Bubble Chamber Detectors with Light Nuclear Targets for Neutrino Scattering

Snowmass Community Summer Study Workshop
University of Washington
July 23rd, 2022
Contemporary Neutrino Physics (Part One)
Neutrino Oscillations as a paths to Beyond-the-Standard-Model Physics

\[ \mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \bar{\ell}_\alpha L \gamma^\mu \nu_\alpha L + \text{h.c.} = \frac{g}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \bar{\ell}_\alpha L \gamma^\mu \sum_{i=1,2,3} U_{\alpha i} \nu_i L + \text{h.c.} \]

PMNS Matrix

\[
|U| = \begin{pmatrix}
|U|_{e1} & |U|_{e2} & |U|_{e3} \\
|U|_{\mu1} & |U|_{\mu2} & |U|_{\mu3} \\
|U|_{\tau1} & |U|_{\tau2} & |U|_{\tau3}
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
= \begin{pmatrix}
c_{13} & 0 & -s_{13} e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta_{CP}} & 0 & c_{13}
\end{pmatrix}
= \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[
U_{\alpha i} \cdot \begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = R_{Atmos}(\theta_{23}) \cdot R_{React}(\theta_{13}, \delta_{CP}) \cdot R_{Solar}(\theta_{12}) \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

The neutrino mixing matrix has parameters and coefficients directly describing the splitting of the mass states and asymmetry between neutrino and anti-neutrinos!

Leptonic CP-violation serves as a proof of concept for the matter-antimatter asymmetry!
Contemporary Neutrino Physics (Part Two)
Neutrino Oscillations as a paths to Beyond-the-Standard-Model Physics

Current $3\sigma$ CL on the best fit for the PMNS matrix gives tight constraints on the mixing angles and mass splitting.

$\delta_{CP}$ and the NH/IH question are the biggest uncertainties as of Oct 2021.

<table>
<thead>
<tr>
<th></th>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering ($\Delta\chi^2 = 7.0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bfp $\pm 1\sigma$</td>
<td>3$\sigma$ range</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.304^{+0.012}_{-0.012}$</td>
<td>$0.269 \rightarrow 0.343$</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$33.45^{+0.77}_{-0.75}$</td>
<td>$31.27 \rightarrow 35.87$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.450^{+0.019}_{-0.016}$</td>
<td>$0.408 \rightarrow 0.603$</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$42.1^{+1.1}_{-0.9}$</td>
<td>$39.7 \rightarrow 50.9$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.02246^{+0.00062}_{-0.00062}$</td>
<td>$0.02060 \rightarrow 0.02435$</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.62^{+0.12}_{-0.12}$</td>
<td>$8.25 \rightarrow 8.98$</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$230^{+36}_{-25}$</td>
<td>$144 \rightarrow 350$</td>
</tr>
<tr>
<td>$\Delta m^2_{21}/10^{-5}$ eV$^2$</td>
<td>$7.42^{+0.21}_{-0.20}$</td>
<td>$6.82 \rightarrow 8.04$</td>
</tr>
<tr>
<td>$\Delta m^2_{3f}/10^{-3}$ eV$^2$</td>
<td>$+2.510^{+0.027}_{-0.027}$</td>
<td>$+2.430 \rightarrow +2.593$</td>
</tr>
</tbody>
</table>

NuFit 5.1, October 2021
NOvA and T2K are dual detector oscillations experiments currently taking data and producing results. As of 2022, NOvA and T2K are leaders in resolving oscillation parameters and leptonic CP-violation using neutrinos.
Uncertainties in an Oscillation Analysis

A Brief Look at Uncertainties on $\delta_{CP}$

Supplementary Table 1: The systematic uncertainty on the predicted relative number of electron neutrinos and electron antineutrinos candidates is the Super-K sample with no decay electrons.

<table>
<thead>
<tr>
<th>Type of Uncertainty</th>
<th>$\sigma_{R}$, Candidate Relative Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K Detector Model</td>
<td>3.5</td>
</tr>
<tr>
<td>Final State Interaction and Rescattering Model</td>
<td>1.6</td>
</tr>
<tr>
<td>Neutrino Production and Interaction Model Constrained by ND280 Data</td>
<td>2.7</td>
</tr>
<tr>
<td>Electron Neutrino and Antineutrino Interaction Model</td>
<td>3.0</td>
</tr>
<tr>
<td>Neutrino Removal Energy in Interaction Model</td>
<td>3.7</td>
</tr>
<tr>
<td>Modeling of Neutral Current Interactions with Single $\gamma$ Production</td>
<td>3.5</td>
</tr>
<tr>
<td>Modeling of Other Neutral Current Interactions</td>
<td>0.2</td>
</tr>
<tr>
<td>Total Systematic Uncertainty</td>
<td>6.0</td>
</tr>
</tbody>
</table>

As of 2022, largest uncertainties are due to statistics limited, but the next generation of experiments will surpass the precision of current experiments! How to control the systematics budget?

~19% of the total systematics budget
The Neutrino-Nucleus Cross Section Problem (Part One)

Where is the Problem?

Many neutrino scattering measurements but to first order must understand interplay between four different types of scattering (QE/Elastic, RES, DIS, MEC/MNI).

To second order, must also deal with FSI effects (nuclear matter effects, absorption, interaction with cold nuclear matter)!
Many neutrino scattering measurements but to first order must understand interplay between four different types of scattering (QE/Elastic, RES, DIS, MEC).

To second order, must also deal with FSI effects (nuclear matter effects, absorption, interaction with cold nuclear matter)!
Statistics in the relevant regions for Long-Baseline experiments are low \(\sim O(10^4)\) and systematic uncertainties are high.

Generator predictions based on these data have low exclusionary power at DUNE/Hyper-K precision.
The Next Generation of Long-Baseline Experiments

DUNE: the future long-baseline oscillation experiment

- Leptonic CP-violation ($\delta_{CP}, \Delta L = 0$?)
- Oscillation Parameters ($\theta_{23}$)
- Neutrino Mass Hierarchy (NH/IH?)
- Proton Decay (GUT?)
- Supernova Burst Neutrinos
ND-LAr functionally similar to FD modules with the same target nucleus. ND-GAr gives charge separation and some analysis of secondary interactions with the same target nucleus. System for on-Axis Neutrino Detection (SAND) serves as always on beam monitoring system with CH. From the ND CDR, 50 tons of LAr at 1.2 MW neutrino beam should yield about \(59 \text{ million } \nu_\mu \text{ CC events per year.}\)
DUNE-PRISM will have the Argon detectors move in order to deconvolve the flux from the cross sections.

Will constrain beam flux shape and normalization to ~1%!

Phase 2 includes intensity upgrade to higher intensity!
Motivating a Hydrogen Bubble Chamber Prototype

A Solution to the Neutrino-Nucleus Cross-Sections Problem!

Event rate can be estimated from the DUNE ND-LAr event rate!

We get about 60k events per year for each ton of LH$_2$ at *perfect efficiency* (about two-fifths of MiniBooNE’s entire contribution every year!).

The Fermilab 15’ bubble chamber had an estimated 2 tons of hydrogen.

*We should build a ~5L prototype!*
Historic Chamber Design

How Did the “Dirty” Chambers Work?

Superheated fluid prepared for expansion period. As piston expands, ionizing (charged) particles deposit energy and overcome nucleation threshold, causing bubbles.

Event selection of analog pictures done by eye in the 60s-90s.
Bubble Microphysics

A Tunable Medium

Charge deposits on metastable, “microbubble” medium causes bubble nucleation, the size and density are controlled by the state of the working fluid.

Older experiments used bubble density as a way to measure energy deposition in the medium.
The Current Generation of Chambers (Part One)

Updates to Bubble Chamber Technology!

Newer chambers have focus on dark matter and novel detector design!

Unsuitable for cross sections measurements without further development (different operational regime).

Still at prototype stages, various sizes, largest prototype is 60L.

Transparent silica glass jar for containment of liquid target.

Acoustic Signals from Alphas in Fast Radon Decay Chain
The Current Generation of Chambers (Part Two)

Updates to Bubble Chamber Technology!

Newer chambers have focus on dark matter and novel detector design!

Scintillating Bubble Chamber (SBC) 30g prototype with xenon shows acoustic modeling and scintillation photon counters!
The Current Generation of Chambers (Part Three)

The Scintillating Bubble Chamber (SBC)!

SBC designed to use Xenon doped Liquid Argon as the target fluid

“Clean” style inner jar in pressure vessel

Refrigerator integrated into flange and attached to pressure vessel along with cameras.

Hydraulic cylinder attached to pressure vessel and a carbon fluoride hydraulic fluid is used to offset the temperature gradient.

Achievable live times ~1 hour.
Initial plan is to use the SBC pressure vessel design in another previously available vacuum jacket in the old MiniBooNE Hall.
Objectives for Building a MMBC
Current goals of the newly funded project!

In the process of finalizing the project scope!

• **First Objective (FY23.5)** A fully leak checked, pressure ready, and vacuum ready device in MiniBooNE Hall.
• **Second Objective (FY23.5)** Device active time long enough to capture an entire spill from the LBNF beam (at minimum 10 microseconds).
• **Third Objective (FY24.0)** 1 Hz cycling time.
• **Fourth Objective (FY24.0)** Minimum possible cycling time.
• **Fifth Objective (FY24.0/FY24.5)** Maximum active time without interior changes. Polish, coating, or plating and retest maximum active time.
• **Sixth Objective (FY25/FY25.5)** Precision track reconstruction on cosmic ray muons.
• **Seventh objective (FY25/FY25.5)** Sync to the Fermilab Testbeam clock and observe hadron decays.
New dataset would be largest (anti)neutrino \( \text{H}_2/\text{D}_2 \) sample ever made, surpassing current world data in the relevant regions by at least a couple orders of magnitude!

Resolve tension in current experiments by factorizing underlying cross-section physics from secondary nuclear effects/FSI.

Helps to properly constrain possible largest cross-section dataset to ever exist \( \sim O(10^8) \) from ND-LAr/ND-GAr.

Needs isoscalar (\( \text{D}_2 \)) nucleus to completely disentangle but also get absolute minimum of MEC/MNI contributions.

A boon to neutrino physics!
The NuTeV Experiment: Precision Electroweak Pioneer

A highly precise direct measurement of the weak mixing angle!

Neutrino DIS has clean access to the Weinberg angle through the Paschos-Wolfenstein ratio!

\[ R^- \equiv \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\nu_\mu N \rightarrow \nu_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\nu_\mu N \rightarrow \mu^+ X)} = \frac{1}{2} - \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} \]

NuTeV Experiment measured the Paschos-Wolfenstein ratio on Fe through a comparison of “long” and “short” events, found a \( \sim 3\sigma \) offset from the standard model!

The NuTeV Anomaly in Context

New and Complementary Physics?


Broad strokes on experiment highlights:

High energy events, 20 GeV < E_{vis} < 180 GeV from 800 GeV Tevatron Beam.

Measurement was \textasciitilde1.62 \text{ million } CC and \textasciitilde351 \text{ thousand } NC events.

Two largest corrections are mis-ID of CC/NC events (30%) and beam contamination by $\nu_e$ (10%)

Explanations for the anomaly exist and they have implications for PVDIS (arXiv:0908.3198v3):

**Nuclear Effects** - Excess neutrons in the experiment steel contribute nuclear modifications on the order of $1\sigma$.

**Charge Symmetry Violation** - Mass difference of u/d disturbs charge symmetry assumption and QED splitting on the order of $1\sigma$.

**Asymmetry in Strangeness** - Dearth of measurements with strangeness, unknown if s and anti-s have similar contributions, on the order of $1\sigma$.
The NuTeV Anomaly *in Present Context*

Recent Interest in the NuTeV Anomaly with New Measurements of W-Mass!

NuTeV measurement also gives an indirect measurement of the W-Mass by fixing the mass of the Z.

Recent measurement of W-Mass by CDF II drives new interest in NuTeV experiment: is there new physics hiding in the W to which neutrinos might also be sensitive?

Investigating W-mass measurement, allows us to update the measurement and address all three of the previous issues. *Strangeness and CSV also affect PVDIS.*

(CDF Collaboration, 2022)
Current cross-section sample underlying event generators does not have the precision to effectively constrain measurements from the next generation of long-baseline neutrino oscillations experiments.

Next generation experiments will have their own robust cross-section measurements, but measurements on light nuclear targets will allow for a better understanding of the underlying nucleon structure and an increase in precision.

A bubble chamber physics program is robust, novel, and complementary to measurements in nuclear physics, including measurements made at JLab, the EIC, and the Forward Physics Facility.

Please checkout the Snowmass White Papers!
Bubble Chamber: https://arxiv.org/abs/2203.11319
Backup
Shadowing and EMC Effect show nuclear modifications to cross sections dependent on the size of the nucleus!

Investigation from MINERvA shows shadowing in low-x region but demonstration of EMC effect is inconclusive.

Bubble chamber would be perfect instrument for investigation of nuclear modification with (anti)neutrinos!

Argon, Xenon, and Flourine based compounds already demonstrated as possible targets, consider other noble gasses?

Possible to do with QE and resonant scattering? What do we learn?
Neutrinos Act Like Polarized Electrons?

Another way of accessing electroweak physics.

Neutrino scattering can be handled similarly to PVDIS except with inherent longitudinal polarization:

\[
\frac{d^2 \sigma^{\nu\bar{\nu}}}{dx \, dy} = \frac{G_F^2 M E}{\pi (1 + Q^2/M_{W,Z}^2)^2} \left[ \begin{array}{c}
\frac{y^2}{2} 2 x F_1(x, Q^2) + (1 - y - \frac{M x y}{2E}) F_2(x, Q^2) \\
\pm y \left( 1 - \frac{y}{2} \right) x F_3(x, Q^2)
\end{array} \right]
\]

\[\frac{d^2 \sigma}{dx \, dy} = \frac{4 \pi \alpha^2 S}{Q^4} [x y^2 F_1(x, Q^2) + (1 - y - x y \frac{M^2}{S}) F_2(x, Q^2)]
\]

PVDIS gains similar structure by introducing polarization but has interference of vector and axial contributions from the quark and electron. Parity violation is in these terms.

(D. Wang, Thesis, 2013)

\[A_{PV} = \left( \frac{3 G_F Q^2}{10 \sqrt{2} \pi \alpha} \right) [(2C_{1u} - C_{1d}) + Y_3 (2C_{2u} - C_{2d})]
\]

*Assuming no nucleon sea, charge symmetry, and an isoscalar target.

Neutrinos cannot directly contribute here but provide complementary indirect probes of EW physics!
Neutrinos as a Novel Nuclear Probe

Precision Selection of Quark Flavor

\[
\frac{d\sigma^{\nu/\bar{\nu}}_{CC}}{dx dy} = \frac{G_F^2 s}{2\pi (1 + Q^2 / M_W^2)^2} \left[ F_1^{CC} x y^2 + F_2^{CC} \left( 1 - y - \frac{M x y}{2 E} \right) \pm F_3^{CC} x y \left( 1 - \frac{y}{2} \right) \right]
\]

- \( F_2^{\nu p}^{(CC)} = 2x (d + s + \bar{u} + \bar{c}) \),
- \( x F_3^{\nu p}^{(CC)} = 2x (d + s - \bar{u} - \bar{c}) \),
- \( F_2^{\bar{\nu} p}^{(CC)} = 2x (u + c + \bar{d} + \bar{s}) \),
- \( x F_3^{\bar{\nu} p}^{(CC)} = 2x (u + c - \bar{d} - \bar{s}) \),

- \( F_2^{\nu/\bar{\nu} p}^{(NC)} = 2x \left[ (u_L^2 + u_R^2) (u^+ + c^+) + (d_L^2 + d_R^2) (d^+ + s^+) \right] \)

- \( x F_3^{\nu/\bar{\nu} p}^{(NC)} = 2x \left[ (u_L^2 - u_R^2) (u^- + c^-) + (d_L^2 - d_R^2) (d^- + s^-) \right] \)

Complementarity especially attractive in DIS region where quark flavor and handedness is selectable!

Possible probe of nucleon intrinsic strangeness, this could mean \textit{strange form factors}.
Spin and Polarization
Applications to Nucleon Structure

If we consider quark, nucleon, and gluon momentum and interactions in 3D (as opposed to only longitudinally) in regimes where the transverse energy scale is much smaller than the interaction energy, we get access to Transverse Momentum Dependent correlations.

<table>
<thead>
<tr>
<th>N</th>
<th>q</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>f₁</td>
<td></td>
<td>g₁</td>
<td>h₁</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>g₁</td>
<td>h₁L</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>f₁T</td>
<td>g₁T</td>
<td>h₁</td>
<td>h₁T</td>
</tr>
</tbody>
</table>

\[
\Phi^{[γ^+]} = f_1(x, k_{1}^2) - \frac{e_1^i k_1^i S_1^i}{M} f_{1T}^t(x, k_{1}^2)
\]

\[
\Phi^{[γ^+ γ_S]} = S_z g_1(x, k_{1}^2) + \frac{k_1 \cdot S_1}{M} g_{1T}(x, k_{1}^2)
\]

\[
\Phi^{[σ^+ γ_S]} = S_{1T} h_1(x, k_{1}^2) + S_z \frac{k_1^j}{M} h_{1L}^t(x, k_{1}^2)
\]

\[
+ \frac{e_T^i k_1^i}{M} h_1^t(x, k_{1}^2) + S_1^i 2k_1^i k_1^j - k_1^2δ^{ij} \frac{2}{M^2} h_{1T}^t(x, k_{1}^2),
\]
Contemporary Neutrino Physics (Part One)

Neutrino Oscillations as a path to Beyond-the-Standard-Model Physics

\[ \mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \bar{\ell}_\alpha \gamma^\mu \nu_\alpha + \text{h.c.} = \frac{g}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \bar{\ell}_\alpha \gamma^\mu \sum_{i=1,2,3} U_{\alpha i} \nu_{iL} + \text{h.c.} \]

Only one Euler angle is needed.

If we assume only two flavor and mass states:

\[ \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = R(\theta) \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \]

Only one Euler angle is needed.
Bubble Microphysics

A Tunable Medium

Charge deposits on metastable, “microbubble” medium causes bubble nucleation, the size and density are controlled by the state of the working fluid.

Older experiments used bubble density as a way to measure energy deposition in the medium.
Formulation of GPDs from mapping of the nucleon gives new dimensions to scattering and information about the complicated spin structure of the nucleon.
**Problem 1:** Detector would be in direct path of LBNF beam, 62m underground. DOE safety guidelines allow only 15 gal/~57L to be used underground without additional safety measures.

**Problem 2:** There doesn’t seem to be much space in the ND Hall underground for detector or supporting equipment. Build somewhere else (Dedicated Underground Hall or On the Surface?)
Biggest Challenges: Source of Neutrinos?

Different Options for Beam at Fermilab

Assuming LBNF beam has a similar structure to NuMI beam but is more intense, $6 \times 10^{13}$ POT/Spill in 9.5 $\mu$s at 0.75 Hz rep rate, indicates about an event more or less every second at minimum.

BNB has much lower intensity beam and at a lower energy but at a higher repetition rate, $5 \times 10^{12}$ POT/Spill in 1.6 $\mu$s at 5-20 Hz rep rate which is much faster than older chambers could cycle.

Note: Also includes contributions from highly off-axis NuMI Beam.
Neutrinos from LBNF probe well into the non-perturbative region and give complementary kinematics at a range of Bjorken-x in DIS.

Neutrinos are a novel probe in this region, only probe with access to the axial-vector components/form factors/currents!
Considering Solutions
How to get Hydrogen into DUNE?

We need a detector in high intensity neutrino beam with hydrogen and deuterium to make new cross-section measurements! Options:

**SAND**
- Put hydrogen in an existing detector: The Strawtube Tracker in SAND (CH)?
- Add hydrogen to an existing detector: Add Methane to ND-GAr (CH₄)?
- Create new dedicated detector: Bubble Chamber (H₂/D₂+)?

**ND-GAr**

I argue we should do all of these!
Spin and Polarization (Part One)

Spin and polarization can be factorized in the cross section into spin directions given the source.

Polarization of lepton, target nucleon, or recoil nucleon in one of the three directions, longitudinal, transverse, or the normal directions.

One use is the determination of scattering parameters as a function of polarization.

\[
\frac{d\sigma}{dQ^2} = \frac{d\sigma_0}{dQ^2} \left( 1 + P_l s\mu + T_N s\mu + P_{N'} s\mu + s\mu s\nu A_{\mu N} + \right.
\]
\[
+ \left. s\mu s\nu B_{\mu N} + s\mu s\nu C_{\mu N} + s\mu s\nu s\alpha D_{\mu \nu \alpha \mu N} \right)
\]

Graczyk & Kowal, arXiv:1902.03671v2
Considering Mixed Media Targets

Analysis of Hydrogen Integrated into Existing Detectors?

Regardless of choice, mixed media targets must involve challenging background subtraction.

\{X, Y\}
\ = \{p, \pi^+\} \text{ for } \nu + p \rightarrow l^- + \Delta^{++}
\text{ or } \{p, \pi^-\} \text{ for } \bar{\nu} + p \rightarrow l^+ + \Delta^0

Examining component perpendicular to both neutrino and lepton momentum shows contributions from Fermi motion inside of nucleon. Adds irreducible systematics to measurements. (also blunts understanding of quark d.o.f., more on that later)
MiniBooNE Axial Mass estimated to be about 1.31 GeV with amazing statistics, however world hydrogen/deuterium data from ANL, BNL, FNAL, and BEBC put axial mass at ~1.0 GeV!
Consequences of Misunderstandings in Cross Sections

Example of an Issue with MEC in NOvA

NOvA uses GENIE to model neutrino interactions, but no ‘vanilla’ model describes excess data.

Custom ‘2p2h’ tune does not perfectly describe low energy bins.

MEC exists (!) but no older experiments around to bound the effect.

Each neutrino experiment requires significant tunes to match any given generator and tunes bring experiments out of agreement with each other!

Data driven corrections can not completely substitute for a fundamental understanding of the physics!
It describes the underlying symmetries governing the scattering of particles from each other and only excludes *gravity*. **Doing particle physics means testing the standard model.**
NOvA and T2K are dual detector oscillations experiments currently taking data and producing results. As of 2020, NOvA and T2K are leaders in resolving oscillation parameters and leptonic CP-violation in the neutrino sector.
The DUNE Far Detector
Necessary for Observation of Oscillations

FD designed to directly observe $\nu_\mu$ disappearance and $\nu_e$ appearance over ~800 mile baseline!

Four-17 kt fiducial volume detectors, first and second modules are planned to be single phase (HD/VD), with the other modules still in planning.

First prototype of single phase FD published ensemble study in 2020!
Very Optimistic Expected DUNE Sensitivities

Last Generation of Accelerator Driven Long-Baseline Experiments?

<table>
<thead>
<tr>
<th>Physics Milestone</th>
<th>Exposure (staged years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5σ mass ordering</td>
<td>1</td>
</tr>
<tr>
<td>($\delta_{CP} = -\pi/2$)</td>
<td></td>
</tr>
<tr>
<td>5σ mass ordering</td>
<td>2</td>
</tr>
<tr>
<td>(100% of $\delta_{CP}$ values)</td>
<td></td>
</tr>
<tr>
<td>3σ CPV</td>
<td>3</td>
</tr>
<tr>
<td>($\delta_{CP} = -\pi/2$)</td>
<td></td>
</tr>
<tr>
<td>3σ CPV</td>
<td>5</td>
</tr>
<tr>
<td>(50% of $\delta_{CP}$ values)</td>
<td></td>
</tr>
<tr>
<td>5σ CPV</td>
<td>7</td>
</tr>
<tr>
<td>($\delta_{CP} = -\pi/2$)</td>
<td></td>
</tr>
<tr>
<td>5σ CPV</td>
<td>10</td>
</tr>
<tr>
<td>(50% of $\delta_{CP}$ values)</td>
<td></td>
</tr>
<tr>
<td>3σ CPV</td>
<td>13</td>
</tr>
<tr>
<td>(75% of $\delta_{CP}$ values)</td>
<td></td>
</tr>
<tr>
<td>$\delta_{CP}$ resolution of 10 degrees</td>
<td>8</td>
</tr>
<tr>
<td>($\delta_{CP} = 0$)</td>
<td></td>
</tr>
<tr>
<td>$\delta_{CP}$ resolution of 20 degrees</td>
<td>12</td>
</tr>
<tr>
<td>($\delta_{CP} = -\pi/2$)</td>
<td></td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$ resolution of 0.004</td>
<td>15</td>
</tr>
</tbody>
</table>

DUNE will have the statistical power to measure to 5σ significance or significantly constrain the mass hierarchy and PMNS elements, including $\delta_{CP}$!
Neutrinos have a very low cross-section and thus interact very rarely compared to other types of particles (10^{-14} difference from electron scattering). Very difficult to measure.
Particle Scattering is How We Learn About the Universe

We learn about the interior of objects by using other particles as probes, the higher the energy, the smaller the length scale that can be probed.

We encode information about the probability of particles scattering in *cross sections* which can be measured differentially with respect to various kinematics.
How to Do an Oscillations Analysis
A Brief Conceptual Overview for Experiments Like DUNE

\[ N_{\mu/e}(E_\nu) = P(\nu_\mu \rightarrow \nu_{\mu/e})\sigma(E_\nu)\Phi(E_\nu)e(E_\nu) \]

\[ \Phi_{ND}(E_\nu)\sigma(E_\nu) \]

\[ \epsilon_{ND}(E_\nu) \]

\[ \frac{\Phi_{FD}(E_\nu)e_{FD}(E_\nu)}{\Phi_{ND}(E_\nu)e_{ND}(E_\nu)} \]

Major questions about whether uncertainties on flux, acceptance, and efficiency can be tightly controlled across all long baseline experiments.
## Old Style Versus New Style
### Advantages
With strong magnet (>2T), high detection efficiency for most charged tracks.

High precision reconstruction ~300 microns vertex resolution, possible to go higher resolution.

Particle ID dependent on bubble density, directly controllable by expansion time.

Large significant history of successful use.

## Disadvantages
Will require additional detectors to measure high energy/hadronic calorimetry and muons.

Slow 1-2s reset time depending on size.

Hard to detect neutral particles.

Distortion across larger chambers, as chamber gets larger distortion gets worse.

Expansion time limited by bubble nucleation at walls.
Uncertainties in an Oscillations Analysis

How Well Does NOvA Do?

Biggest uncertainties in $\theta_{23}$ and $\Delta m_{32}^2$ are from detector calibration and neutron uncertainties, all measurements are currently statistics limited!