Living with uncertainty in the precision era: constraining systematics in neutrino oscillation experiments

- Introduction to neutrinos and neutrino oscillation
- Experiment design and status
- Systematics in accelerator-based oscillation experiments

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BNL Physics Colloquium
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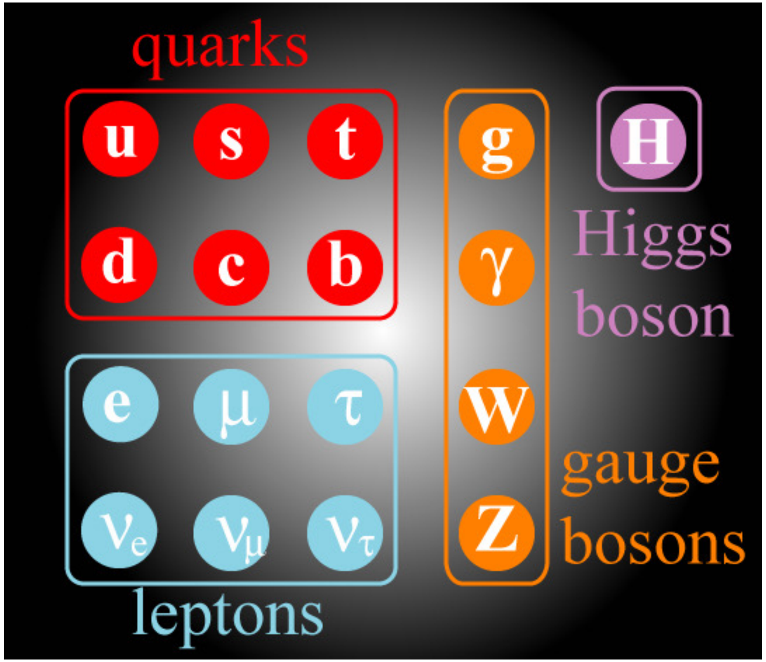
She/her

Brookhaven National Laboratory DUNE

Introduction to Neutrinos

All Known Elementary Particles:

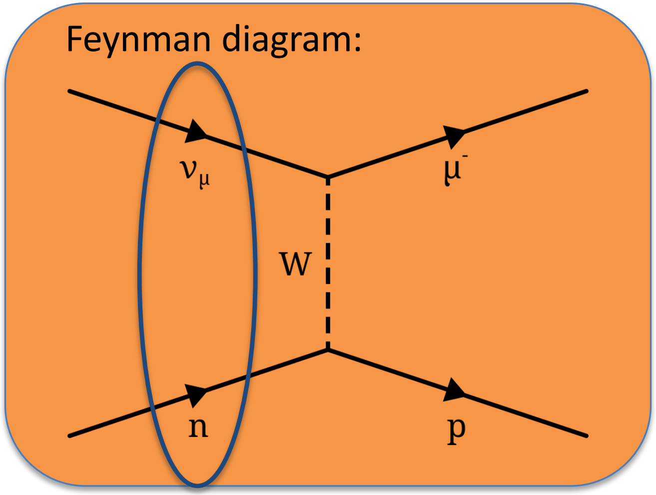


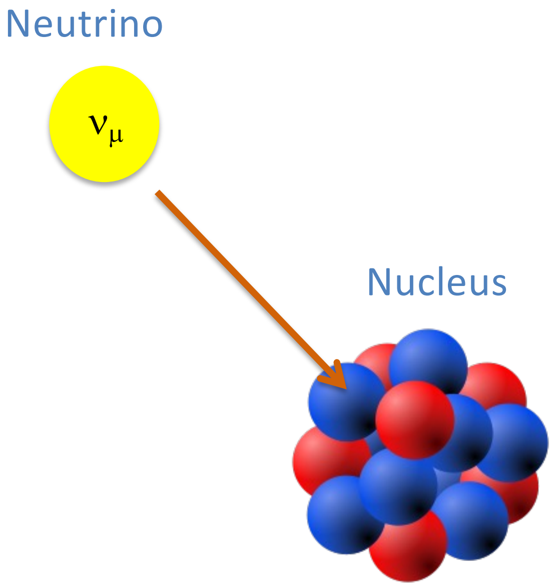
+antiparticles…

- Neutral leptons in three flavors: ν_e, ν_μ, ν_τ
- Interact weakly
  - Cross section varies with energy, $\mathcal{O}(10^{-38}$ cm^2/nucleon) for accelerator neutrino energies
  - "A typical [solar] neutrino could pass through a light year of lead before experiencing a single interaction"
- Neutrino masses are very small and unknown but **not** zero
  - Existing limits on sum of neutrino masses are order few hundred meV
- Neutrinos detectable only via their interaction products

Observing Neutrino Interactions

We observe neutrinos only via their interactions





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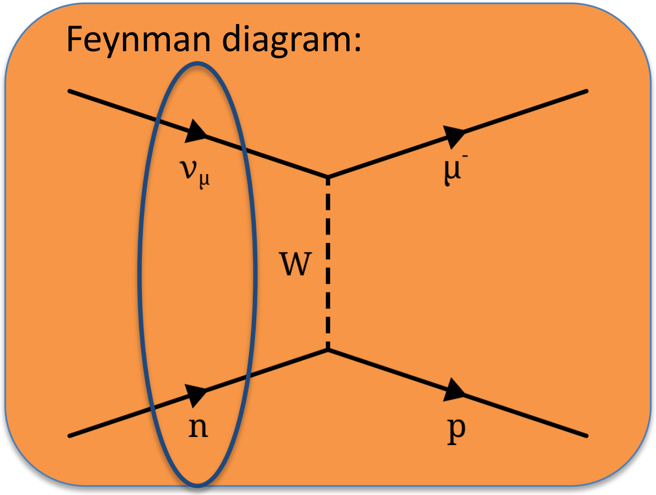

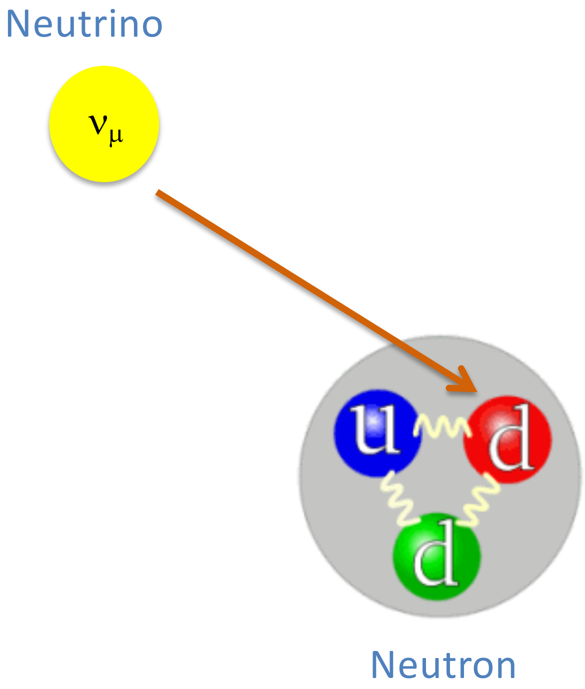

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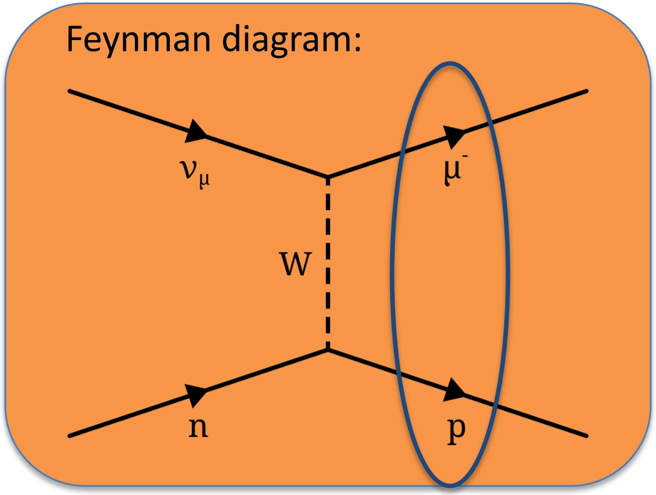
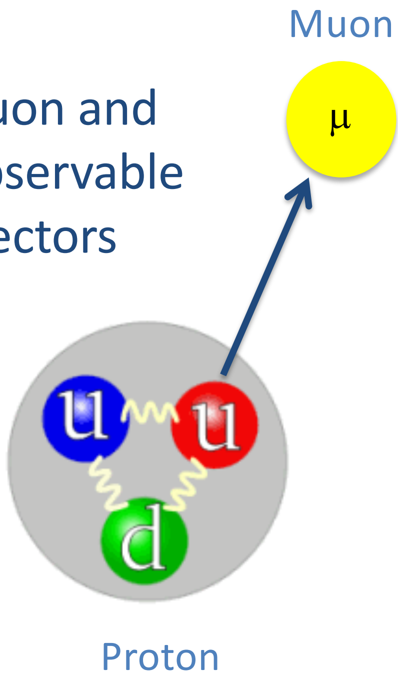
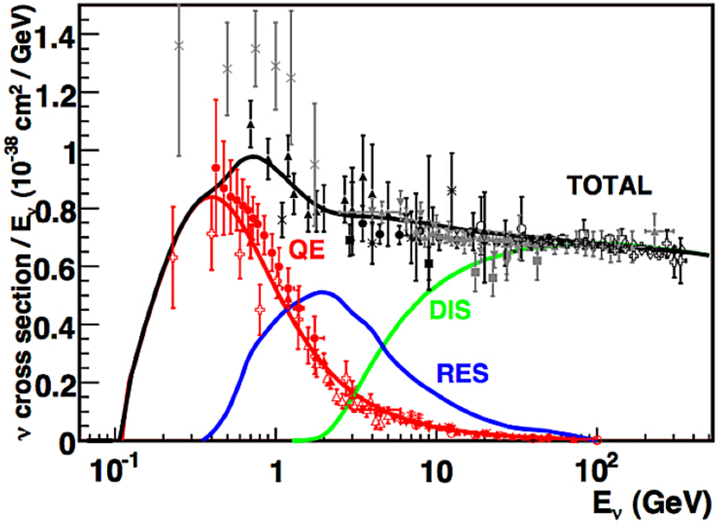


Final state muon and proton are observable with HEP detectors



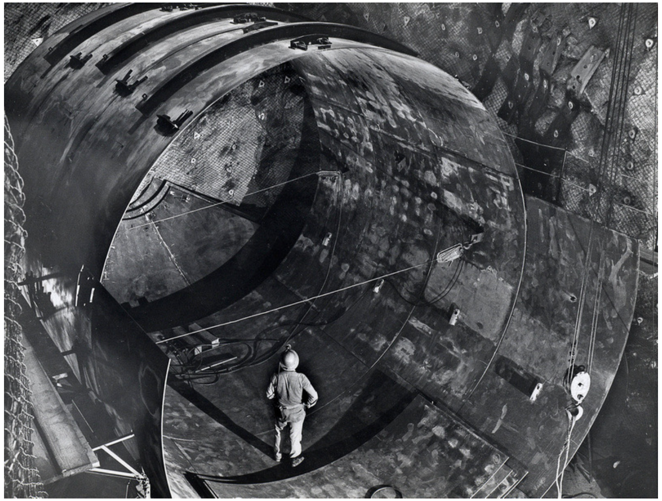
GeV-Scale Neutrino Interactions

- Multiple neutrino-nucleus interaction processes, including quasielastic, meson-exchange current, resonance, and deep-inelastic scattering, contribute at GeV-scale



- ν_μ CC Interactions:
  - QE: $\nu_\mu n \rightarrow \mu^- p$
  - RES: $\nu_\mu N \rightarrow \mu^- N^*$, $N^* \rightarrow \pi N'$
  - DIS: $\nu_\mu N \rightarrow \mu^- X$
- Similar processes for ν_e and antineutrinos + neutral current interactions
- Details of initial nuclear state and final state interactions matter
- Detectors that are able to observe details of the final state should be better able to reconstruct incoming neutrino kinematics

Neutrino Oscillation



First evidence for neutrino oscillation came from the Ray Davis experiment in the 1960s, where 2-3 times fewer solar ν_e interactions were observed than expected.

- Neutrinos are created by the weak interaction in definite flavor states, which are linear combinations of the mass states: $|\nu_\alpha> = \sum_{k=1,2} U_{\alpha k}|\nu_k>$
- As they propagate through space, the mass states (ν_k) evolve governed by the Schrodinger Equation such that the flavor state becomes:

$$\phi_k = E_k t - p_k x$$

$$|\nu_\alpha(x,t)> = \sum_{k=1,2} U_{\alpha k}|\nu_k(x,t)> = \sum_{k=1,2} U_{\alpha k} e^{-i\phi_k}|\nu_k(0,0)>$$

Time evolved flavor state

Time evolved mass states

- Oscillation probability is:

$$A(\nu_\alpha(0,0) \rightarrow \nu_\beta(x,t)) = <\nu_\beta(x,t)|\nu_\alpha(0,0)>$$

Neutrino Oscillation

- Two neutrino case: $P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
  - Oscillation amplitude depends on θ (mixing angle); oscillation frequency depends on Δm^2 (mass difference), baseline (L), and energy (E).

3 Flavor Neutrino Mixing

PMNS Mixing Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

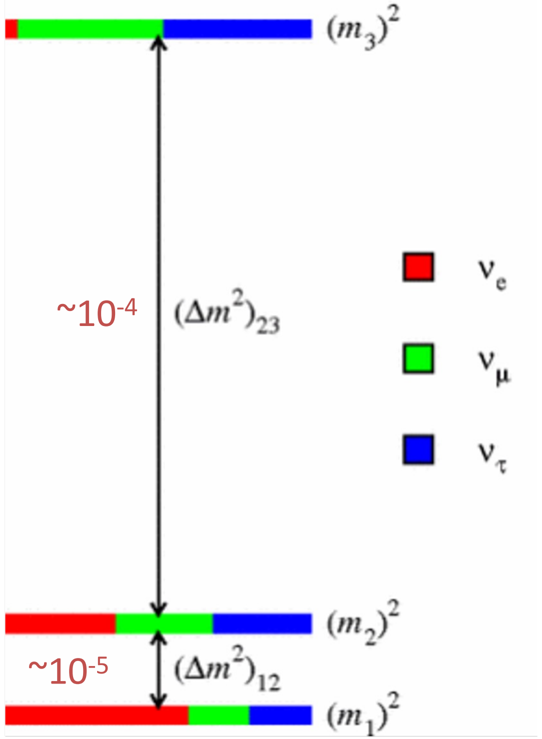
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **$\theta_{23} \approx 45^o$**
- Octant unknown (new symmetry?)

- **$\theta_{13} \approx 10^o$**
- δ_{CP} unknown (CP violation?)

- **$\theta_{12} \approx 35^o$**

Normal ordering



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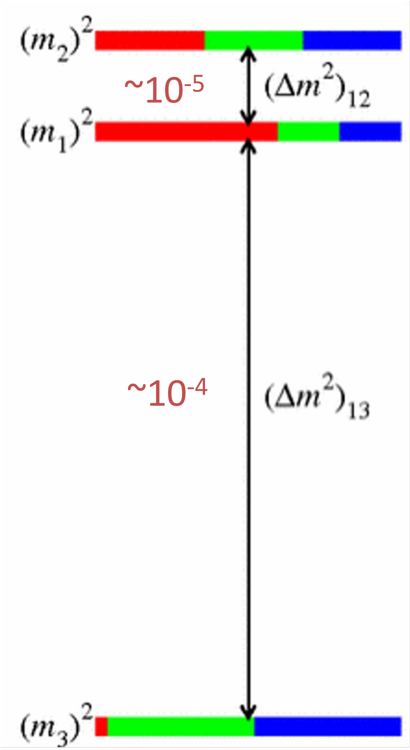
Inverted ordering



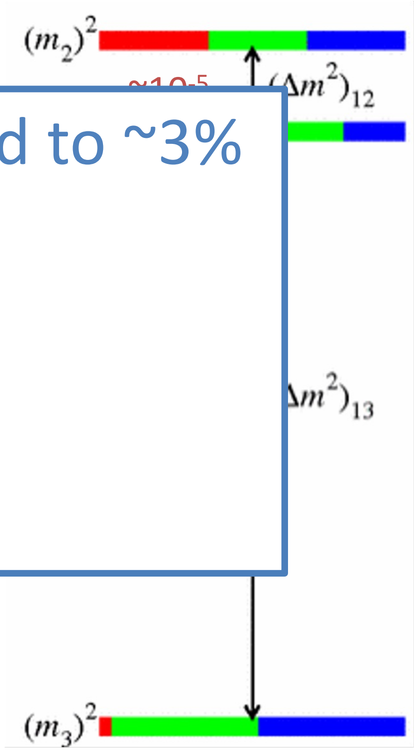
3 Flavor Neutrino Mixing

PMNS Mixing Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U & U & U \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_2 \\ 0 & -\sin\theta_{23} & \cos\theta_2 \end{pmatrix}$$

Inverted ordering



Most parameters currently measured to ~3%

Open questions:

- Mass ordering ($\Delta m^2_{32} > 0$?)
- Octant ($\sin^2\theta_{23} = 0.5$?)
- CP violation ($\delta_{CP} \neq 0, \pi$?)
- Only 3 flavors? PMNS unitary?

- **$\theta_{23} \approx 45^o$**
- Octant unknown (new symmetry?)

- δ_{CP} unknown (CP violation?)

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3 Flavor Neutrino Oscillation

- Full oscillation probability for three-neutrino mixing in matter is more complicated:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

$a = G_F N_e/\sqrt{2}$

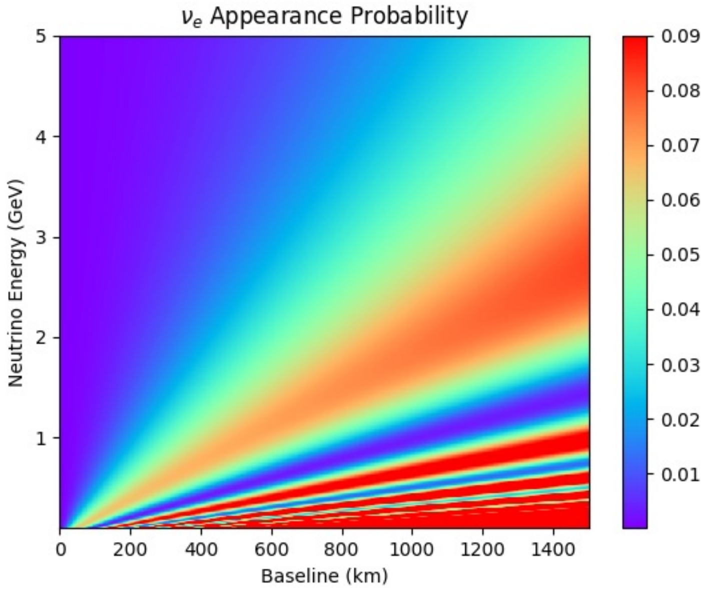
Matter effect from coherent forward scattering on electrons

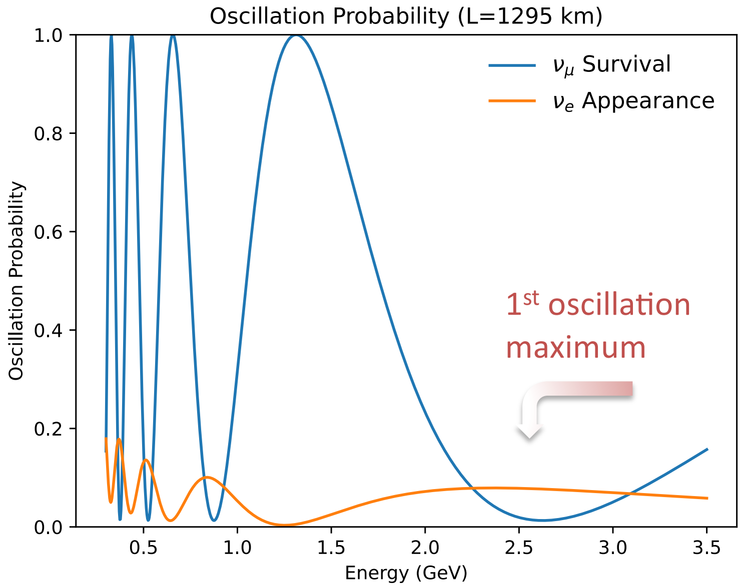
CP violation

- Appearance probability depends primarily on Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}, and matter effects

Long-Baseline Oscillation

- Measure ν_μ survival and ν_e appearance in a ν_μ dominated beam
- Optimize choice of baseline and energy for desired measurement (1st/2nd oscillation maxima)





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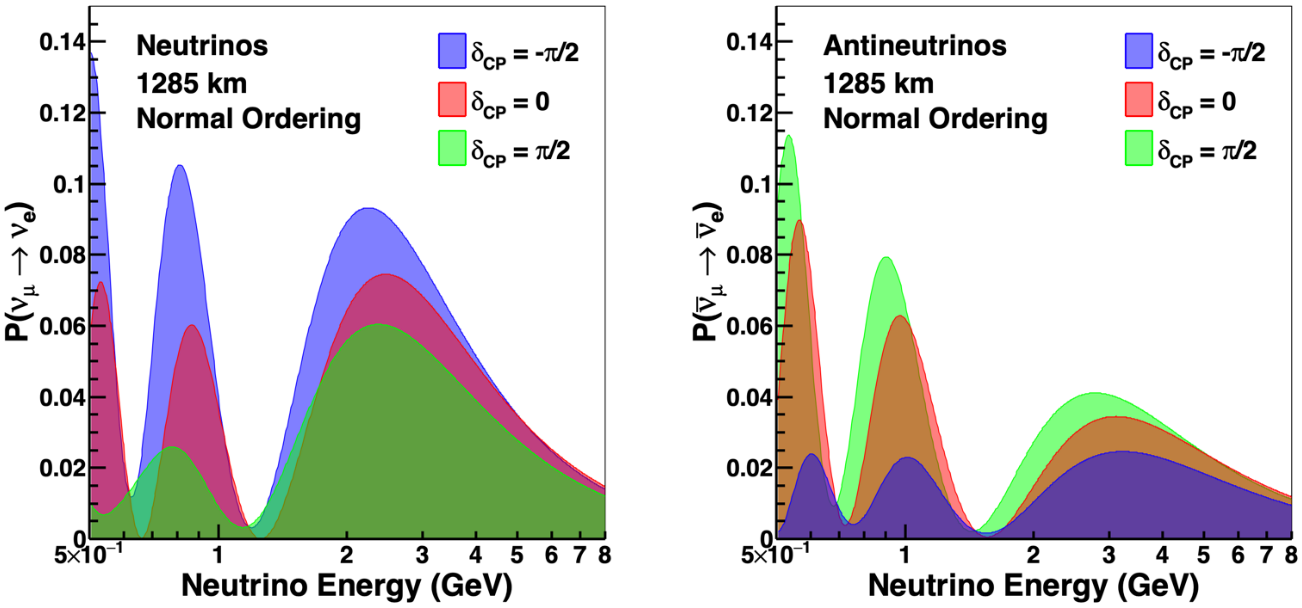
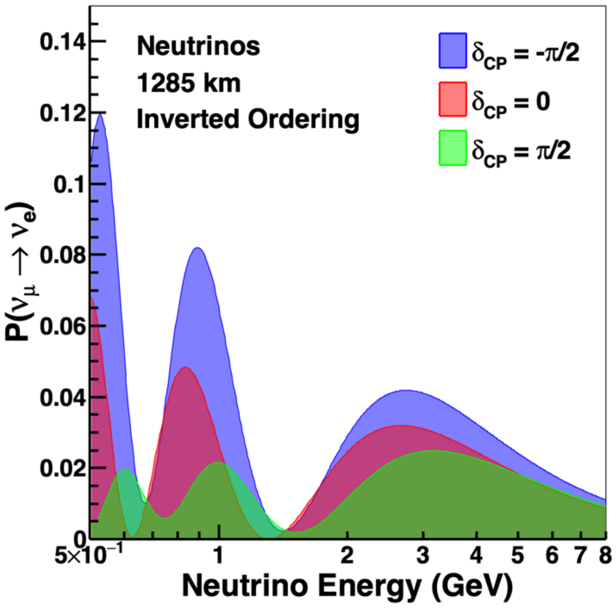
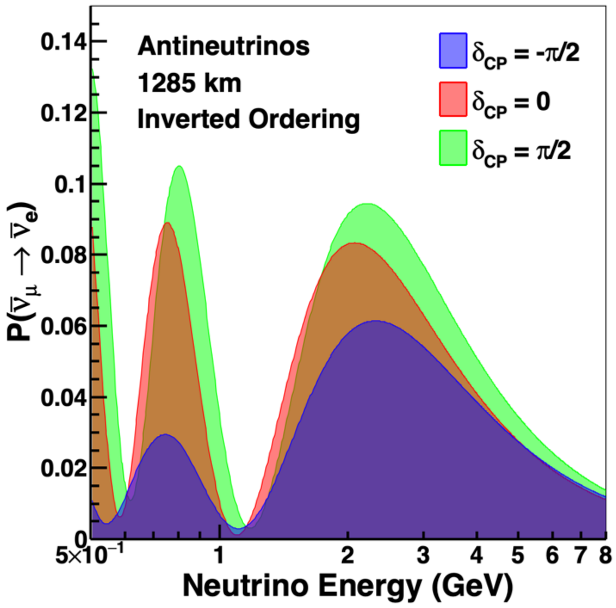


- Value of δ_{CP} affects both rate and shape of appearance probability, with asymmetric impact on neutrinos and antineutrinos
- Matter effect enhances appearance probability for neutrinos and reduces it for antineutrinos if ordering is <u>normal</u>

Long-Baseline Oscillation





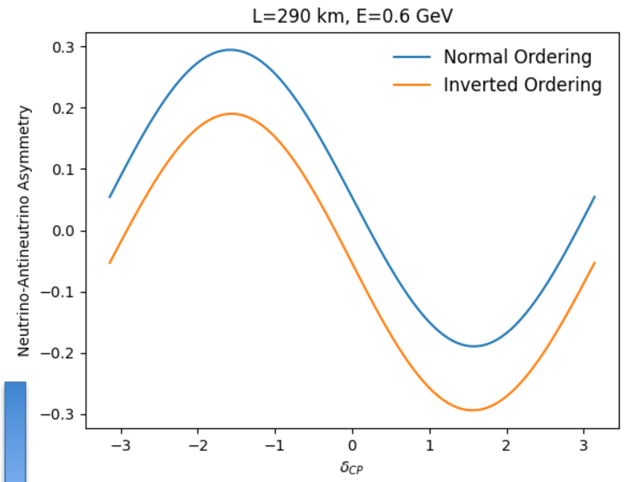
- Value of δ_{CP} affects both rate and shape of appearance probability, with asymmetric impact on neutrinos and antineutrinos
- Matter effect reduces appearance probability for neutrinos and enhances it for antineutrinos if ordering is <u>inverted</u>

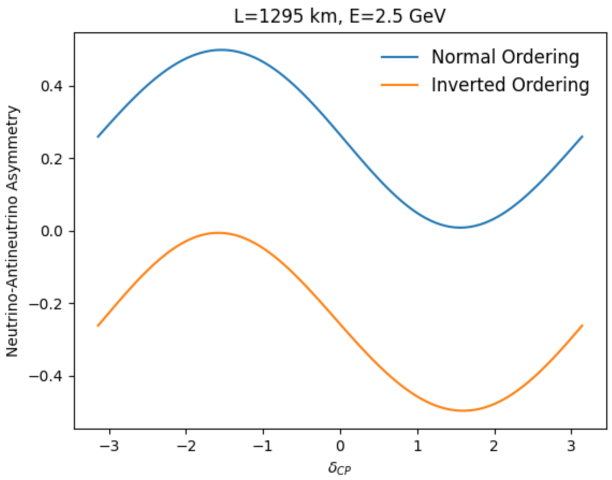
Both matter effect and δ_{CP} induce matter-antimatter asymmetry!

Long-Baseline Oscillation

Baseline of 290 km
(very little matter effect)

Baseline of 1295 km
(large matter effect)



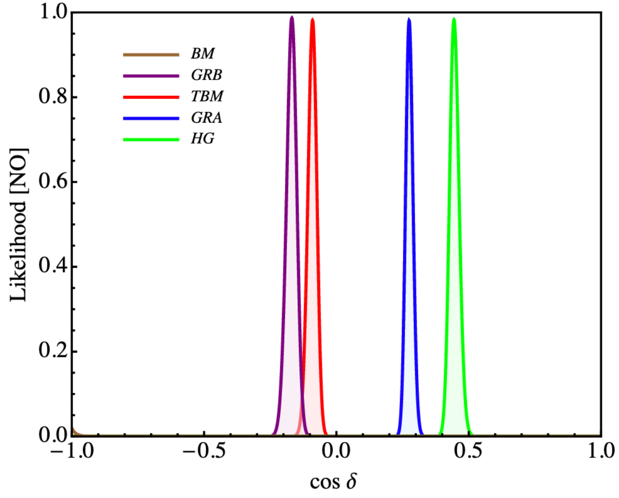


Degeneracy between δ_{CP} and matter effects is lifted for baselines greater than ~1000 km because matter effect produces larger asymmetry

Matter-antimatter asymmetry

What Can We Discover with LBL Oscillations?

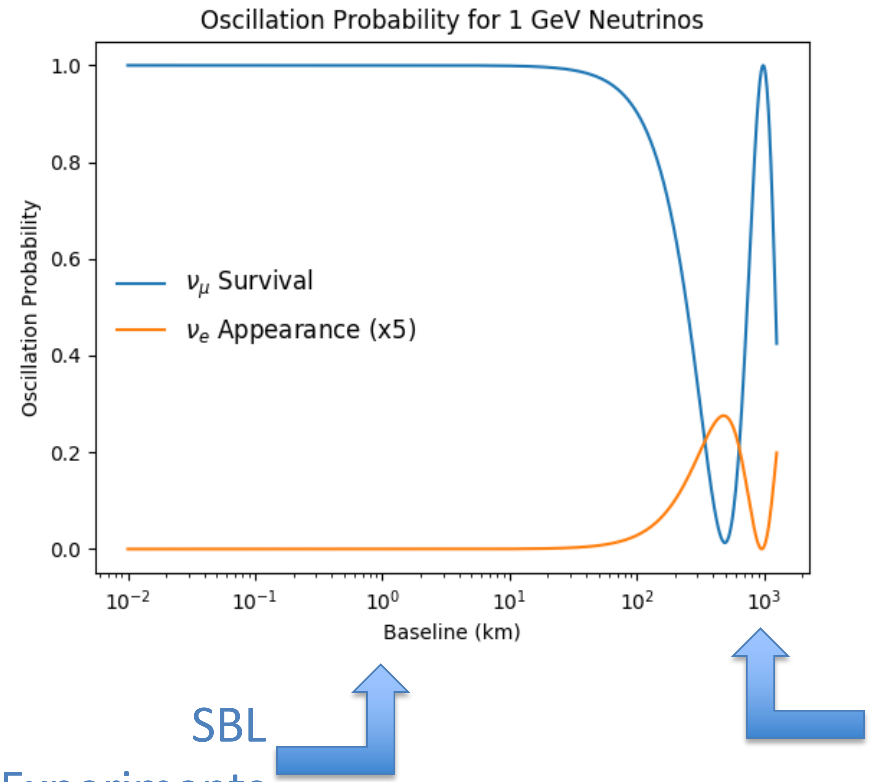
- LBL oscillation sensitive to θ_{13}, θ_{23}, Δm^2_{32}, δ_{CP}
- CP Violation
  - Symmetry and symmetry violation has been a major driver of discovery in particle physics
  - Leptogenesis requires CPV in high-energy Lagrangian (incl. right-handed neutrinos)
    - No model-independent connection between low-energy (PMNS) CPV and high-energy CPV required for leptogenesis
- Flavor structure
  - Why is the structure of the ν mixing matrix different from that of the quark mixing matrix
  - What flavor symmetry can produce this pattern of mixing and how is it broken?
  - Is $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric? If so, why?
- Model discrimination
  - Many flavor and BSM models make specific predictions for values of oscillation parameters



arXiv:1410.8056

- BSM physics in neutrino oscillation (additional particles or interactions)

Why Short-Baseline?



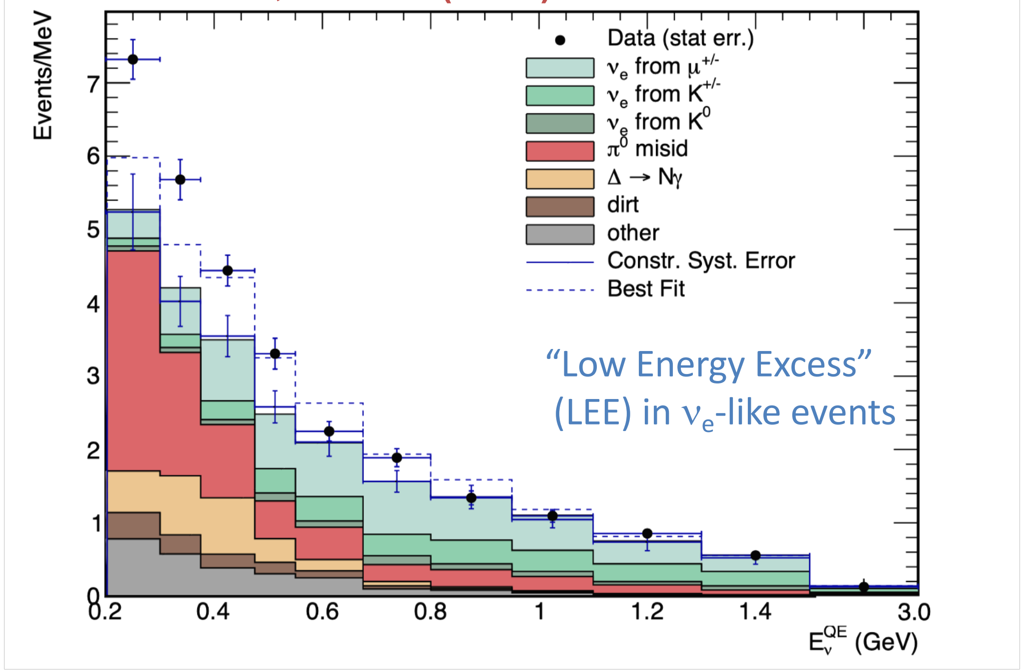
SBL Experiments

LBL Experiments

- Based on the already-measured oscillation parameters, we do not expect to see muon neutrino oscillation at small values of L/E
  - i.e.: ν_μ survival probability should be ~1 and ν_e appearance probability should be ~0 for order 1 GeV neutrinos with baselines < 100 km
  - **Any evidence for ν_μ disappearance or ν_e appearance at these L/E values would require a larger mass splitting, which would require at least 1 additional neutrino mass state**

Why Short-Baseline?

MiniBooNE (BNB)
PRD 103, 052002 (2021)



The significance of the excess observed by LSND is 3.8σ and by MiniBooNE is 4.8σ, for a combined significance of 6.1σ

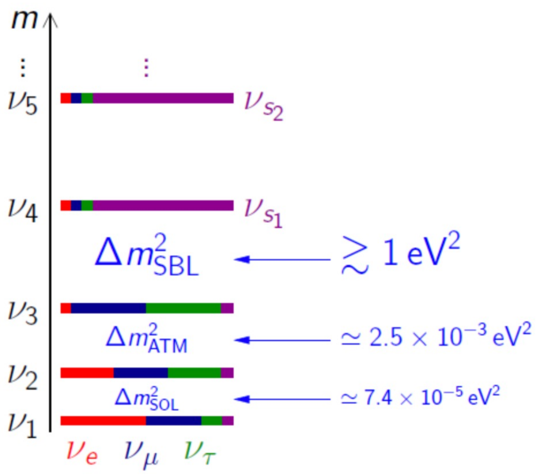
Based on the already-measured oscillation parameters, we do not expect to see muon neutrino oscillation at small values of L/E

- i.e.: ν_μ survival probability should be ~1 and ν_e appearance probability should be ~0 for order 1 GeV neutrinos with baselines < 100 km
- **Any evidence for ν_μ disappearance or ν_e appearance at these L/E values would require a larger mass splitting, which would require at least 1 additional neutrino mass state**
- Several experiments have observations consistent with ν_e appearance at L/E ~ 1 (+other anomalies)

Possible LEE Explanation? Sterile Neutrinos…

- 3 neutrino model → 3 + x neutrino model, where there are x additional, "sterile" neutrinos
- Sterile neutrinos mix with standard neutrinos (allows for additional oscillation), but do not have weak charge, (consistent with # of neutrinos from LEP/astrophysics)
- "3+1" model is simplest scenario; while this model is nearly excluded by data, we often quote sterile neutrino parameters in a simplified "2 flavor" version of this model
  - $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ (ν_e appearance)
  - $\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$ (ν_μ disappearance)
  - $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$ (ν_e disappearance)

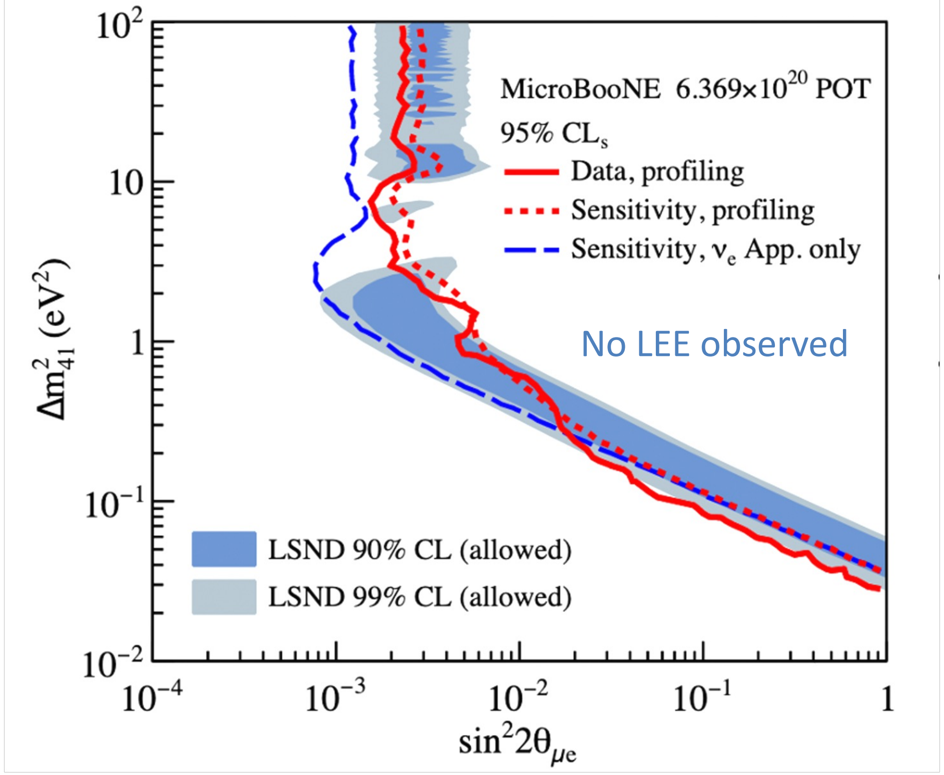
2 independent matrix elements



Other possible explanations for these anomalies proposed by theory community will also be investigated in SBN

Why Short-Baseline?

MicroBooNE (BNB)
Phys.Rev.Lett. 130 (2023) 1, 011801



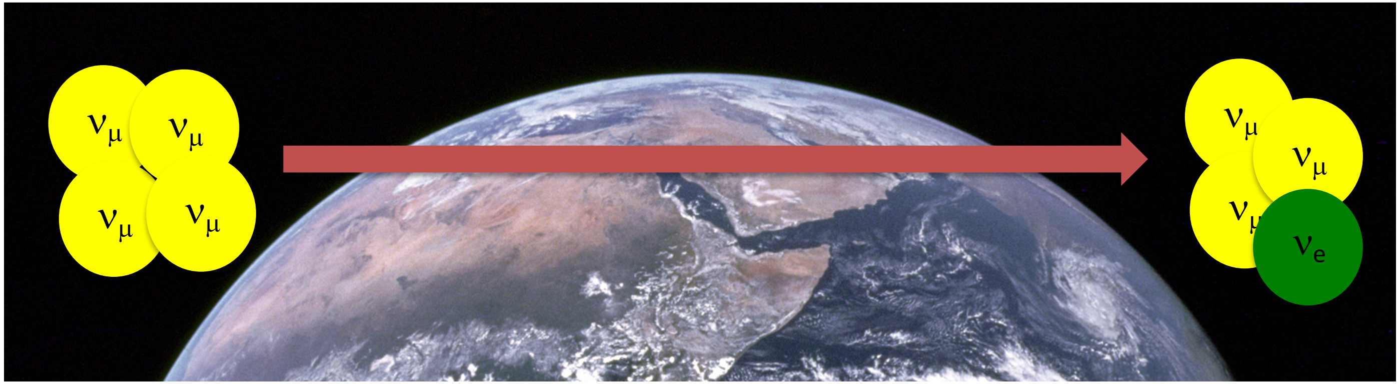
- Based on the already-measured oscillation parameters, we do not expect to see muon neutrino oscillation at small values of L/E
  - i.e.: ν_μ survival probability should be ~1 and ν_e appearance probability should be ~0 for order 1 GeV neutrinos with baselines < 100 km
  - **Any evidence for ν_μ disappearance or ν_e appearance at these L/E values would require a larger mass splitting, which would require at least 1 additional neutrino mass state**
  - Several experiments have observations consistent with ν_e appearance at L/E ~ 1 (+other anomalies)
  - However, MicroBooNE does not observe LEE and there is no evidence for ν_μ disappearance at L/E~1

Accelerator-Based Oscillation Experiments

Basics of an oscillation experiment

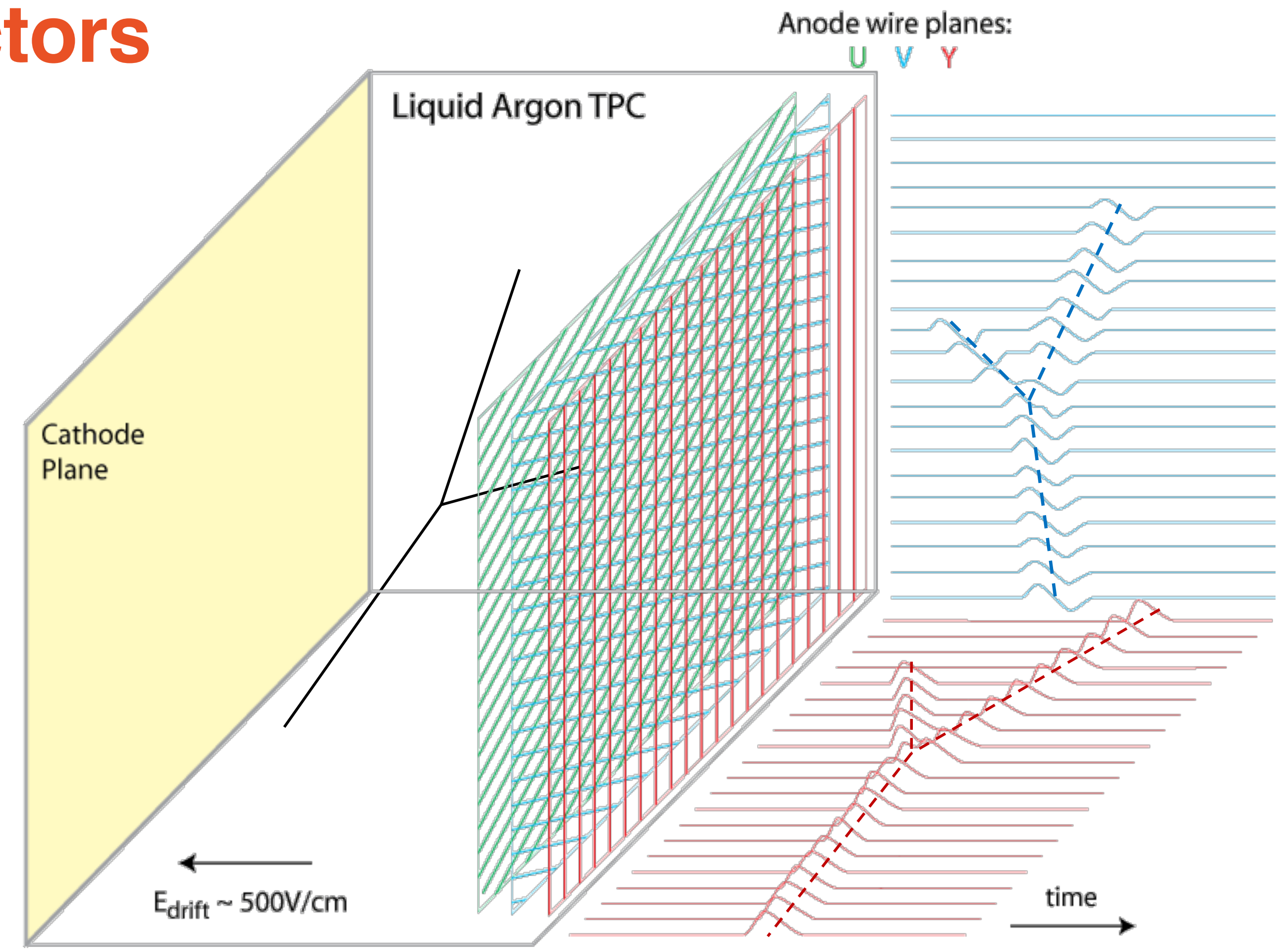
“Muon” neutrino beam created at accelerator complex → Composition of neutrino beam measured by near detector → Neutrinos travel desired baseline (up to 100s of kms) → Composition of neutrino beam after oscillation measured by far detector → Neutrino spectra analyzed to extract oscillation parameters

Two operational modes make either neutrino or antineutrino dominated beam

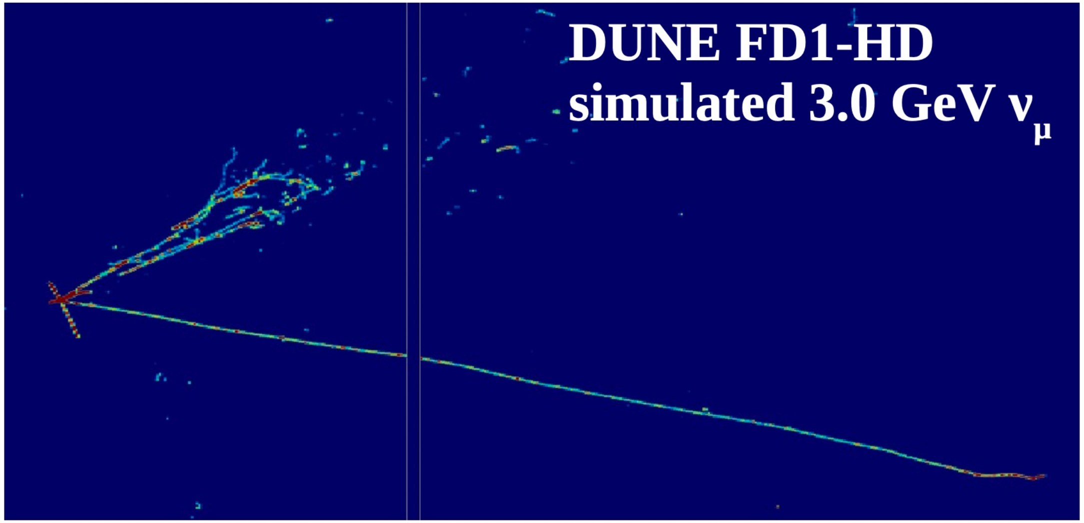


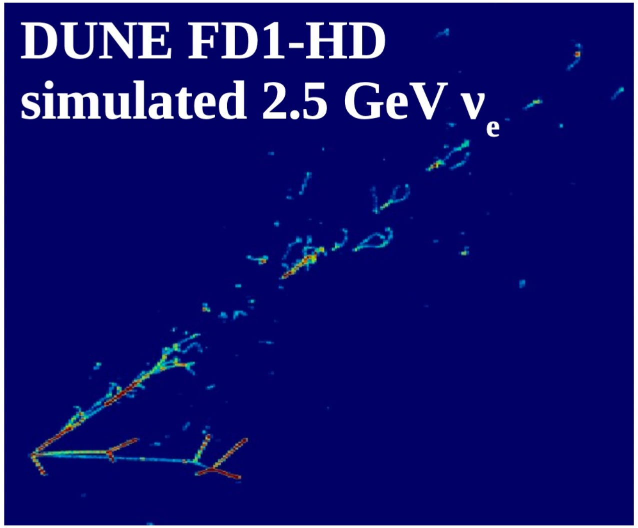
LArTPC Detectors

- Detailed images of final state particle trajectories
- Clean separation of ν_μ and ν_e interactions
- Good energy reconstruction over broad energy range
- Low threshold (few MeV)
- Integrated photon detection to establish event timing and potentially improve energy reconstruction



LArTPC Detectors





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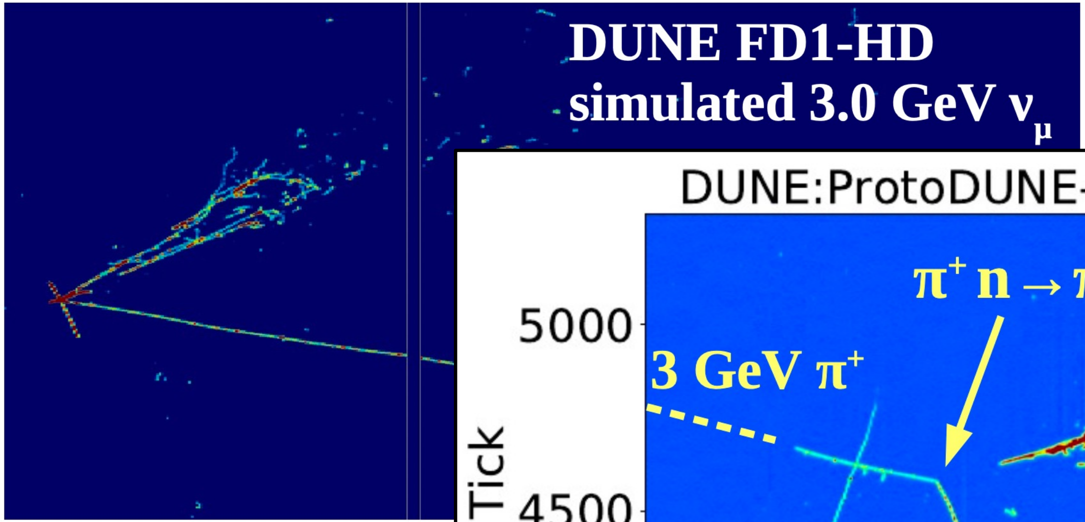
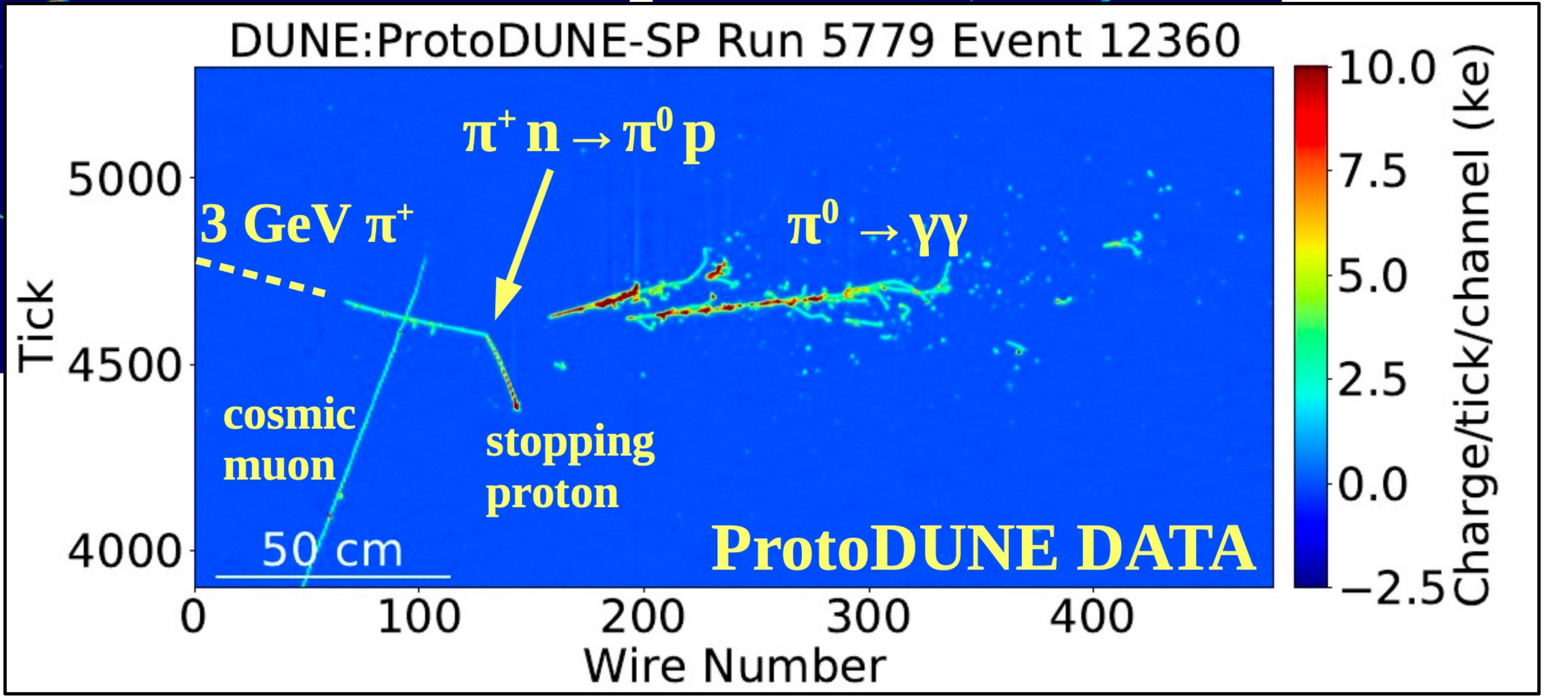
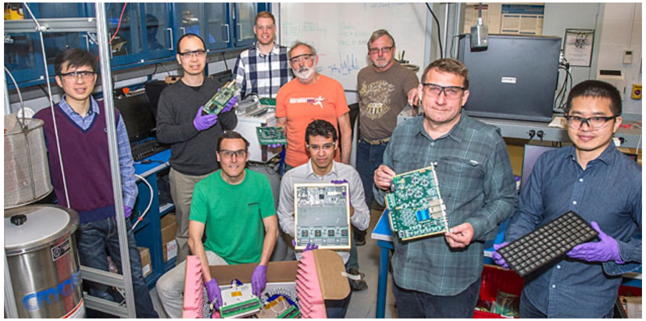
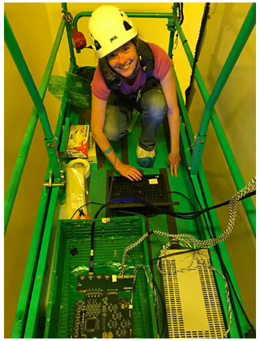


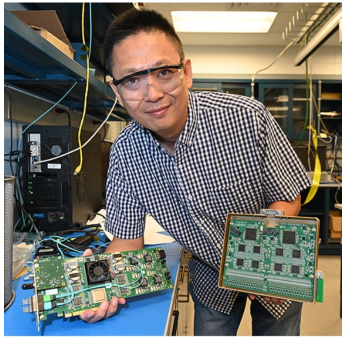


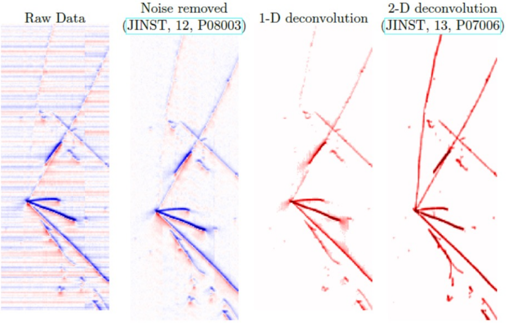
BNL LArTPC Expertise

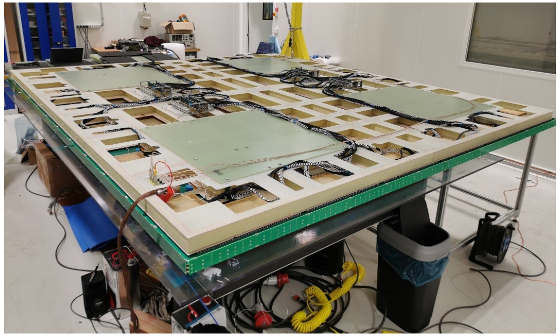
- Custom readout electronics that operate in liquid argon (“cold electronics”)
- Field cage design
- Readout plane for vertical drift LArTPCs (“CRPs”)
- Improved photon detection systems for precise energy reconstruction
- Signal processing and reconstruction software (“Wire-Cell”)





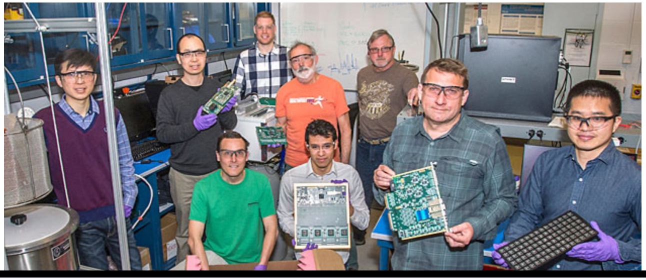


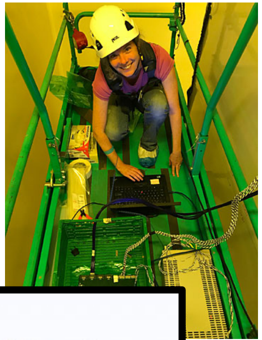




BNL LArTPC Expertise

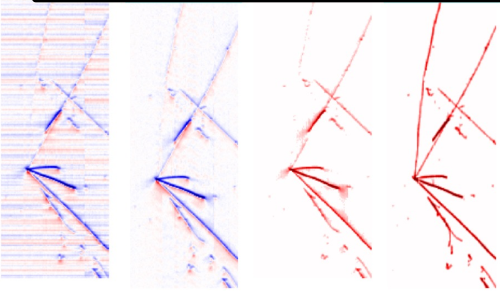
- Custom readout electronics that operate in liquid argon (“cold electronics”)

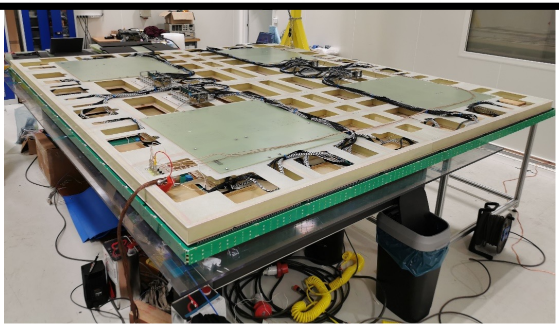




AI Answer — Learn more

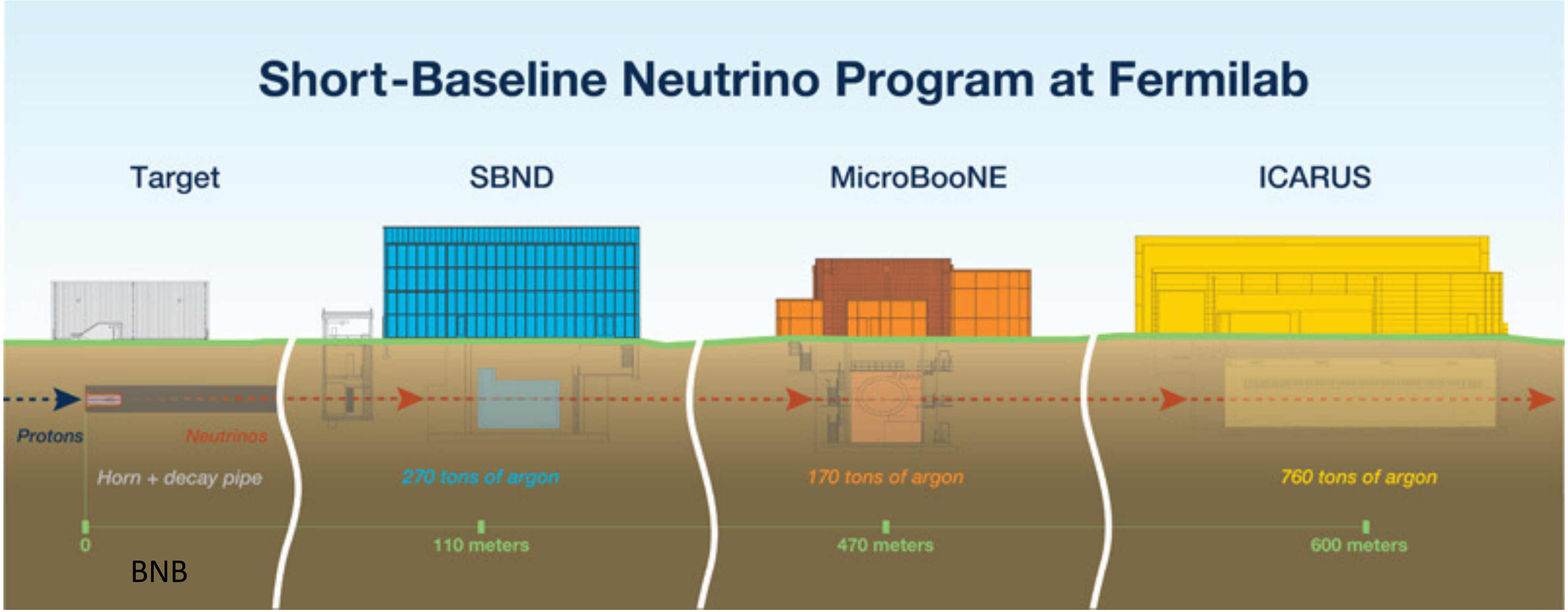
Cold electronics can refer to **a system that separates the electrode and cryostat design from the readout design**. Cold electronics can also refer to the Cold Electronics Review, which took place in Elizabeth Worcester from October 12–14, 2016.





Short-Baseline Program

3 LArTPC detectors in the Booster Neutrino Beam



Commissioning in progress

Taking data 2015-2022

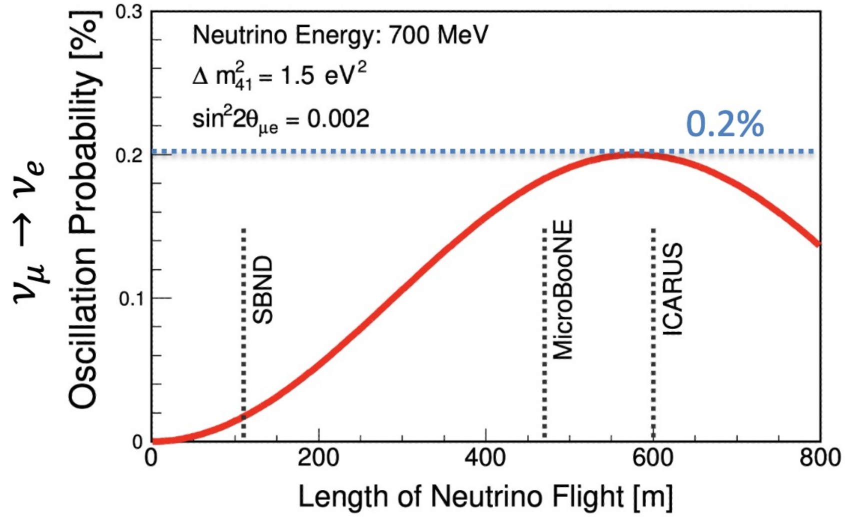
Taking physics data since June 2022

SBN Program

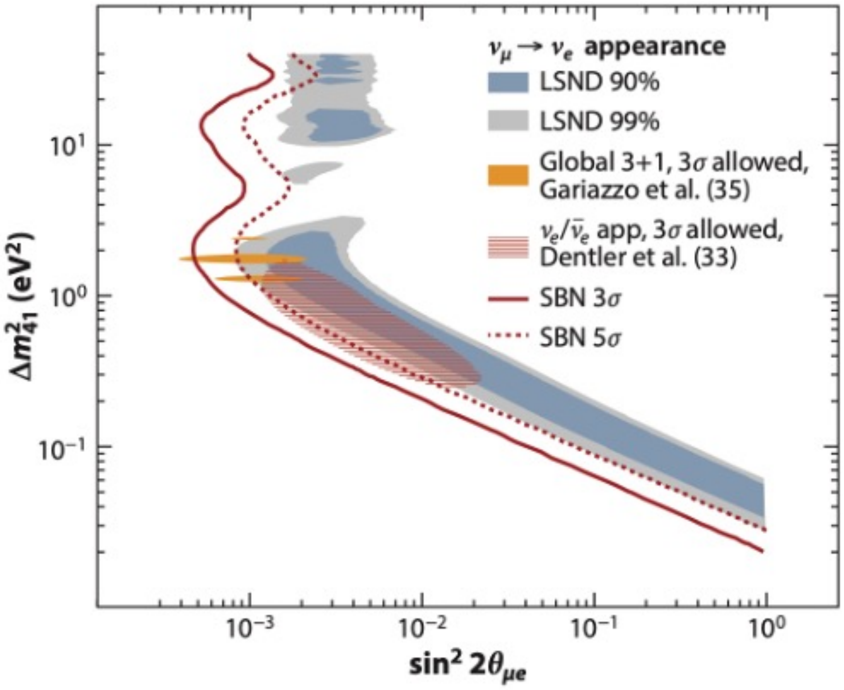
- Multiple detectors, at different baselines, using the same detector technology

Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146

Example oscillation at BNB peak energy

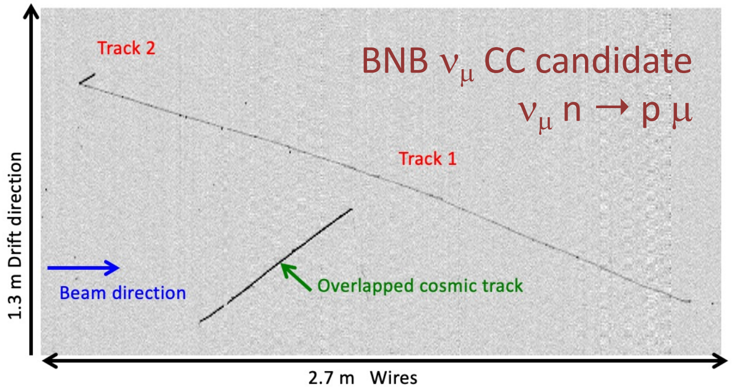


ν_e sensitivity projection assuming 6.6E20 POT



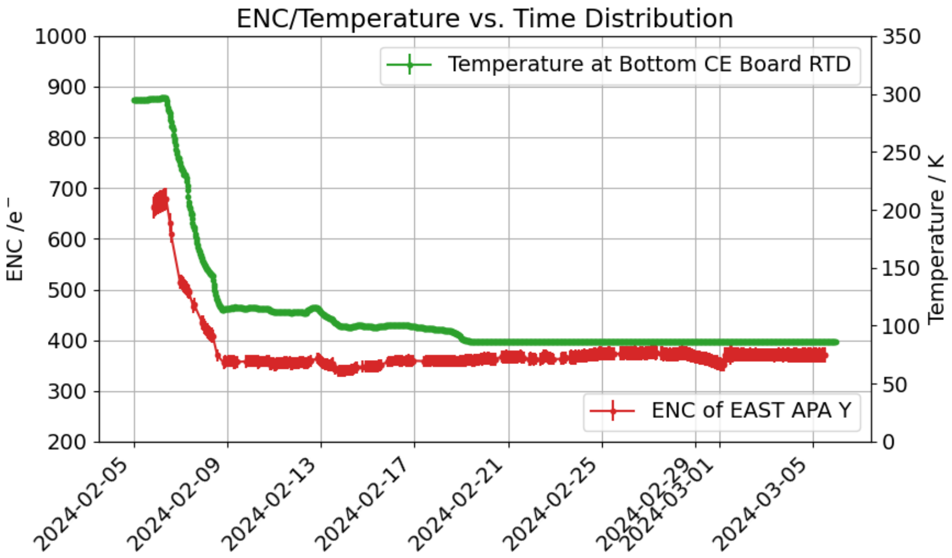
SBN Status

- ICARUS has been taking physics data since June 2022 and is planning to report first charged current selections at Neutrino 2024



  - BNL/SBU graduate student Jacob Larkin defended his thesis on a 1μNp CC selection yesterday!

- SBND is full of liquid argon and commissioning is in progress



SBN Status

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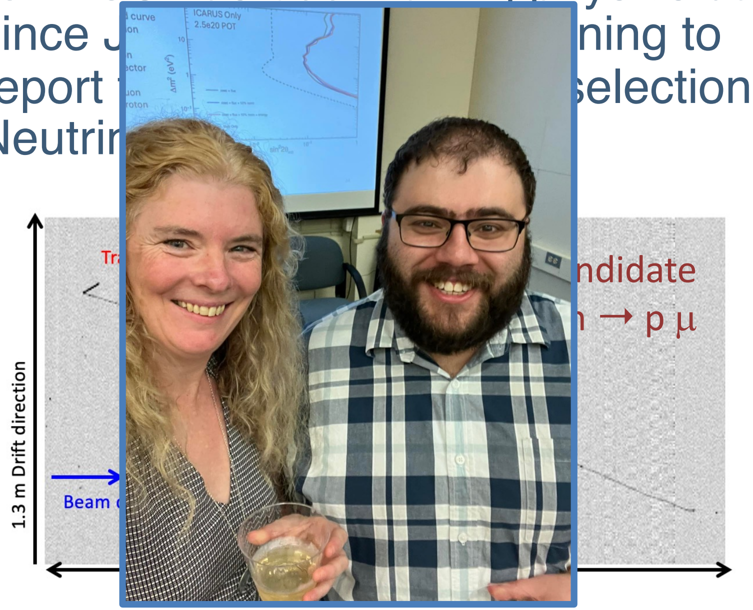

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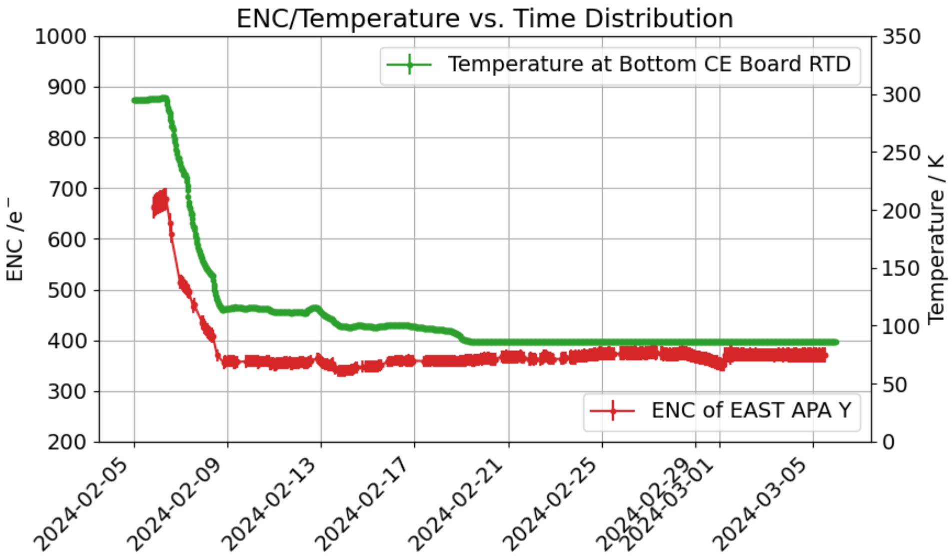
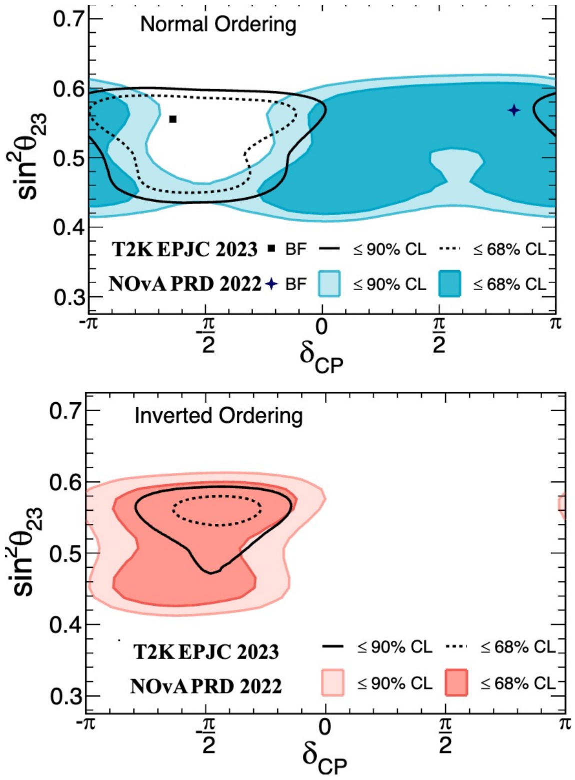


Long Baseline Experimental Status

NOvA & T2K 2020 Results



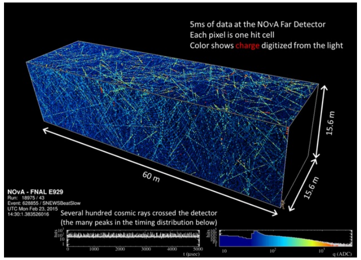
Mild tension between latest best-fit values for NOvA and T2K results. Mild individual preference for normal ordering. Joint fit recently announced (see talks next week from Leona Woods Fellow, Z. Vallari)

T2K: Tokai to Kamioka

Baseline: 295 km

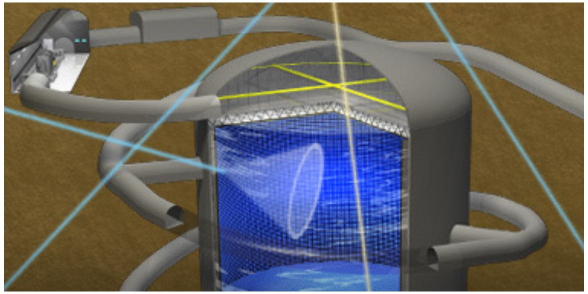
NOvA: FNAL to Ash River

Baseline: 810 km



Future LBL Experiments

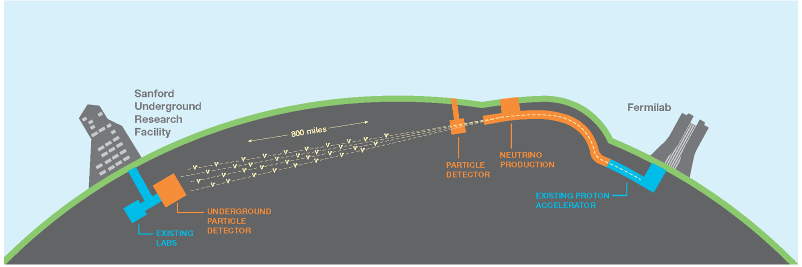
T2HK: Tokai to HyperK



- Maximize statistics and minimize matter effect to focus on CPV discovery (short baseline, very large far detector)
  - Requires separate atmospheric neutrino sample to determine mass ordering
- Beam: J-PARC, 1.3 MW
- Far detector: WCD (187 kt fiducial)
- Baseline: 295 km
- Far detector located off-axis such that observed ν flux is peaked at ~600 MeV

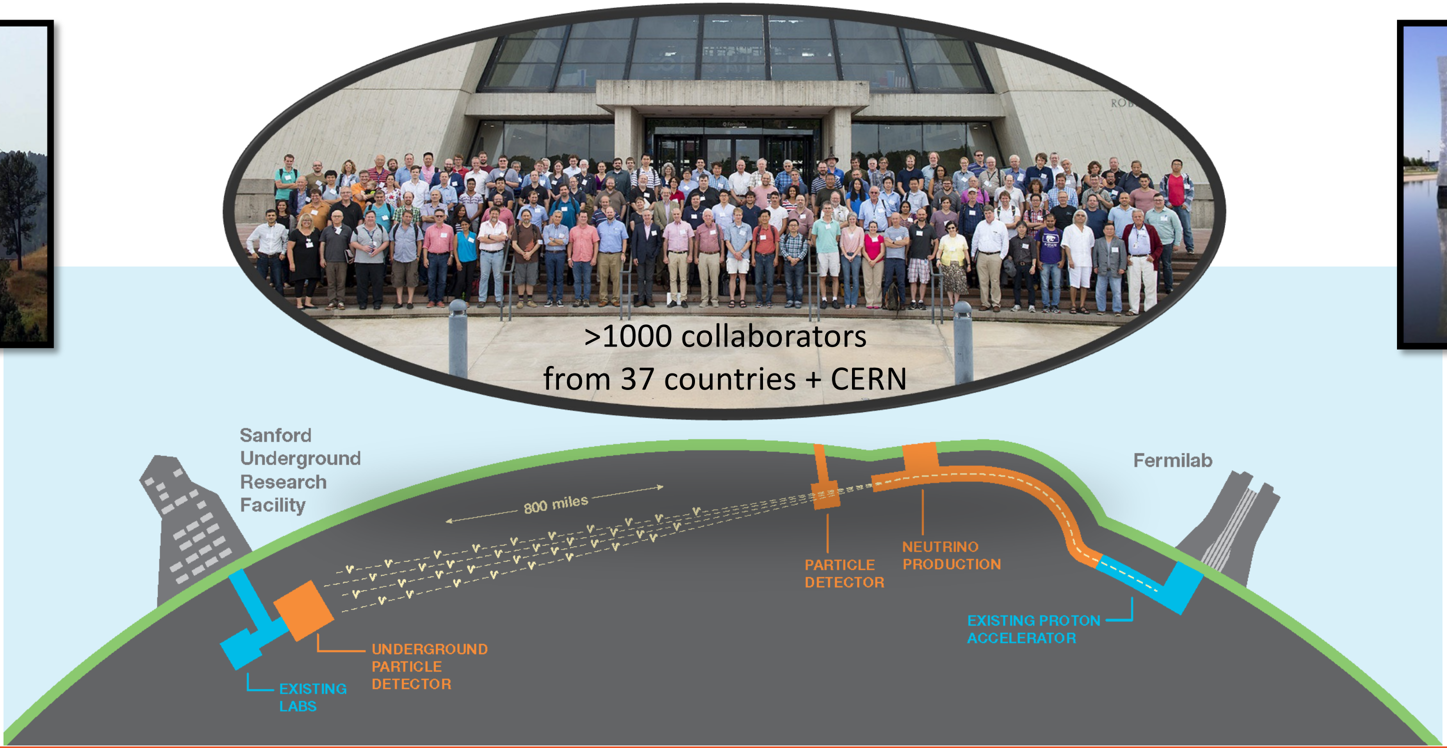
DUNE: FNAL to SURF

- Measure all LBL parameters (incl. MO) in a single dataset and map oscillation pattern as a function of energy for precision measurements (long baseline, broadband beam, precision imaging far detector)
- Beam: LBNF (FNAL), 1.2-2.4 MW,
- Far detector: LArTPC (>40 kt fiducial)
- Baseline: 1300 km
- Far detector located on-axis such that observed ν flux is a broad spectrum (0.5-5 GeV)



DUNE Experiment

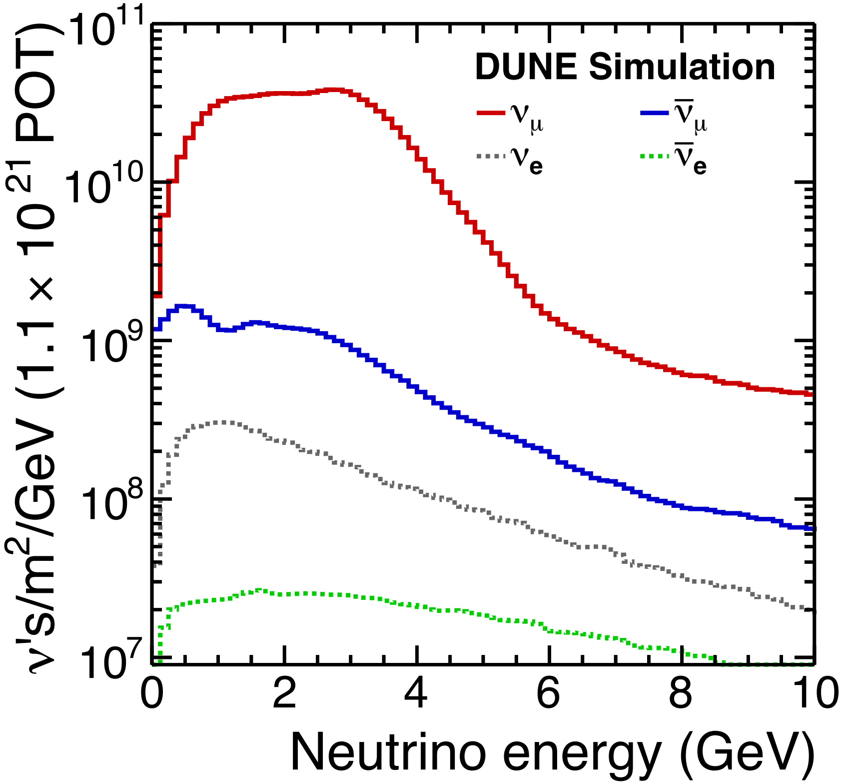
Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure MO, CPV, and neutrino mixing parameters in a single experiment. Large detector, deep underground provides sensitivity to low energy neutrinos (supernova, solar) and baryon number violating processes.



LBNF Neutrino Beam

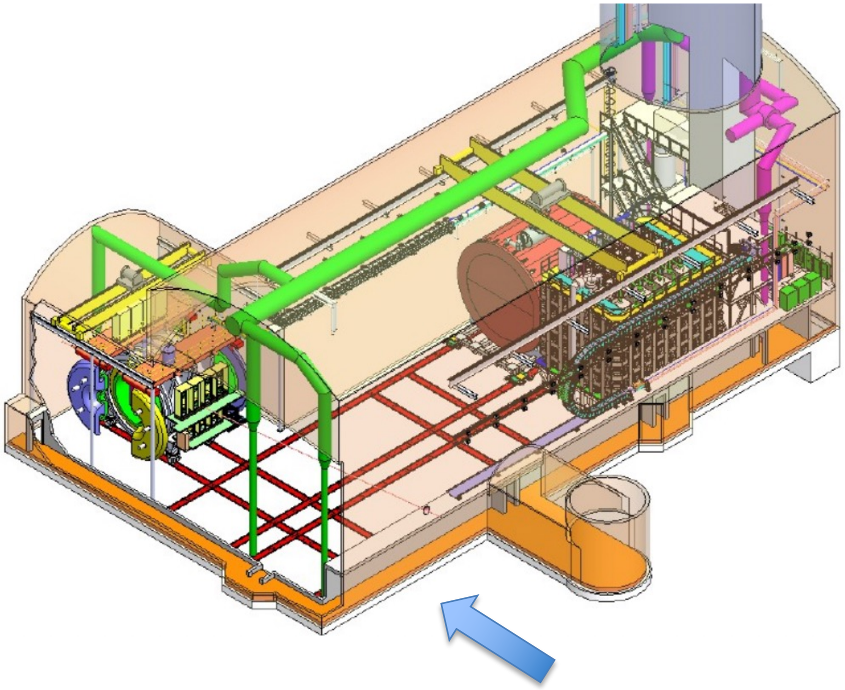
- 120-GeV protons from FNAL accelerator complex
  – 2 MW initial beam power with ACE-MIRT, ultimately upgradeable to 2.4 MW
- Horn-focused neutrino beam line designed using genetic algorithm to optimize CP violation sensitivity

Neutrino Mode Flux:



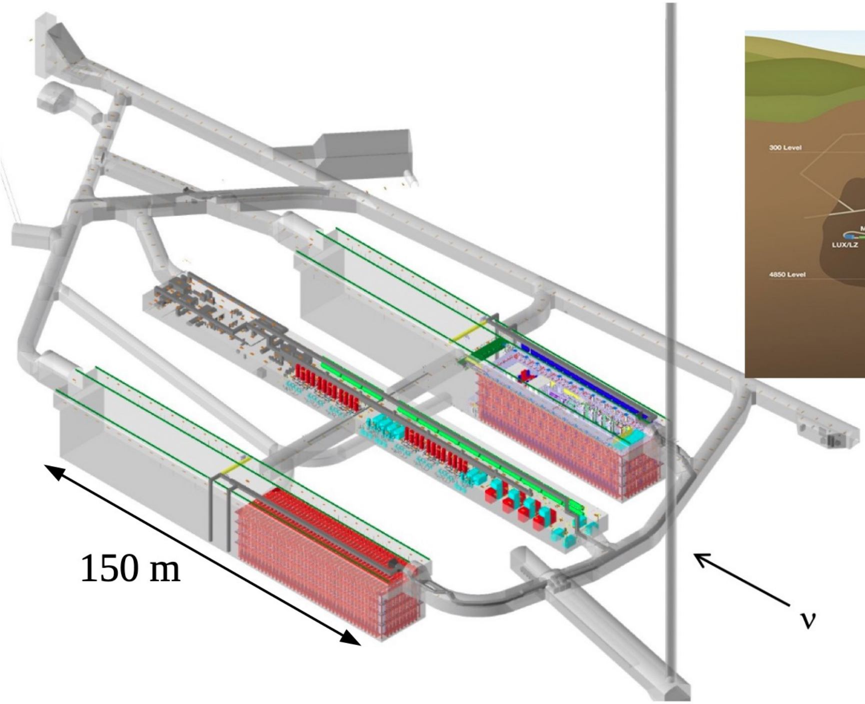
DUNE Near Detector

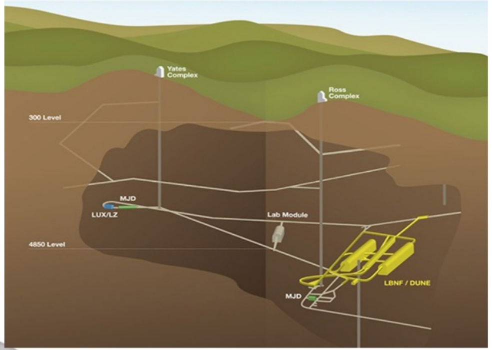
- Suite of ND components are designed to provide constraint on systematic uncertainty from flux, neutrino interaction modeling, and detector effects
- **LArTPC**
  - Same nuclear target and detection technology far and near
  - Differences in ND design required to handle higher rate environment at the near detector
- The Muon Spectrometer (**TMS**)
  - Serves as “muon catcher” for LArTPC
  - Upgradable to more capable ND for improved systematics constraints
- **PRISM**
  - LArTPC and TMS move up to 30m off axis to facilitate measurements in different neutrino fluxes
- **SAND**
  - On-axis magnetized low-density tracker and spectrometer, re-using magnet and ECAL from KLOE



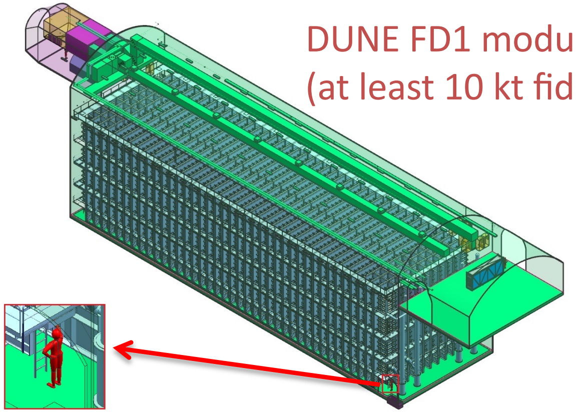
DUNE Far Detector at SURF

SURF: Sanford Underground Research Facility (Lead, SD)





- 4850 level of SURF
- Space for 70kt LAr detector



Brookhaven National Laboratory DUNE

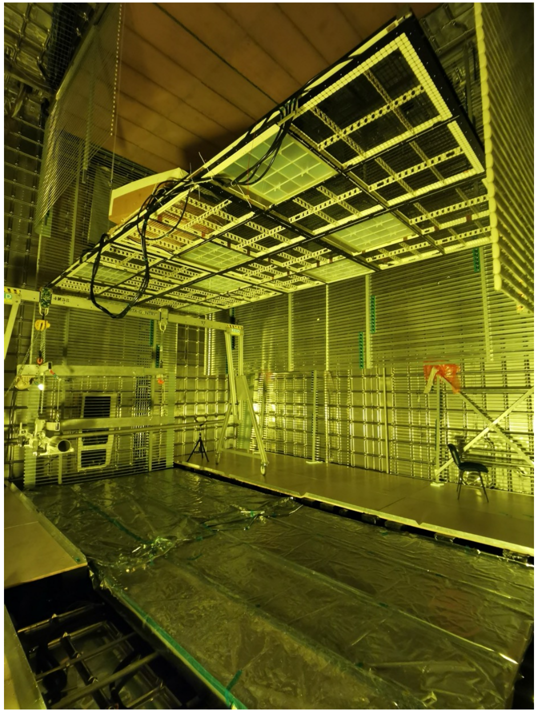
DUNE is under construction now

Excavation is complete!
Construction of LArTPC components underway with installation in the cryostat beginning in 2027

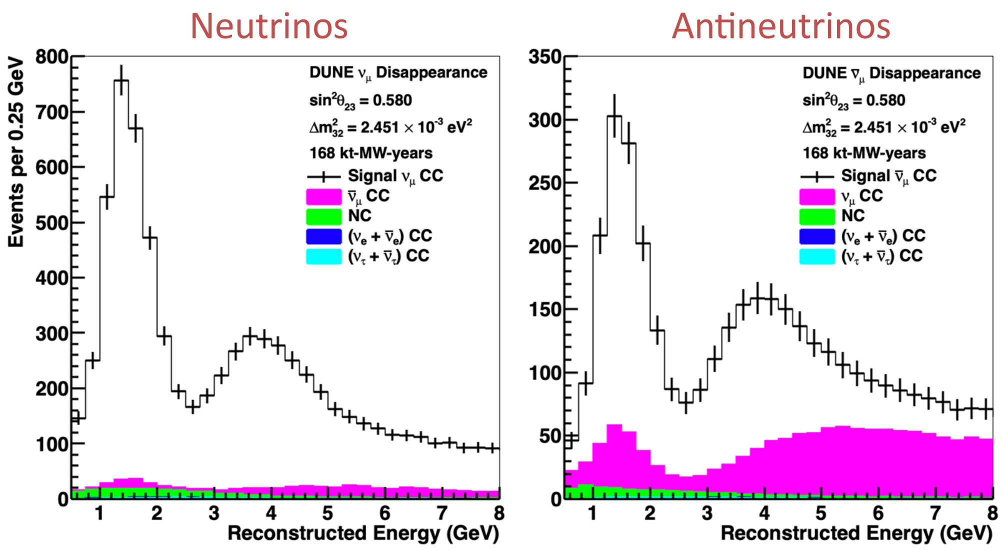
North cavern

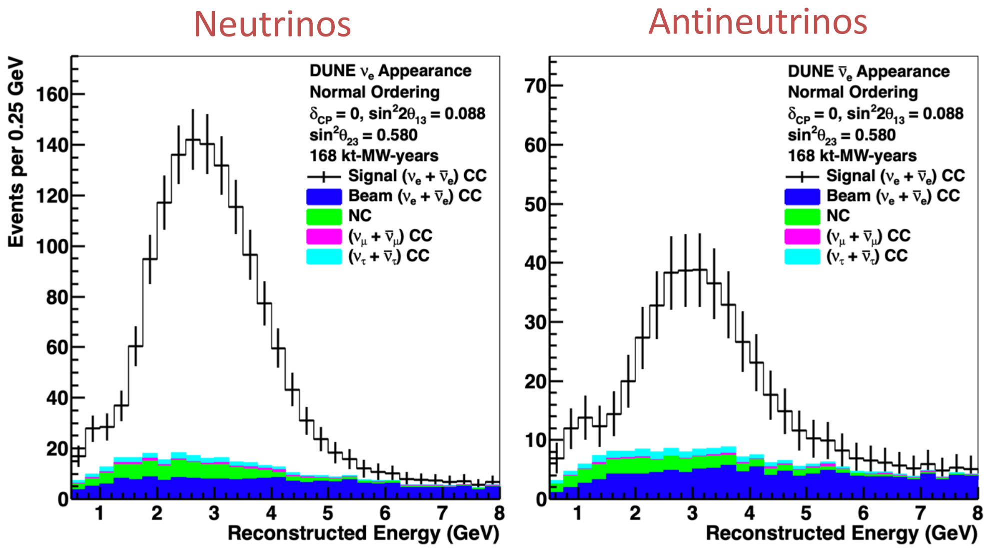
Central utility cavern

CRP Prototypes



DUNE Spectra





ν_μ Disappearance

Order 10000 events

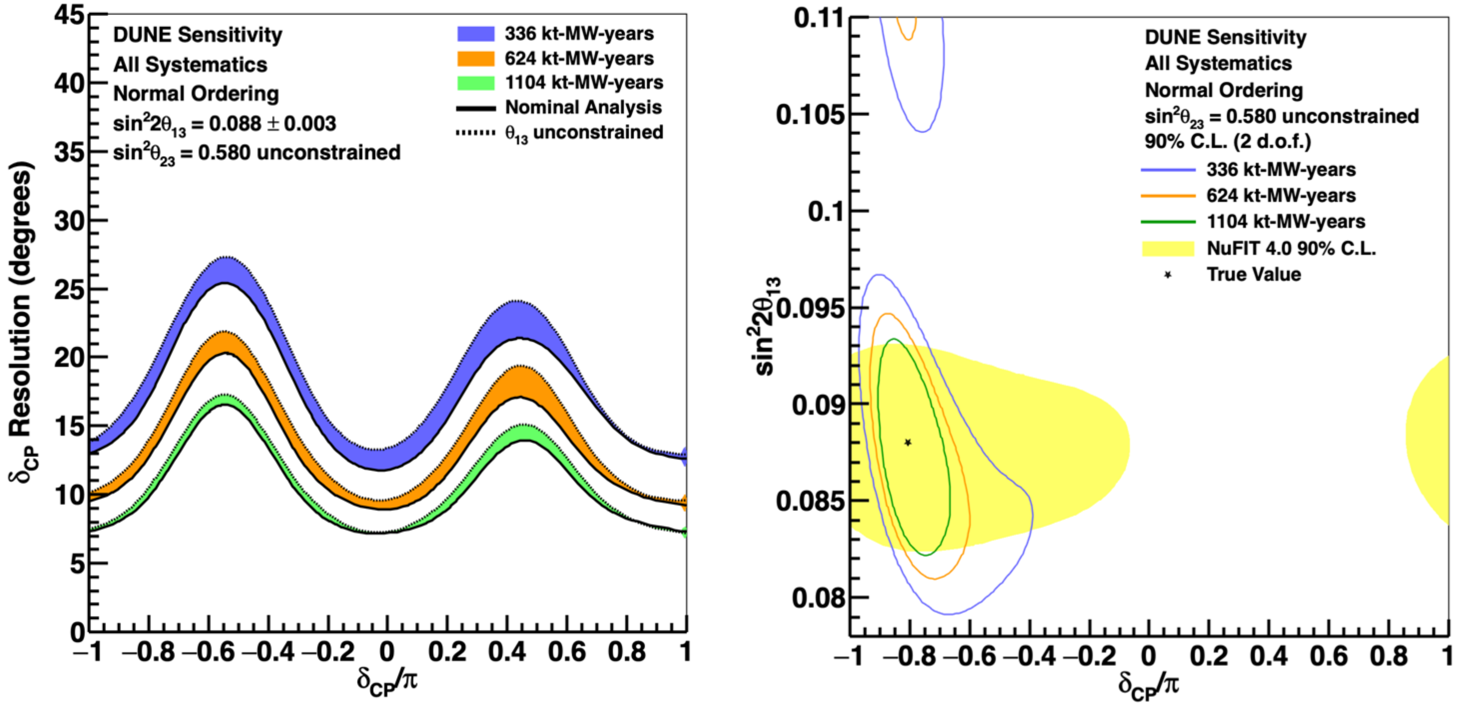
ν_e Appearance

Order 1000 events

DUNE Sensitivity

arXiv:2006.16043
arXiv:2109.01304

Precision Measurements:

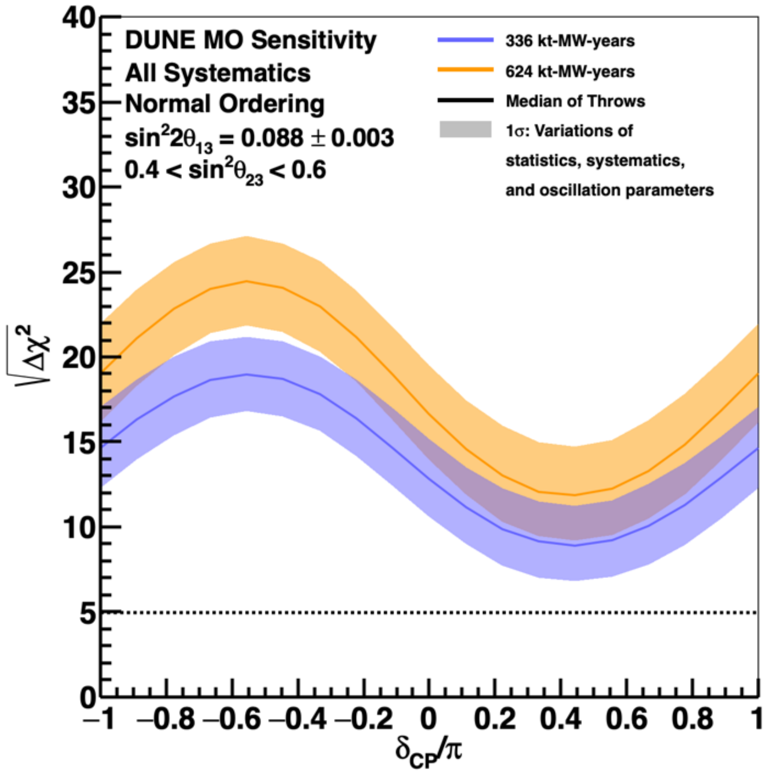


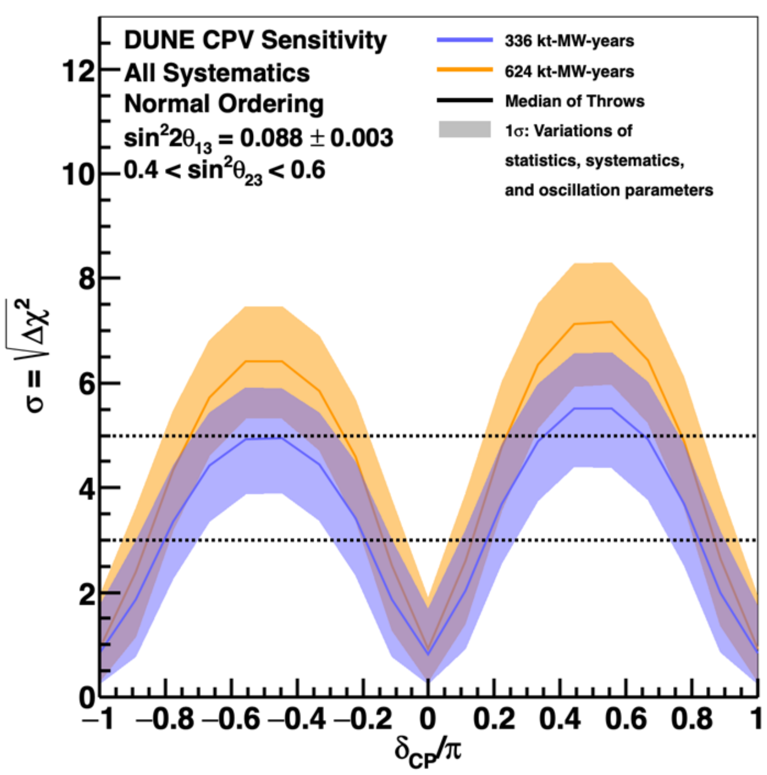
Width of band represents difference between sensitivity with and without external constraint on θ_{13}

θ_{13} precision comparable to that of reactor experiments for large exposures

DUNE Sensitivity

arXiv:2006.16043
arXiv:2109.01304

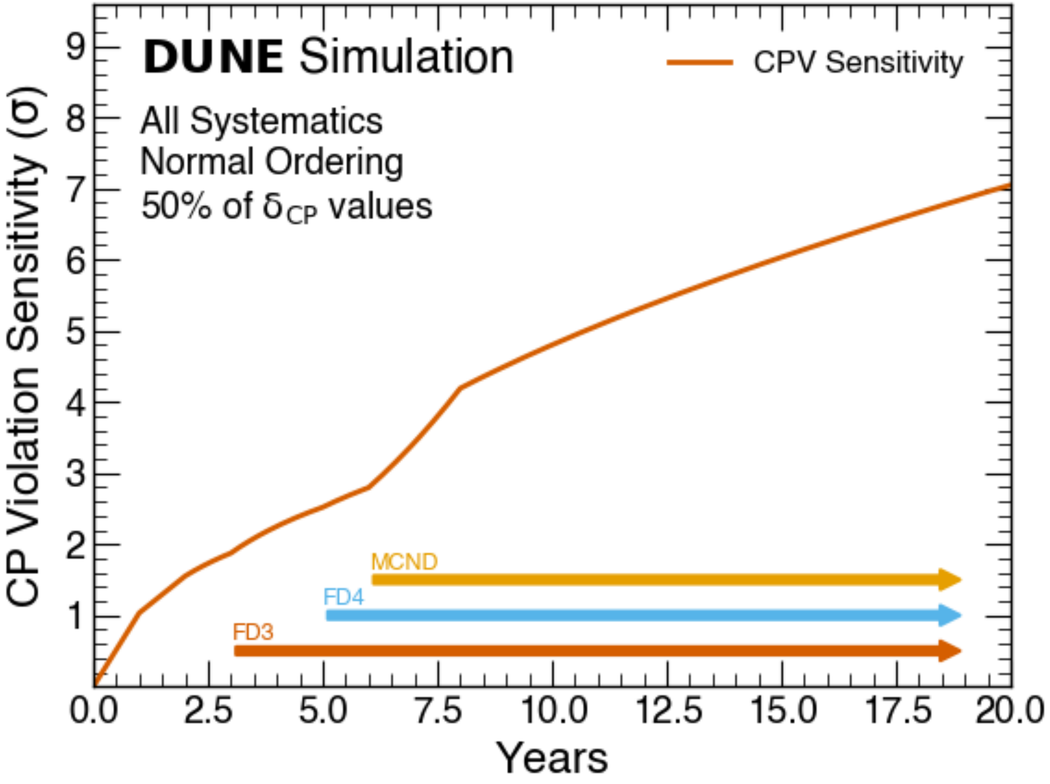




Width of band shows 1σ variations of statistics, systematic parameters, and oscillation parameters.
Unambiguous determination of neutrino mass ordering and 5σ sensitivity to δ_{CP} for a large range of parameter space.

DUNE Sensitivity

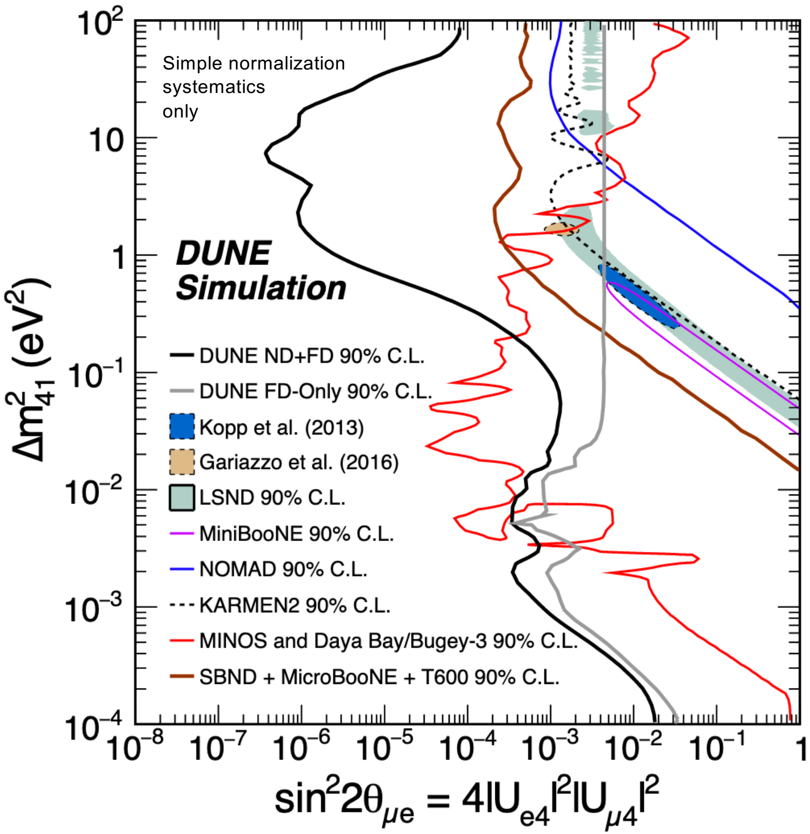
arXiv:2006.16043
arXiv:2109.01304



- DUNE will be built in phases
- Phase I: Beam, half of the far detector mass (2 modules), and a near detector
- Phase II: Add two additional far detector modules, potentially with additional capabilities to expand physics scope, and a more capable near detector to constrain systematic uncertainty for precision measurements

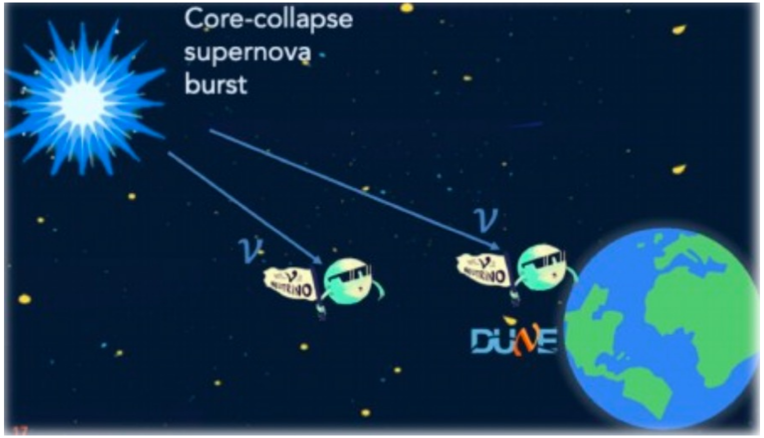
Physics Beyond the Standard Model arXiv:2008.12769

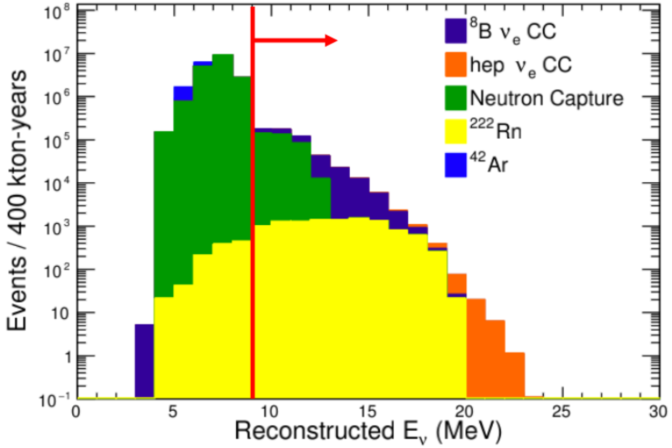
- Sensitivity to many new physics scenarios being investigated both by the collaboration and phenomenologists
- Deviations from 3-flavor oscillation (sterile ν, NSI, PMNS non-unitarity, CPT violation, etc)
- Complementary measurements at both DUNE and HK may help disentangle degeneracy between BSM signatures and 3-flavor oscillation parameters.
- Other (non-neutrino) new physics signatures (neutrino trident rate, dark matter, baryon number violation, etc – both ND and FD)



Brookhaven National Laboratory

Astrophysical Neutrino Sources [arXiv:2008.06647]





- Thousands of neutrinos will be observed by DUNE for a typical galactic supernova burst
  - Probe core collapse mechanism, supernova evolution, etc.
- Flux complementary to other detectors: CC absorption (ν_e) dominates
- Pointing capability (multi-messenger astrophysics)

- DUNE will see ~100 solar neutrinos per day
  - Large background at low energies due to neutron capture
- DUNE can observe hep solar flux at >5σ (first time!)
- Measurements of solar oscillation parameters can be compared with JUNO (arXiv:1808.08232)

Systematic Uncertainty in Accelerator-Based Neutrino Experiments

Systematic Uncertainty

- All oscillation measurements are made by comparing observed event spectra to the event spectra predicted for different oscillation parameters, to determine the oscillation parameters most compatible with observation

$$\chi^2 = -2\log\mathcal{L} = 2\sum_{i}^{N_{bins}}\left[M_i(\theta) - D_i + D_i \log\left(\frac{D_i}{M_i(\theta)}\right)\right] + P(\theta)$$

Observed (D_i), Expected ($M_i(\theta)$), Penalty ($P(\theta)$)

Example of log-likelihood fit function

- This means any uncertainty in the predicted spectrum leads to uncertainty in the measurement of oscillation parameters

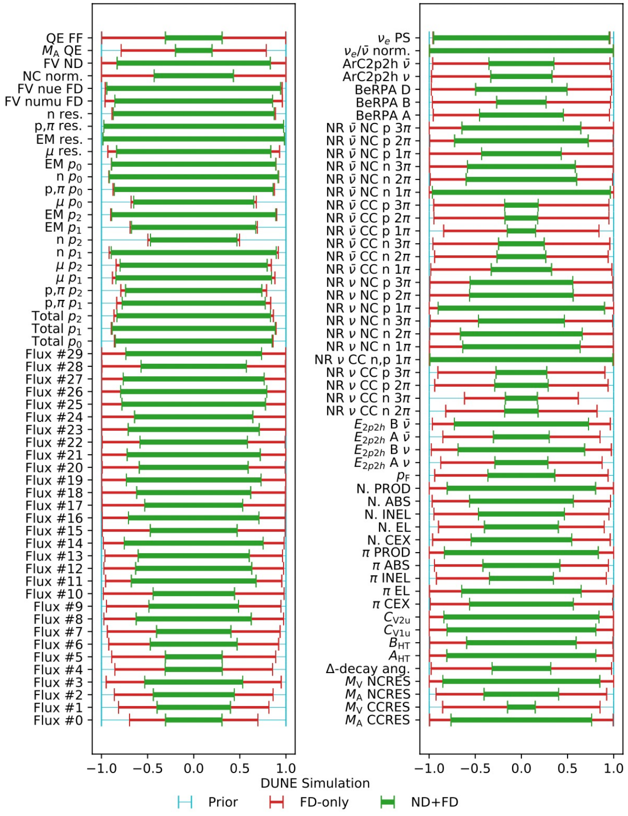
- The observed spectrum depends on the neutrino flux (varies with energy and position), neutrino interactions (vary with energy and detector material), and ability to reconstruct neutrino properties from detector observations (varies with energy, interaction final state, and detector)

- Near detectors are necessary to constrain uncertainty in far detector predictions, but doing so is not always straightforward or possible with a single near detector measurement

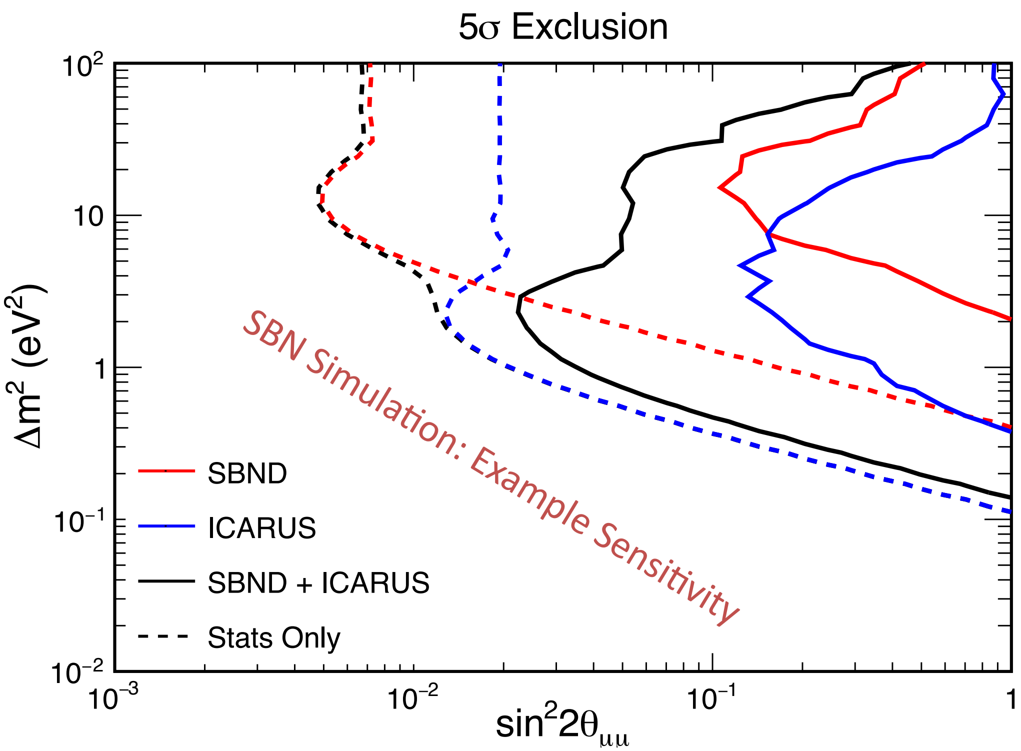
Systematic Uncertainty

- Order few percent uncertainty required for precision measurements
- Sources of uncertainty:
  - Neutrino flux
  - Neutrino interaction model
  - Detector effects
- Sensitivity projections include detailed analysis of impact from individual source of systematics
- Near detectors are critical to achieve precision measurement goals!
- Impact of biases due to shortcomings in the interaction model is large (several examples upcoming)

Systematics included in DUNE sensitivity projections (arXiv:2006.16043):

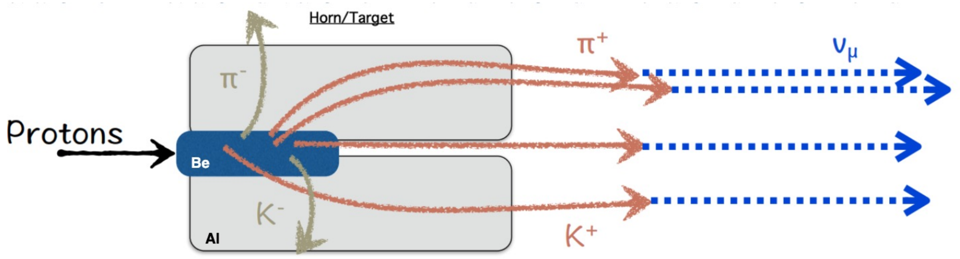


Impact of Near Detector in SBN



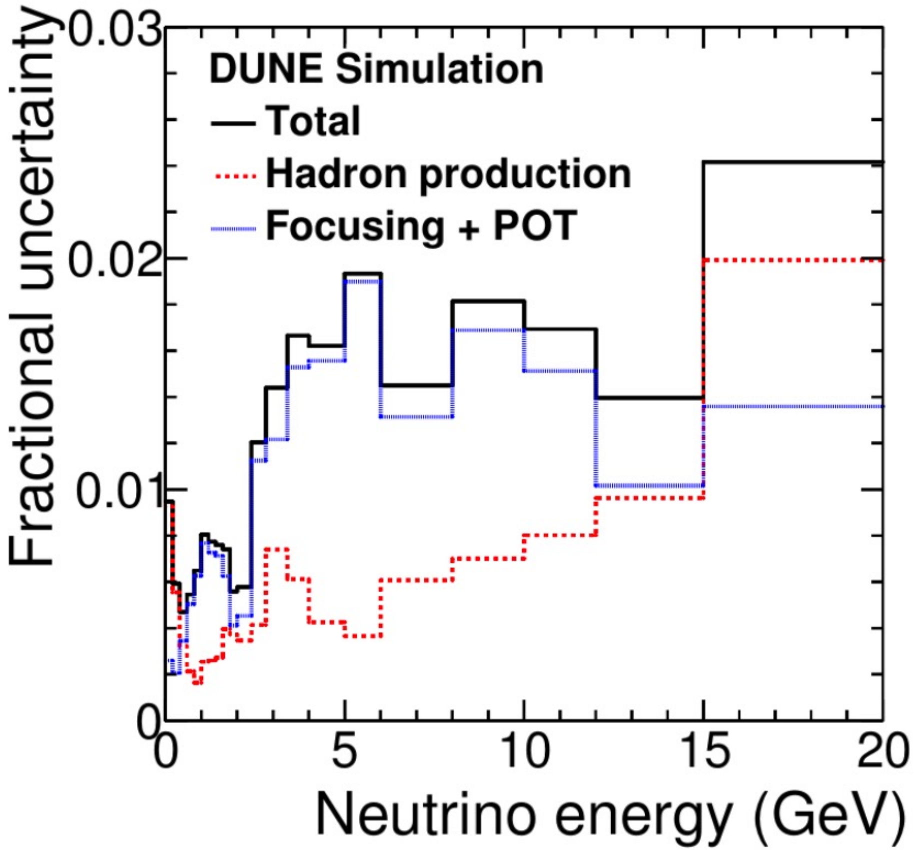
- Example ν_μ disappearance sensitivity demonstrating the impact of the two-detector analysis in constraining systematic uncertainty
- Flux and (partial) interaction systematics only

Flux Uncertainty



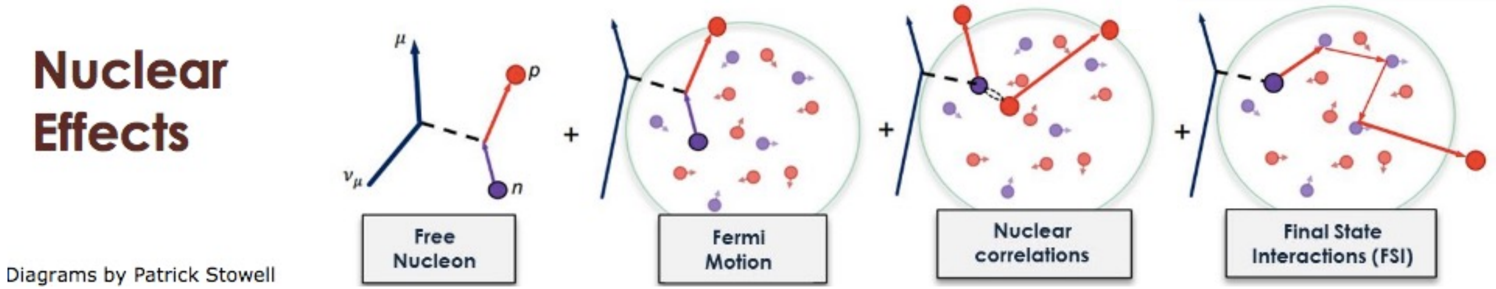
- Flux uncertainties can come from uncertainty in predicting hadron production or from uncertainty in the target/focusing system (horn currents, geometry, etc)
- Absolute scale of hadron production uncertainties usually much larger than focusing uncertainties
- Much of the uncertainty cancels in a ND/FD flux ratio, which is most relevant for oscillation systematics

Fractional uncertainty on FD/ND flux ratio for ν_μ in DUNE



Neutrino Interaction Modeling

Neutrinos in DUNE are not interacting with bare nucleons…structure of the nucleus matters!

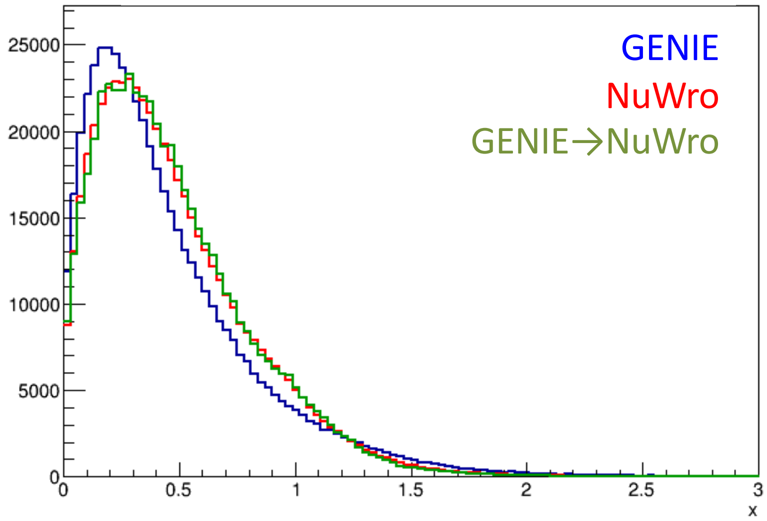


- Modeling neutrino interactions requires detailed modeling of complex nuclei!
- Interaction model affects energy reconstruction – mis-reconstructed energy can significantly bias results
- Neutrino-nucleus interaction model does not currently describe world neutrino interaction data → program of neutrino interaction experiments, model-building, and event generator development very important for precision measurements in neutrino physics
- Neutrino oscillation experiments are being designed to provide experimental solutions to imperfect interaction model
  - Improve model constraints by making precise measurements of final states
  - Reduce sensitivity to details of model by making data-driven predictions

Studies of Interaction Model Systematics in DUNE

- Use BDT to reweight between alternative generators (GENIE→NuWro) in a space of 18 kinematic variables
- FD fit χ^2/d.o.f. < 1, but produces bias in fit for δ_{CP}
- ND-FD fit has χ^2/d.o.f. > 30
- Without ND to validate interaction model, would have to include possibility of this kind of bias as systematic uncertainty
- Exclusive final state samples in the near detector may be used to reduce this bias if a sufficiently capable near detector is available

Example: ν x distribution, FD FHC ν_e



More on multivariate reweighting:
C. Vilela at NPML 2020

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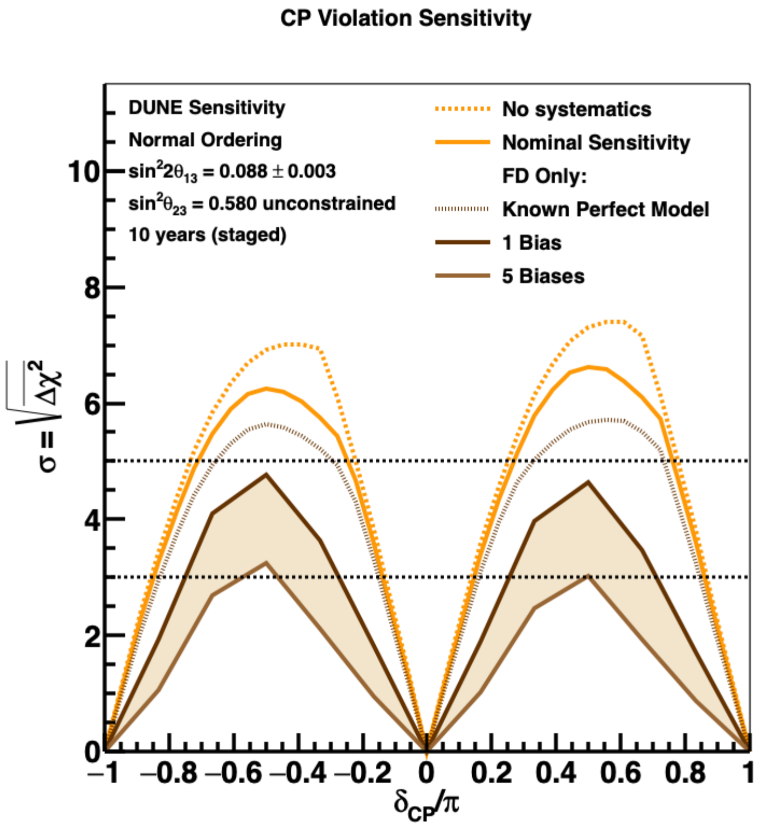
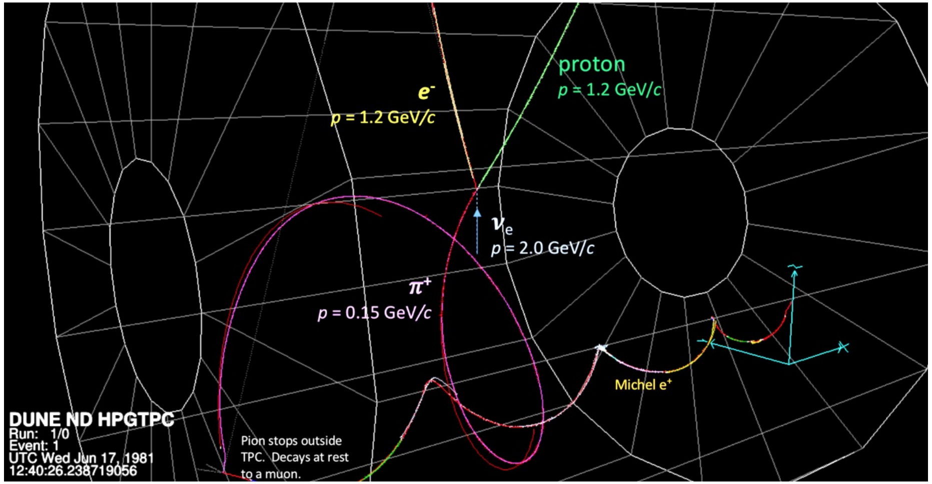
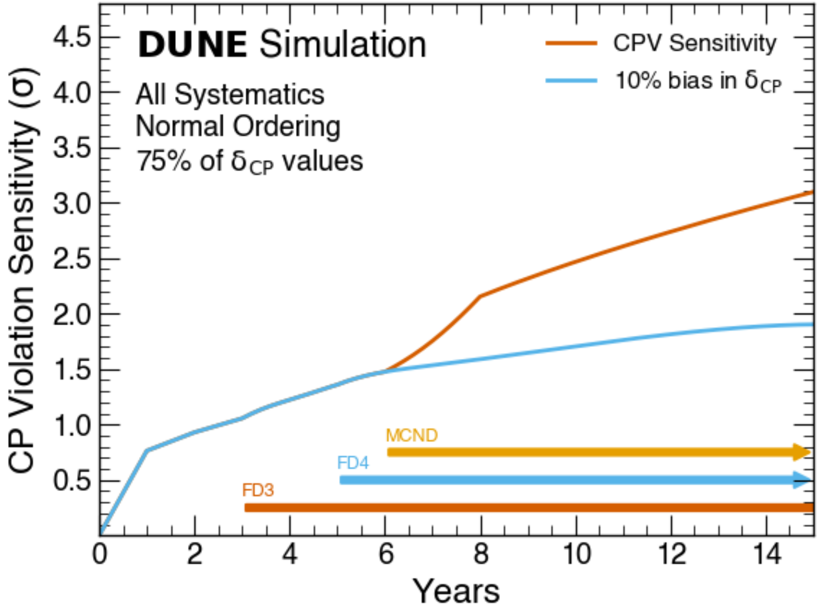


Impact of DUNE's MCND

- MCND: More Capable Near Detector
- Important capability is precise identification of complex final state topologies

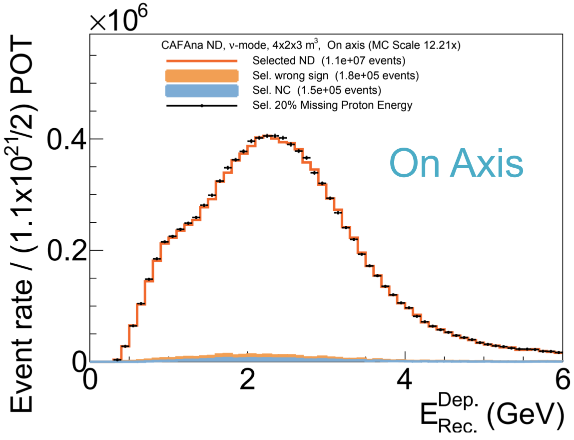


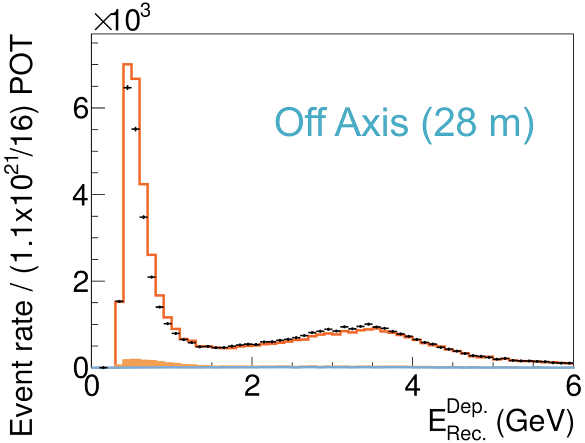


Bias observed in NuWro study can be removed by using samples with different final state pion multiplicity to reweight the FD prediction

Studies of Interaction Model Systematics in DUNE

- Study where on-axis ND measurements are not sufficient to constrain uncertainty
- 20% of proton energy is removed and added to (largely invisible) neutrons
  - Significant modification to relationship between reconstructed and true energy
  - An artificial but plausible example of a way in which the interaction model could be off
- Use BDT to adjust model parameters such that **on-axis** ND reconstructed distributions agree with the nominal sample





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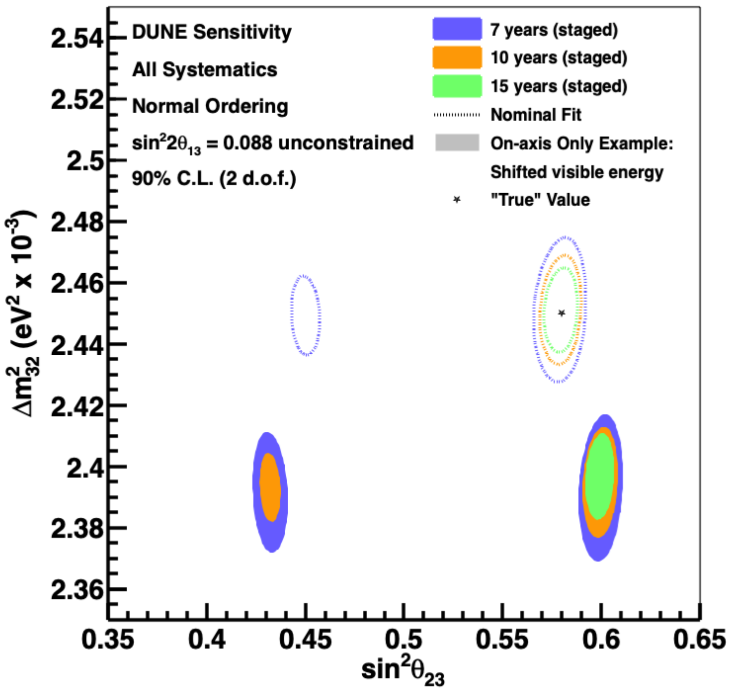
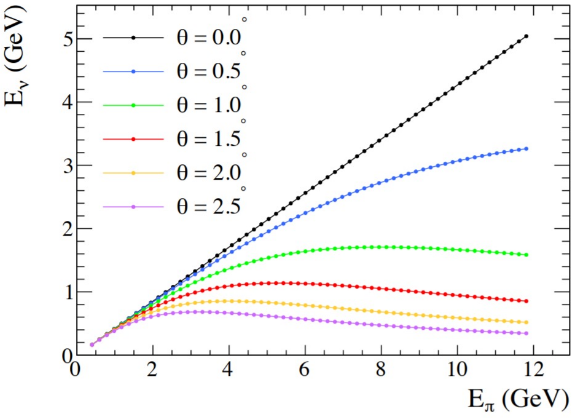
  - An artificial but plausible example of a way in which the interaction model could be off
- Use BDT to adjust model parameters such that **on-axis** ND reconstructed distributions agree with the nominal sample
- Mismodeling leads to significant bias in measured oscillation parameters

Δm^2_{32} vs $\sin^2\theta_{23}$

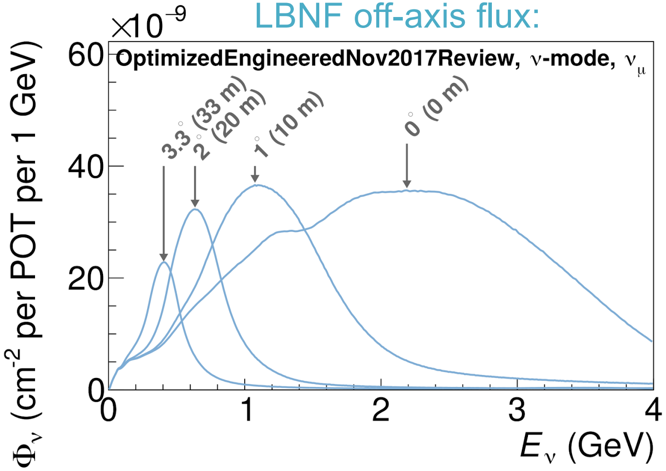


DUNE PRISM

Off-axis neutrino energy:



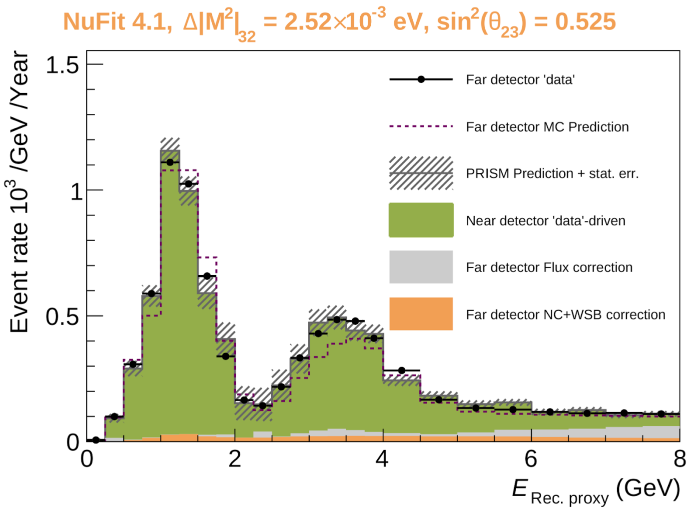
LBNF off-axis flux:

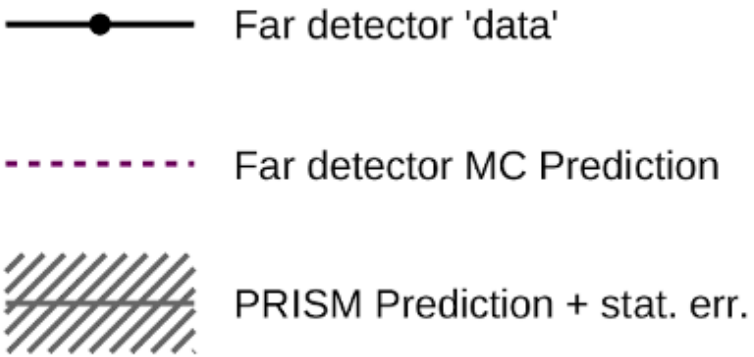


PRISM (Precision Reaction-Independent Spectrum Measurement) concept is to use linear combinations of off-axis fluxes to construct any flux: can ~reproduce FD flux prediction or a Gaussian flux at a given energy. Same weights can then be applied to ND data to construct a "data driven" predicted event rate for a given flux.

DUNE PRISM Example

Energy bias study with PRISM:



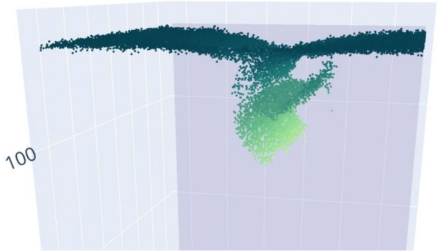


- With nominal MC, prediction badly mismatched to data, leading to biased measurement of oscillation parameters
- PRISM prediction is well-matched to data and no bias in parameter measurement is observed!

Detector Modeling Systematics

- Most difficult to predict in advance, because these can vary from detector to detector as they often represent imperfections in detector performance

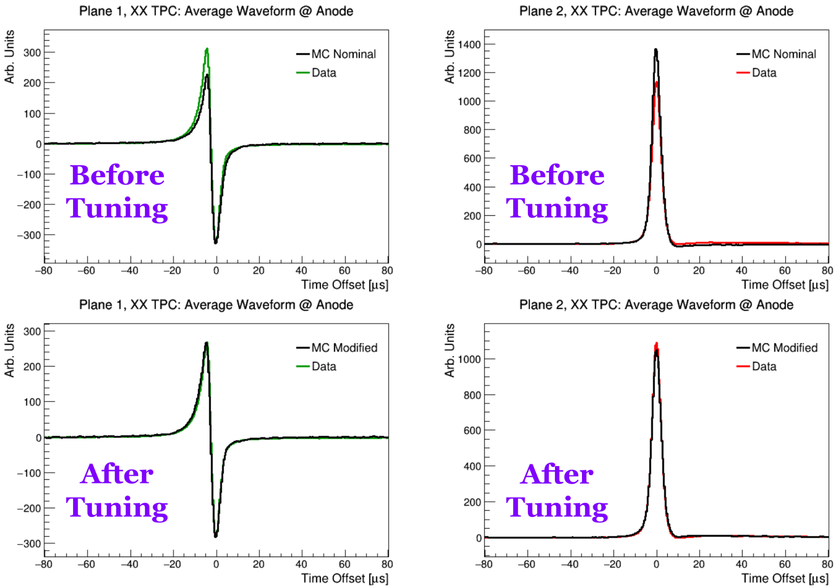
Example: impact of field distortion thought to be the result of a cable accidentally hanging down into the active volume of the detector



- Detector uncertainties having to do with physical detector properties may be correlated between sufficiently similar near and far detectors (eg: argon properties when ND and FD are both LArTPCs)

- Some detector systematics must be constrained and characterized by careful calibration and simulation

Example: data driven pulse shape tuning (M. Mooney)



Summary

- LArTPC detector technology is enabling unprecedented precision in neutrino oscillation physics
- Important precision measurements and significant potential for new discoveries in both short- and long-baseline neutrino oscillation experiments
  - SBN is producing results <u>now</u>!
  - DUNE is under construction <u>now</u>!
- DUNE represents a major experimental advance for long-baseline oscillation experiments: thousands of events, 5σ-level sensitivity to CPV, precision measurements of oscillation parameters, including δ_{CP}, significant sensitivity to physics beyond the Standard Model and astrophysics
- Techniques to constrain systematic uncertainty, including sophisticated near and far detectors and novel analysis ideas, are critical for reaching the precision required to make these exciting discoveries