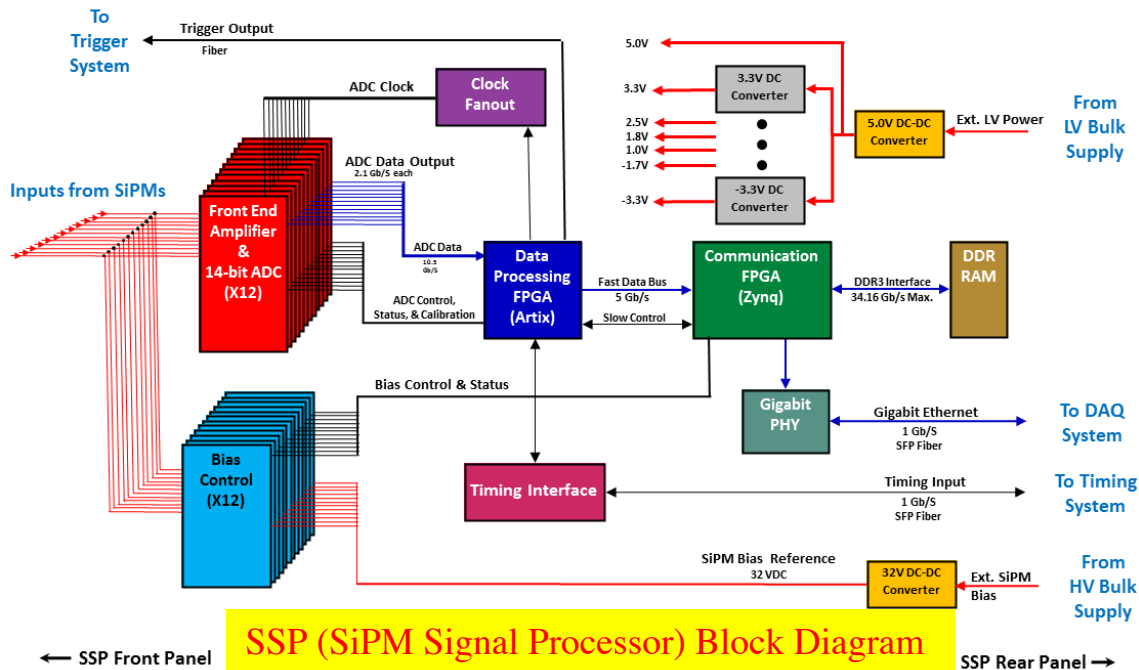


# Photon-Detector in ProtoDUNE-SP

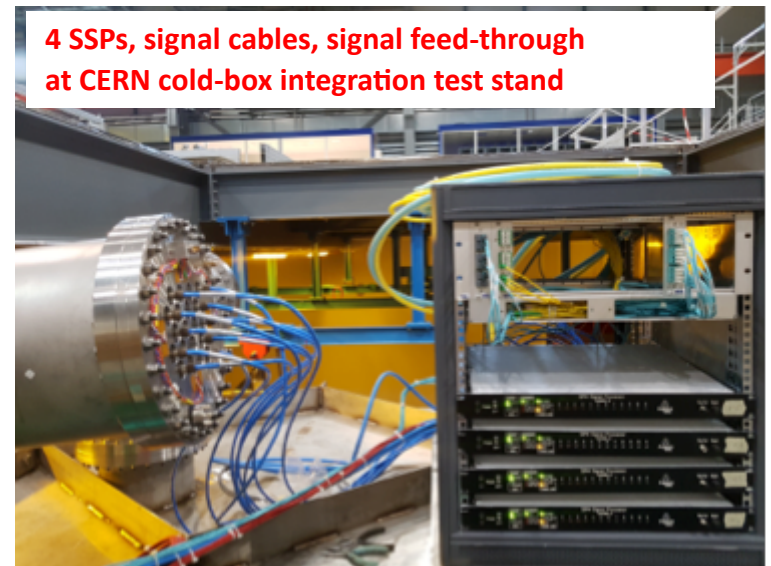


# Photon-Detector Readout in ProtoDUNE-SP

- A dedicated photon-detector readout system (SSP) was developed for ProtoDUNE



- Fast 150MS/s ADC sampling, 14bit dynamic range
- Timing/Trigger and DAQ interfaces



- Twenty-four custom SiPM Signal Processor (SSP) units were produced to read out the 58 light guide and 2 ARAPUCAs photon collectors in final ProtoDUNE
- 288 readout channels



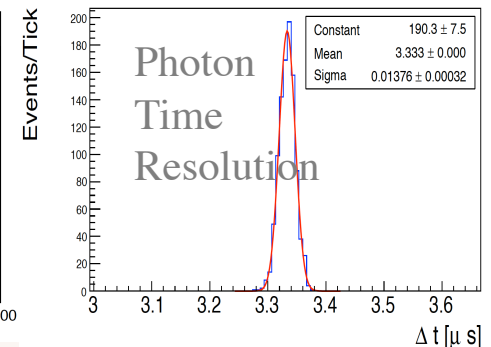
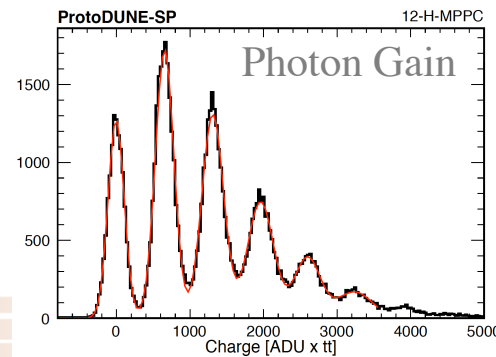
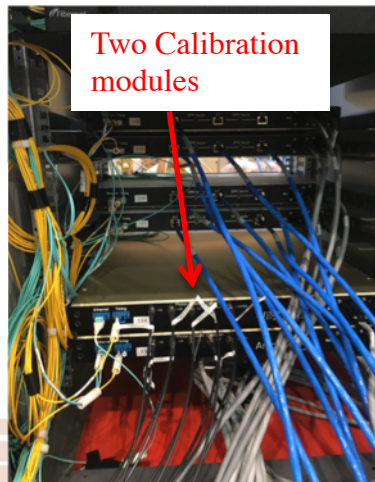
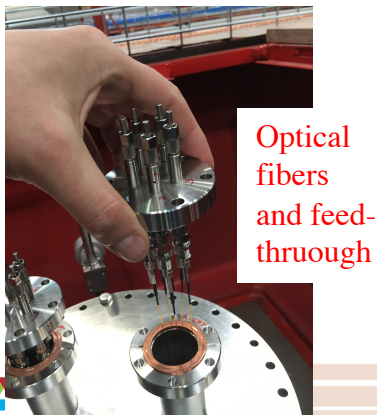
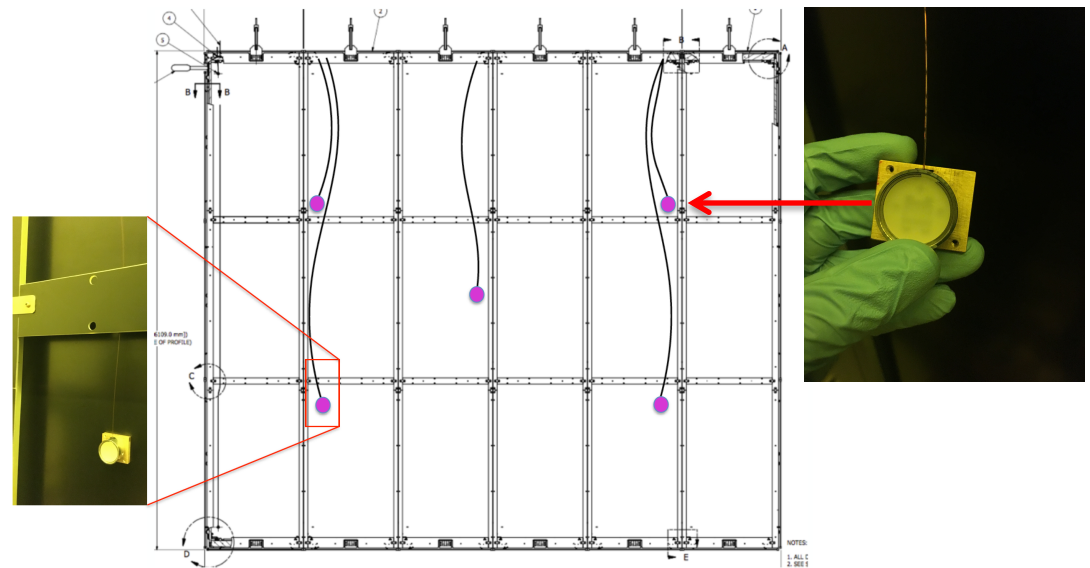
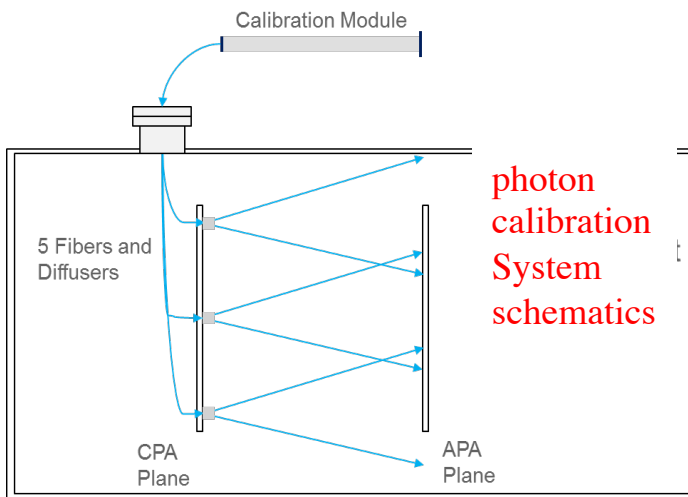
# Photon-Detector Readout in ProtoDUNE-SP



- The ProtoDUNE detector is filled with liquid argon, and is taking data
- The flashing **lights** in the crates on the top are the photon-detector readout boards

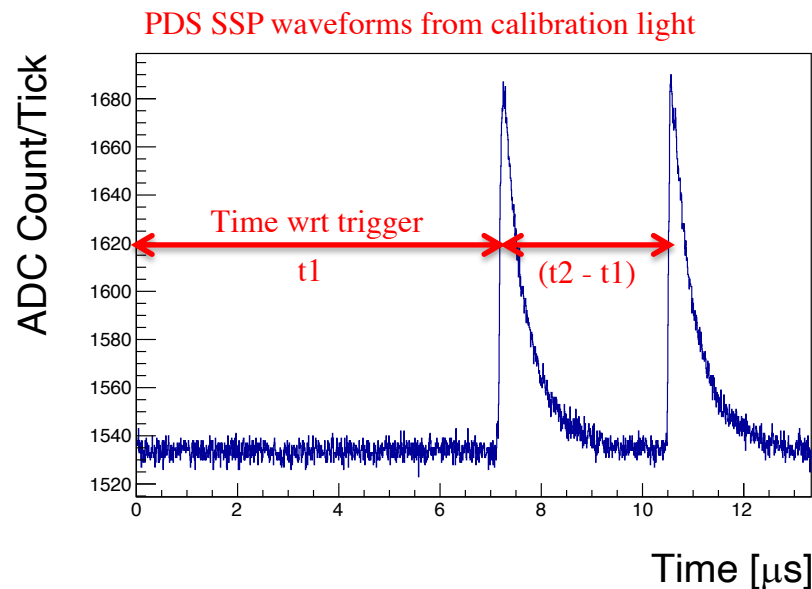
# Photon Detection (cont.)

- Related photon-detection R&D at Argonne: DUNE photon-detector calibration system
  - The system emits UV-light: electronics module -> fiber (through cryostat) -> point-like diffusers
    - Result: distribute UV light from cathode to photon detector at anode
    - Fully integrated with DAQ/timing, emits light with desired intensity and repetition rate
    - Full test and verification completed with ProtoDUNE => will equip full DUNE SP FD



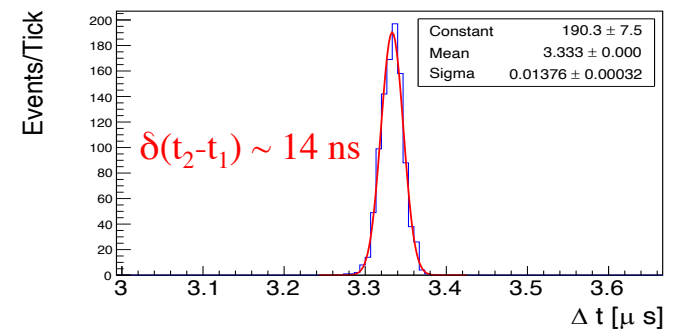
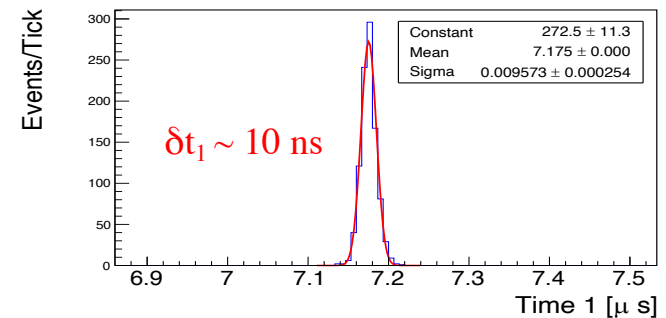
# Data Analysis

- The primary goal of photon-detector system (PDS) is to provide a time (“T0”) of event
  - We studied the time capabilities of PDS and measured time resolution
    - Measured by UV light from calibration system, triggered by ProtoDUNE-SP timing system
    - Light recorded by PDS photo-sensors and SSP readout.



- Distribution of time wrt external trigger ( $t_1$ ), and ability to observe two separate pulses ( $t_2 - t_1$ ) demonstrate good time resolution in the 10-20 ns range.

Time distributions from 1000 waveforms



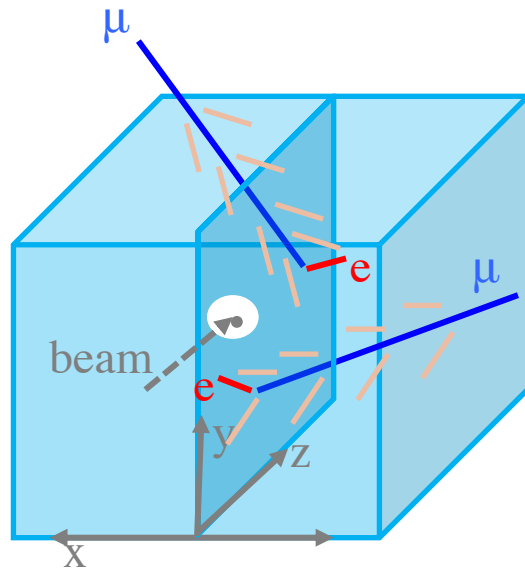
- Understanding of time resolution and time delays wrt detector trigger is an important input for the next step to correlate event times between TPC (charge) and PDS (light)



# Data Analysis

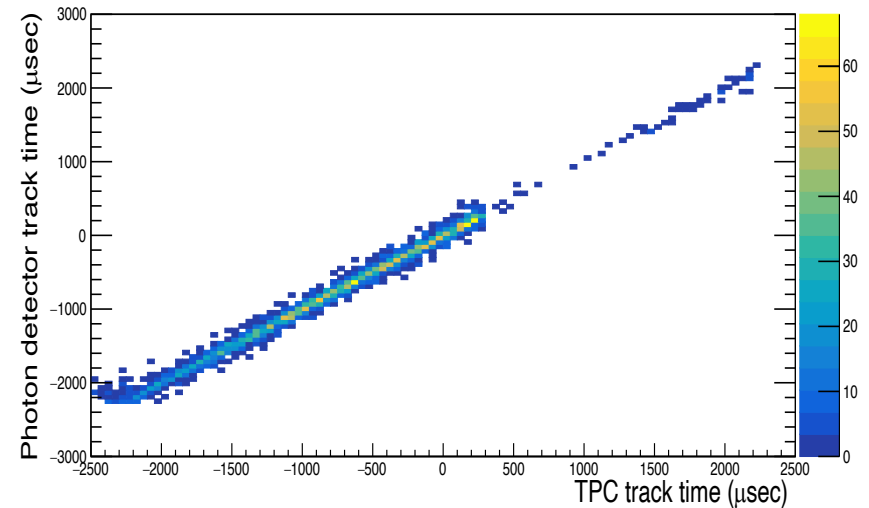
- We studied how to correlate PDS and TPC timing with Muon data and MC samples
  - Required development of an analysis that combined TPC and PDS detector systems
  - Included the selection of stopping muons with tracks in both drift volumes

$T_0$  reconstructed by TPC (cathode crossing) tracks

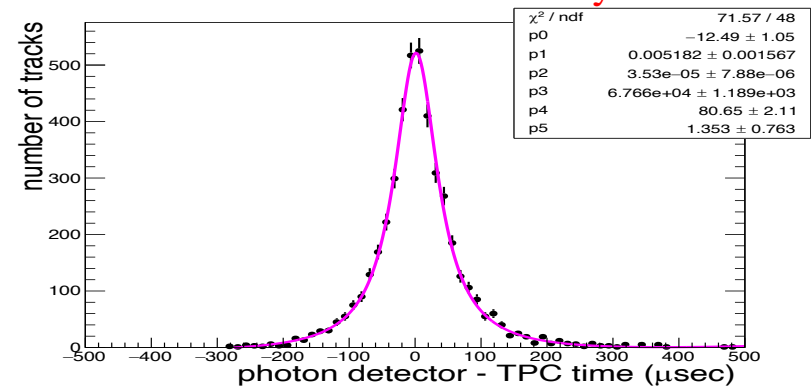


$T_0$  measured by photon system

## ➤ Demonstration of correlated timing



## ➤ Time resolution dominated by TPC effects



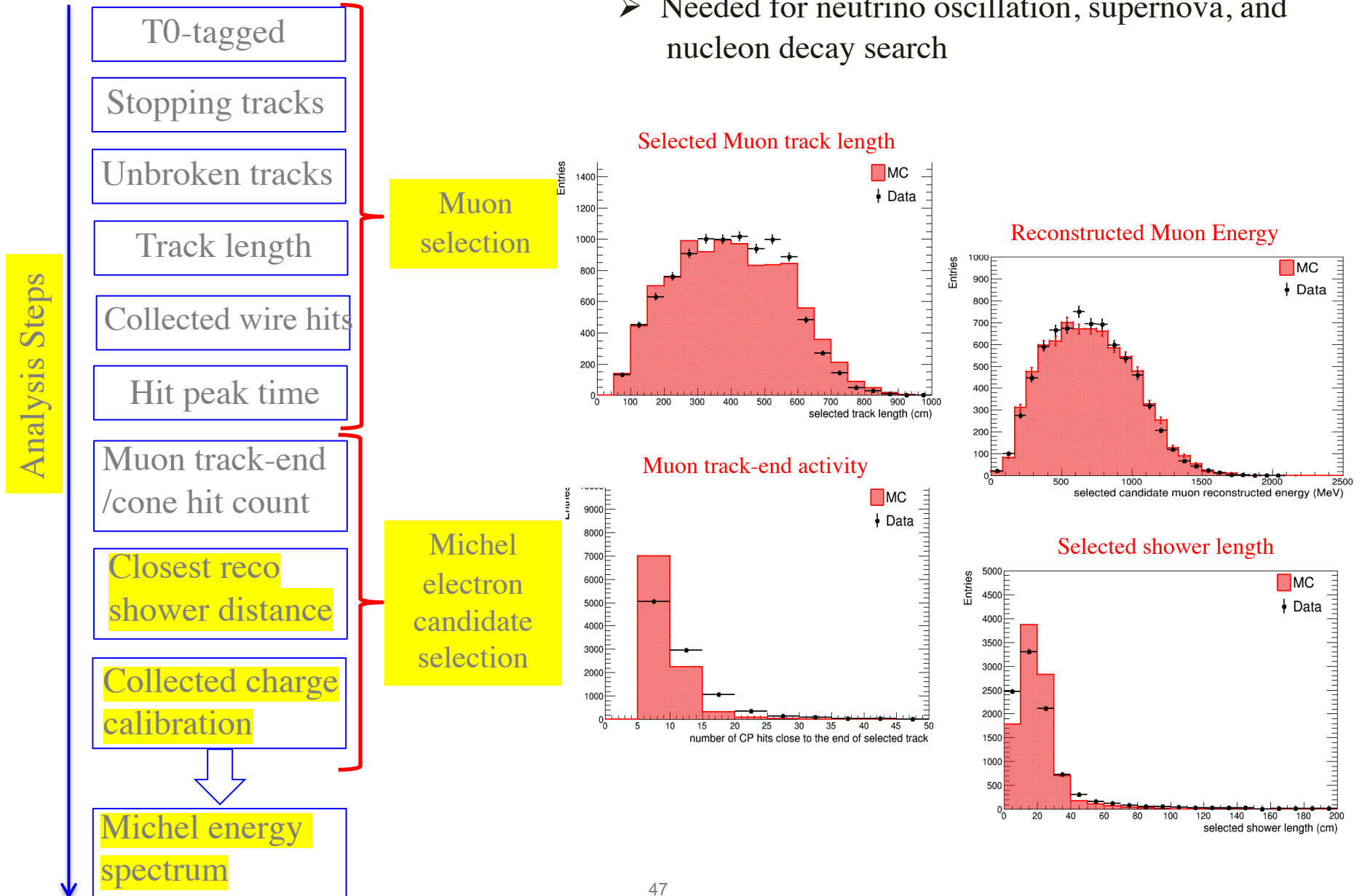
- Next “natural” step was selection of stopping muons with Michel electrons



# Data Analysis and Interim Results

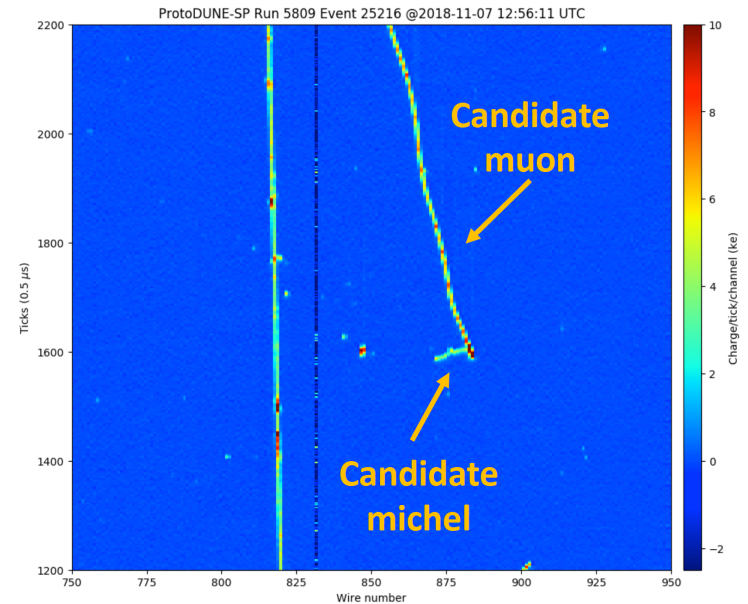
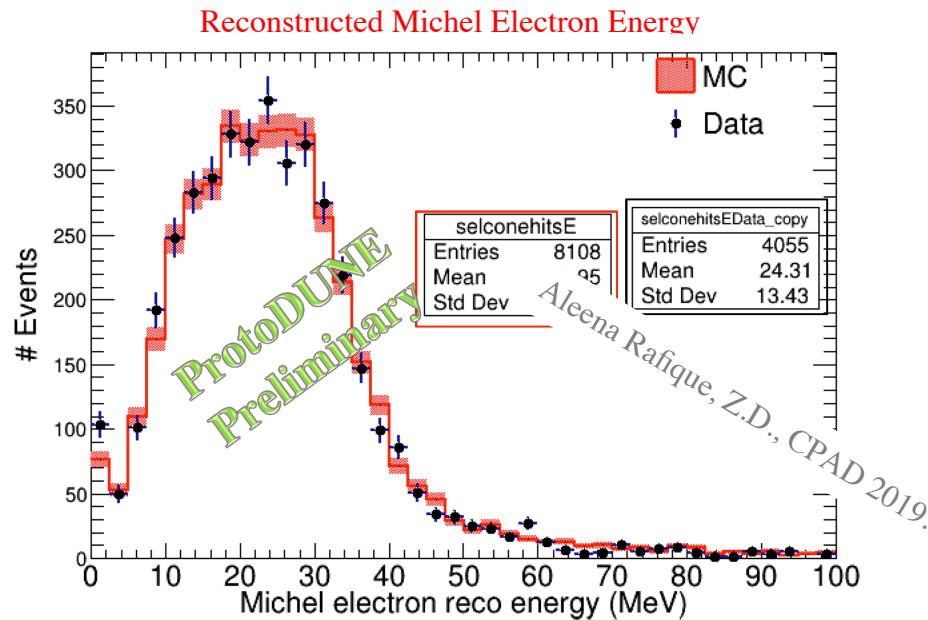
- Extended the analysis introduced above to Michel electron search

➤ Needed for neutrino oscillation, supernova, and nucleon decay search



# Our First Science Results

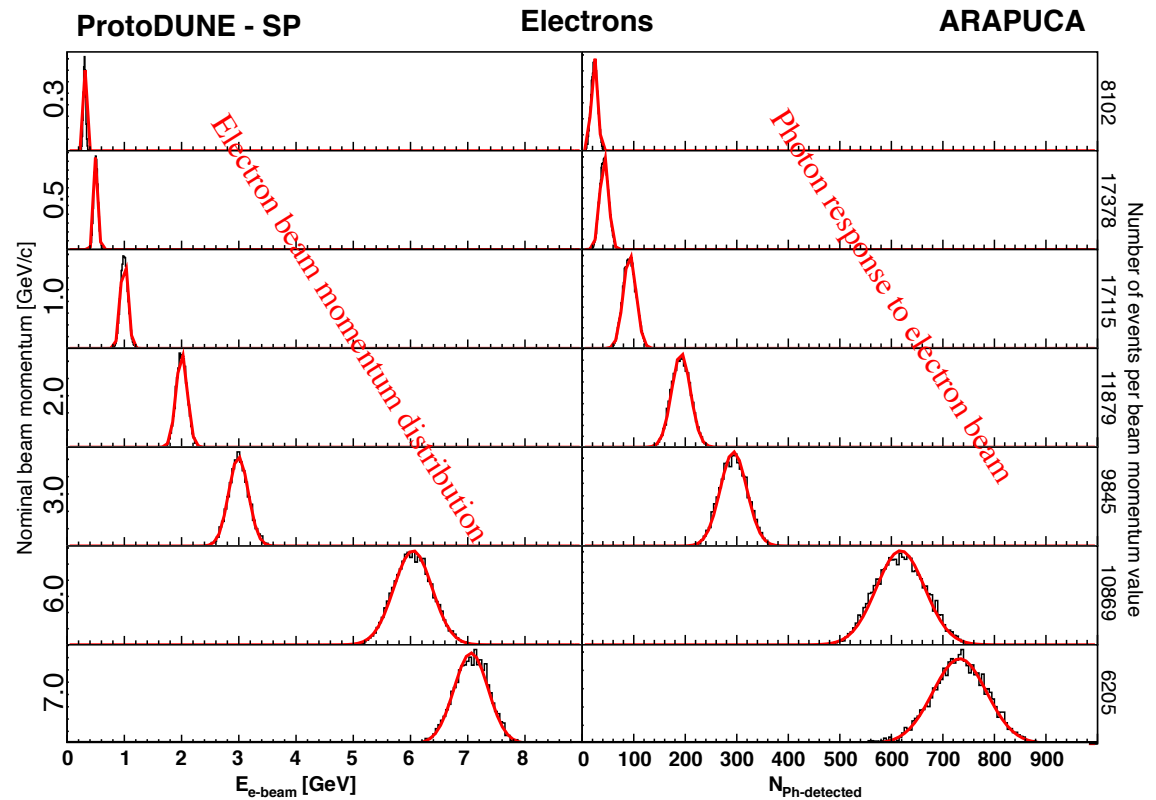
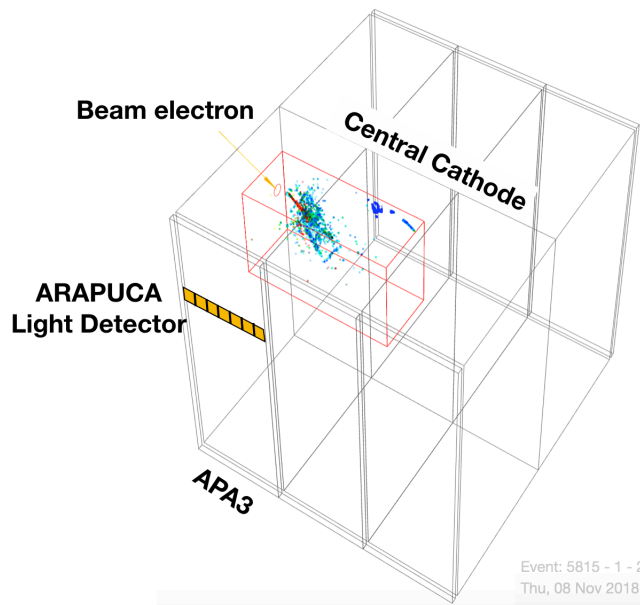
- Energy spectrum of selected Michel electron candidates



- Addressing DUNE low-energy physics via Michel electron studies
  - Our goal is to provide reconstruction and calibration algorithm to be used from Far Detector day one
  - Potential for application in Near Detector

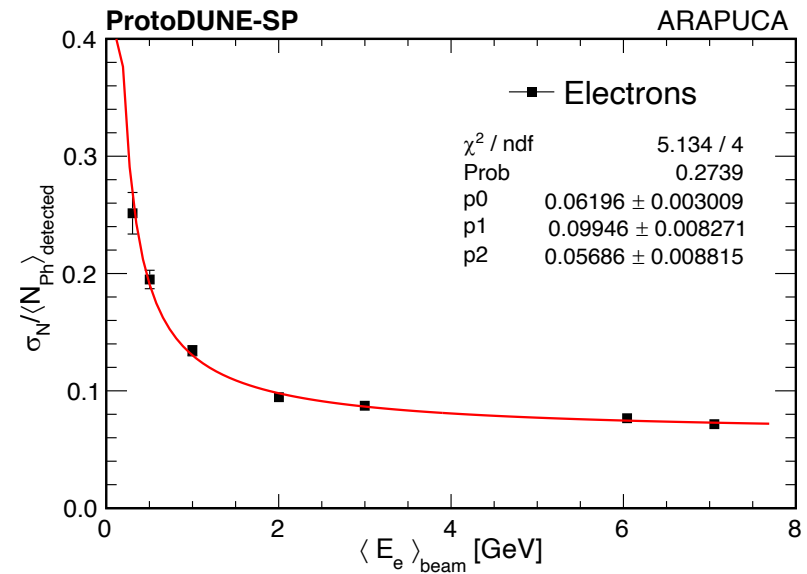
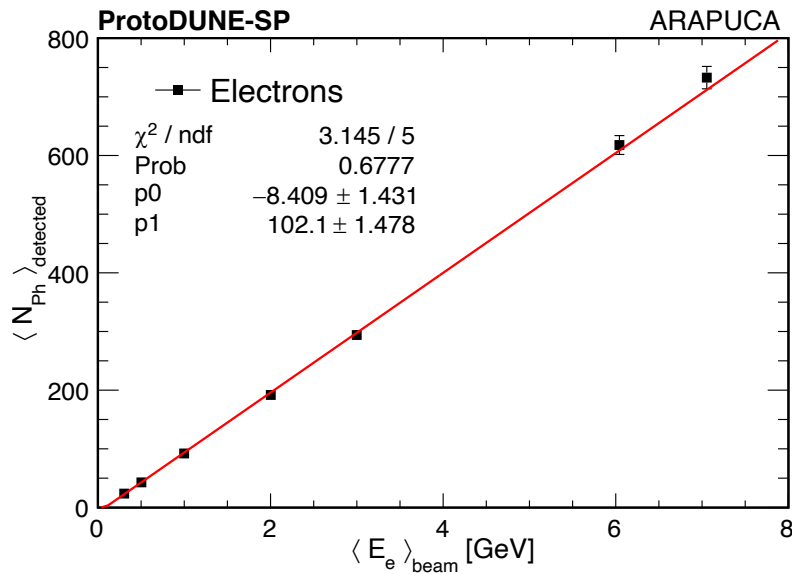
# Response to Electron Beam

- Operating on the H4-VLE charged particle test beam offers an opportunity to directly probe the calorimetric photon-detector response to EM and hadronic showers in the sub-to few-GeV momentum range.
- Showing calorimetric response from light signal from a single ARAPUCA module ( $\sim 0.5\%$  photo-sensitive area coverage) to EM shower at  $\sim 3$  m distance in the



# Response to Electron Beam

- Gaussian mean value (left) and the ratio of the standard deviation to the mean (right) numbers of detected photoelectrons as functions of the beam electron energy.



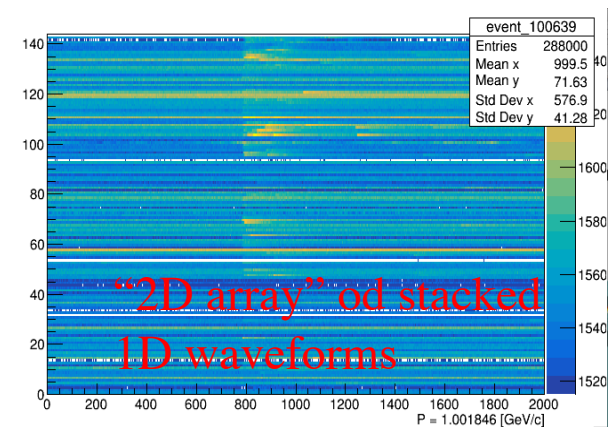
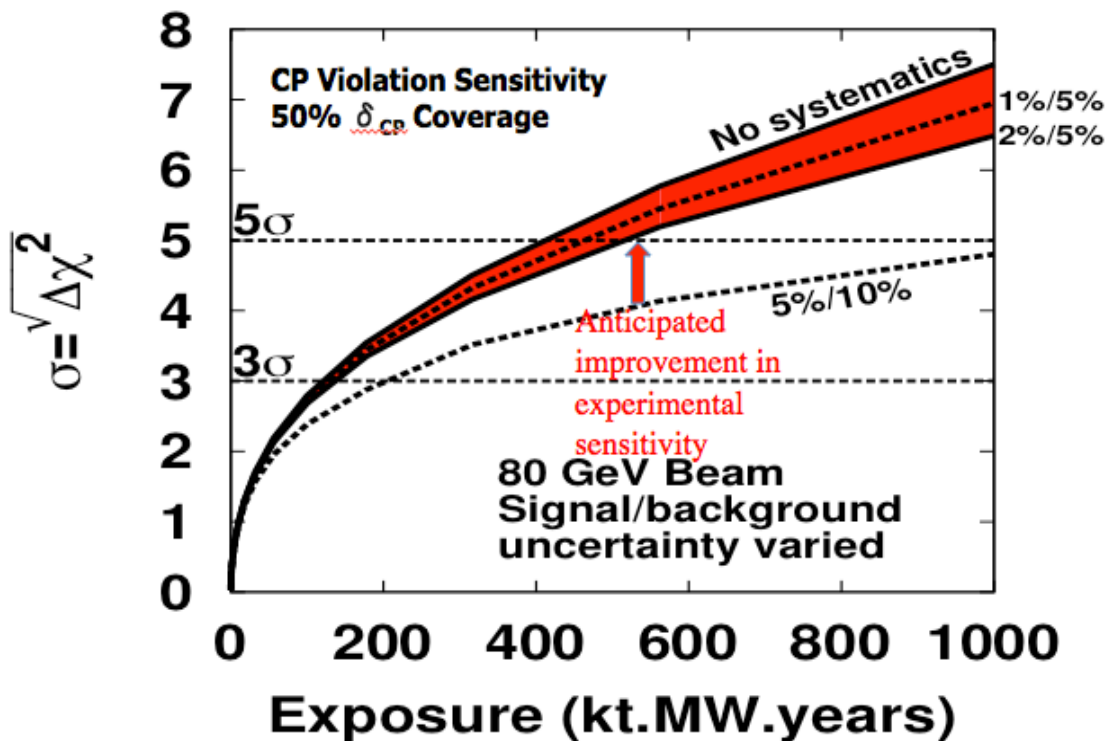
- **Linearity of light response** over the entire range of energies. The slope gives the light yield from (only) one ARAPUCA module, relative to a diffused light source (EM shower) at a distance of  $\sim 3$  m

- **Energy resolution of light response**

$$\frac{\sigma E}{E} = p_0 \oplus \frac{p_1}{\sqrt{E}} \oplus \frac{p_2}{E}$$

# Science Opportunities

- Ultimate science goal is to provide a definite measurement of CP-violation, and to enhance a sensitivity to other deep underground physics
- Further Opportunities
  - Understand how to combine light and charge to achieve unprecedented energy resolution (potential improvement in energy resolution / background rejection)
  - TPC data is 2D image data with a slow timescale, while the optical data is 1D time series data/channel; combining these datasets in a meaningful way is an important and unfilled challenge.



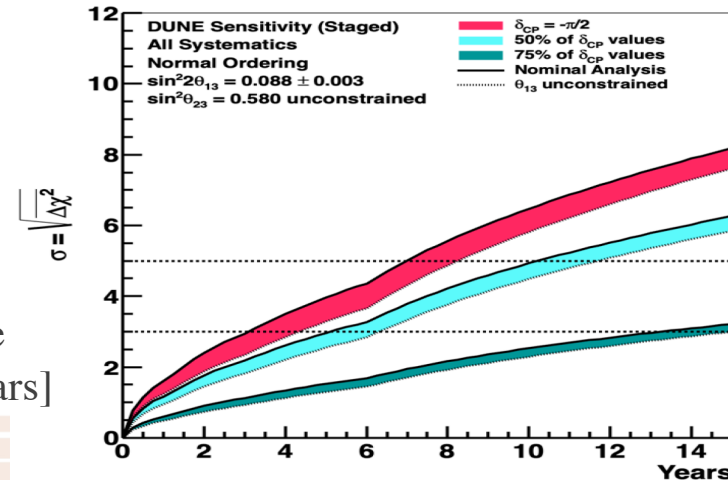
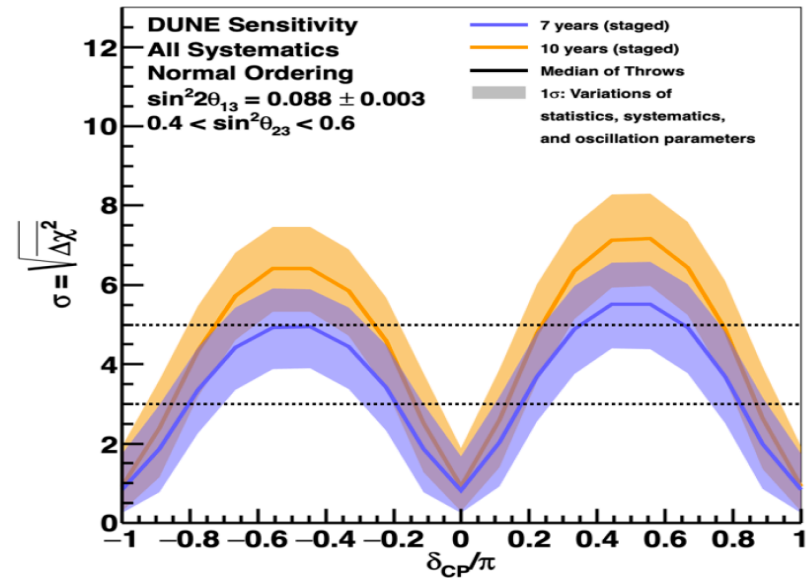
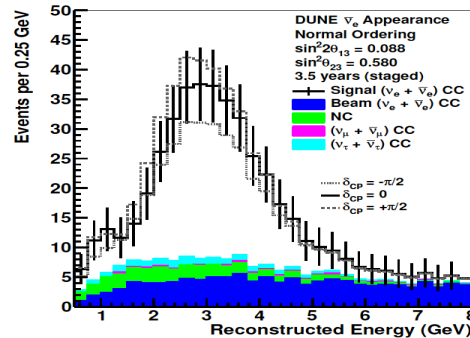
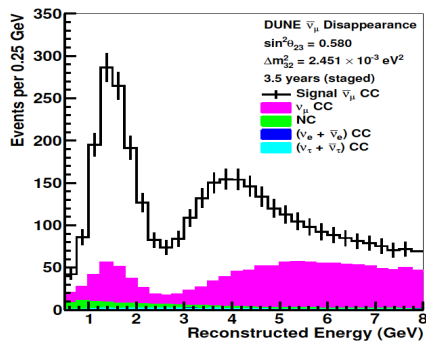
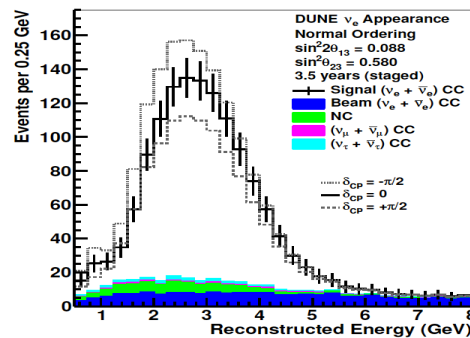
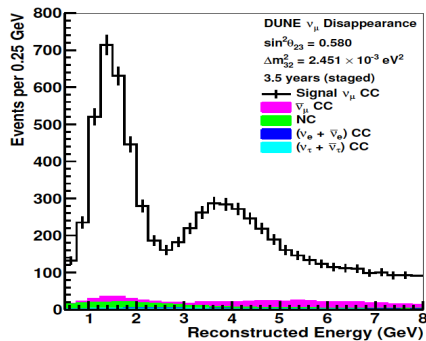
=> An older sensitivity study we performed at ANL: assumed improvement in energy resolution and background reduction. Potential for Q-pix.

# DUNE Sensitivity

- The DUNE Experiment is expected to meet or exceed the following sensitivities

-Far Detector oscillation spectra (7y)  
 -example: normal mass ordering:

- Significance of determination of CP-violation as a function of the true value of CP, for seven (blue) and ten (orange) years of exposure.



CP-violation significance  
 as a function of time [years]



# DUNE Sensitivity

Physics Milestone	Exposure (staged years, $\sin^2 \theta_{23} = 0.580$ )
5 $\sigma$ Mass Ordering $\delta_{CP} = -\pi/2$	1
5 $\sigma$ Mass Ordering 100% of $\delta_{CP}$ values	2
3 $\sigma$ CP Violation $\delta_{CP} = -\pi/2$	3
3 $\sigma$ CP Violation 50% of $\delta_{CP}$ values	5
5 $\sigma$ CP Violation $\delta_{CP} = -\pi/2$	7
5 $\sigma$ CP Violation 50% of $\delta_{CP}$ values	10
3 $\sigma$ CP Violation 75% of $\delta_{CP}$ values	13
$\delta_{CP}$ Resolution of 10 degrees $\delta_{CP} = 0$	8
$\delta_{CP}$ Resolution of 20 degrees $\delta_{CP} = -\pi/2$	12
$\sin^2 2\theta_{13}$ Resolution of 0.004	15

- DUNE Exposure in years
  - assume true normal ordering and equal running in neutrino and antineutrino mode
  - required to reach selected physics milestones in the nominal analysis, using the current (NuFIT 4.0 best-fit) values for the oscillation parameters.



# Summarize What we Have Learned So Far

- To incorporate new knowledge into the three-neutrino oscillation framework one usually performs global fits, where all available results on neutrino oscillation parameters are combined.

- Neutrino oscillation parameters:

-MNSP matrix:

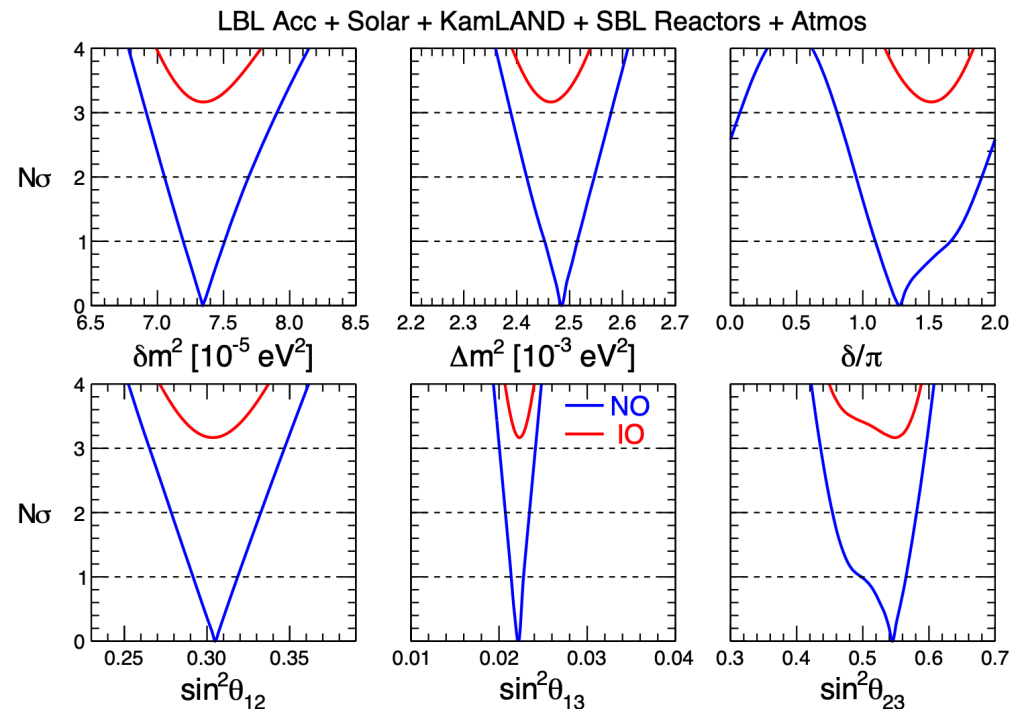
3 mixing angles:  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$

1 phase:  $\delta \Rightarrow$  CP-violation in  $\nu$ -sector

-Mass differences:

2 mass difference scales:  $\Delta m^2_{12}$ ,  $\Delta m^2_{23}$ .

- Example of recent global fit to three neutrino mixing is given in arXiv:2003.05811, by F. Capozzi et al.



- How well we know the oscillation parameters?



# Combining all Oscillation Results Together

- Current Picture

Parameter	Ordering	Best fit	$1\sigma$ range	$2\sigma$ range	$3\sigma$ range	" $1\sigma$ " (%)
$\delta m^2/10^{-5} \text{ eV}^2$	NO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.90	2.2
	IO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
$\sin^2 \theta_{12}/10^{-1}$	NO	3.05	2.92 – 3.19	2.78 – 3.32	2.65 – 3.47	4.5
	IO	3.03	2.90 – 3.17	2.77 – 3.31	2.64 – 3.45	4.5
$ \Delta m^2 /10^{-3} \text{ eV}^2$	NO	2.485	2.453 – 2.514	2.419 – 2.547	2.389 – 2.578	1.3
	IO	2.465	2.434 – 2.495	2.404 – 2.526	2.374 – 2.556	1.2
$\sin^2 \theta_{13}/10^{-2}$	NO	2.22	2.14 – 2.28	2.07 – 2.34	2.01 – 2.41	3.0
	IO	2.23	2.17 – 2.30	2.10 – 2.37	2.03 – 2.43	3.0
$\sin^2 \theta_{23}/10^{-1}$	NO	5.45	4.98 – 5.65	4.54 – 5.81	4.36 – 5.95	4.9
	IO	5.51	5.17 – 5.67	4.60 – 5.82	4.39 – 5.96	4.7
$\delta/\pi$	NO	1.28	1.10 – 1.66	0.95 – 1.90	$0 - 0.07 \oplus 0.81 - 2$	16
	IO	1.52	1.37 – 1.65	1.23 – 1.78	1.09 – 1.90	9

- What is the value of  $\delta_{\text{CP}}$ ?
  - $-\sin\delta_{\text{CP}} > 0$  but CPC value  $\sin\delta_{\text{CP}} = \pi$  allowed at  $1.6\sigma$
- What's next? Can these results be further improved?
  - DUNE/Hyper-K
- How well we need to know CP-violation phase  $\delta_{\text{CP}}$ ?
- Are there other sources of CP-violation?

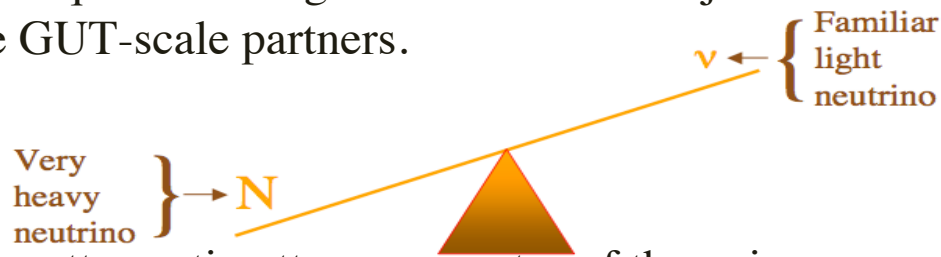


# Why is CP-violation with neutrinos so important?

-Need to understand the striking feature of the Universe: only matter, virtually no anti-matter!

-Observation of CP-violation would make it more likely that the baryon-antibaryon asymmetry of the universe arose through leptogenesis.

-The theory of leptogenesis is linked to the see-saw theory and as a consequence the light neutrinos are Majorana and have GUT-scale partners.



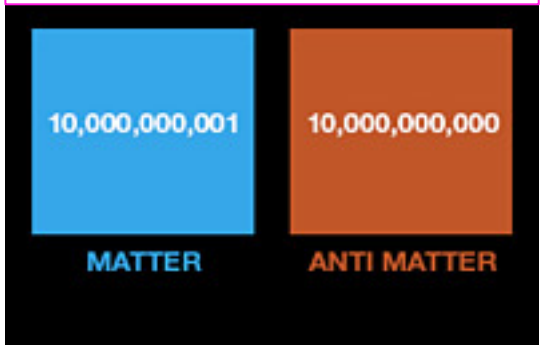
-The matter-antimatter asymmetry of the universe may be explained through CP-violating decays of the heavy partners, producing a state with unequal numbers of Standard Model leptons and antileptons.



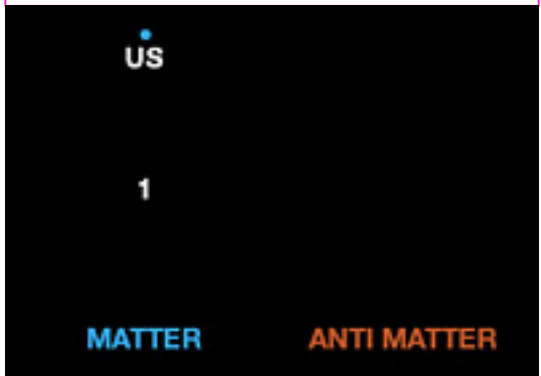
-The Standard Model processes convert such a state into the world around us with an unequal number of baryons and antibaryons.

-It is thought that CP-violation would be very unlikely to appear in the heavy sector without happening in light neutrinos.

Big Bang produced slightly different amounts of matter and anti-matter, with some tiny asymmetry?

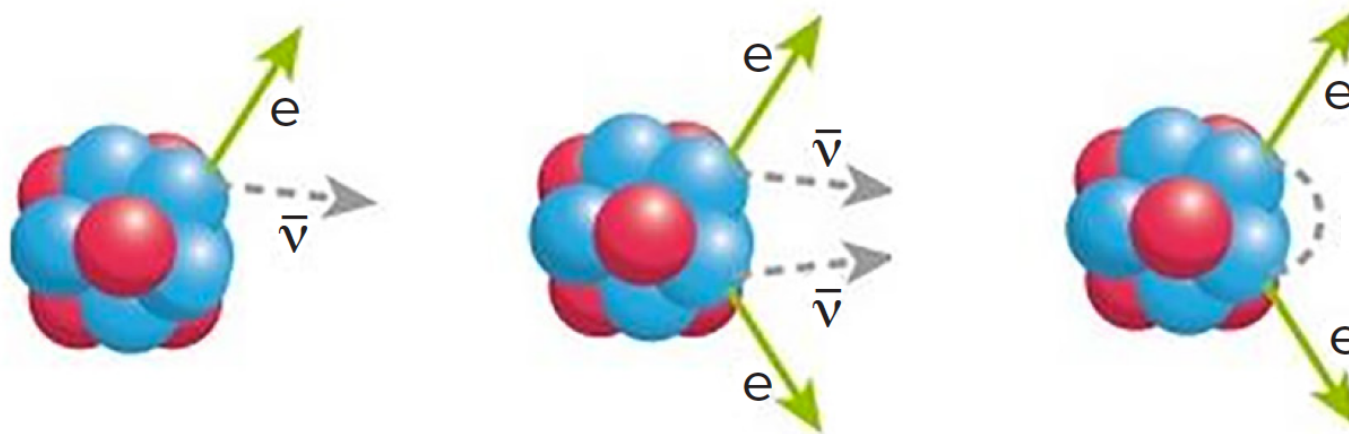


Then matter and anti-matter annihilated leaving just us?



# Majorana Neutrino

- With the demonstration on non-zero neutrino mass we are now positioned to look into the difference between Majorana and Dirac masses.
- What neutrino scientists hope to accomplish in the next generation of experiments is to observe
  - CP-violation in neutrinos
  - Discover Majorana fermions.
- Neutrinoless double-beta decay ( $0\nu\beta\beta$ ) is a powerful tool to investigate Lepton Number Violation (LNV), and the only known practical way to assess the nature of the neutrinos.



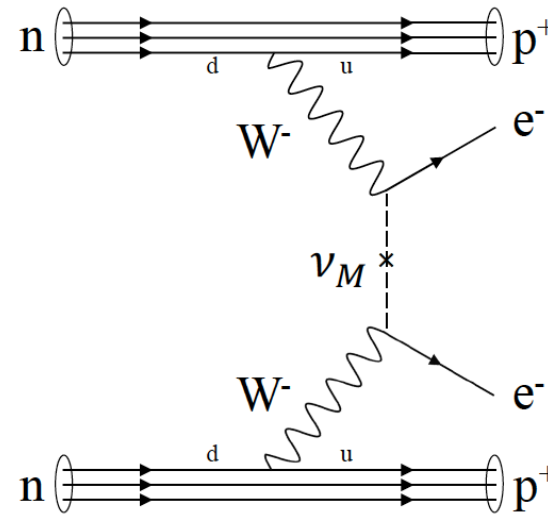
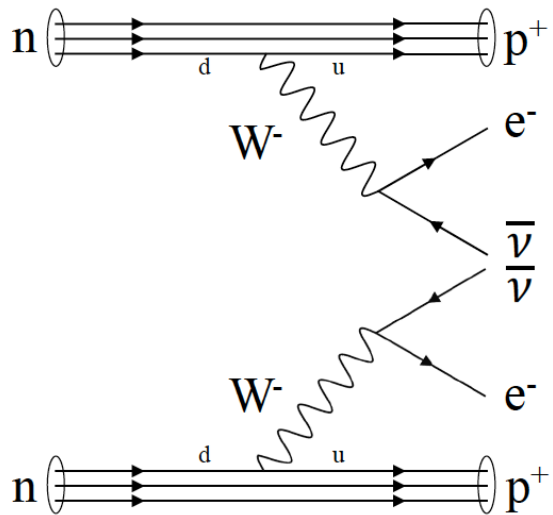
Standard  $\beta$  Decay

Double  $\beta$  Decay

Neutrinoless Double  $\beta$  Decay

# Neutrinoless double-beta decay

- If observed, the  $0\nu\beta\beta$  decay would demonstrate the explicit existence of lepton number violation.
  - Majorana mass term effectively produces excess of matter over anti-matter
  - If the neutrinoless double beta-decay process occurs it may be responsible for seeding the Early Universe with ordinary matter.

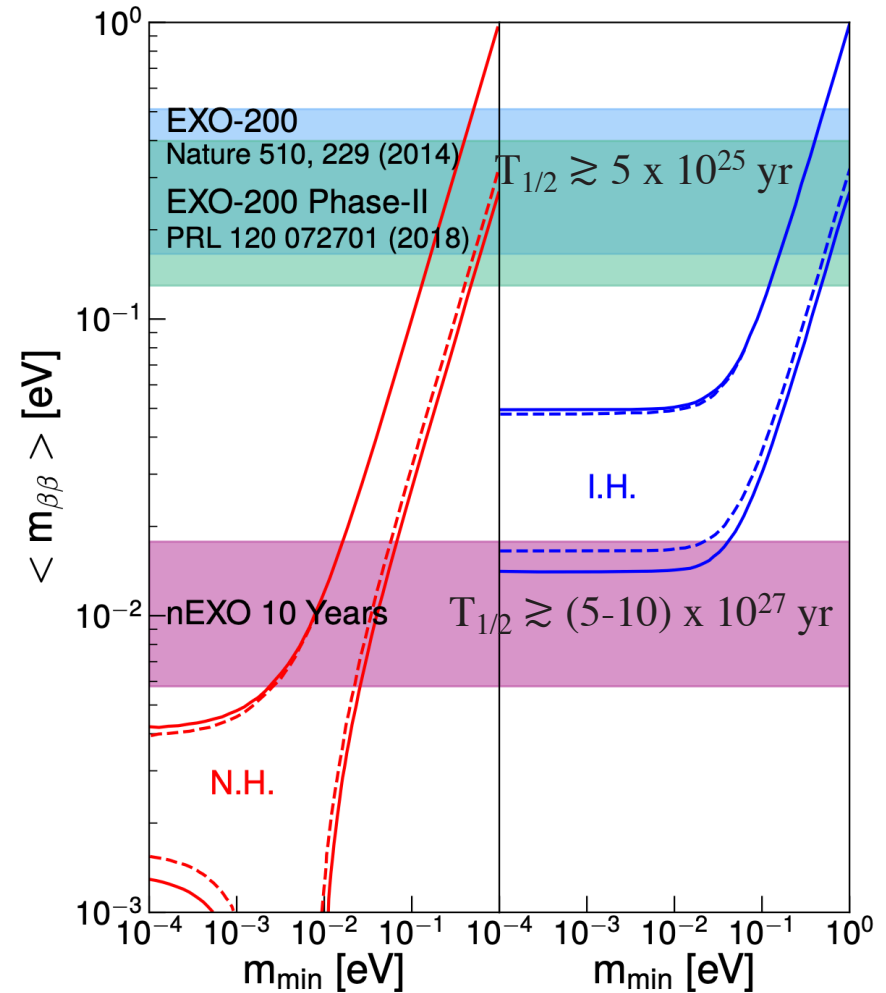
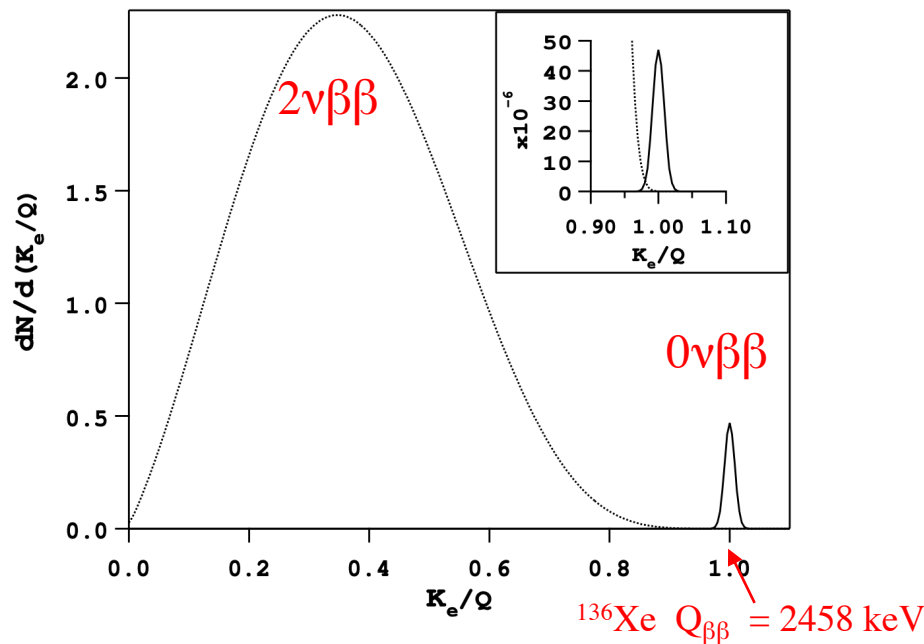


- As the SM process the  $2\nu\beta\beta$  decay process conserves both baryon and lepton number separately
  - observed in about a dozen isotopes.
- The  $0\nu\beta\beta$  decay is a leptogenic process that creates two out-going leptons - only possible if neutrinos are Majorana-type particles.
  - current searches setting half-life limits of  $> 10^{25}$  years



# Enriched Xenon Observatory (EXO) Experiment

- EXO (Enriched Xenon Observatory) is the program put together to search for neutrinoless double beta-decay in  $^{136}\text{Xe}$ 
  - EXO-200: initial EXO phase
  - nEXO: next phase with 5 tonne LXe TPC



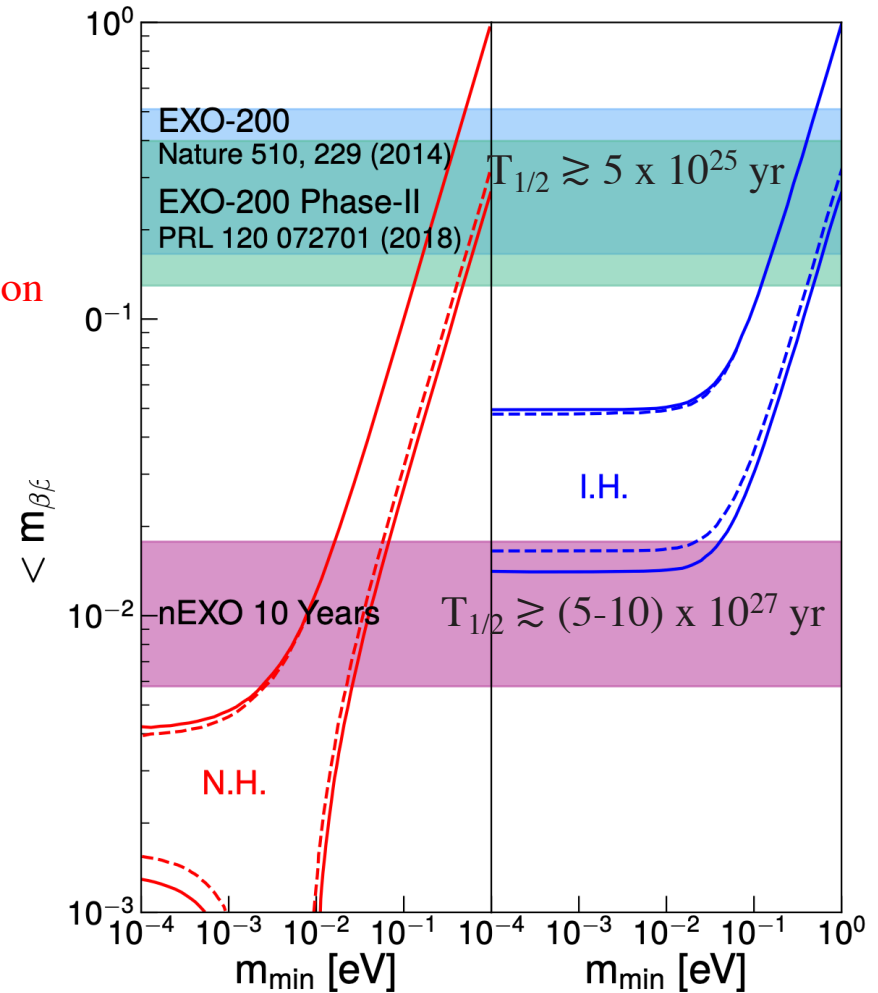
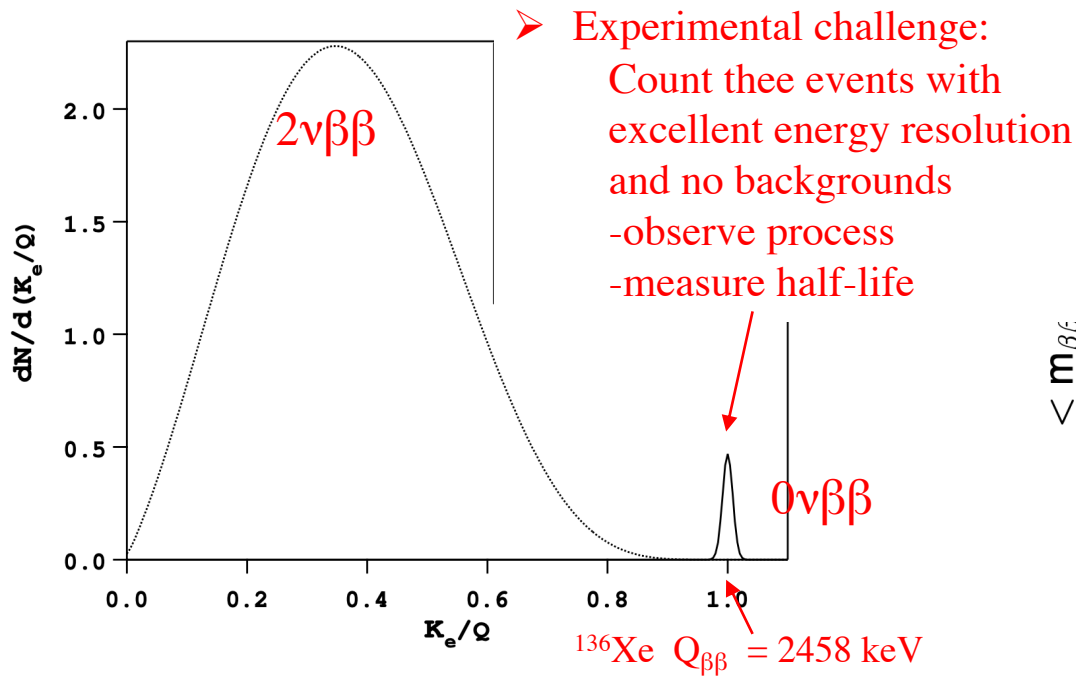
$$[T_{1/2}^{0\nu}]^{-1} = \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2} G^{0\nu} |M^{0\nu}|^2$$

$$\langle m_{\beta\beta} \rangle = ||U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i1} + |U_{e3}|^2 m_3 e^{i2}|$$



# Enriched Xenon Observatory (EXO) Experiment

- EXO (Enriched Xenon Observatory) is the program put together to search for neutrinoless double beta-decay in  $^{136}\text{Xe}$ 
  - EXO-200: initial EXO phase
  - nEXO: next phase with 5 tonne LXe TPC



$$[T_{1/2}^{0\nu}]^{-1} = \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2} G^{0\nu} |M^{0\nu}|^2$$

$$\langle m_{\beta\beta} \rangle = ||U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i1} + |U_{e3}|^2 m_3 e^{i2}|$$



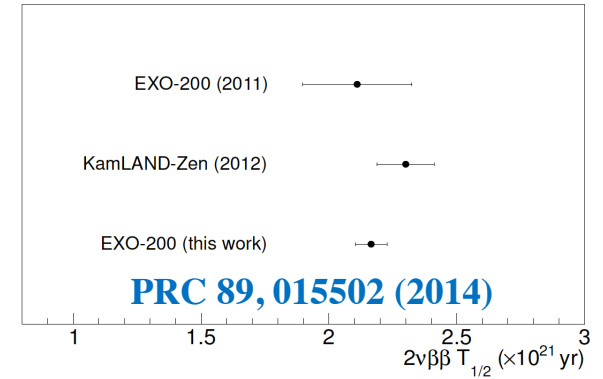
# Enriched Xenon Observatory (EXO) Experiment

➤ EXO-200: initial EXO phase provided the following:

- Both the first and the most-precise measurement of  $2\nu\beta\beta$  decay mode of  $^{136}\text{Xe}$

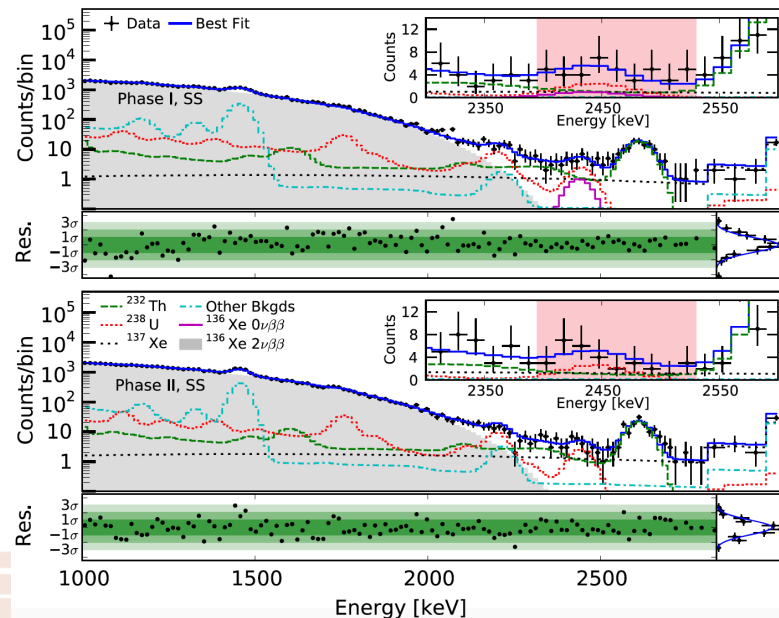
Observation of Two-Neutrino Double-Beta Decay in  $^{136}\text{Xe}$  with EXO-200 **PRL 107, 212501 (2011)**

N. Ackerman,<sup>1,\*</sup> B. Aharmim,<sup>2</sup> M. Auger,<sup>3</sup> D.J. Auty,<sup>4</sup> P.S. Barbeau,<sup>5</sup> K. Barry,<sup>5</sup> L. Bartoszek,<sup>5</sup> E. Beauchamp,<sup>2</sup> V. Belov,<sup>6</sup> C. Benitez-Medina,<sup>7</sup> M. Breidenbach,<sup>1</sup> A. Burenkov,<sup>6</sup> B. Cleveland,<sup>2</sup> R. Conley,<sup>1</sup> E. Conti,<sup>1,†</sup> J. Cook,<sup>8</sup> S. Cook,<sup>7</sup> A. Coppens,<sup>9</sup> I. Counts,<sup>5</sup> W. Craddock,<sup>1</sup> T. Daniels,<sup>8</sup> M.V. Danilov,<sup>6</sup> C.G. Davis,<sup>10</sup> J. Davis,<sup>9</sup> R. deVoe,<sup>5</sup> Z. Djurcic,<sup>4,‡</sup> A. Dobi,<sup>10</sup> A.G. Dolgolenko,<sup>6</sup> M.J. Dolinski,<sup>5</sup> K. Donato,<sup>2</sup> M. Dunford,<sup>9</sup> W. Fairbank Jr.,<sup>7</sup> J. Farine,<sup>2</sup> P. Fierlinger,<sup>11</sup> D. Franco,<sup>3</sup> D. Freytag,<sup>1</sup> G. Giroux,<sup>3</sup> R. Gornea,<sup>3</sup> K. Graham,<sup>9</sup> G. Gratta,<sup>5</sup> M.P. Green,<sup>5</sup> C. Hagemann,<sup>9</sup> C. Hall,<sup>10</sup> K. Hall,<sup>7</sup> G. Haller,<sup>1</sup> C. Hargrove,<sup>9</sup> R. Herbst,<sup>1</sup> S. Herrin,<sup>1</sup> J. Hodgson,<sup>1</sup> M. Hughes,<sup>4</sup> A. Johnson,<sup>1</sup> A. Karelina,<sup>6</sup> L.J. Kaufman,<sup>12</sup> T. Koffas,<sup>5,§</sup> A. Kuchenko,<sup>6</sup> A. Kumar,<sup>5</sup> K.S. Kumar,<sup>8</sup> D.S. Leonard,<sup>13</sup> F. Leonard,<sup>9</sup> F. LePort,<sup>5,¶</sup> D. Mackay,<sup>1</sup> R. MacLellan,<sup>4</sup> M. Marino,<sup>11</sup> Y. Martin,<sup>3,\*\*</sup> B. Mong,<sup>7</sup> M. Montero Diez,<sup>5</sup> P. Morgan,<sup>8</sup> A.R. Müller,<sup>5</sup> R. Neilson,<sup>5</sup> R. Nelson,<sup>14</sup> A. Odian,<sup>1</sup> K. O'Sullivan,<sup>5</sup> C. Ouellet,<sup>9</sup> A. Piepke,<sup>4</sup> A. Pocar,<sup>8</sup> C.Y. Prescott,<sup>1</sup> K. Pushkin,<sup>4</sup> A. Rivas,<sup>5</sup> E. Rollin,<sup>9</sup> P.C. Rowson,<sup>1</sup> J.J. Russell,<sup>1</sup> A. Sabourov,<sup>5</sup> D. Sinclair,<sup>9,††</sup> K. Skarpaas,<sup>1</sup> S. Slutsky,<sup>10</sup> V. Stekhanov,<sup>6</sup> V. Strickland,<sup>9,††</sup> M. Swift,<sup>1</sup> D. Tosi,<sup>5</sup> K. Twelker,<sup>5</sup> P. Vogel,<sup>15</sup> J.-L. Vuilleumier,<sup>3</sup> J.-M. Vuilleumier,<sup>3</sup> A. Waite,<sup>1</sup> S. Waldman,<sup>5,‡‡</sup> T. Walton,<sup>7</sup> K. Wamba,<sup>1</sup> M. Weber,<sup>3</sup> U. Wichoski,<sup>2</sup> J. Wodin,<sup>1</sup> J.D. Wright,<sup>8</sup> L. Yang,<sup>1</sup> Y.-R. Yen,<sup>10</sup> and O.Ya. Zeldovich<sup>6</sup>



- One of the most competitive limits on  $0\nu\beta\beta$  half-life **PRL 123, 161802 (2019)**

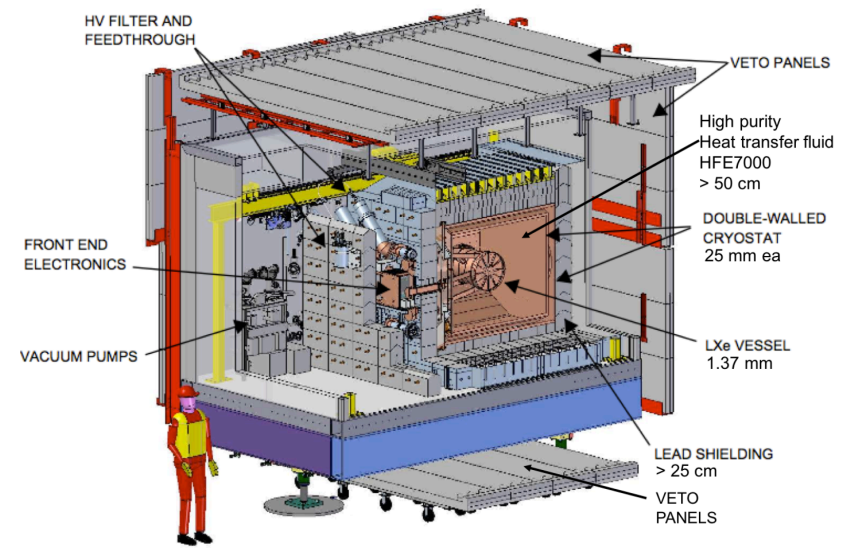
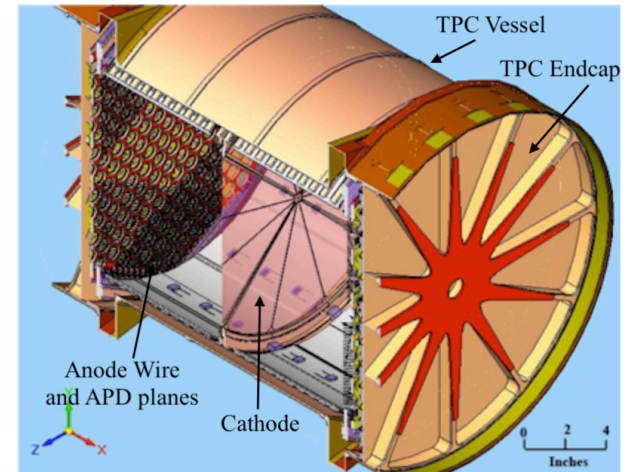
$T_{1/2} > 3.5 \times 10^{25} \text{yr}$  (90% CL)



# Enriched Xenon Observatory (EXO) Experiment

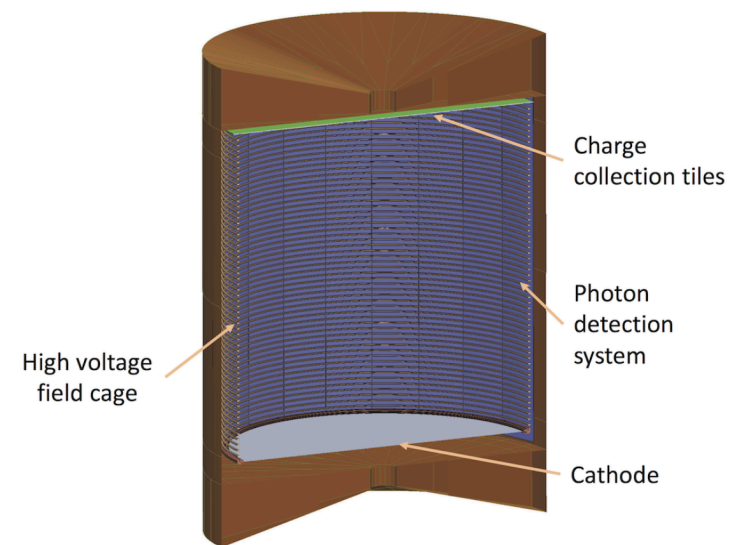
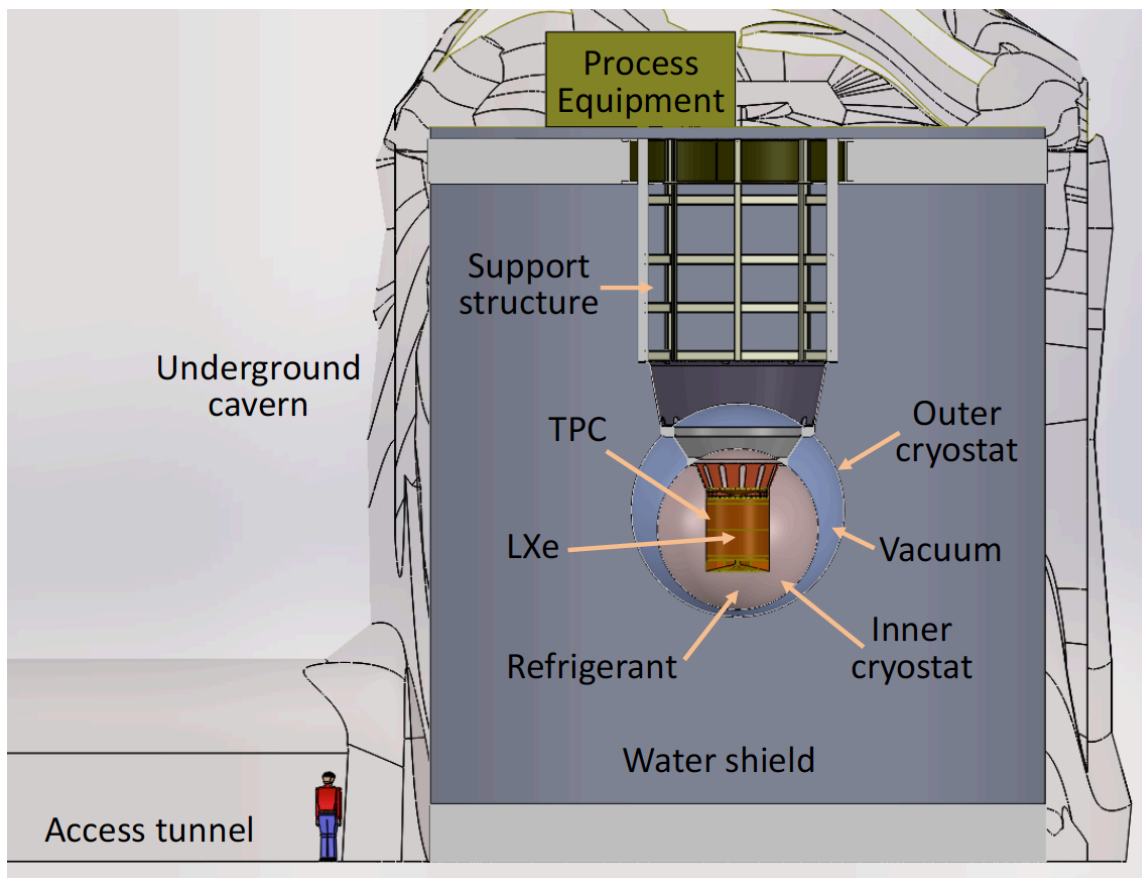
➤ EXO-200: initial EXO phase provided the following:

- Established the unique capabilities of a monolithic LXe TPC
  - optimal energy resolution
  - enhanced signal detection efficiency
  - strong topological discrimination of backgrounds
  - reproducible background model
- These achievements provided a path forward for nEXO
  - planned five-ton scale successor to EXO-200
  - designed to achieve a sensitivity to the  $0\nu\beta\beta$  half-life of  $\sim 10^{28}$  yr in  $^{136}\text{Xe}$ .



# Enriched Xenon Observatory (EXO) Experiment

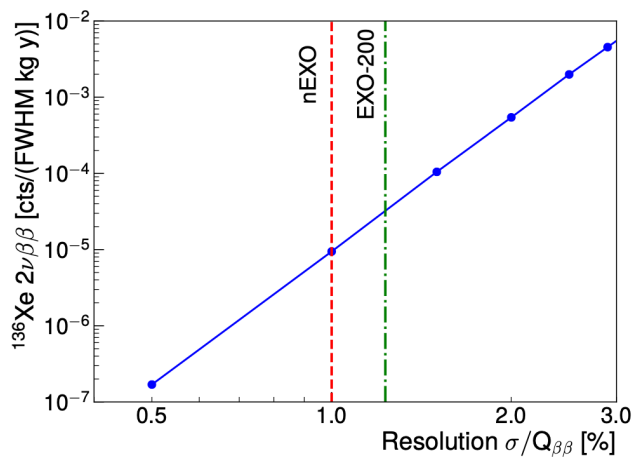
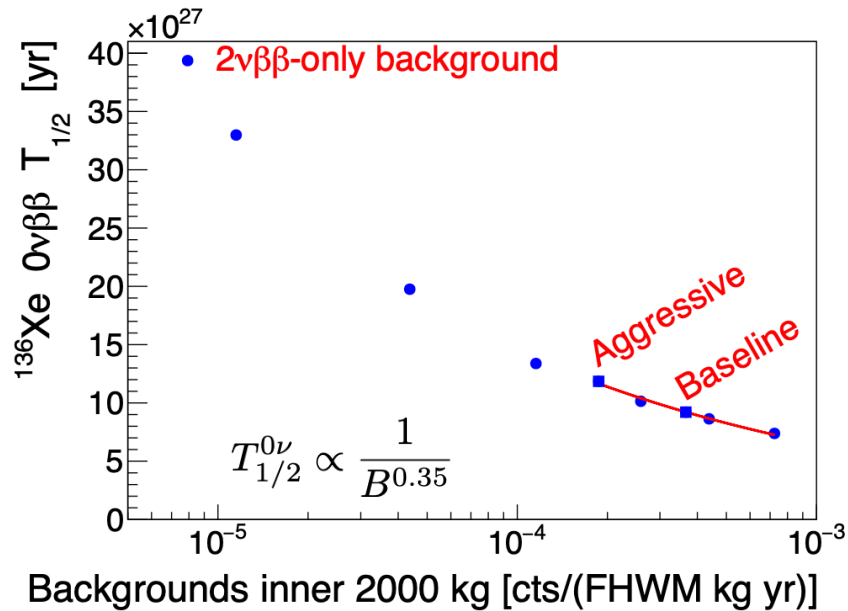
- nEXO detector design
  - LXe TPC located inside a vacuum insulated cryostat filled with HFE-7000
  - Outer detector is composed of a large active water tank



Cross-section of the TPC

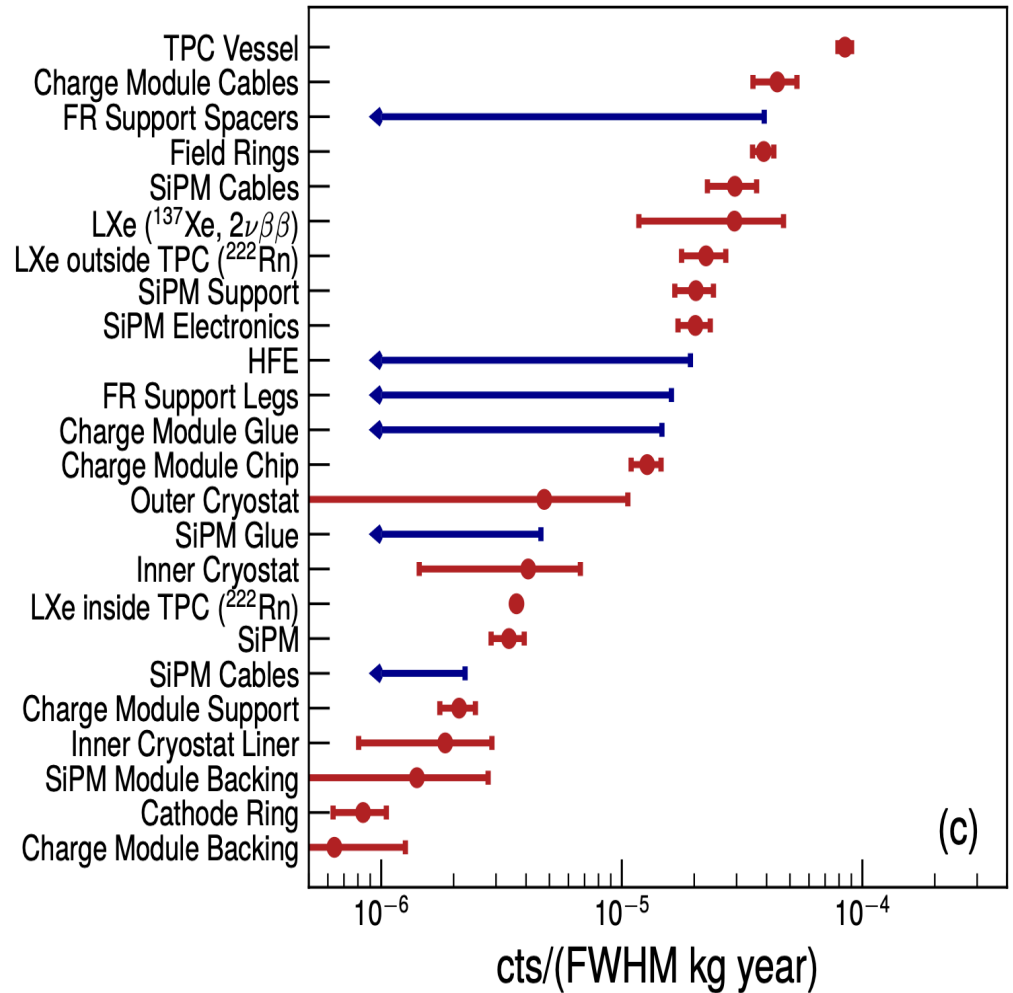
# EXO Discovery Potential

- Sensitivity as a function of background within the FWHM  $Q_{\beta\beta}$  region



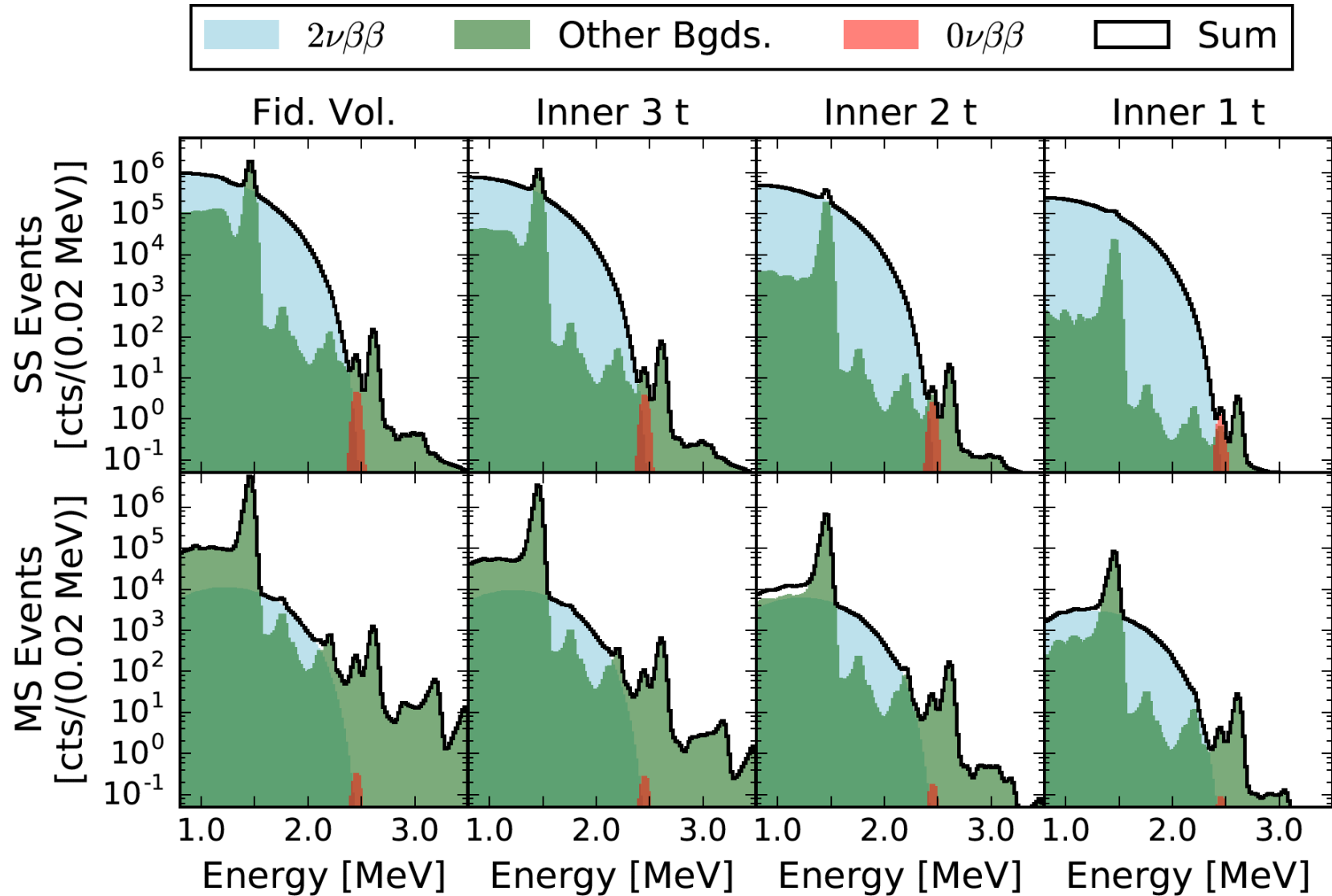
PRC 97, 065503 (2018)

Breakdown of background components:



# EXO Discovery Potential

PRC 97,065503 (2018)

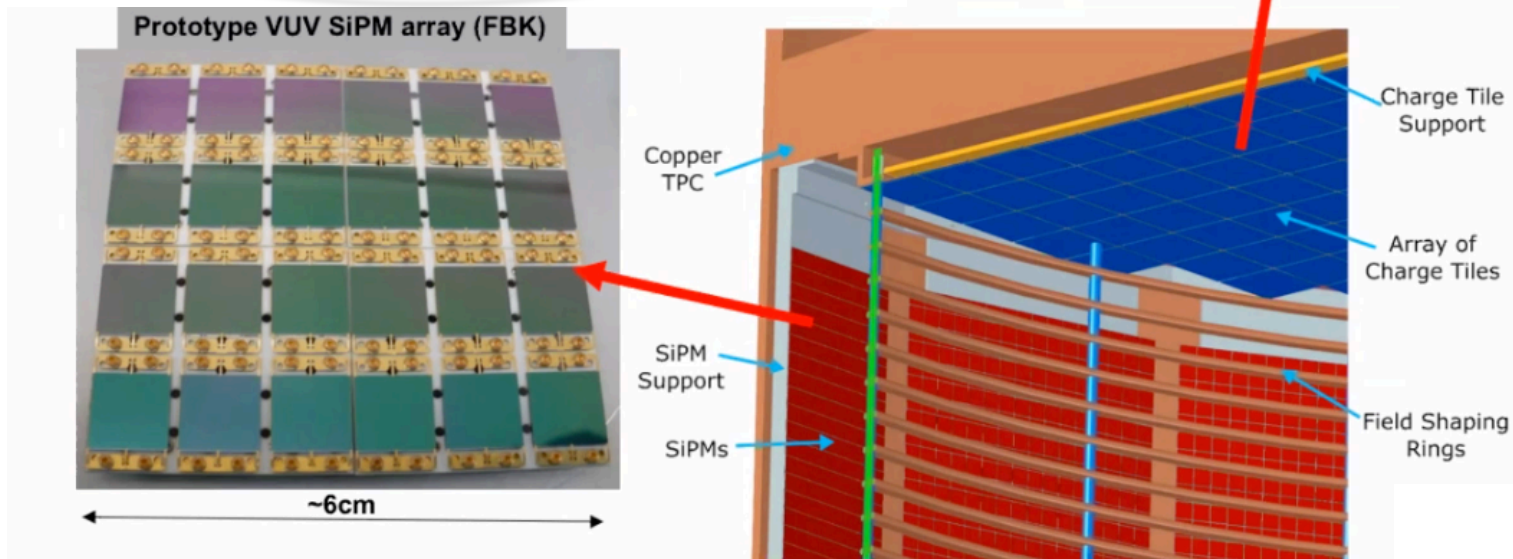
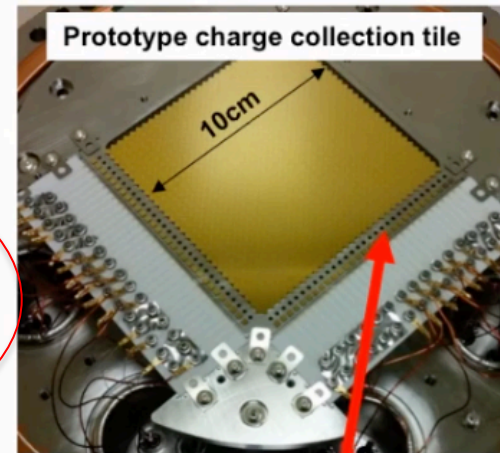


➤ nEXO 10-year discovery potential at  $T_{1/2} = 5.7 \times 10^{27}$  yr.



# nEXO: Active Detector Elements

- EXO Detector components
  - Monolithic TPC
  - Single drift volume
  - Cold Electronics (ASIC) to reach adequate energy resolution
  - Purification methods to control and maintain LXe purity
  - Radiopure materials (silica, sapphire) to reach low-background levels



Picture From Michelle D./APS April 2020

- The red indicated areas where SLAC group established leadership roles.



# More on CP-violation Phase(s)

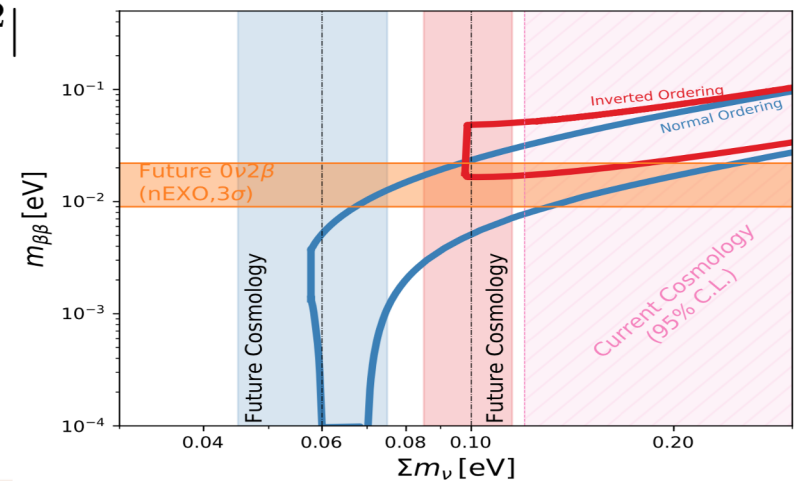
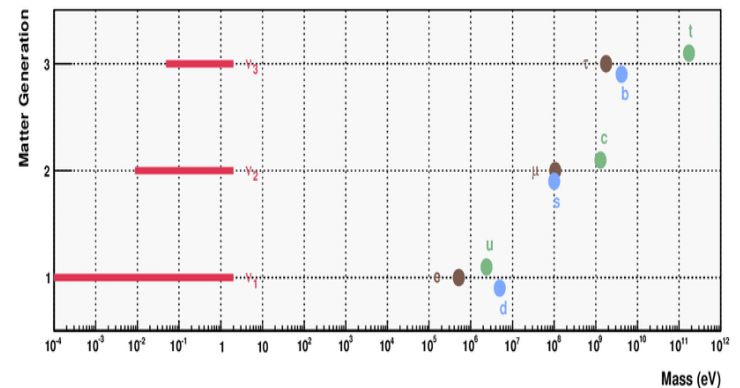
- Long-baseline measurements measurements, based on neutrino oscillation are sensitive to  $\delta_{CP}$  phase, but cannot measure Majorana phases, should the neutrino be a Majorana particle.
- Can these Majorana phases be observed?
  - Yes, if NLDBD is observed and if neutrino mass is directly measured in tritium beta decay (or cosmology)  $\sum_i m_i$
  - We would combine these measurements

$$M_{\beta\beta} = ||U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i1} + |U_{e3}|^2 m_3 e^{i2}|$$

$$m_{\beta}^2 = \sum_i |U_{ei}|^2 m_i^2$$

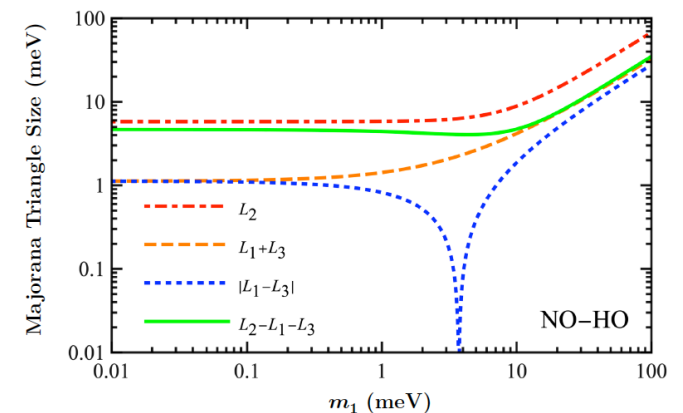
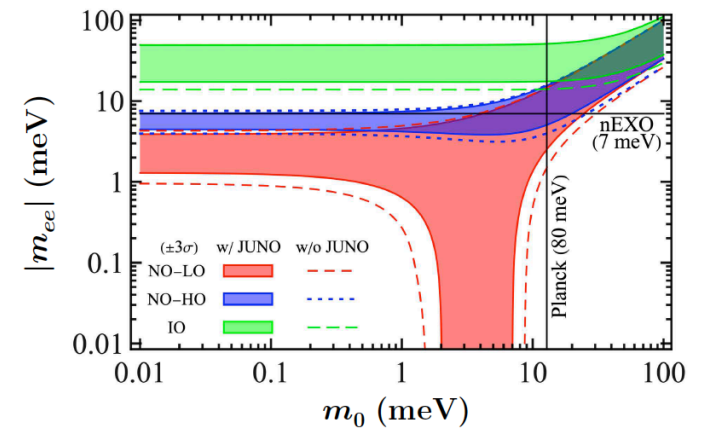
-In a reasonable approximation  $\Delta m_{12}^2 \ll \Delta m_{13}^2$  one Majorana phase dominates, and could be extracted as

$$\cos \alpha_1 \approx 1 - \frac{2}{\sin^2 \theta_{12}} \left( 1 - \frac{M_{\beta\beta}^2}{m_{\beta}^2} \right)$$



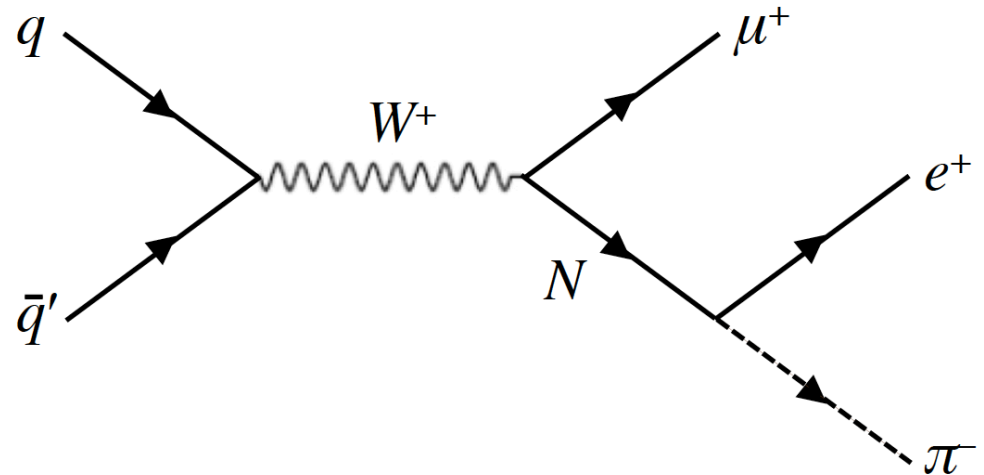
# More on CP-violation Phase(s)

- There is an idea where authors in principle hope for a negative outcome of  $0\nu\beta\beta$ :
  - “The Normal Neutrino Mass Hierarchy is Exactly What We Need”, arXiv: 1910.02666
  - In this scenario Normal ordering opens up the possibility of simultaneously measuring the two Majorana CP phases.
  - Other goal is to test NSI models that might affect solar LMA solution (HO).
- It requires two challenging things to happen, assuming the neutrino is a Majorana particle:
  - Push the sensitivity of  $0\nu\beta\beta$  to unprecedented value of  $M_{\beta\beta} \lesssim 1$  meV
  - Discover Majorana neutrino through a process other than  $0\nu\beta\beta$
- This brings me to tell you about one other method to look for Majorana neutrinos.



# Alternative Majorana Neutrino Searches

- Search for a heavy neutral lepton N.
- Example: the following process would violate lepton number conservation, to indicate that N is a Majorana neutrino
  - requires a charge-sensitive detector.



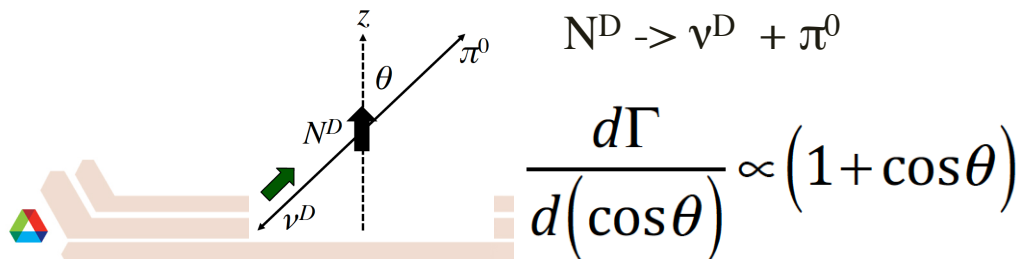
- The decays of the form  $N \rightarrow \nu + X$  could also reveal whether neutrinos are Dirac or Majorana particles.

$$\nu = \nu_1, \nu_2, \nu_3, \text{ but } X = \bar{X}$$

Depending on the mass of N:  
 $X = \gamma, \pi^0, \rho^0, Z^0, H^0$ .

- What is different in two cases?

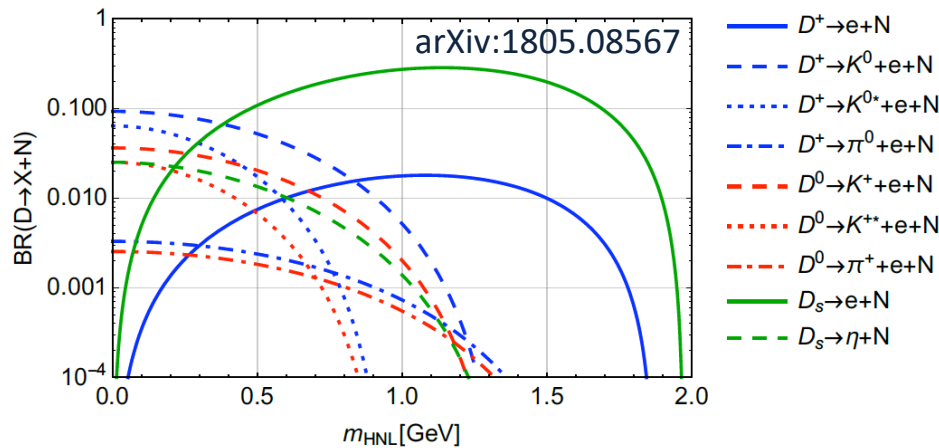
- Decay rates (but depend on unknown mixing angles):  $\Gamma(N^M \rightarrow \nu^M + X) = 2\Gamma(N^D \rightarrow \nu^D + X)$
- Angular distribution of Dirac vs Majorana decays



Dirac case: Not isotropic  
 Majorana case: Isotropic

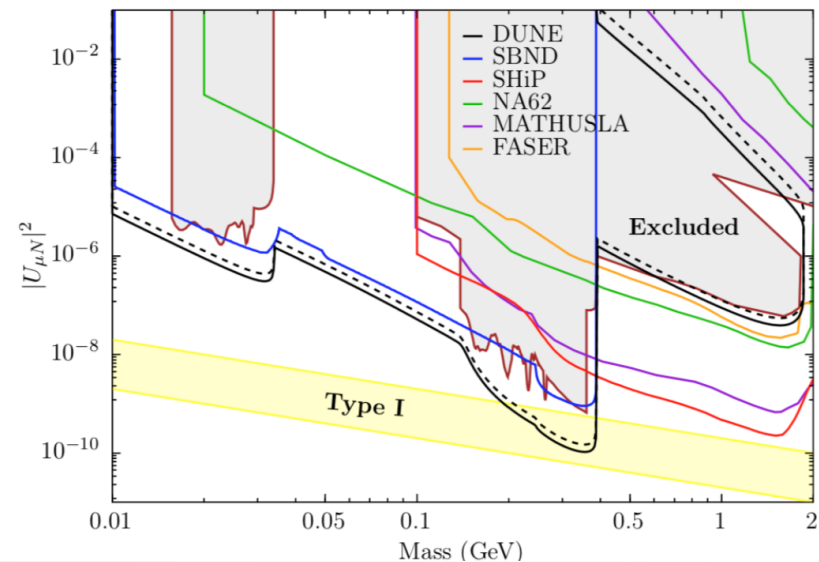
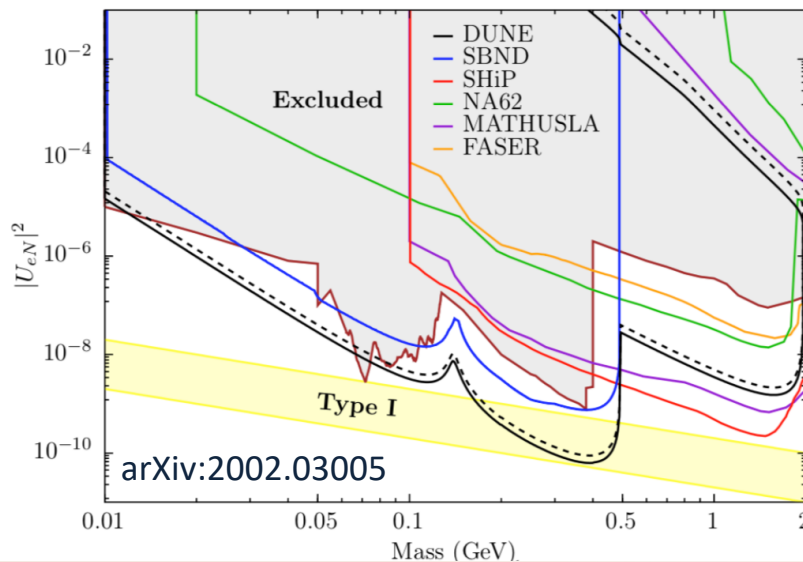
# Heavy Neutral Leptons could be search with DUNE Near Detector(s)

- Production of charge and bottom mesons in beams (such as LBNF) enables search for weakly interacting HNLs such as right-handed partners of active neutrinos



➤ Dominant branching ratios of a potential HNL production from different charmed and beauty mesons.

- DUNE ND sensitivity (90% CL) for  $N \rightarrow \nu ee, \nu e\mu, \nu\mu\mu, \nu\pi^0, e\pi,$  and  $\mu\pi$  (combined)



# Summary

- With the demonstration on non-zero neutrino mass we are now positioned to look into the the question of CP-violation, and to search for differences between Majorana and Dirac masses.
- What we hope to accomplish in the next generation of experiments is to observe
  - CP-violation in neutrinos
  - Discover Majorana fermions.
- The DUNE, with Near and Far Detectors, is planned to measure a non-zero  $\delta_{CP}$  over a large range of values.
  - In addition, the DUNE results will be augmented with T2K and NOvA measurements.
- Neutrinoless double-beta decay ( $0\nu\beta\beta$ ) is a powerful tool to investigate Lepton Number Violation (LNV), and the only known practical way to assess the nature of the neutrinos
  - Majorana phase could present additional source of CP-violation
  - Determination of absolute neutrino mass.
- EXO program will probe  $0\nu\beta\beta$  half-life at  $\sim 10^{28}$  yr level
  - We hope for a discovery!

