Fermilab's Neutrino Experiment Program

Steve Brice

Neutrino Theory Network (NTN) Workshop

Thursday 23 June 2022

Overview

- Neutrino Science
  - Why are Neutrinos Important
  - Neutrino Science in 2022
  - The Big Neutrino Questions and Fermilab's Role
- Experiments: Operations Complete
  - MINERvA
  - MicroBooNE
- Experiments: Operating
  - NOvA
  - ANNIE
  - ICARUS
- Experiments: Building
  - SBND
  - DUNE

It all leads to DUNE

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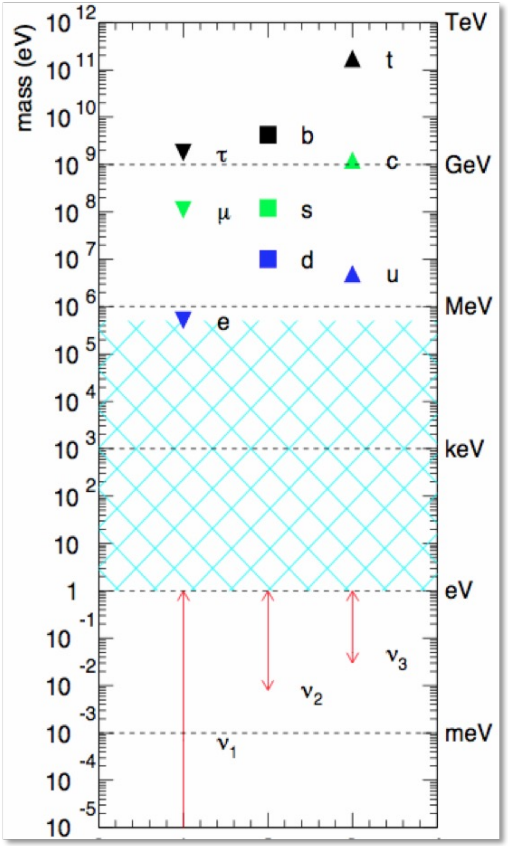
What is not in this talk

- Neutrino Facilities
  - I'll talk about R&D, but not the facilities like PAB and the new labs in the Edwards Building (IERC) that enable them
- Neutrino Projects
  - I'll talk about DUNE, but not the LBNF/DUNE 413b Project that is building the facility and experiment
- Neutrino Personnel
  - I'll mention theorist work by name, but not the experimentalists
  - I'll not discuss hiring strategy and demographic plans for neutrino personnel at the lab
  - I'll not talk about the Neutrino Physics Center (NPC) or other initiatives to promote Neutrino Science

Why are Neutrinos Important

- Particle Physics has made great progress in the last half century probing the quark half of the fundamental particles. We are now in a position to propose doing similar for the neutrinos.

- Neutrinos are the real oddities of the fundamental particles (only interact Weakly, ultra small, but non-zero masses). Science often advances when studying the oddities



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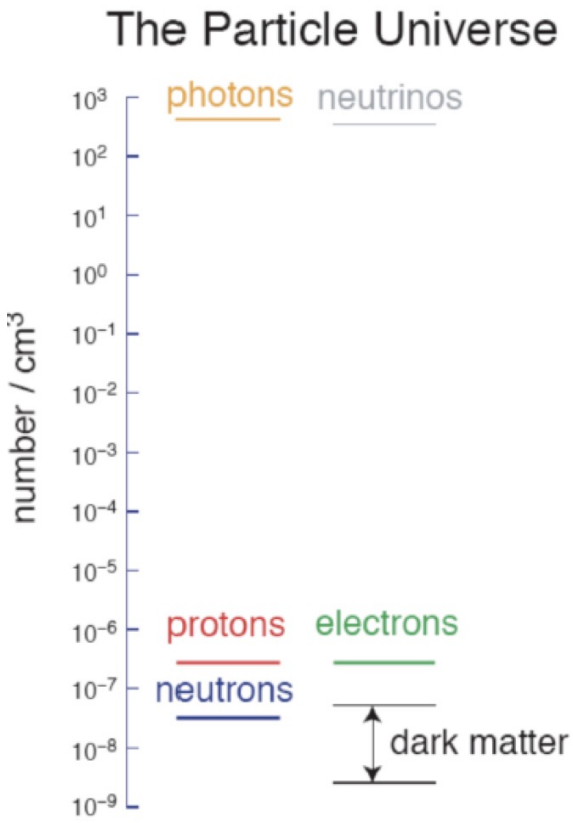
Why are Neutrinos Important?

- Neutrinos may only interact Weakly, but they are the most abundant particle in the universe with a pivotal role in the evolution of our universe

- A difference between how the neutrino types mix and how the antineutrino types mix is postulated to be the reason why matter dominates over anti-matter in our universe (i.e. why we exist)



Neutrino and Quark Mixing and Masses

$$V_{PMNS} \approx \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Neutrino Masses < 2 eV

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Quark Masses = 3×10^{6} eV
to
1.7×10^{11} eV

Very different
No idea why, but it is probably important

The Present Neutrino Landscape

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\Delta m_{21}^2 = 7.42\ ^{+0.21}_{-0.20} \times 10^{-5}\ eV^2$

$|\Delta m_{32}^2| = 2.51\ ^{+0.027}_{-0.027} \times 10^{-3}\ eV^2$

$m(\nu_e) < 0.8$ eV (90% CL)

$\theta_{12} = 33.45\ ^{+0.77}_{-0.75}$ deg

$\theta_{23} = 42.1\ ^{+1.1}_{-0.9}$ deg

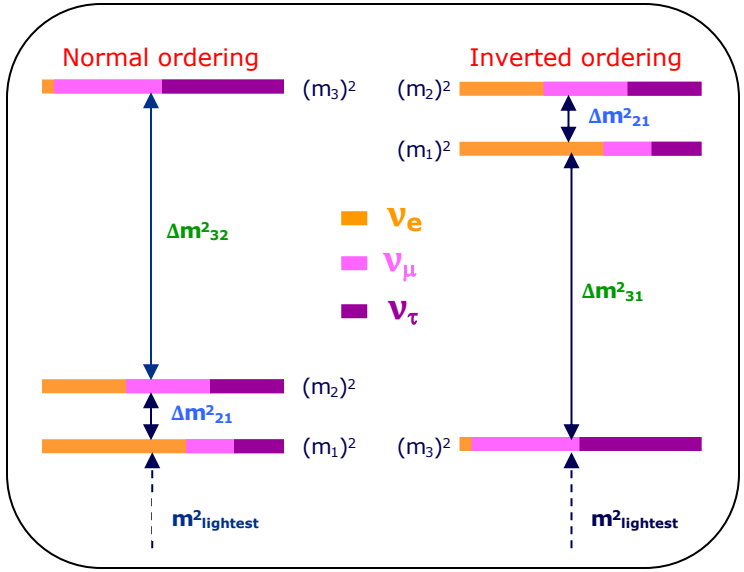
$\theta_{13} = 8.62\ ^{+0.12}_{-0.12}$ deg

θ_{23} octant = ?

Sign Δm_{32}^2 = ?

δ = ?

$m_{lightest}$ = ?



1σ uncertainties, normal ordering assumed, Th. Schwetz, Neutrino 2022, Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

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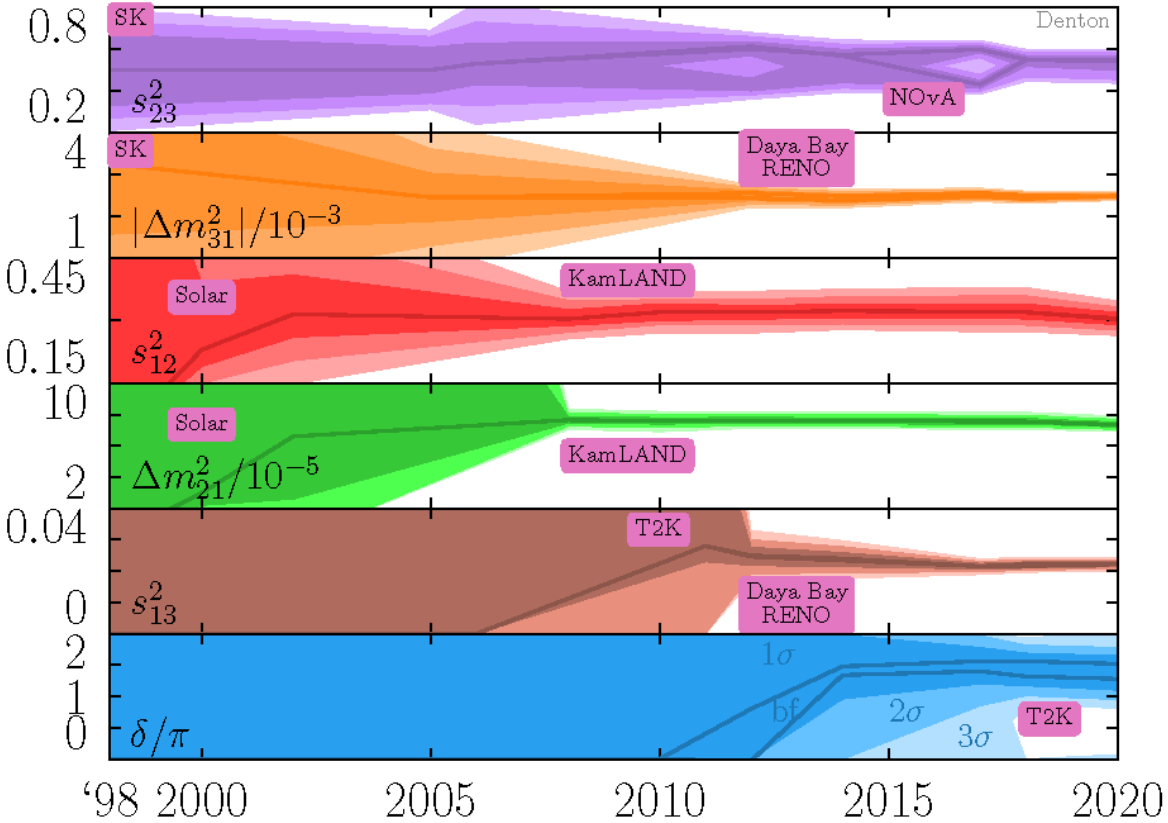
The Last 20 Years



Peter B. Denton (BNL) Neutrino 2022: June 1/2, 2022 2/34

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Experimental Thrusts in Neutrino Physics and Fermilab's Role

1) Reveal the pattern of neutrino masses and mixings
   - In which octant is θ_{23}? **NOvA → DUNE**
   - How are the masses ordered? **NOvA → DUNE**
   - Is CP violated? **DUNE**
   - What are the neutrino masses? **No plans to address at Fermilab**
   - Are neutrinos their own anti-particles? **No plans to address at Fermilab**

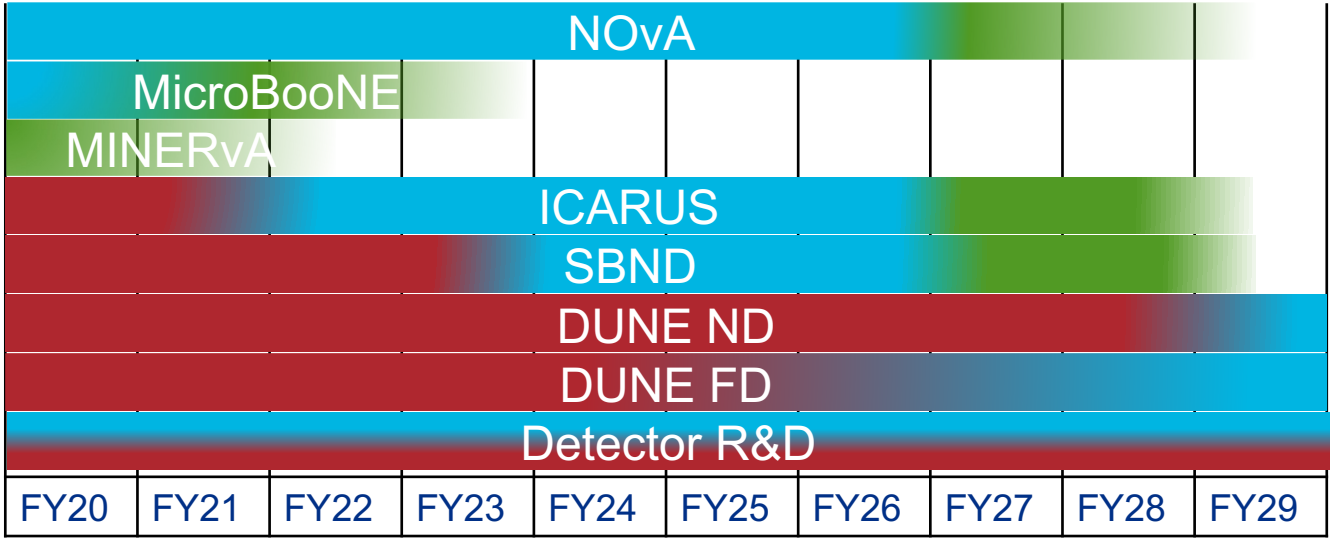
2) Discover if the situation is more complex than 3 neutrinos with Standard Model interactions
   - Do neutrinos interact with matter in any non-standard ways? **MINERvA, NOvA, MicroBooNE → SBND, ICARUS → DUNE**
   - Are the LSND and MiniBooNE anomalies new physics? **MicroBooNE → ICARUS, SBND**

3) Carry out the neutrino engineering measurements that make 1) and 2) possible
   MINERvA, ANNIE, MicroBooNE, SBND, ICARUS

Recent, Current, and Planned Fermilab Neutrino Experiments

Beamline	Experiment	Neutrino Operations Status	Main purpose(s)
NuMI	ArgoNeut	Completed 2010	ν-Ar xsecs, LAr TPC technology
	MINOS(+)	Completed 2016	Confirm atmospheric ν oscillations, measure ν mixing parameters
	MINERvA	Completed 2019	ν xsecs
	NOvA	Running	Measure ν mixing parameters, determine ν mass ordering, ν xsecs
BNB	SciBooNE	Completed 2008	ν xsecs, look for SBL ν_μ disappearance
	MiniBooNE	Completed 2012	Look for SBL ν_e appearance, ν xsecs
	MicroBooNE	Completed 2020	Study ν_e-like events, ν-Ar xsecs, LAr TPC technology
	ANNIE	Running	Neutron production in ν interactions, LAPPD technology
	ICARUS	Running	Look for SBL ν_e appearance, ν-Ar xsecs, LAr TPC technology
	SBND	Expected Late 2023	Look for SBL ν_e appearance, ν-Ar xsecs, LAr TPC technology
LBNF	DUNE	Seeking CD1RR 2022	Search for CP violation, probe 3ν mixing, supernova νs, proton decay

Rough Neutrino Experiment Timeline



- Testbeam, ICEBERG, PAB, ANNIE all folded into Detector R&D
- The beginning and termination times are deliberately vague
- It all culminates in DUNE

Design & construction
Operations & analysis
Analysis

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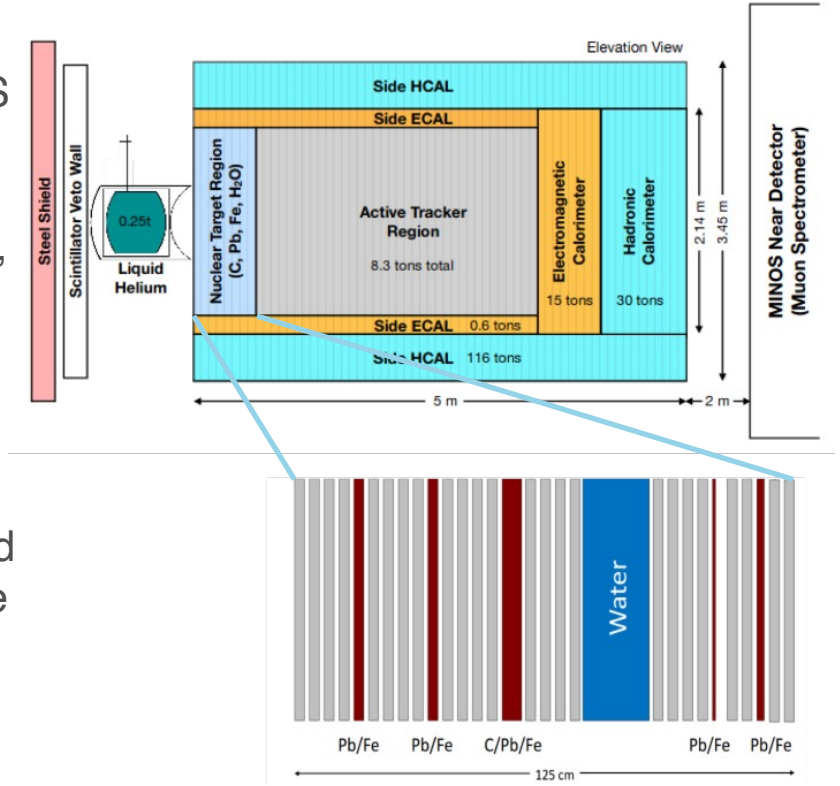
MINERvA Overview

- MINERvA is the only currently active experiment that has high statistics and controlled systematics, different nuclear targets, and access to the DIS/SIS region
- Fine-grained tracking detector and targets of C, Fe, Pb (solid), H_2O and He (liquid)
- Ran from 2009-2019 on axis in NuMI beam, both 3GeV and 6GeV, neutrino and antineutrino beams
- Crazy low flux uncertainties -- 3.3% in ν mode, and 4.9% in $\bar{\nu}$ mode thanks to $\nu(\bar{\nu}) - e$ scattering (to be used by DUNE)
- 36 Physics publications so far (1/3 PRL's)



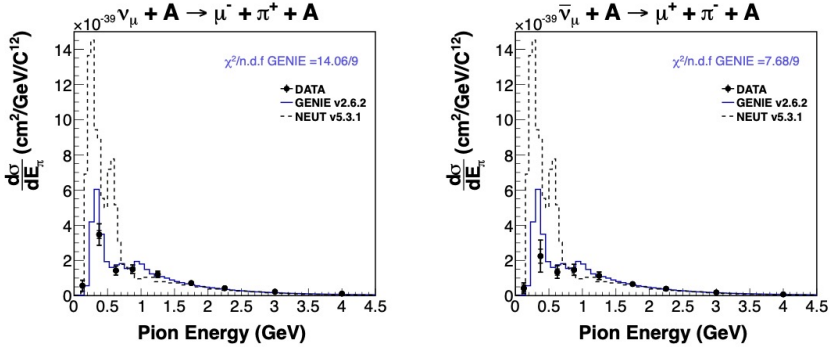
Previous MINERvA Accomplishments

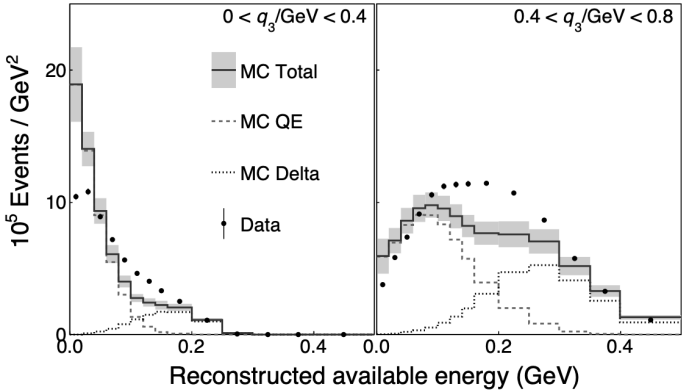
- "solved" the coherent pion SciBooNE mystery and provided a model down-selection and tune *Phys. Rev. Lett. 113, 261802 (2014)*

- showed experimental evidence for a strong multinucleon effect (presumably the reason for the MiniBooNE high axial mass result)

- provided a way for experiments (NOvA) to constrain multinucleon its effect in oscillation measurements. *Phys. Rev. Lett. 116, 071802 (2016)*

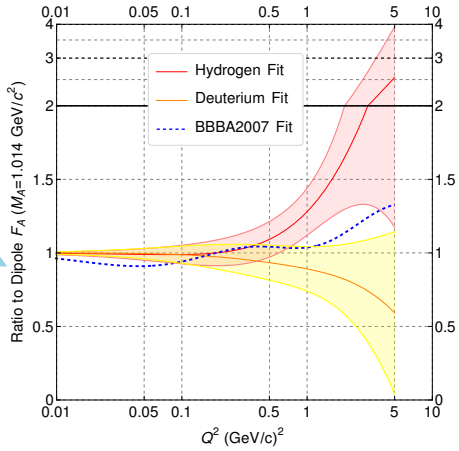
- Many exclusive channel measurements, neutrino and antineutrinos, quantifying several different effects of the nucleus on neutrino scattering.

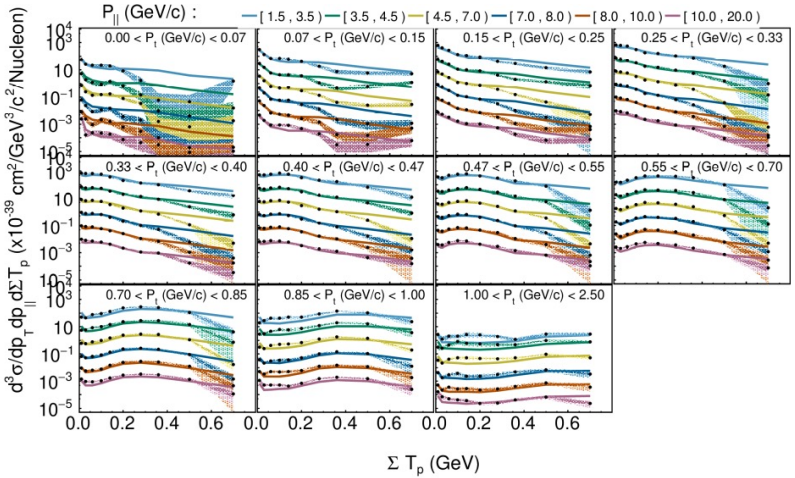




Future MINERvA Physics Program

- 2 exciting new results submitted:
  - Simultaneous muon & hadron 3-dimensional cross sections for ν quasielastic-like scattering on CH
  - Novel $\bar{\nu}$ quasielastic scattering on H to extract nucleon form factor F_A





https://arxiv.org/abs/2203.08022

Data Preservation product under construction:
To ensure the community can extract more physics from these data after collaboration stops operating (a la Astronomical Observatory Data Releases)

- Nuclear Target Suite of results: QE-like, π^+ and π^0 Production paper drafts will hit the press this year!

MicroBooNE

MicroBooNE is the longest running liquid argon neutrino detector to date

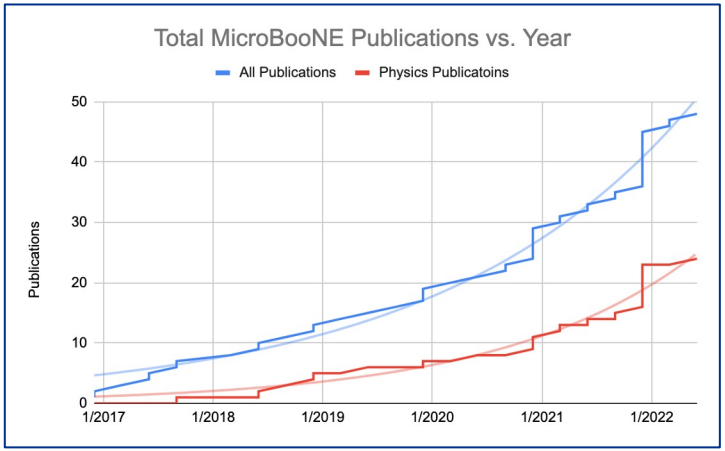
Significant body of pioneering work

- 48 physics papers, 80 public notes
  - Split 50/50 between technical & physics results

Large team of students and postdocs looking at this one-of-a-kind data in MicroBooNE and asking:

- *What can we learn about neutrinos with such high-definition detectors?*
- *What is the source of the MiniBooNE anomaly?*
- *Is there other new physics out there?*

MicroBooNE is producing a lot of firsts & critical work for SBN, DUNE → training the next generation



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Past MicroBooNE science accomplishments

Extensive array of cross section measurements

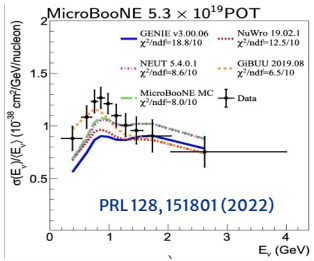
- Including many first measurements on argon

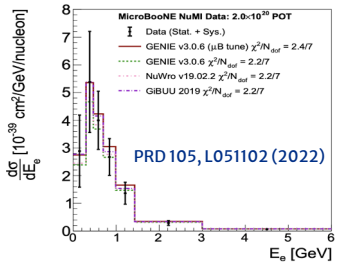
Groundbreaking results probing the MiniBooNE anomaly

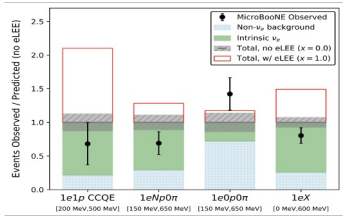
- No excess of ν_e or NC $\Delta \rightarrow N\gamma$ events observed
- Reject x3.18 enhancement of NC $\Delta \rightarrow N\gamma$ rate at 94.8% C.L.
- Reject hypothesis that ν_e CC interactions are fully responsible for the excess at >97% CL

Pioneering BSM program

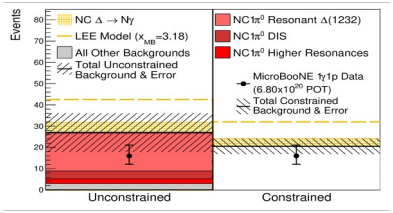
- First LArTPC limits on heavy neutral leptons
- First LArTPC dark sector search for e^+e^- final states



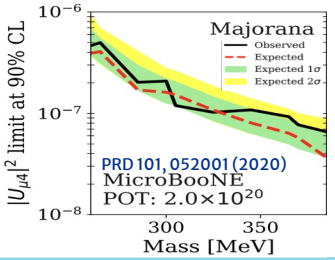


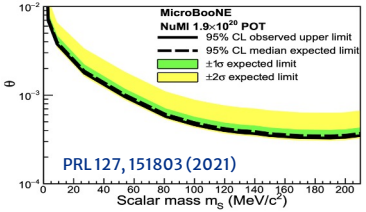


arXiv:2110.14054
(accepted by PRL)



PRL 128, 111801 (2022)





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Future MicroBooNE science accomplishments

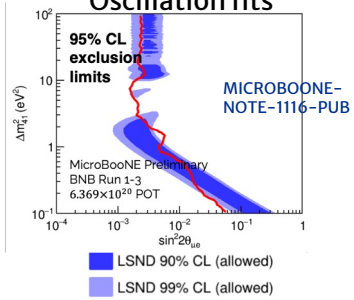
Sterile neutrino oscillation fits

- New results for Neutrino 2022
- Extend to full dataset, including off-axis NuMI beam data

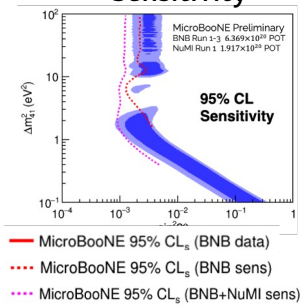
Expanded BSM searches for the origin of the MiniBooNE anomaly, including single photon and e^+e^- final states

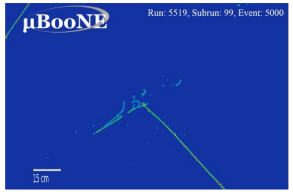
Suite of legacy cross section results, including rare process and multi-differential measurements

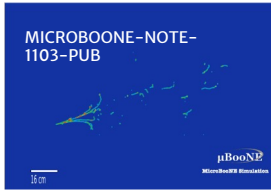
Oscillation fits



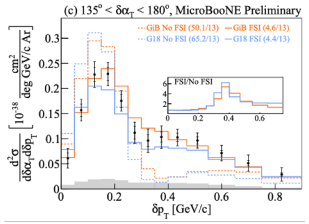
Projected Sensitivity







MICROBOONE-NOTE-1108-PUB



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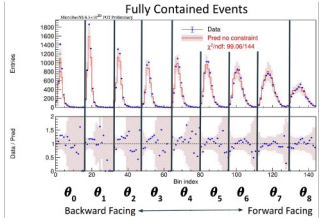

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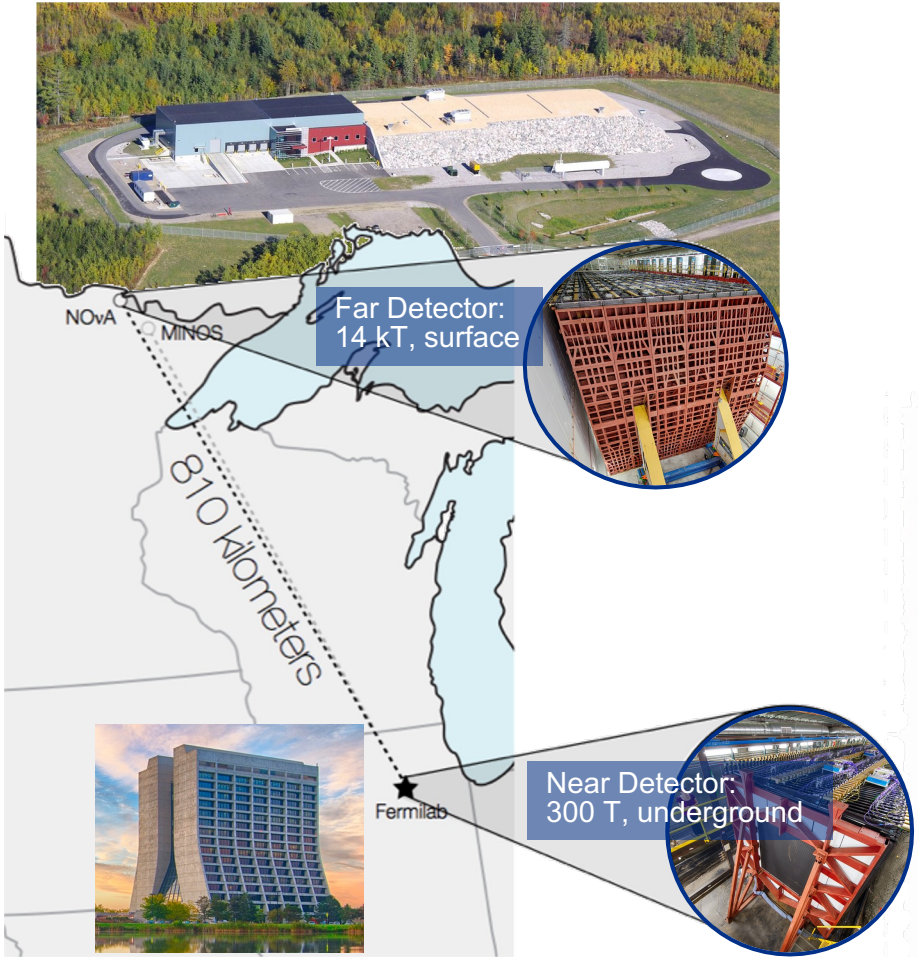
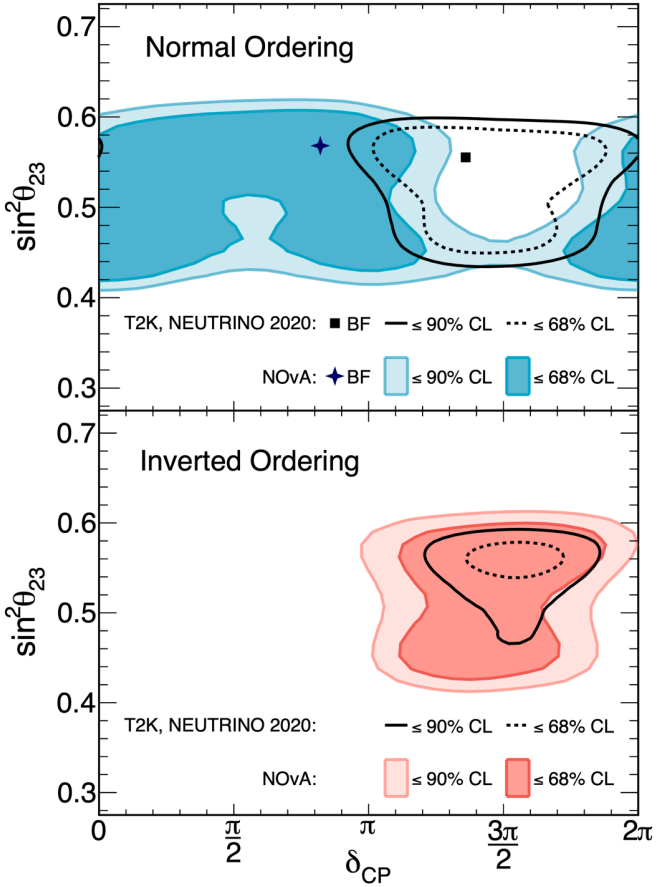
The NOvA Experiment



- Long-baseline neutrino oscillation experiment
  - 2 functionally identical, tracking calorimeter detectors
  - NuMI beam: ν_μ or $\bar{\nu}_\mu$
  - Off-axis, narrow beam
- Broad physics program:
  - 3-flavor oscillations
  - Exotic oscillations
  - Neutrino scattering
  - Astrophysics
  - BSM physics
- 266 collaborators from 49 institutions in 8 countries

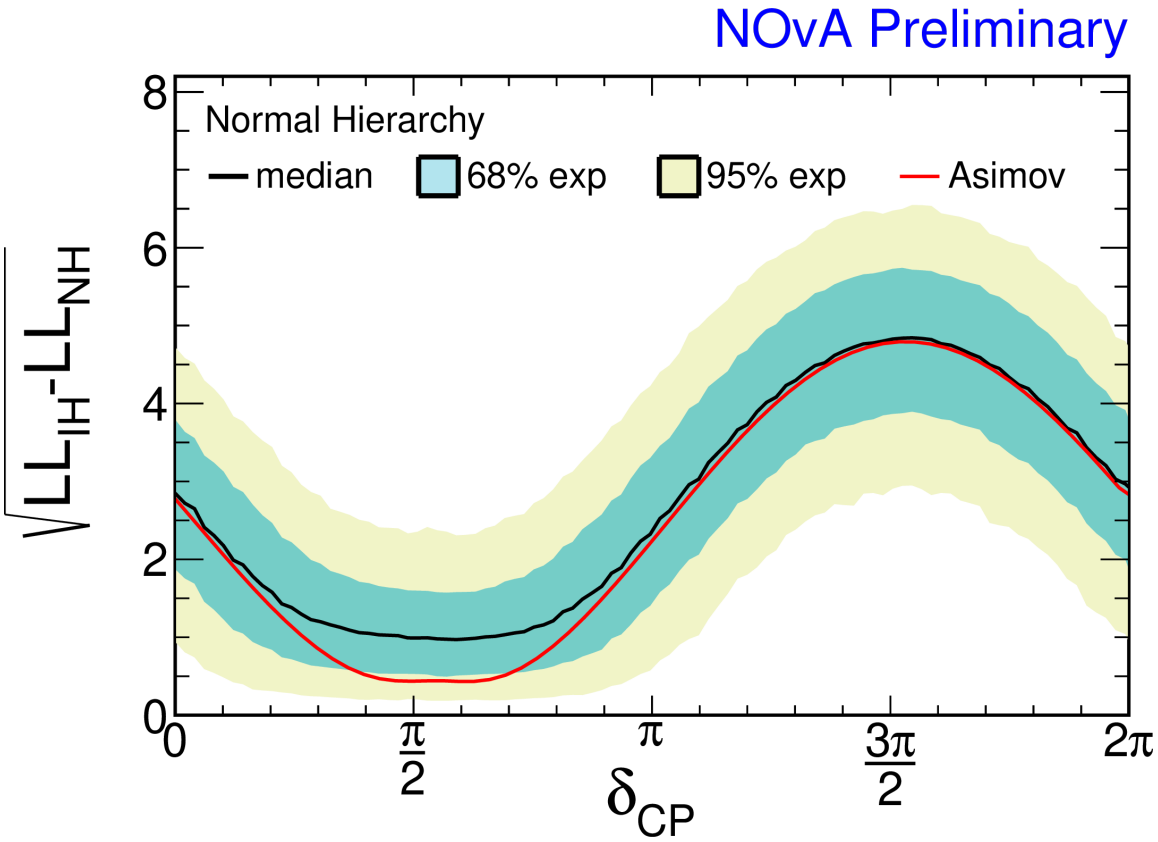
Past NOvA Accomplishments

- High-impact measurements of 3-flavor neutrino oscillations
- 16 full collaboration publications (5 PRL, 9 PRD)
  - Plus 1 more accepted, and 2 more in review
  - Most cited: 280, 5 more >100
- 53 PhD and 12 Master's theses
- Groundwork for the future:
  - First HEP experiment to use deep learning in a measurement
  - Developed analysis framework now in common use
  - HPC-enabled statistical analysis
  - Experience operating high-power neutrino beams



Future NOvA Goals: 3 Flavor

- Expect to accumulate ~7×10^{21} POT by the long shutdown for LBNF.
  - ~2.5 time more data than our last oscillation results.
- Full exposure may allow a >3σ determination of the mass ordering.
  - Precision on ν_e/anti-ν_e appearance asymmetry will improve from 21% to 14%.
  - Mass ordering determination depends on true parameters in nature.
  - Statistical errors will still dominate over systematics at the end of the run.



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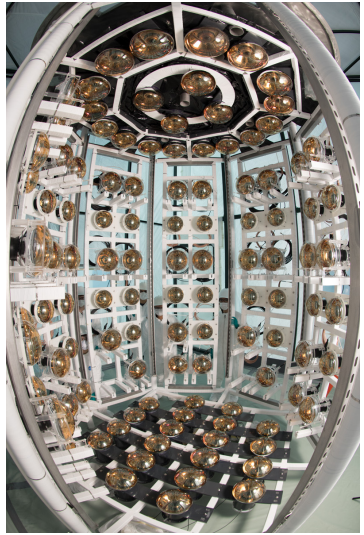
ANNIE Experiment

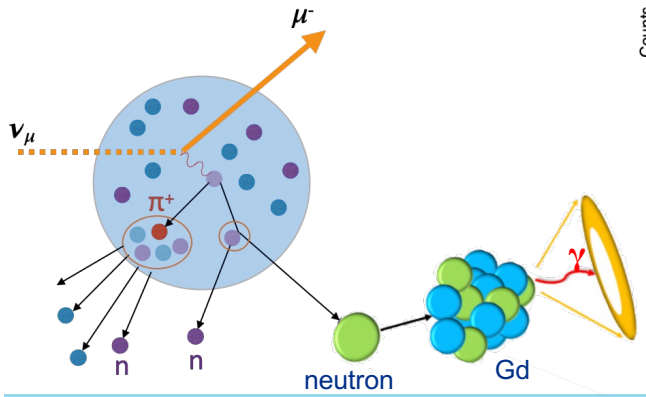
Accelerator Neutrino Nucleus Interaction Experiment

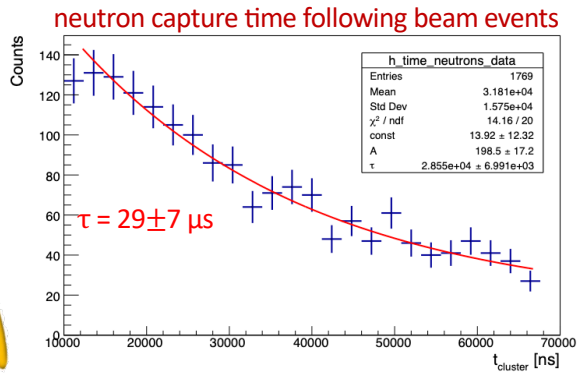
27-ton (Gd-loaded) Water Cherenkov Detector running in the **BNB neutrino beam**

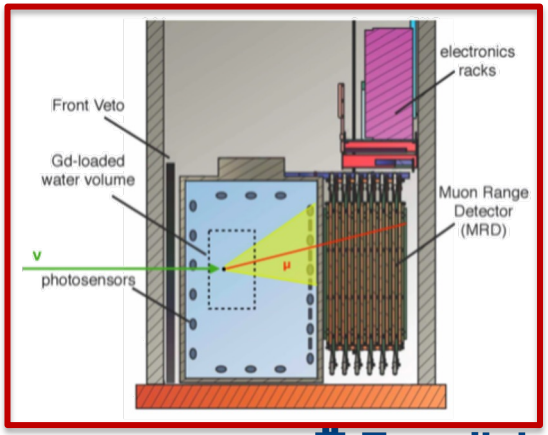
- Measurement of neutron mutiplicity and GeV neutrino differential cross-sections
- Physics data taking started in early 2021
- R&D program for new technologies
  → Gd-water → LAPPDs → WbLS



ANNIE Detector Layout







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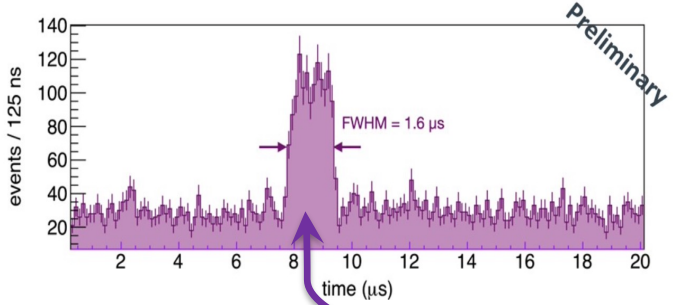
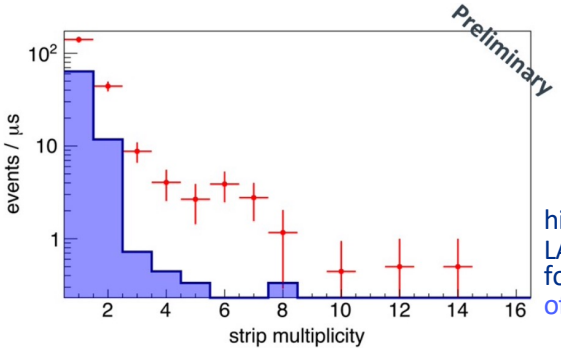
ANNIE: First LAPPD installed

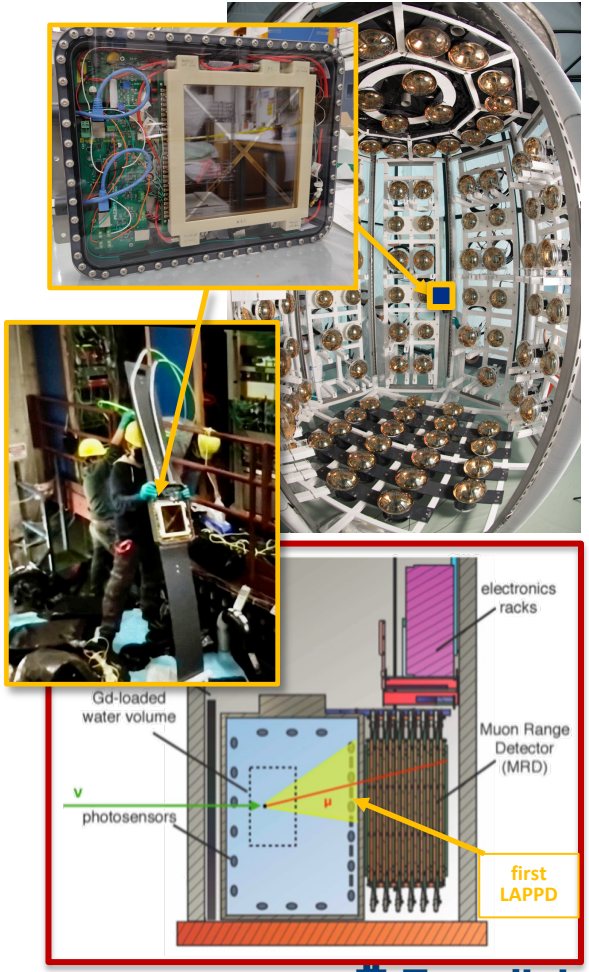
- Major Milestone: World's first LAPPD installed in March 2022, detected first light from neutrinos
- In progress: *in-situ* timing calibration
- Additional 4+ LAPPDs to be installed this summer



event time distribution around the BNB beam spill as observed by the LAPPD



hit multiplicity on LAPPD strip readout for on-beam and off-beam events



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ANNIE+SANDI: WbLS test deployment

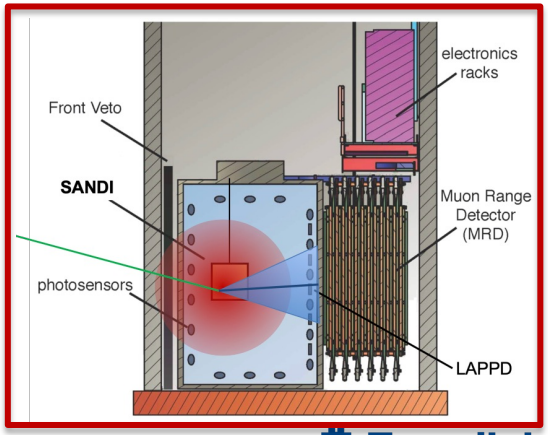
→ **Next step: SANDI**
acrylic vessel with 365 kg of WbLS submerged in ANNIE

- Resolve scintillation light from hadronic recoils, improve neutrino energy determination
- Higher light output for neutron captures on gadolinium
  → improved neutron detection efficiency & vertex reco
- Study C/S separation for neutrinos with LAPPDs

→ test WbLS performance for future use in long-baseline exp.s!

SANDI vessel at Davis

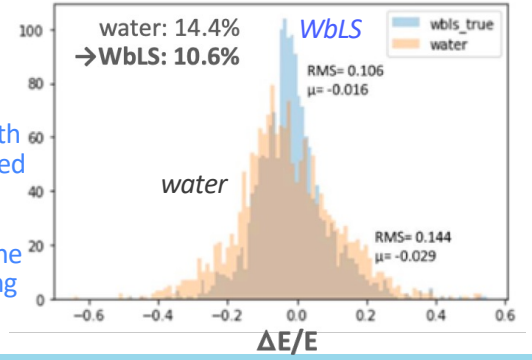
ANNIE vs. SANDI WbLS vessel



Preparations are on-going

- 3‘ x 3‘ vessel already on-site at Fermilab
- (Gd-loaded) WbLS to be produced at BNL (M. Yeh)

MC with idealized reco and machine learning



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ICARUS Installation and Commissioning

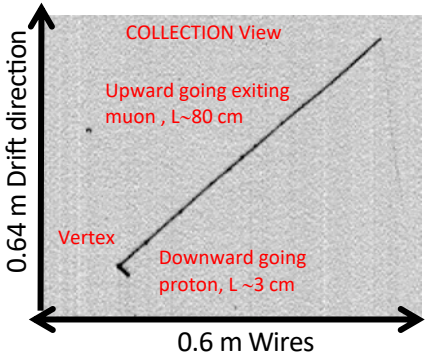
Aug. 28th 2020:
start of TPC/PMT operation

Dec. 2021:
completion of CRT installation

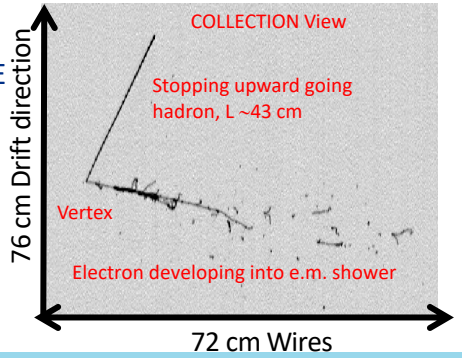
June 2022:
completion of overburden installation

Steady data taking with BNB, NuMI beams since March 2021, in parallel with commissioning activities. Cosmics, ν_μ, and ν_e samples collected for trigger/calibration/reconstruction studies.

BNB CC QE muon neutrino candidate, E_{DEP} ~ 200 MeV



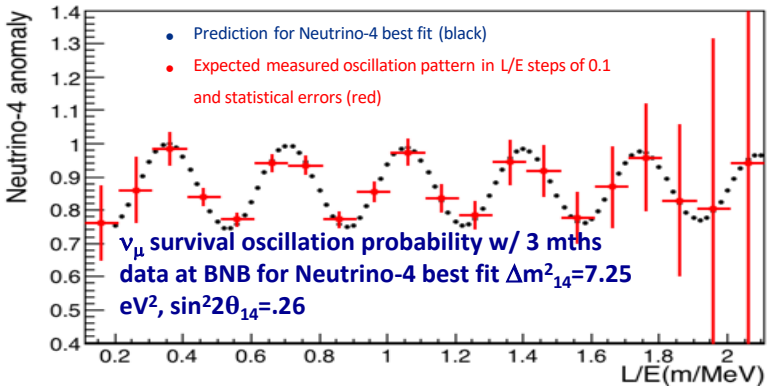
Contained NuMI CC QE electron neutrino candidate, E_{DEP} ~ 800 MeV



Started data taking for Physics with BNB and NuMI beams mid-June 2022

ICARUS Physics Program

- During initial ICARUS only data period, further investigate **two independent (~7 eV^2) sterile ν searches of Neutrino-4 oscillations claim for:**
  - Oscillation produced disappear pattern of ν_μ and ν_e in BNB and NuMI, focusing on contained, quasi-elastic CC interactions;
  - The known contribution of Dark Matter of 26.4%, of the total energy of the Universe may be due to the Neutrino-4 expected sterile neutrino signal of 24% (+ 5% , - 3%)



- **LSND-scale (~1 eV^2) sterile ν search:** Jointly with SBND - study the ν oscillation at BNB, covering the LSND mass/mixing angle parameter region with 5σ significance by measuring simultaneously the ν_μ disappearance and ν_e appearance channels.
- **Further exploit the NuMI beam:**
  - High statistics (~10^5 $\mathbf{\nu_e}$ events/year) measurements of ν-Ar cross sections and interaction models in the few hundred MeV to few GeV energy range important for SBN and DUNE.
  - Develop a rich Beyond Standard Model search program: Higgs portal scalar, ν tridents, light dark matter, heavy neutral leptons …

Overview

- Neutrino Science
  - Why are Neutrinos Important
  - Neutrino Science in 2022
  - The Big Neutrino Questions and Fermilab's Role
- Experiments: Operations Complete
  - MINERvA
  - MicroBooNE
- Experiments: Operating
  - NOvA
  - ANNIE
  - ICARUS
- Experiments: Building
  - SBND
  - DUNE

It all leads to DUNE

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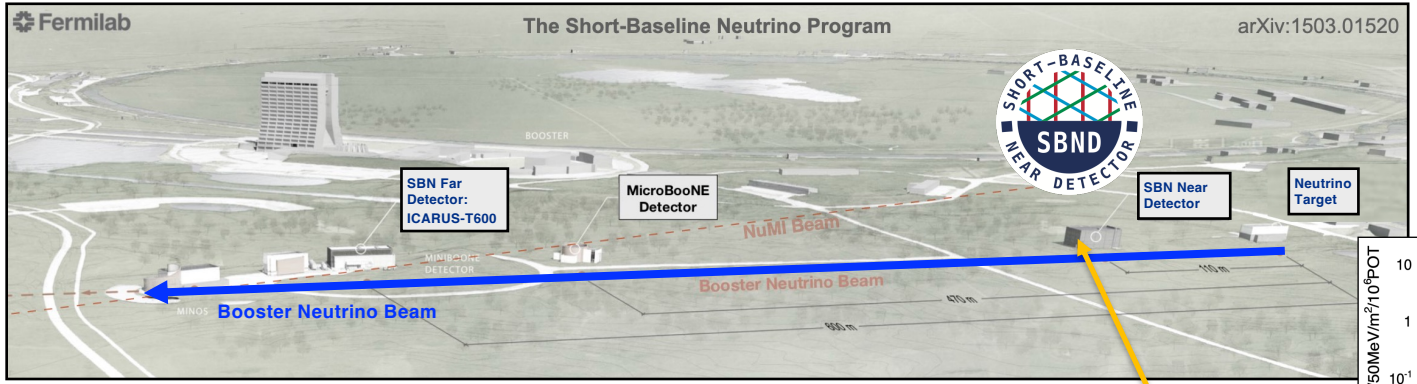
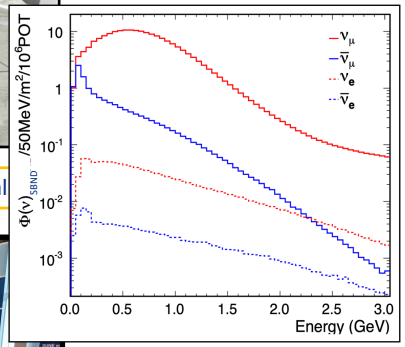
Short-Baseline Near Detector (SBND)



SBND is a 112-ton LArTPC only 110 m from target

SBND Experimental



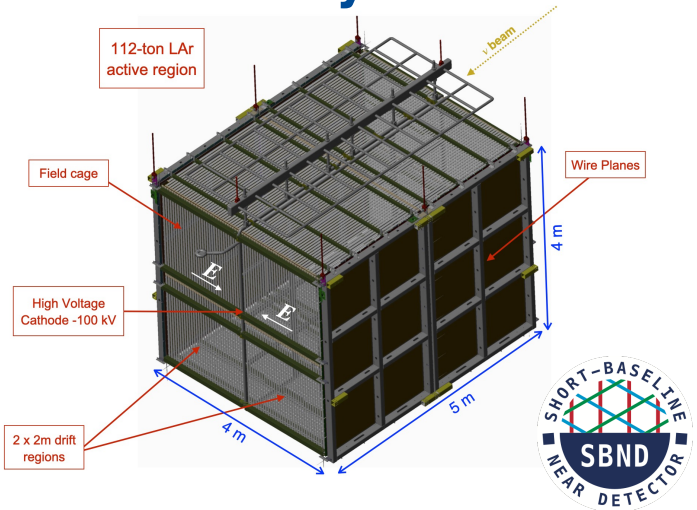
BNB Neutrino Fluxes at SBND

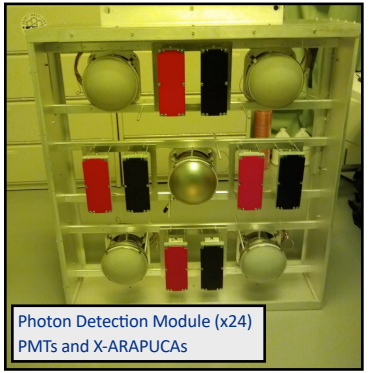
SBND is the near detector in the Short-Baseline Neutrino (SBN) Program at Fermilab.

- eV-scale sterile neutrinos: SBND measures the neutrino flux close to the source enabling very sensitive searches for neutrino oscillations in the FNAL Booster Neutrino Beam.
- Other new physics scenarios: BSM physics program is an evolving landscape, with new search ideas emerging from collaboration with theory community.
- Neutrino-argon cross sections: SBND will record 20-30x more neutrino-argon interactions than is currently available.

SBND assembly is well underway at Fermilab

Ready for LAr fill and commissioning in mid-2023.




Photon Detection Module (x24)
PMTs and X-ARAPUCAs


TPC Cold Electronics Installation


Membrane cryostat construction, May 2022


TPC Assembly at Fermilab
May 2022
2m drift region

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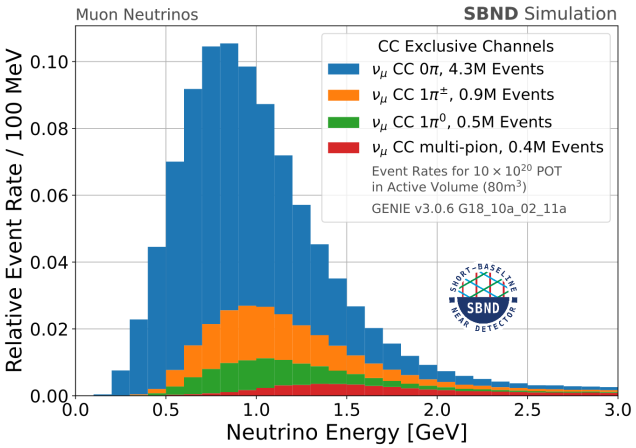
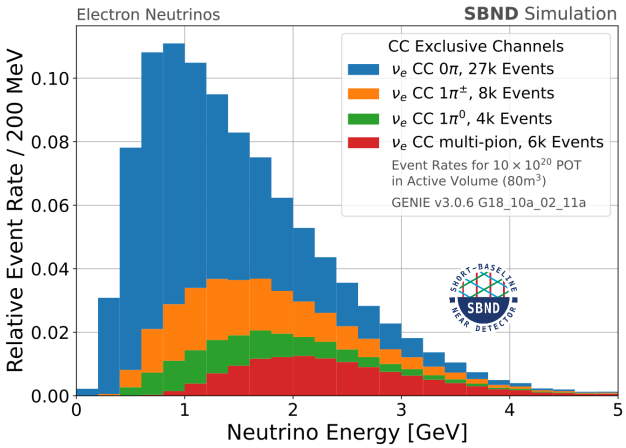
Large SBND Datasets for ν-Ar Physics





~5000 ν events/per day!

SBND data will enable a generational advance in the study of neutrino-argon interactions in the GeV energy range, with low thresholds for particle tracking and calorimetry and enormous event rates (every ~3 months, SBND will collect a full MicroBooNE BNB 5-year dataset)

SBND expects to receive between 8-16x10^{20} POT over a 3-4 year run (2024-2027). This amounts to order 10 million total events (CC+NC), including around 50,000 ν_μ CC events above 2 GeV and 50,000 ν_e CC events

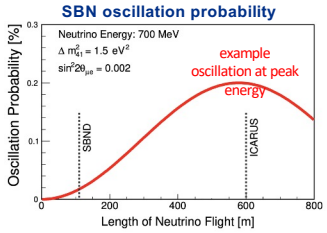
In addition to multi-dimensional investigations of inclusive and dominant channels with <1% statistical errors per bin, SBND data enables measurements of more rare processes such as kaon and lambda production (1000s of events) and ν-electron scattering (100s of events)

SBN Oscillation Sensitivity

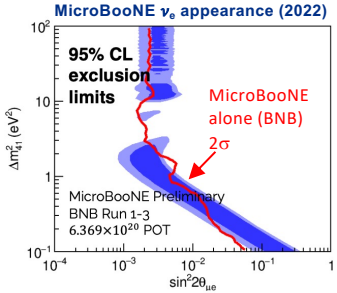
SBND + ICARUS will test the light sterile neutrino hypothesis

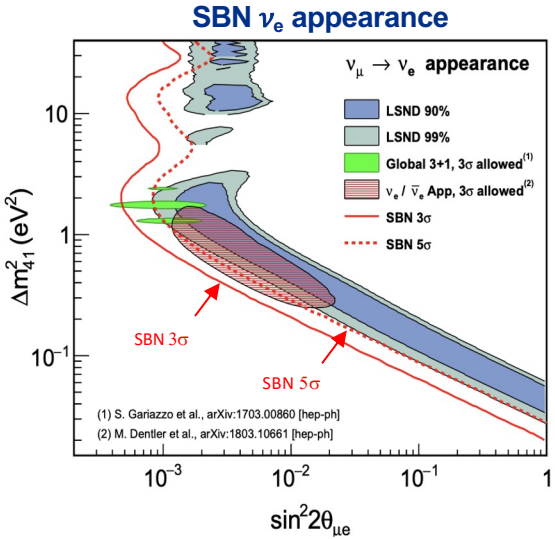
Can cover the parameter space favored by past anomalies with 5σ significance

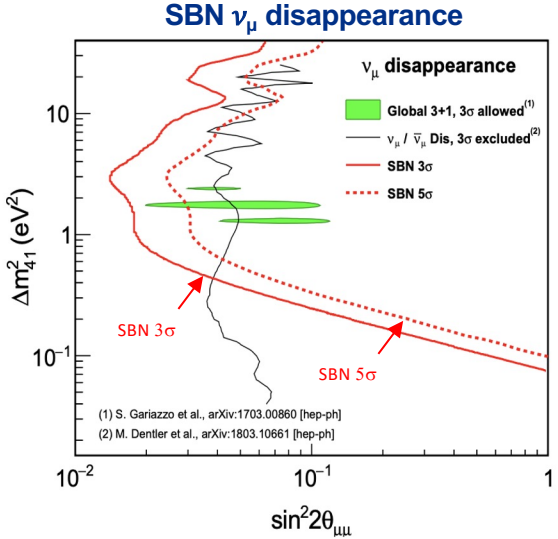
Having Near + Far detectors enables sensitive searches for <u>both</u> ν_e appearance <u>and</u> ν_μ disappearance within the same experiment.



P. Machado et al, arXiv:1903.04608V11







(SBN sensitivities for 6.6 x 10^{20} protons on the BNB target)

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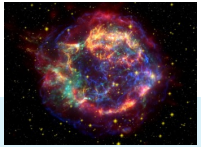
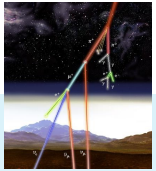
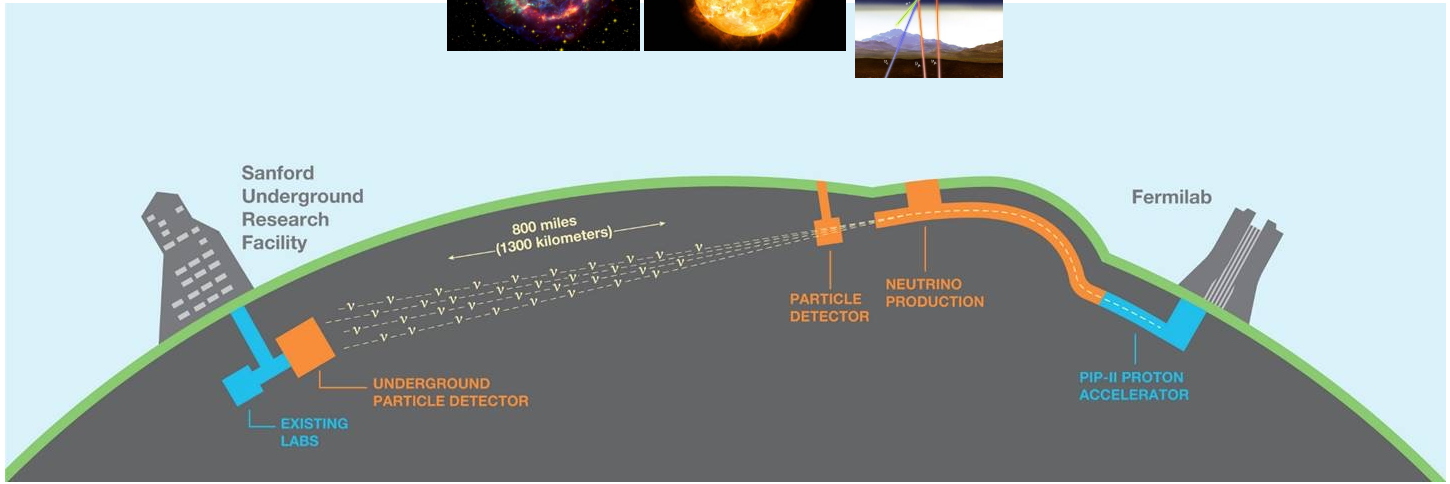
DUNE Physics Goals

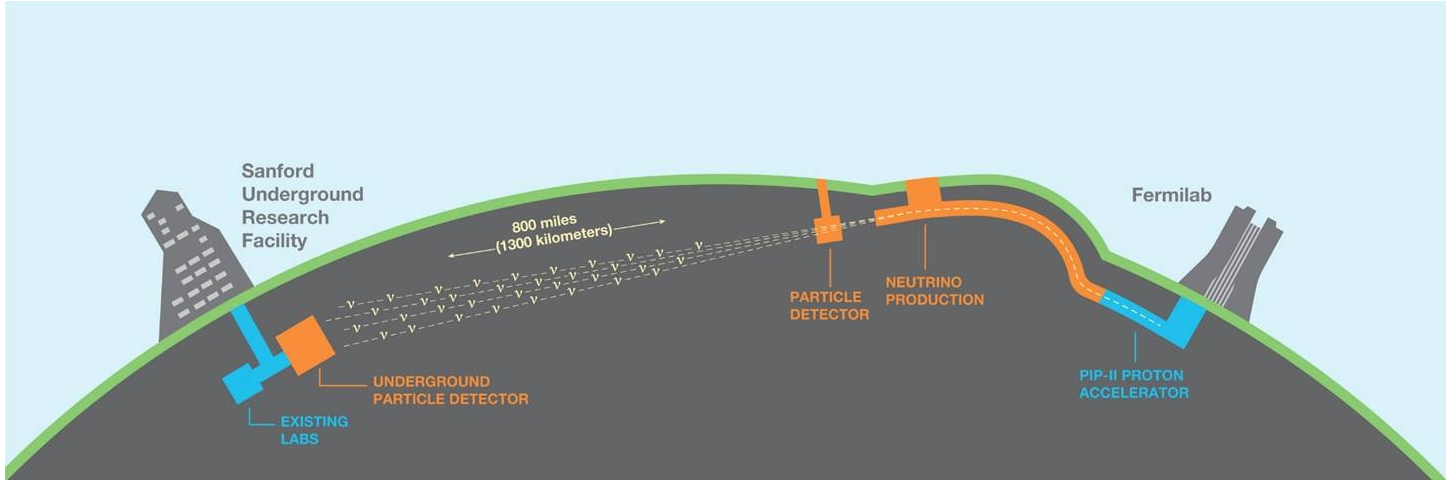






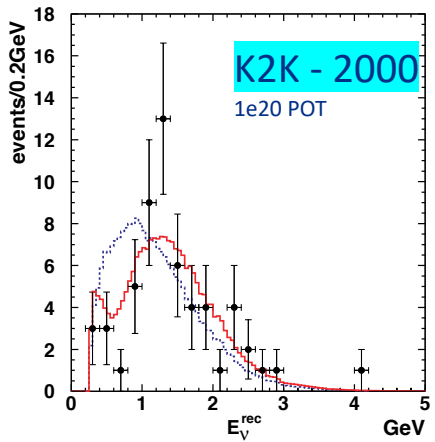
- Unambiguous, high precision measurements of Δm^2_{32}, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ in a single experiment
- Discovery sensitivity to CP violation, mass ordering, θ_{23} octant over a wide range of parameter values
- Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst
- Low backgrounds for sensitivity to BSM physics including baryon number violation

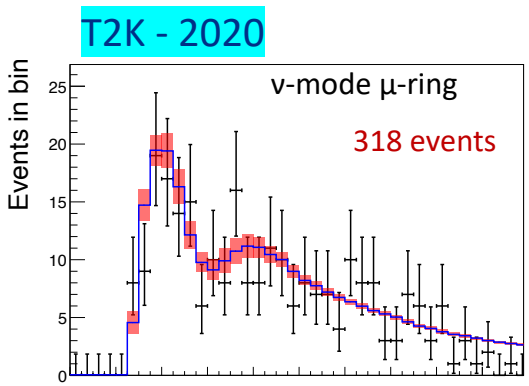
DUNE Oscillation Advantages

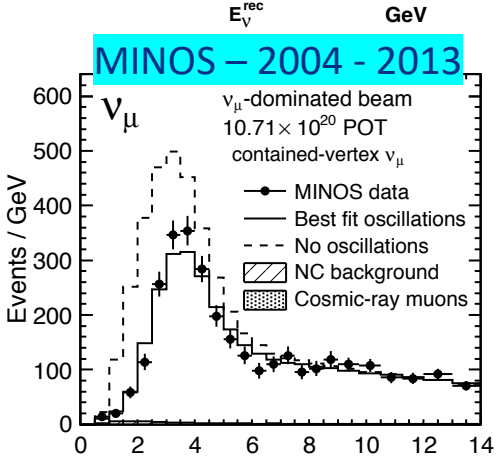


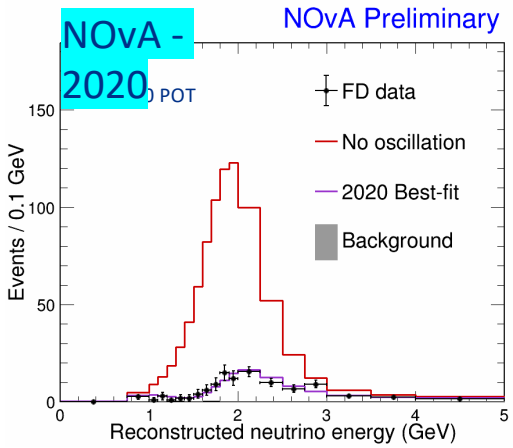
- The DUNE neutrino oscillation program is **exceptional** due to several key features of the experiment and facility design :
  - The **1300 km baseline** between Fermilab and SURF location for the far detectors enables an unambiguous measurement of the neutrino mass ordering (mass hierarchy)
  - The detector's on-axis location provides for a **wide-band energy spectrum of neutrinos** to be seen in the near and far locations enabling detailed fitting of the oscillation parameters
  - The **liquid argon detector technology** enables precise reconstruction of the neutrino interactions
  - The Near Detector complex at Fermilab will support near detectors that will provide **unprecedented control of systematic uncertainties** in the prediction of the un-oscillated neutrino flux

DUNE ν_μ Disappearance

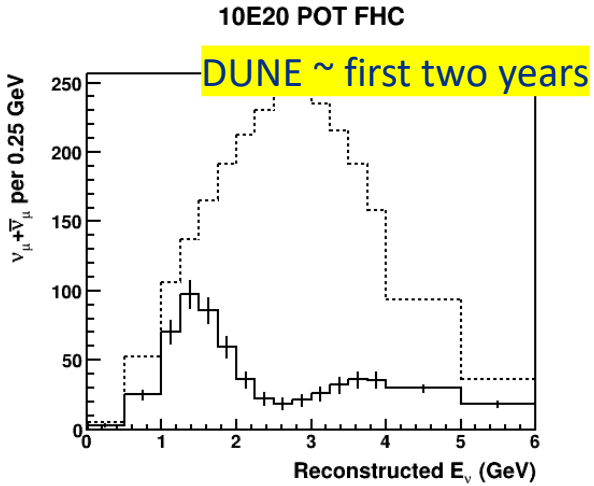








DUNE is a 3rd generation ν_μ disappearance experiment



Unprecedented precision achievable in small amount of running time

Slide taken from Gina Rameika's 4/26/22 "DUNE International Context" talk

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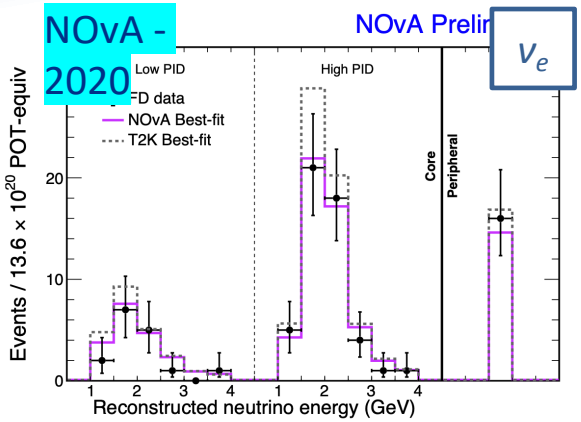
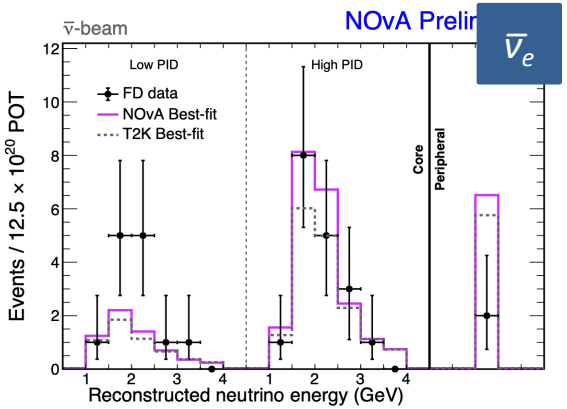
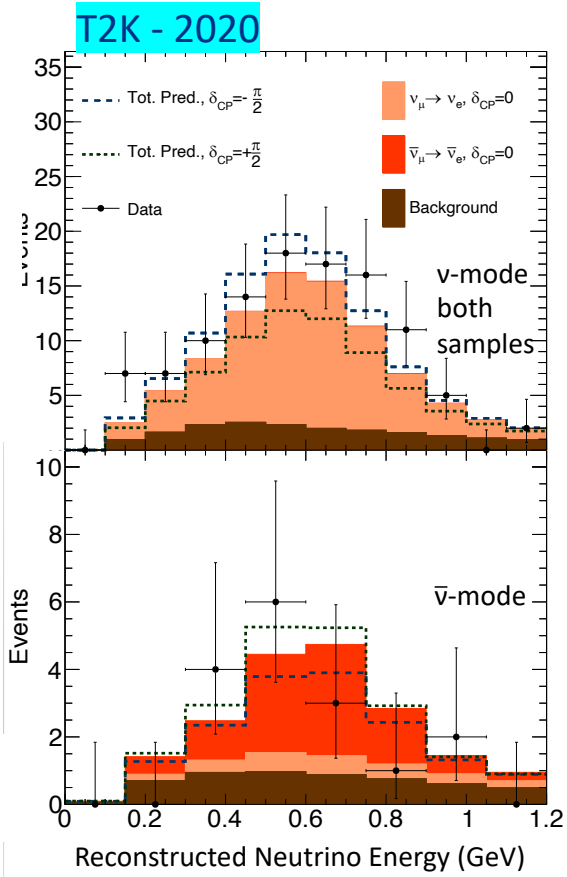
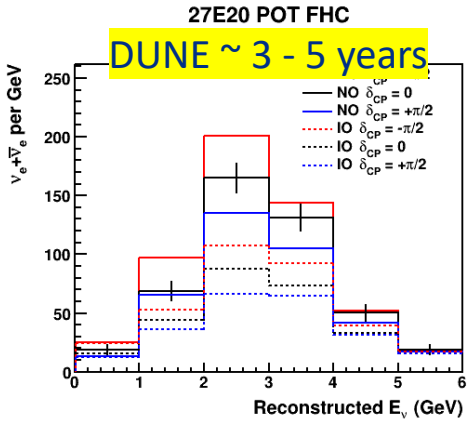
DUNE ν_e Appearance







DUNE is a 2nd generation accelerator ν_e appearance experiment



with unique capability to determine the mass ordering

Slide taken from Gina Rameika's 4/26/22 "DUNE International Context" talk

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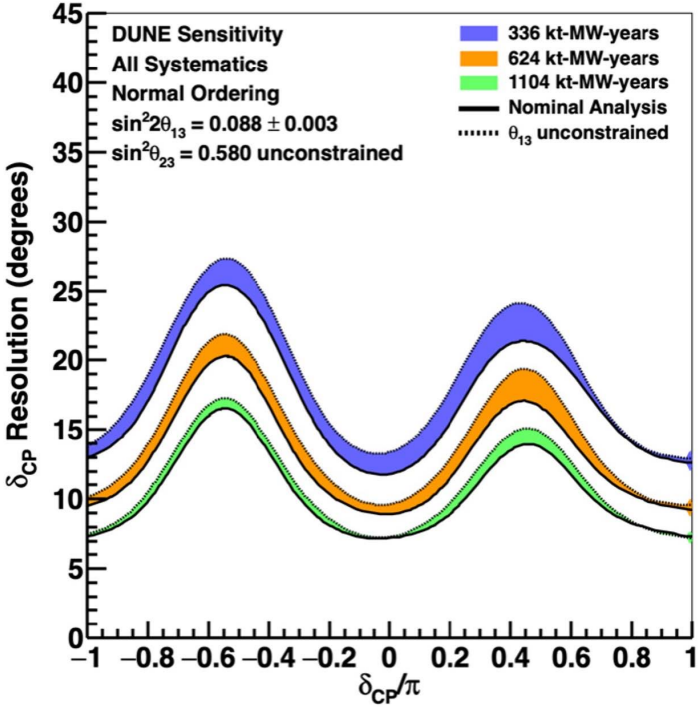
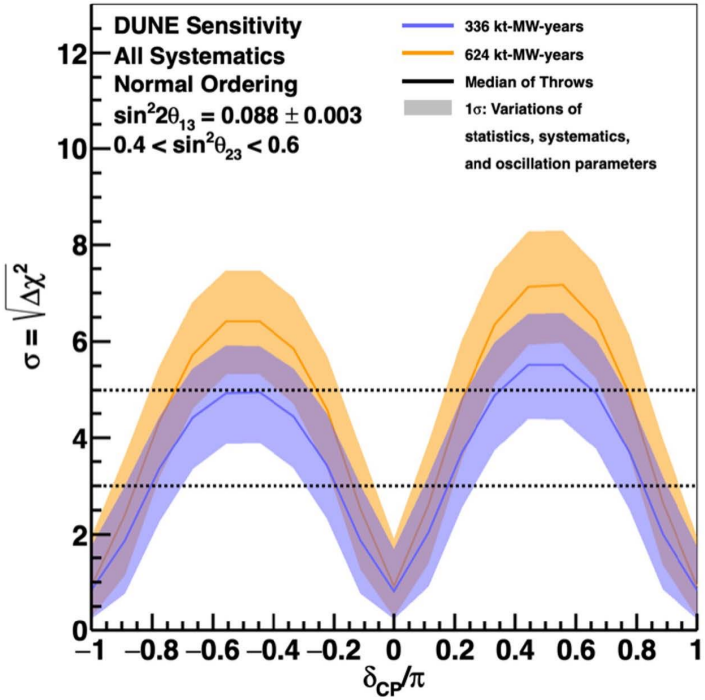
DUNE CP Violation

- 5σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP} with external input only for solar parameters





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It All Leads to DUNE