Delving Deep with DUNE

The Science and Status of the Deep Underground Neutrino Experiment

BNL Colloquium, Nov 28, 2023

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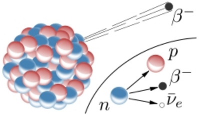
November 28, 2023

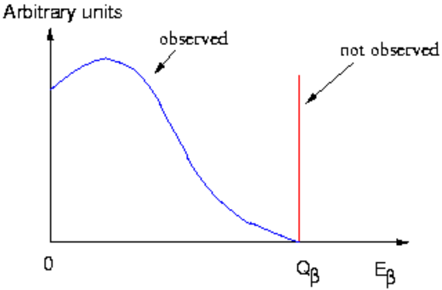
Outline

Introduction to the ν Standard Model

Neutrino Conception



Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



Neutrino Conception

Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen:

Wolfgang Pauli

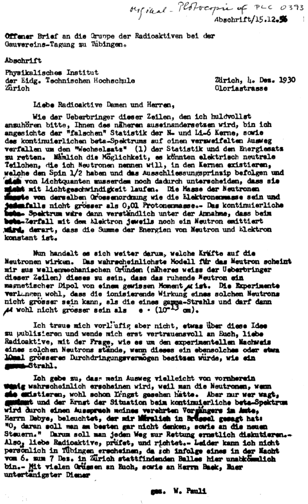
Dear Radioactive Ladies and Gentlemen,

.........., I have hit upon a desparate remedy to save the ”exchange theorem” of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant..........

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

. W. Pauli



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Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

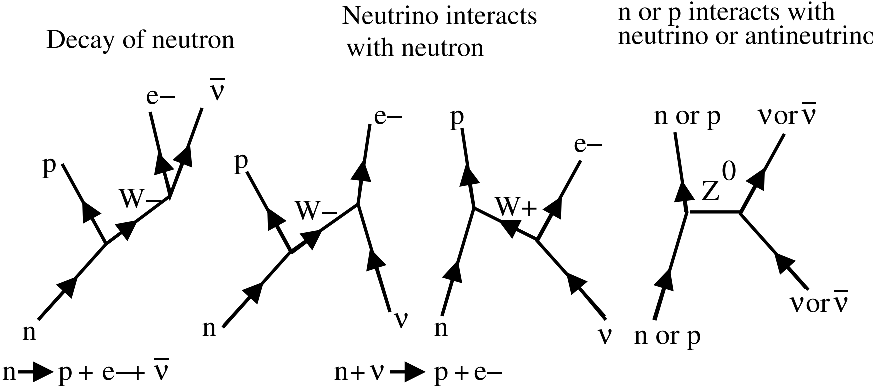
gez. W. Pauli

The Theory of Weak Interactions

$\geq$ **1933:** **Fermi builds his theory of weak interactions and beta decay**

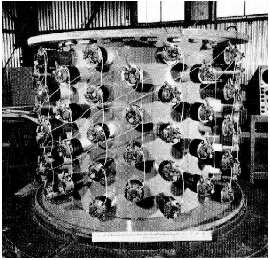
Charged current interactions

Neutral current interactions



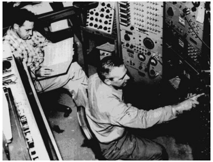
Discovery of Neutrinos

1950's: Fred Reines at Los Alamos and Clyde Cowan use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$
3. $n + {}^{108}Cd \rightarrow {}^{109}Cd* \rightarrow {}^{109}Cd + \gamma$ $(\tau = 5\mu s)$.

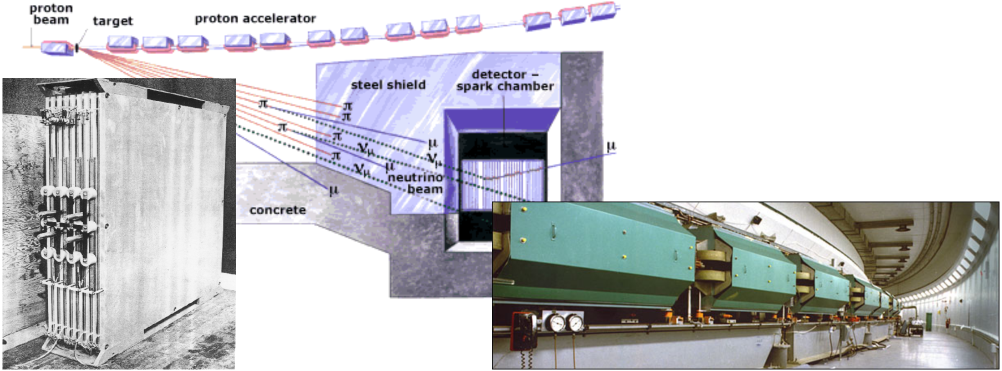


Neutrinos first detected using a nuclear reactor!

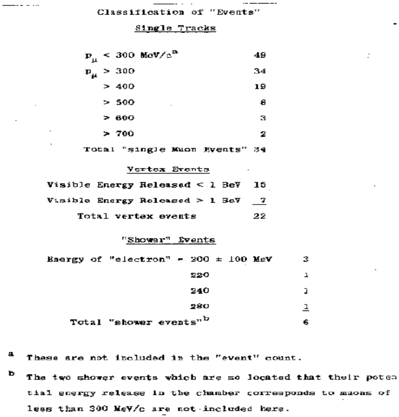
Reines shared 1995 Nobel for work on neutrino physics.

Producing Neutrinos from an Accelerator: Two Neutrino Experiment

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use a proton beam from BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \to \mu\nu_x \Rightarrow$ two neutrino experiment



The Two-Neutrino Experiment



Classification of "Events"

Single Tracks

p_μ < 300 MeV/c[a]	49
p_μ > 300	34
> 400	19
> 500	8
> 600	3
> 700	2
Total "single Muon Events"	34

Vertex Events

Visible Energy Released < 1 BeV	15
Visible Energy Released > 1 BeV	7
Total vertex events	22

"Shower" Events

Energy of "electron" - 200 ± 100 MeV	3
220	1
240	1
280	1
Total "shower events"[b]	6

[a] These are not included in the "event" count.

[b] The two shower events which are so located that their potential energy release in the chamber corresponds to muons of less than 300 MeV/c are not included here.

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

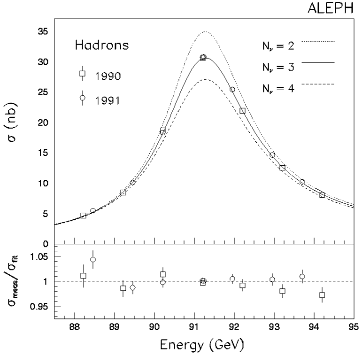
The first successful accelerator neutrino experiment was at Brookhaven Lab. 1998 NOBEL PRIZE

Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.

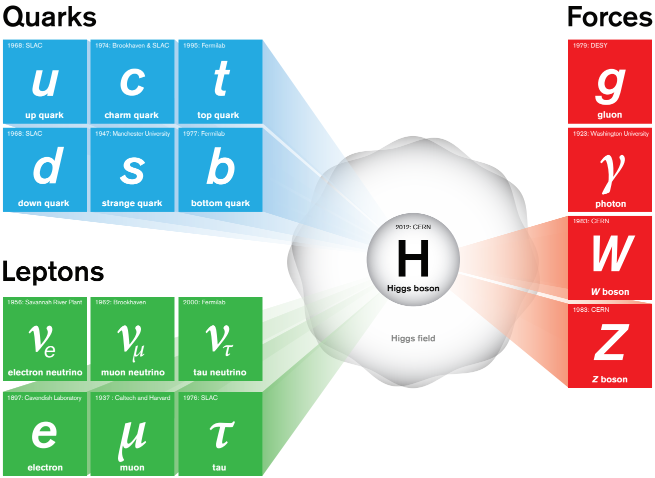
The LEP e^+e^- collider at CERN, Switzerland

The 27km LEP ring was reused to build the Large Hadron Collider



$N_\nu = 2.984 \pm 0.008$

Neutrinos in the Standard Model



Quarks

1968: SLAC
u
up quark

1974: Brookhaven & SLAC
c
charm quark

1995: Fermilab
t
top quark

1968: SLAC
d
down quark

1947: Manchester University
s
strange quark

1977: Fermilab
b
bottom quark

Leptons

1956: Savannah River Plant
ν_e
electron neutrino

1962: Brookhaven
ν_μ
muon neutrino

2000: Fermilab
ν_τ
tau neutrino

1897: Cavendish Laboratory
e
electron

1937 : Caltech and Harvard
μ
muon

1976: SLAC
τ
tau

2012: CERN
H
Higgs boson

Higgs field

Forces

1979: DESY
g
gluon

1923: Washington University
γ
photon

1983: CERN
W
W boson

1983: CERN
Z
Z boson

Neutrino Oscillations

1957,1967: B. Pontecorvo proposes that neutrinos of a particular flavor are a mix of quantum states with different masses:

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

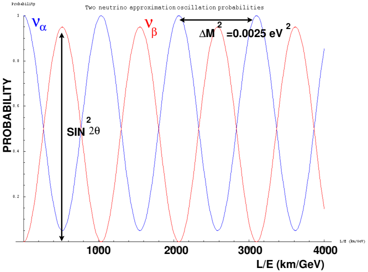
$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$ **where**

$\Delta m^2_{21} = (m^2_2 - m^2_1)$ **in** eV^2**, L (km) and E (GeV).**

At the 1st maximum of appearance $\Delta m^2 = \frac{\pi}{2}\frac{1}{1.27}\left(\frac{E}{L}\right)^{max1}$

Observation of oscillations implies non-zero mass states

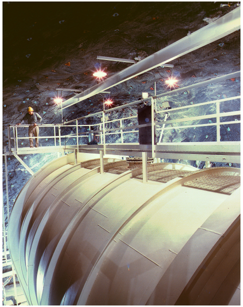


The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.5km underground (4850 ft) in Homestake mine, SD.

1. $\nu_e^{sun} + {}^{37}\mathrm{CL} \rightarrow e^- + {}^{37}\mathrm{Ar}$, $\tau({}^{37}\mathrm{Ar}) = 35$ **days.**
2. **Number of** Ar **atoms** $\approx$ **number of** ν_e^{sun} **interactions.**


Ray Davis



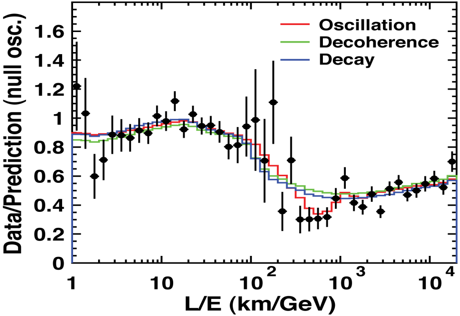
Results: 1969 - 1993 Measured 2.5 ± 0.2 **SNU (1 SNU = 1 neutrino interaction per second for** 10^{36} **target atoms) while theory predicts 8 SNU. This is a** ν_e^{sun} **deficit of 69%.**

$\Rightarrow$ first experimental hint of oscillations

Ray Davis shares 2012 Nobel Prize

More Disappearing Neutrinos ⇒ Two Different Mass Scales!

Super-K, atmospheric ν_μ disappearance

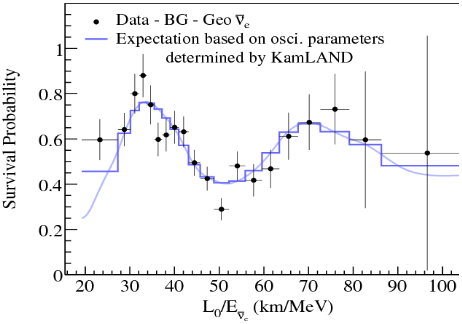


Global fit 2020 (JHEP 09 (2020) 178):

$$\Delta m^2_{\mathrm{atm(31)}} = 2.54 \pm 0.03 \times 10^{-3}\ \mathbf{eV^2}$$
$$\sin^2\theta_{\mathrm{atm(23)}} = 0.571^{+0.018}_{-0.023}$$

Atmospheric $(L/E)^{\mathrm{max1}} \sim$ 500 km/GeV

KamLAND, reactor $\bar{\nu}_e$ disappearance



Global fit 2020:

$$\Delta m^2_{\mathrm{solar(21)}} = 7.41 \pm 0.21 \times 10^{-5}\ \mathbf{eV^2}$$
$$\sin^2\theta_{\mathrm{solar(12)}} = 0.303 \pm 0.012$$

Solar $(L/E)^{\mathrm{max1}} \sim$ 15,000 km/GeV

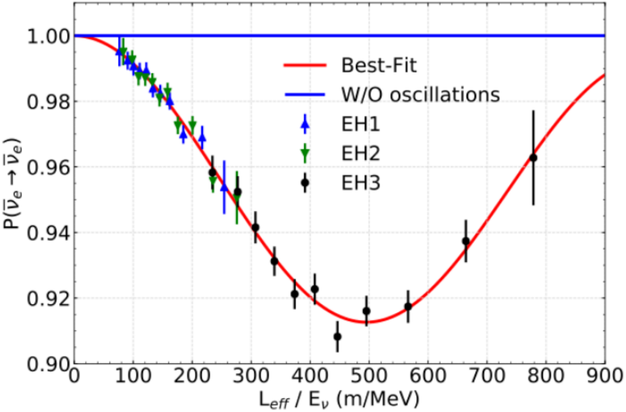
2015 Nobel Prize

Takaaki Kajita (SuperKamiokande)
University of Tokyo, Japan

Arthur B. MacDonald (SNO)
Queens University, Canada

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

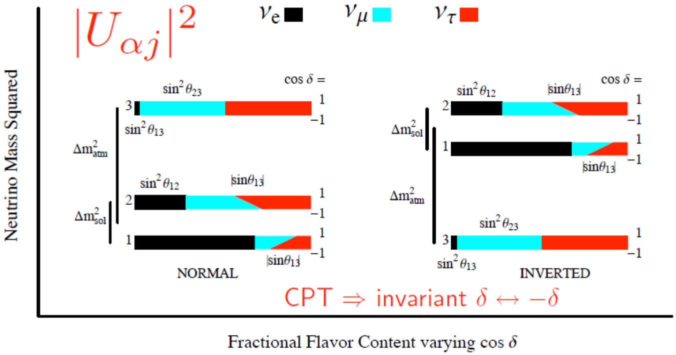
The 3rd Mixing Angle: Daya Bay Reactor $\bar{\nu}_e$ Disappearance Experiment



First to discover non-zero θ_{13} (2012) - latest most precise result (2020):

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.003$$

Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales



The "mixing angles" $(\theta_{13}, \theta_{12}, \theta_{23})$ represent the fraction of ν_e, ν_μ in the 3 mass states. They determine the probability of oscillation from one flavor to the other

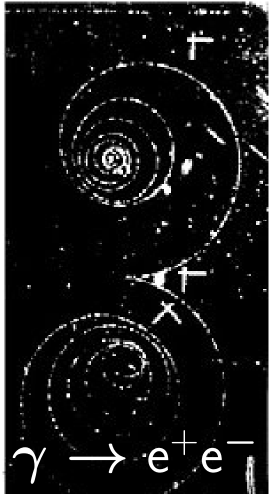
$\sin^2\theta_{12} \approx \sin^2\theta_{\mathrm{solar}}$, $\sin^2\theta_{23} \approx \sin^2\theta_{\mathrm{atmospheric}}$

3 quantum states interfering ⇒ phase δ

Charge-Parity Symmetry

Charge-parity symmetry: laws of physics are the same if a particle is interchanged with its anti-particle and left and right are swapped.

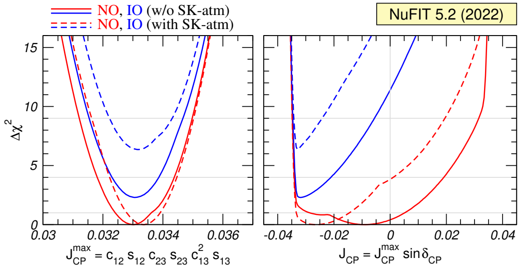
A violation of CP ⇒ matter/anti-matter asymmetry.



CP Violation in PMNS and CKM

In 3-flavor mixing the degree of CP violation is determined by the Jarlskog invariant:

$$J_{CP}^{\mathrm{PMNS}} \equiv \underbrace{\frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}}_{J_{CP}^{max}}\sin\delta_{\mathrm{CP}}.$$



(JHEP 09 (2020) 178, arXiv:2007.14792)

Given the current best-fit values of the ν mixing angles :

$$J_{CP}^{\mathrm{PMNS}} \approx 3\times 10^{-2}\sin\delta_{\mathrm{CP}}.$$

For CKM:

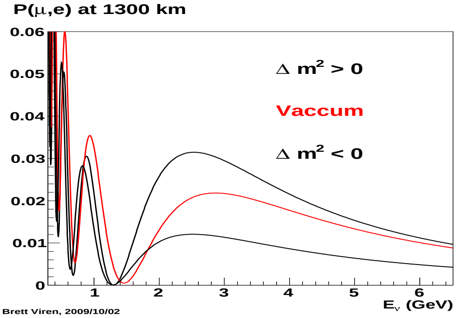
$$J_{CP}^{\mathrm{CKM}} \approx 3\times 10^{-5},$$

despite the large value of $\delta_{CP}^{\mathrm{CKM}} \approx 70°$.

Matter Effect on Neutrino Oscillation

1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter acts as a refrective index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.

For $P_{osc} = P(\nu_\mu \rightarrow \nu_e)$:



Brett Viren, 2009/10/02

We can determine the mass ordering ($m_3 > m_1$ or $m_1 > m_3$) of neutrinos using $\nu_\mu \rightarrow \nu_e$ oscillations over long distances in the earth.

$\nu_\mu \rightarrow \nu_e$ Oscillations

$\nu_\mu \rightarrow \nu_e$ oscillations are sensitive to all mixing parameters contributing to the Jarlskog invariant. **With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} = 0.03$ and $\sin^2\theta_{13} = 0.02$, (M. Freund. Phys. Rev. D 64, 053003):**

$$P(\nu_\mu \rightarrow \nu_e) \cong P(\nu_e \rightarrow \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + \underbrace{P_{\cos\delta}}_{\text{CP conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

for oscillations in vacuum: $\Delta = \Delta m^2_{31} L/4E$

$$P_0 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta),$$

$$P_{\sin\delta} = \alpha\, 8J_{cp}\sin^3(\Delta),$$

$$P_{\cos\delta} = \alpha\, 8J_{cp}\cot\delta_{CP}\cos\Delta\sin^2(\Delta),$$

$$P_3 = \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\Delta),$$

$$\textbf{For } \bar{\nu}_\mu \rightarrow \bar{\nu}_e,\ \underbrace{P_{\sin\delta} \rightarrow -P_{\sin\delta}}_{\text{CP asymmetry } (\delta\neq 0)},$$

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for oscillations in matter with constant density: $\Delta = \Delta m^2_{31} L/4E$, $A = \sqrt{2} G_F N_e 2E/\Delta m^2_{31}$

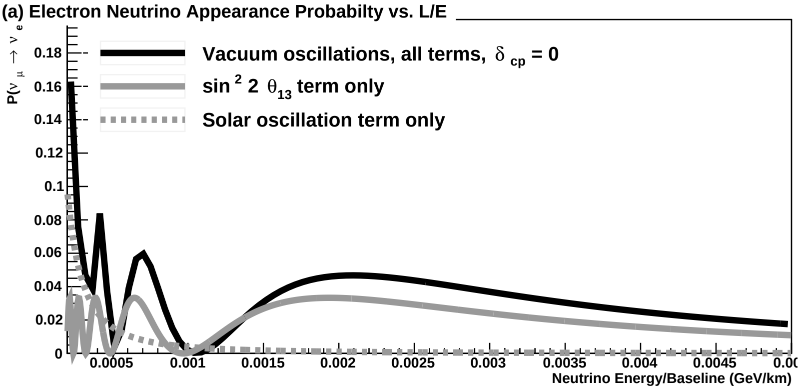
$$\begin{aligned}
P_0 &= \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],\\
P_{\sin\delta} &= \alpha\frac{8J_{cp}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],\\
P_{\cos\delta} &= \alpha\frac{8J_{cp}\cot\delta_{CP}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta],\\
P_3 &= \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta),
\end{aligned}$$

For $\bar\nu_\mu \rightarrow \bar\nu_e$, $\underbrace{P_{\sin\delta} \rightarrow -P_{\sin\delta}}_{\text{CP asymmetry } (\delta\neq 0)}$, $\underbrace{A \rightarrow -A}_{\text{matter asymmetry}}$

$\nu_\mu \to \nu_e$ Oscillations in the 3-flavor ν SM

The $\nu_\mu \to \nu_e$ probability maxima due to the atmospheric oscillation scale occur at

$$\frac{L_n\,(\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27\times\Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1)\times\frac{515\ \mathrm{km}}{\mathrm{GeV}}$$



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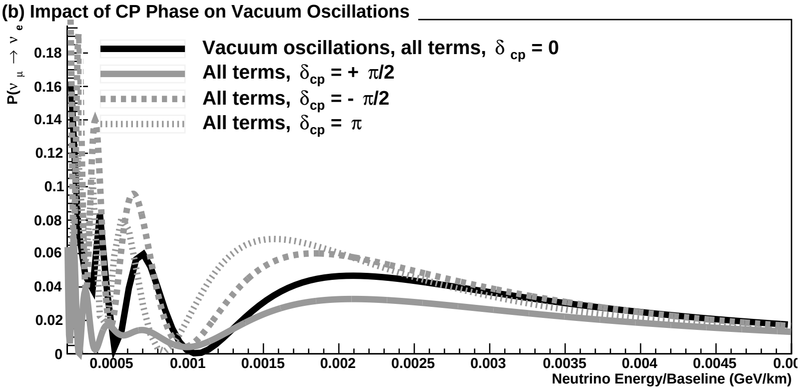

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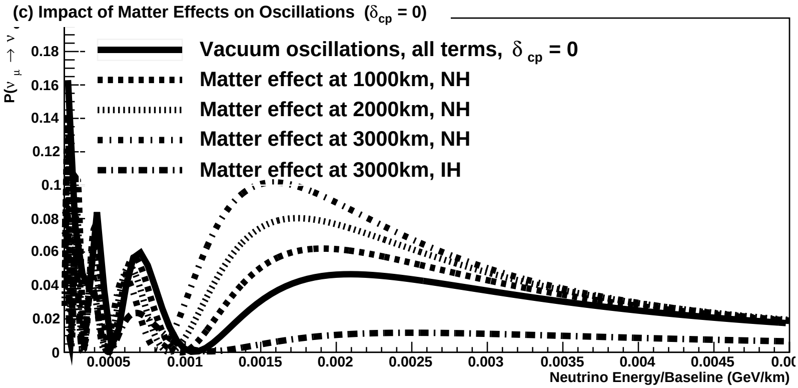


Experimental Baselines and $\nu_\mu \rightarrow \nu_e$ Event Rates

The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N^{\mathrm{appear}}_{\nu_e}(L) = N_{\mathrm{target}} \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \rightarrow \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

Assume the neutrino beam source produces a wide coverage that is flat in energy in the oscillation region and approximate the probability with the dominant term (no matter effect)

$$\begin{aligned}
\Phi^{\nu_\mu}(E_\nu, L) &\approx \frac{C}{L^2}, \quad C = \mathbf{number\ of}\ \nu_\mu/\mathrm{m}^2/\mathrm{GeV}/\mathrm{MW}/\mathrm{yr\ at\ 1\ km} \\
P^{\nu_\mu \rightarrow \nu_e}(E_\nu, L) &\approx \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{31} L/E_\nu)}_{P_0} \\
\sigma^{\nu_e}(E_\nu) &= 0.7 \times 10^{-42}(\mathrm{m}^2/\mathrm{GeV}/N) \times E_\nu, \quad E_\nu > 1\ \mathrm{GeV} \\
N_{\mathrm{target}} &= 6.022 \times 10^{32} N/\mathrm{kt}
\end{aligned}$$

Assuming constant flux: $C \approx 1.2 \times 10^{17}\ \nu_\mu/\mathrm{m}^2/\mathrm{GeV}/(\mathrm{MW/yr})$ **at 1 km:**

$$N^{\mathrm{appear}}_{\nu_e}(L) \approx (2 \times 10^6 \mathrm{events}/(\mathrm{kt/MW/yr}))(\mathrm{km/GeV})^2 \times \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx, \quad x \equiv L/E_\nu, \ a \equiv 1.27\Delta m^2_{31}.$$

For $x_0 = 100$ **km/GeV and** $x_1 = 2000$ **km/GeV (1st and 2nd oscillation maxima)**

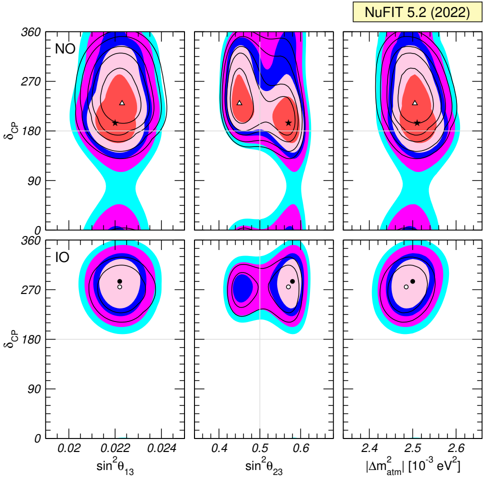
$N^{\mathrm{appear}}_{\nu_e}(L) \sim \mathcal{O}(20)$ events/(kt/MW/yr) **independent of baseline**

Need massive detectors $\sim \mathcal{O}(100)$ kt *deep underground* and MW beams to study oscillations

Latest results on δ_{cp} and MH

- **Allowed regions from global fit 2020.**
- **Colored regions (black contour curves) are obtained without (with) the inclusion of the tabulated SK-atm χ^2 data.**
- **The different contours correspond to the two-dimensional allowed regions at 1σ, 90%, 2σ, 99%, 3σ CL (2 dof).**
- **Atmospheric mass splitting Δm^2_{31} used for normal ordering (NO) and Δm^2_{32} for inverted ordering (IO).**

I. Esteban *et. al* **JHEP 09 (2020), 178**



Results from current ν oscillation expts still inconclusive on mass ordering and δ_{cp}

Beyond the ν 3-flavor “standard model”

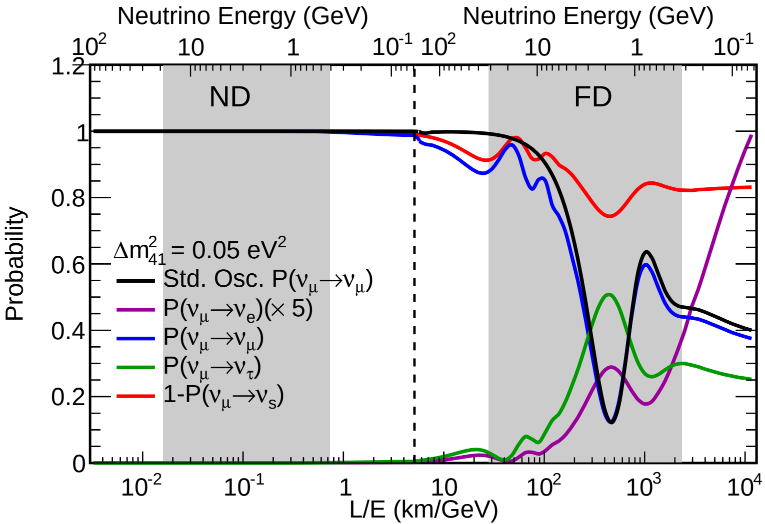
Physics Beyond ν SM

Due to the very small masses and large mixing of neutrinos, their oscillations over a long distance act as *an exquisitely precise interferometer with high sensitivity to very small perturbations (W. Marciano, BNL)* **caused by new physics phenomena, such as:**

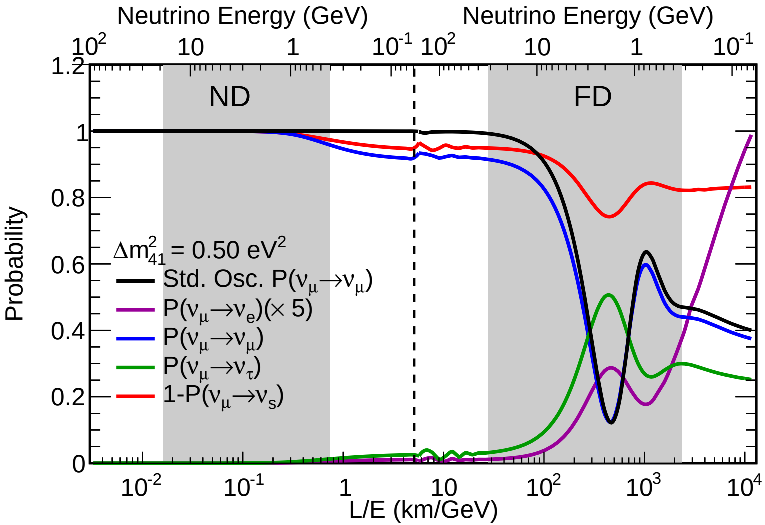
- **sterile neutrino states that mix with the three known active neutrino states**
- **nonstandard interactions in matter that manifest in long-baseline oscillations as deviations from the three-flavor mixing model**
- **new long-distance potentials arising from discrete symmetries that manifest as small perturbations on neutrino and antineutrino oscillations over a long baseline**
- **large compactified extra dimensions from String Theory models that manifest through mixing between the Kaluza-Klein states and the three active neutrino states**

We need more guidance from theory

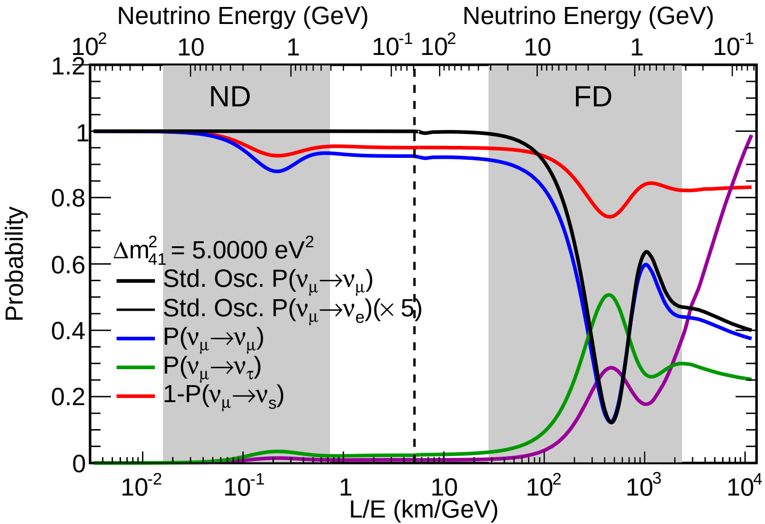
Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



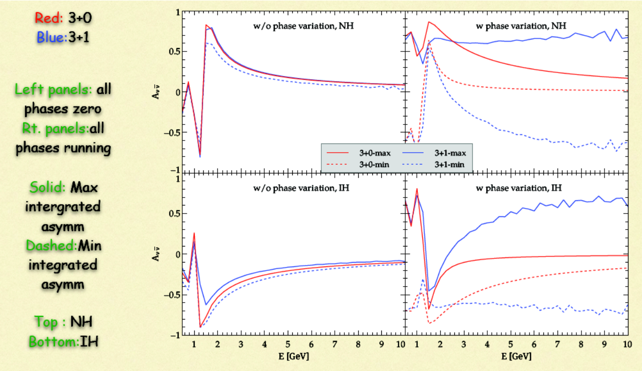
CP Asymmetry 3-flavor and with a Sterile Neutrino

$\Delta m^2_{41} \sim 1\ \text{eV}^2$

The charge-parity (CP) asymmetry is defined as

$$\mathcal{A}_{cp} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

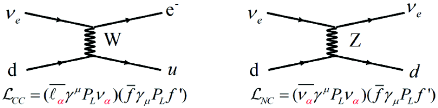
The integrated CP asymmetry at a baseline of 1300km (D. Dutta *et al.* JHEP 1511 (2015) 039):



Observation of a CP asymmetry is not sufficient to determine its origin.

Non-Standard Interactions

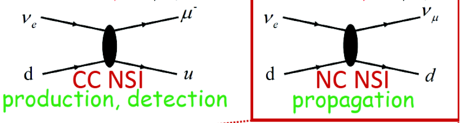
- In the Standard Model,



$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma_\mu P_L f') \qquad \mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma_\mu P_L f')$$

- With new physics, we could have

$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f') \qquad \mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$



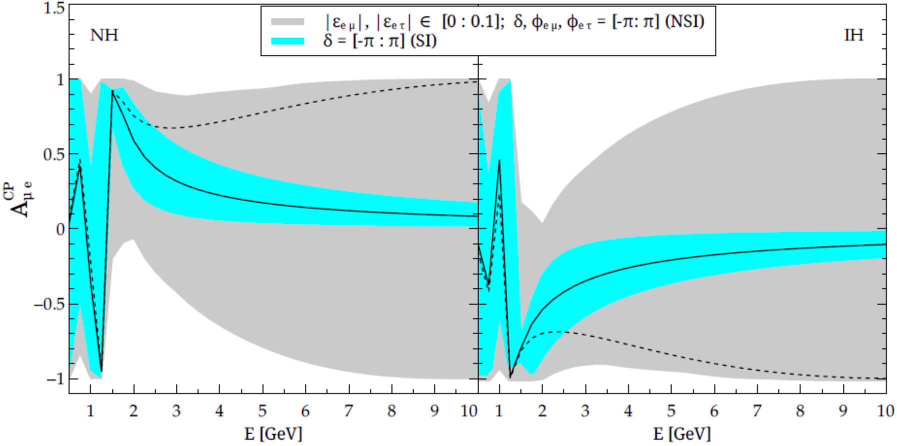
$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}}$$

$$\tilde{V}_{\mathrm{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

Non-Standard Interactions

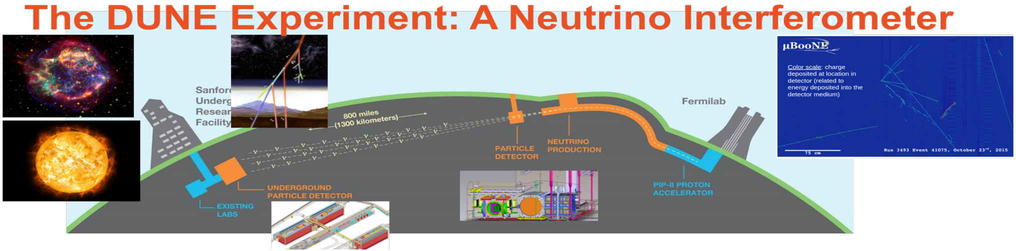
NSI could also impact CPV interpretation in long-baseline

(M. Masud, A. Chatterjee, P. Mehta arXiv:1510.08261):



The Deep Underground Neutrino Experiment (DUNE) at the Long Baseline Neutrino Facility (LBNF)

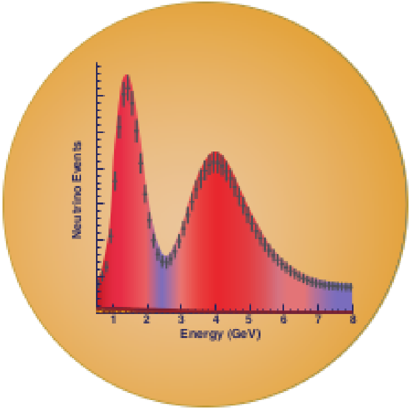
The Deep Underground Neutrino Experiment



- **A very long baseline experiment:** **1300km from Fermilab in Batavia, IL to the Sanford Underground Research Facility (former Homestake Mine) in Lead, SD.**
- **A highly capable near detector facility at Fermilab.**
- **Very deep (1 mile underground) far detectors: 4 × 10-kiloton fiducial (17 kt total) Liquid-Argon Time-Projection-Chambers with state-of-the-art instrumentation.**
- **High intensity *tunable* wide-band neutrino beam produced from 120 GeV Main Injector proton accelerator at Fermilab upgraded to 2MW.**

Scientific Objectives of DUNE (4 experiments-in-one)

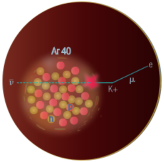
A long-baseline neutrino oscillation experiment:



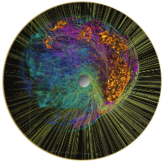
- **precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ oscillations; this includes precision measurement of the third mixing angle θ_{13}, measurement of the charge-parity (CP) violating phase $\delta_{\rm CP}$, and determination of the neutrino mass ordering (the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$), the so-called mass hierarchy**
- **precision measurements of the mixing angle θ_{23}, including the determination of the octant in which this angle lies.**
- **Searches for physics beyond the 3 flavor model using neutrino oscillations**

Scientific Objectives of DUNE (4 experiments-in-one)

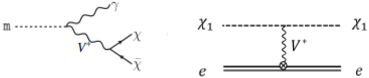
A proton decay experiment:



A neutrino telescope:



A fixed target experiment:

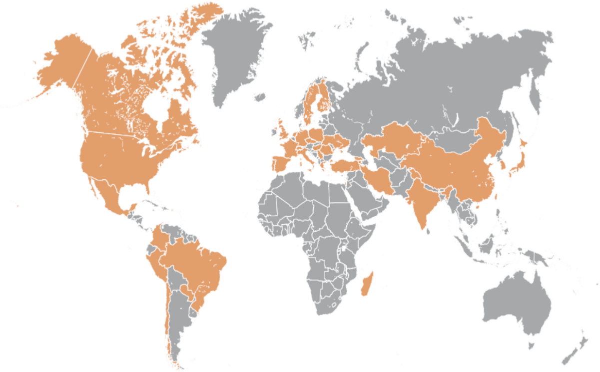


- **complemantary searches for proton decay in several important candidate decay modes, e.g., $p \rightarrow K^+\overline{\nu}$ as well as other baryon number violating signals.**

- **detection and measurement of the neutrino flux, spectrum and time evolution from a core-collapse supernova within our galaxy, should one occur during the lifetime of DUNE**

- **Unique searches for heavy neutral leptons, dark matter scattering, precision electroweak measurements, nuclear form factors and other measurements made possible by the high power proton beam and neutrino scattering in the near detector**

The DUNE Scientific Collaboration



As of Oct 2023

- **1508 members**
- **1419 active collaborators (657 US + 762 non-US)**
- **37 active countries including CERN**
- **209 active institutions**

The DUNE Scientific Collaboration

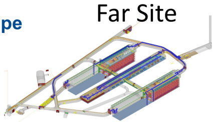
DUNE Coll. Meet. at CERN, Jan 2023

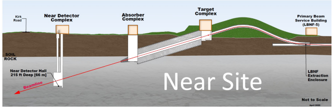
Total participants : 581 In person: 354 (largest on record) Zoom:227

The LBNF and DUNE Project Realization Plan

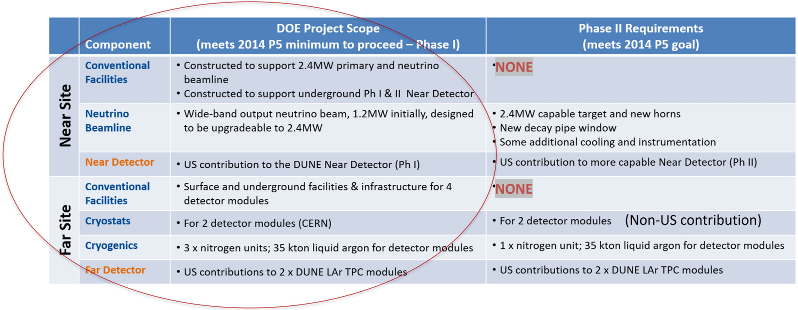
LBNF and DUNE were reconstituted in 2015 (CD1R) from the LBNE experiment as a staged program with the goal to reach CP violation sensitivity with a precision of 3σ for 75% of δ_{cp} values as specified by the 2014 P5 (Particle Physics Project Prioritization Panel)

LBNF/DUNE-US Project Scope





LBNF/DUNE-US Project Scope



	Component	DOE Project Scope (meets 2014 P5 minimum to proceed – Phase I)	Phase II Requirements (meets 2014 P5 goal)
Near Site	**Conventional Facilities**	• Constructed to support 2.4MW primary and neutrino beamline • Constructed to support underground Ph I & II Near Detector	• NONE
	Neutrino Beamline	• Wide-band output neutrino beam, 1.2MW initially, designed to be upgradeable to 2.4MW	• 2.4MW capable target and new horns • New decay pipe window • Some additional cooling and instrumentation
	Near Detector	• US contribution to the DUNE Near Detector (Ph I)	• US contribution to more capable Near Detector (Ph II)
Far Site	**Conventional Facilities**	• Surface and underground facilities & infrastructure for 4 detector modules	• NONE
	Cryostats	• For 2 detector modules (CERN)	• For 2 detector modules (Non-US contribution)
	Cryogenics	• 3 x nitrogen units; 35 kton liquid argon for detector modules	• 1 x nitrogen unit; 35 kton liquid argon for detector modules
	Far Detector	• US contributions to 2 x DUNE LAr TPC modules	• US contributions to 2 x DUNE LAr TPC modules

The LBNF Phase I facility provides all infrastructure needed for full DUNE scope

Project schedule: Start of physics with far detector 1: 2029
Beamline comes online: 2031

The LBNF and DUNE Project Realization Plan

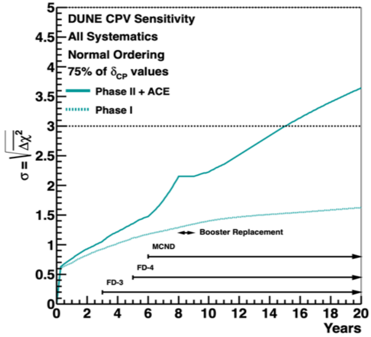
LBNF and DUNE were reconstituted in 2015 (CD1R) from the LBNE experiment as a staged program with the goal to reach CP violation sensitivity with a precision of 3σ for 75% of δ_{cp} values as specified by the 2014 P5 (Particle Physics Project Prioritization Panel)

DUNE Phase I detectors

- **2 FD modules: FD1 “horizontal drift” and FD 2 “vertical drift” LArTPCs**
- **ND LArTPC detector+ muon spectrometer + off-axis system**
- **SAND magnetized low density tracker on-axis near detector for neutrino flux measurements**

Phase I FDs are currently under construction and contributions detailed in DUNE multilateral MOU (signed by DOE, UK, France, Italy, Brazil and CERN on Nov 17, 2023).

ND LAr, TMS and SAND straw-tube tracker prototyping underway



Accelerator Complex Evolution (ACE): 2023 FNAL plan to deliver 1.7-2.1 MW by start of Phase I

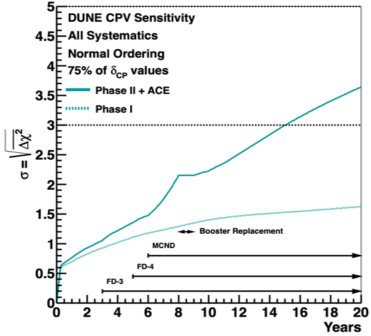
The LBNF and DUNE Project Realization Plan

LBNF and DUNE were reconstituted in 2015 (CD1R) from the LBNE experiment as a staged program with the goal to reach CP violation sensitivity with a precision of 3σ for 75% of δ_{cp} values as specified by the 2014 P5 (Particle Physics Project Prioritization Panel)

DUNE Phase II detectors

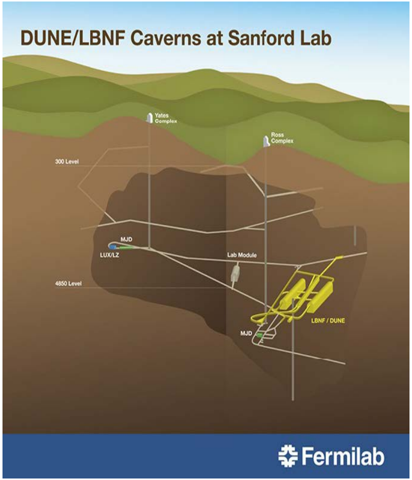
- **Baseline is two additional "vertical drift" LArTPCs which meets all physics goals. R&D ongoing on options to enhance DUNE physics capabilities. Non LArTPC options for FD4 could be considered if performance and timeline requirements of DUNE are met.**
- **More Capable Near Detector (MCND) to ensure completion of the DUNE physics program and open up opportunities for new BSM physics searches.**

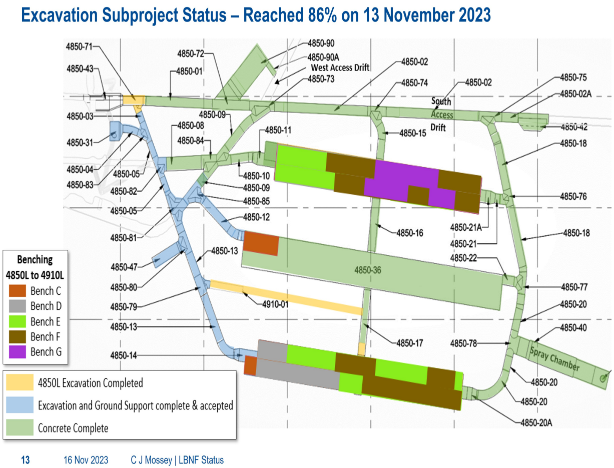
US presented plans for LBNF/DUNE Phase II to 2023 P5 planning effort - report to be presented publicly on Dec 7-8, 2023



Accelerator Complex Evolution (ACE): 2023 FNAL plan to deliver 1.7-2.1 MW by start of Phase I

Status of the LBNF Far Site Excavation





Excavation Subproject Status – Reached 86% on 13 November 2023

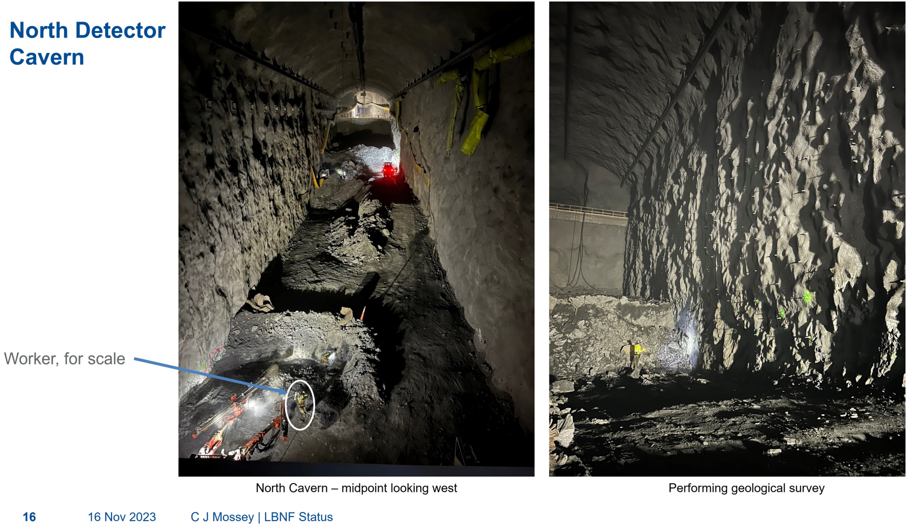
Benching 4850L to 4910L

- 🟧 Bench C
- ⬜ Bench D
- 🟩 Bench E
- 🟫 Bench F
- 🟪 Bench G

- 🟨 4850L Excavation Completed
- 🟦 Excavation and Ground Support complete & accepted
- 🟩 Concrete Complete

13 16 Nov 2023 C J Mossey | LBNF Status

Status of the LBNF Far Site Excavation



North Detector Cavern

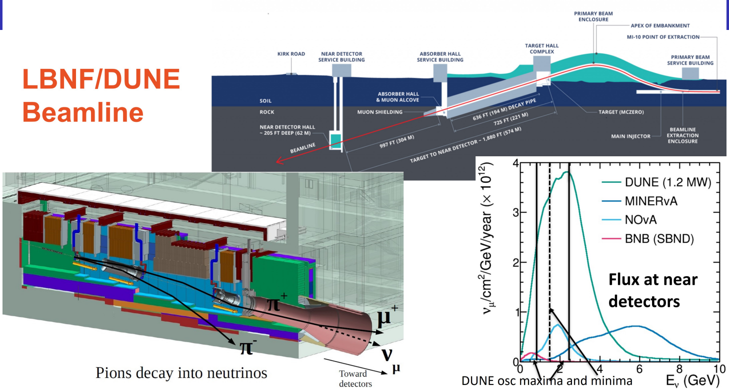
Worker, for scale

North Cavern – midpoint looking west

Performing geological survey

16 16 Nov 2023 C J Mossey | LBNF Status

Overview of the LBNF Beamline



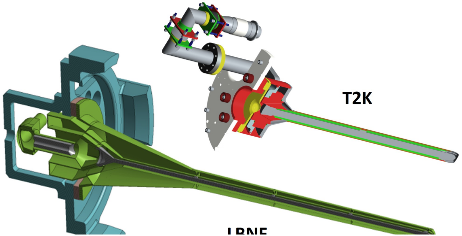
- **Primary proton beam 60-120 GeV with initial 1.2 MW beam power (Phase I), upgradable to 2.4 MW (Phase II). Embankement allows target complex to be at grade (BNL concept)**
- **Wide-band beam (on-axis) optimized for CP violation sensitivity - uses 3 focusing horns to select neutrino beam with a decay pipe 194m long x 4m diameter, He filled**

The LBNF Beamline Target Challenges

Comparison with T2K

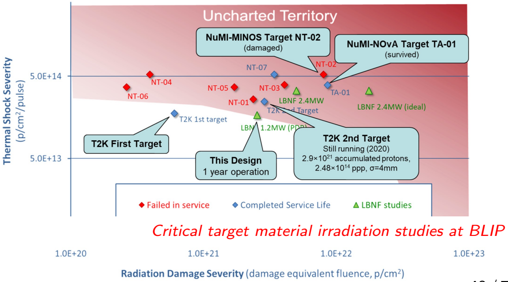
- Higher beam power but lower current and smaller beam spot = lower proton fluence and thermal shock than T2K
- Longer target will require optimised design of cantilever support

Parameter	LBNF Design (1 Year Design Life)	T2K Experience (Target 2 History)
Beam Power (MW)	1.2	0.51
Proton Energy (GeV)	120	30
Beam Current (μA)	10	17
Beam Sigma (mm)	2.7	4
Radiation Damage Severity (p/cm^2)	2.5E+21	3.1E+21
Thermal Shock Severity (p/cm^2/pulse)	1.7E+14	2.6E+14



To scale. Core length = 0.9m T2K, 1.5m LBNF

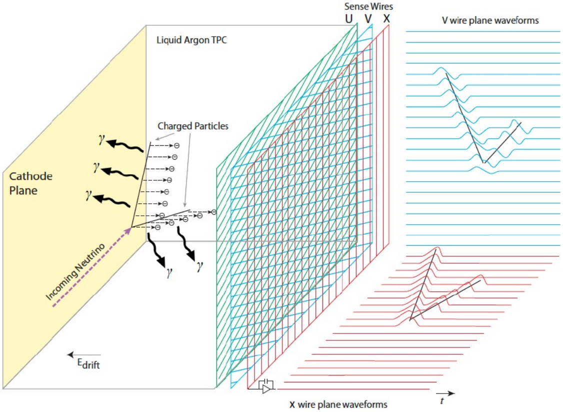
Graphite Neutrino Targets Exploratory Map



Critical target material irradiation studies at BLIP

The DUNE Far Detectors: Liquid-Argon Time-Projection Chambers

Single Phase "horizontal drift" LArTPC with 3 anode wire planes



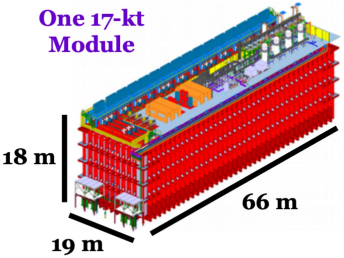
DUNE "horizontal drift" TPC design by Bo Yu (BNL)

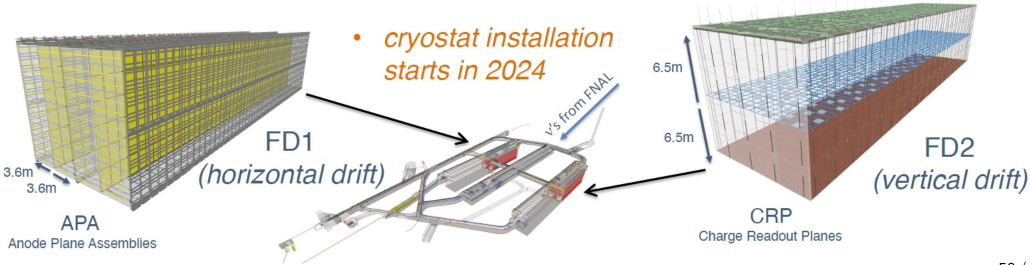
The DUNE anode wireplane assembly

The DUNE Far Detectors: Liquid-Argon Time-Projection Chambers

The DUNE Phase I LArTPCs

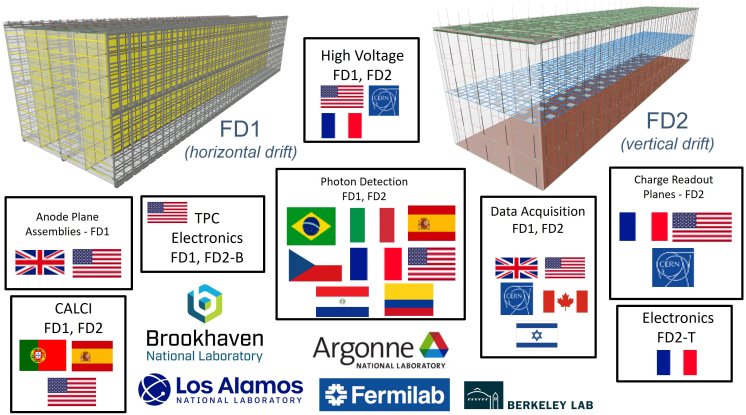
- **Both FD1 and FD2 are LArTPCs using highly modularized TPC design comprising $\mathcal{O}(100)$ identical TPC modules**
- **FD1 is a "horizontal drift" detector using 3 layers of wire planes vertical and ±36° - goes in the NE cavern**
- **FD2 is a "vertical drift" detector that uses 3 layers of strips on PCBs as the charge plane readout.**



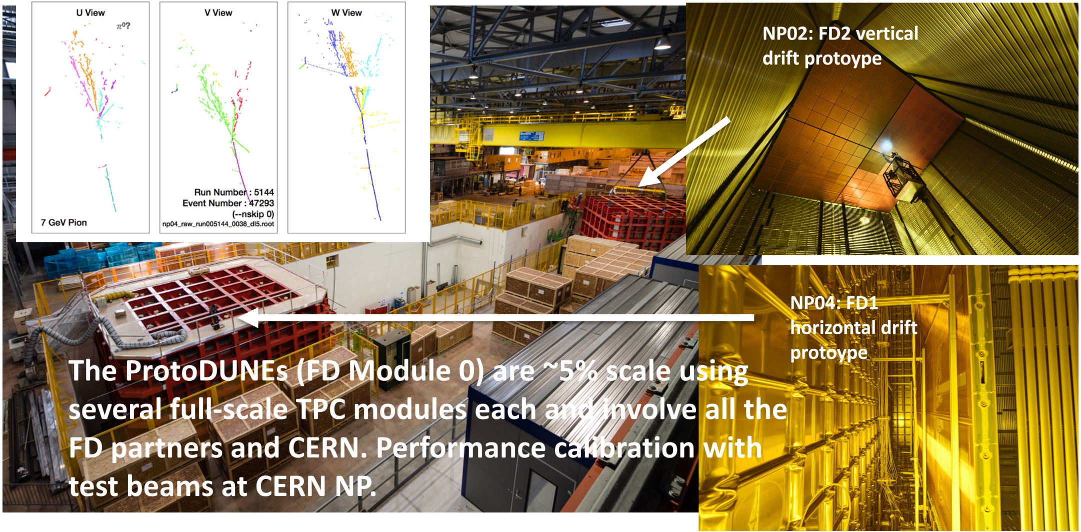


The DUNE Far Detectors: Liquid-Argon Time-Projection Chambers

DUNE Far Detectors are built by international partners contributing 50% of the detector components. CERN contributes 2 cryostats to LBNF in addition to significant contrubtions to cryo infrastructure from Brazil and Poland

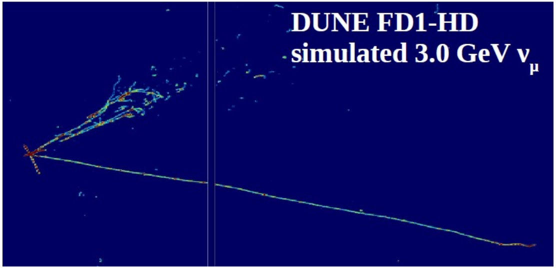


DUNE Prototypes @ CERN Neutrino Platform

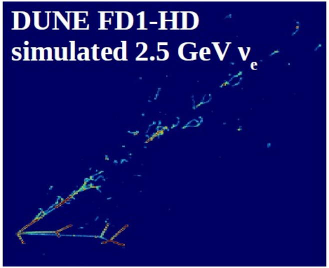


The ProtoDUNEs (FD Module 0) are ~5% scale using several full-scale TPC modules each and involve all the FD partners and CERN. Performance calibration with test beams at CERN NP.

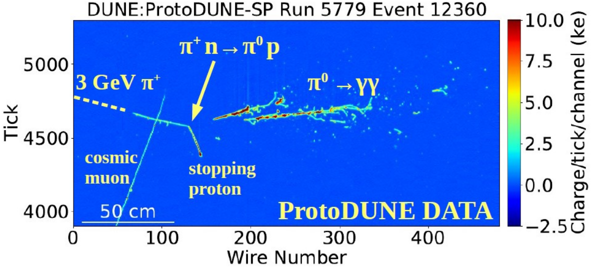
Neutrino Interactions in DUNE Far Detectors



DUNE FD1-HD simulated 3.0 GeV ν_μ

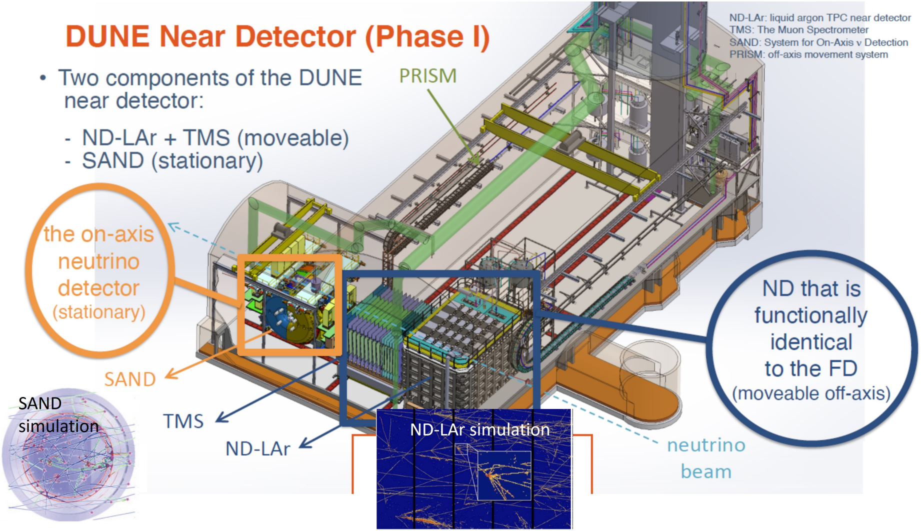


DUNE FD1-HD simulated 2.5 GeV ν_e



DUNE:ProtoDUNE-SP Run 5779 Event 12360

DUNE Near Detectors - Phase I



DUNE Near Detector (Phase I)

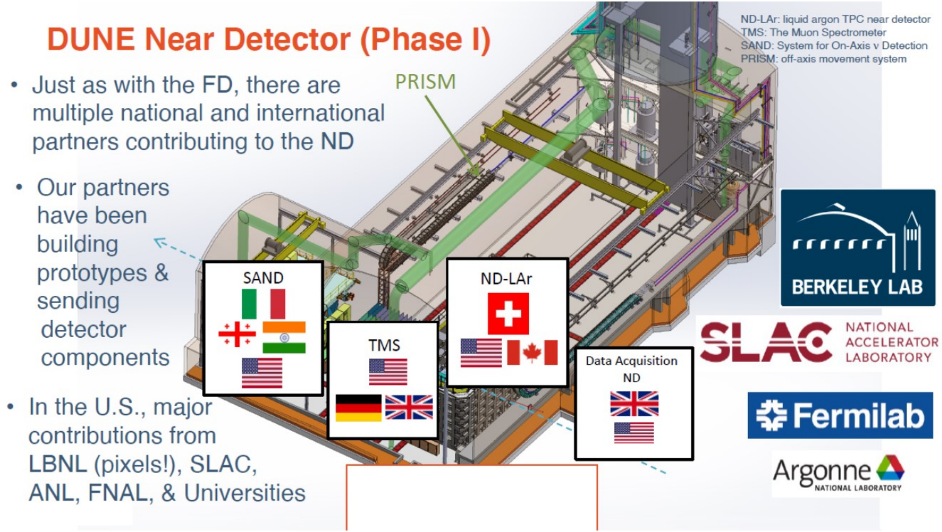
- Two components of the DUNE near detector:
  - ND-LAr + TMS (moveable)
  - SAND (stationary)

ND-LAr: liquid argon TPC near detector
TMS: The Muon Spectrometer
SAND: System for On-Axis ν Detection
PRISM: off-axis movement system

the on-axis neutrino detector (stationary)

ND that is functionally identical to the FD (moveable off-axis)

DUNE Near Detectors - Phase I



DUNE Near Detector (Phase I)

- Just as with the FD, there are multiple national and international partners contributing to the ND
- Our partners have been building prototypes & sending detector components
- In the U.S., major contributions from LBNL (pixels!), SLAC, ANL, FNAL, & Universities

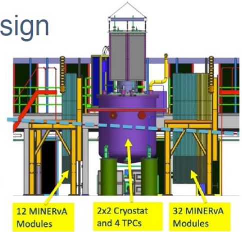
ND-LAr: liquid argon TPC near detector
TMS: The Muon Spectrometer
SAND: System for On-Axis ν Detection
PRISM: off-axis movement system

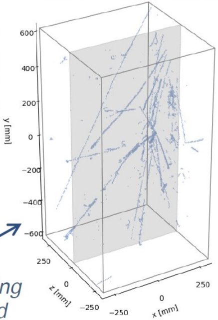
DUNE Near Detectors - Phase I

DUNE Near Detector Status (Phase I)

- We are also building prototypes of the near detector
  - *2x2 Demonstrator in NuMI beam at Fermilab*
  - *Full Scale Demonstrator (FSD) of ND-LAr*
- Important to test pixelated, modular design
- Like with the protoDUNEs, we will be getting physics out of ND prototypes
- ND-LAr 2x2 Demonstrator is being installed in the NuMI beam
  - *this will be the first ν data from DUNE*
- Also, KLOE magnet is currently being disassembled in Frascati for shipment to Fermilab for SAND

INFN National Institute for Nuclear Physics





fully instrumented 20% scale ND-LAr module operating at U Bern, Switzerland

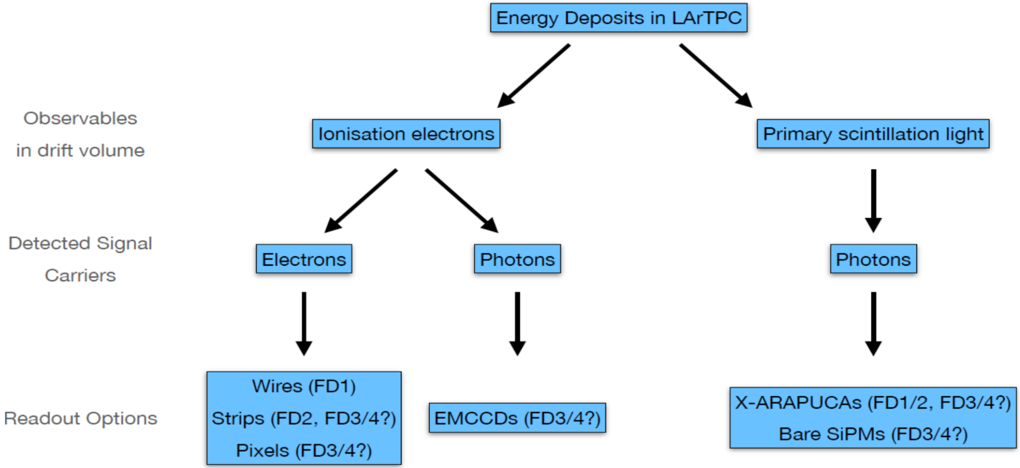
LABORATORIUM FÜR HOCHENERGIEPHYSIK LHEP UNIVERSITÄT BERN

BERKELEY LAB

SLAC

DUNE Phase II R&D

LArTPC R&D Approaches



Energy Deposits in LArTPC

Observables in drift volume

Ionisation electrons

Primary scintillation light

Detected Signal Carriers

Electrons

Photons

Photons

Readout Options

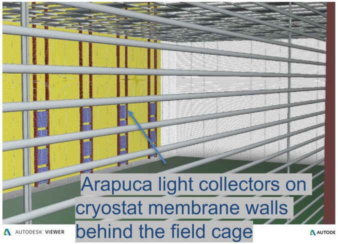
Wires (FD1)
Strips (FD2, FD3/4?)
Pixels (FD3/4?)

EMCCDs (FD3/4?)

X-ARAPUCAs (FD1/2, FD3/4?)
Bare SiPMs (FD3/4?)

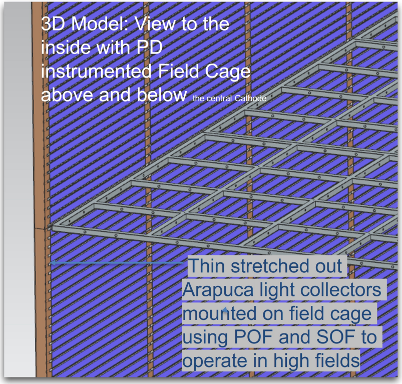
Increasing light collection (x10)

APEX system: light collectors deployed on field cage: FD3/4



Arapuca light collectors on cryostat membrane walls behind the field cage

Using FD2 technological breakthroughs like power-over-fiber and signal-over fiber to increase light collection by instrumenting the field cage.

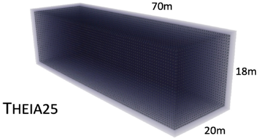


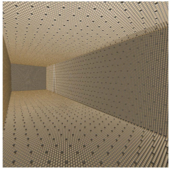
3D Model: View to the inside with PD instrumented Field Cage above and below the central Cathode

Thin stretched out Arapuca light collectors mounted on field cage using POF and SOF to operate in high fields

50% of energy deposited in LAr is in light = improved calorimetery and energy resolution

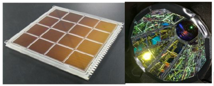
Water Based Liquid Scintillator for FD4 - “Theia”



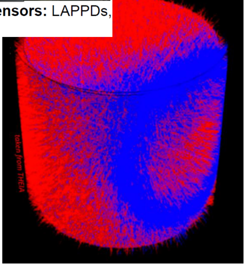


New technologies make this possible

Novel target medium: (Wb)LS



Novel light sensors: LAPPDs, dichroicons



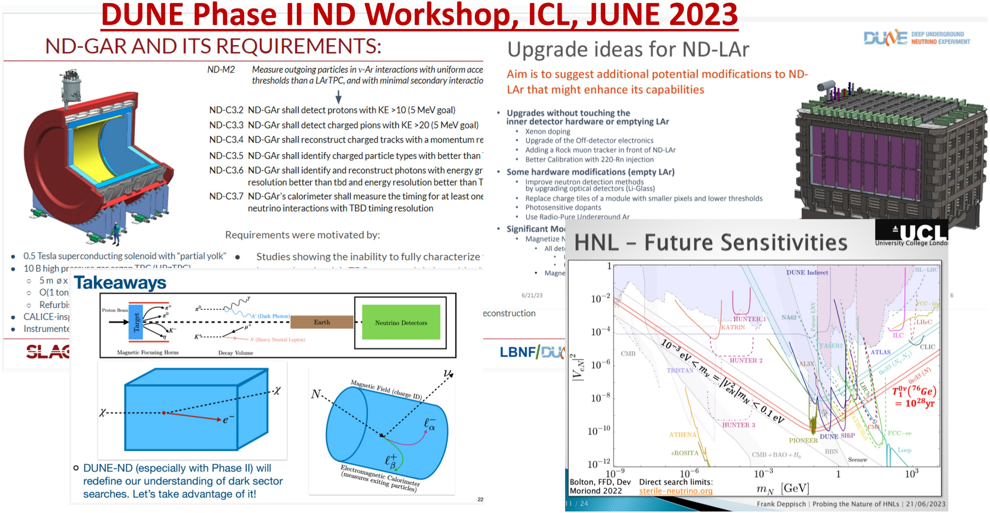
Hybrid signals allow broad extension of DUNE physics

- CP violation with comparable sensitivity to 1 DUNE module
  - Low-Z target allows cross check with Hyper-K
  - Requires changes to ND suite
- Precision low-energy solar neutrinos (CNO, pep, ^{8}B MSW transition)
- Diffuse supernova background neutrinos
- Literally complementary supernova burst signal: anti-ν_e vs. ν_e
- Eventual $0\nu\beta\beta$ experiment with sensitivity beyond inverted ordering

Broad international community interest, with opportunity for new funding sources

DUNE Near Detector Phase II

DUNE Phase II ND Workshop, ICL, JUNE 2023



ND-GAR AND ITS REQUIREMENTS:

ND-M2 Measure outgoing particles in ν-Ar interactions with uniform acce
thresholds than a LArTPC, and with minimal secondary interactio

↓

ND-C3.2 ND-GAr shall detect protons with KE >10 (5 MeV goal)
ND-C3.3 ND-GAr shall detect charged pions with KE >20 (5 MeV goal)
ND-C3.4 ND-GAr shall reconstruct charged tracks with a momentum re
ND-C3.5 ND-GAr shall identify charged particle types with better than
ND-C3.6 ND-GAr shall identify and reconstruct photons with energy gr resolution better than tbd and energy resolution better than T
ND-C3.7 ND-GAr's calorimeter shall measure the timing for at least one neutrino interactions with TBD timing resolution

Requirements were motivated by:

- Studies showing the inability to fully characterize

- 0.5 Tesla superconducting solenoid with "partial yolk"
- 10 B high pr
  - 5 m ø x
  - O(1 ton
  - Refurbi
- CALICE-insp
- Instrumente

SLAC

Upgrade ideas for ND-LAr

Aim is to suggest additional potential modifications to ND-LAr that might enhance its capabilities

- **Upgrades without touching the inner detector hardware or emptying LAr**
  - Xenon doping
  - Upgrade of the Off-detector electronics
  - Adding a Rock muon tracker in front of ND-LAr
  - Better Calibration with 220-Rn injection
- **Some hardware modifications (empty LAr)**
  - Improve neutron detection methods by upgrading optical detectors (Li-Glass)
  - Replace charge tiles of a module with smaller pixels and lower thresholds
  - Photosensitive dopants
  - Use Radio-Pure Underground Ar
- **Significant Mo**
  - Magnetize N
    - All det
  - Magne

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

6/21/23 6

econstruction

LBNF/DU

Takeaways

- DUNE-ND (especially with Phase II) will redefine our understanding of dark sector searches. Let's take advantage of it!

22

HNL – Future Sensitivities

UCL University College London

Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

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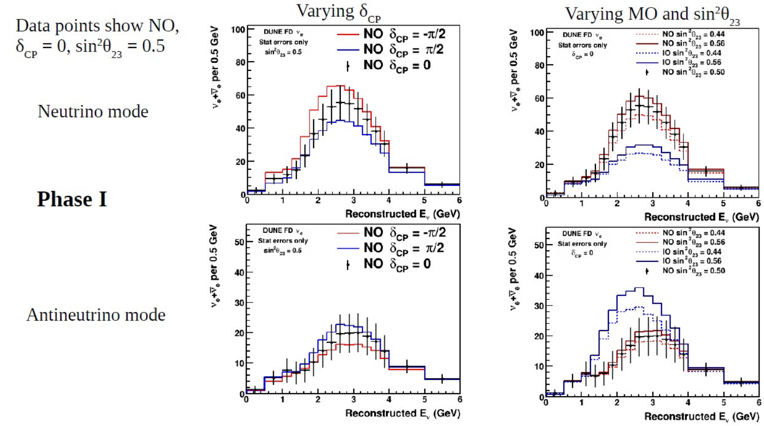
Frank Deppisch | Probing the Nature of HNLs | 21/06/2023

DUNE Physics Highlights

DUNE Long-Baseline Oscillation Measurements

DUNE Phase I - determines the mass ordering



Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Neutrino mode

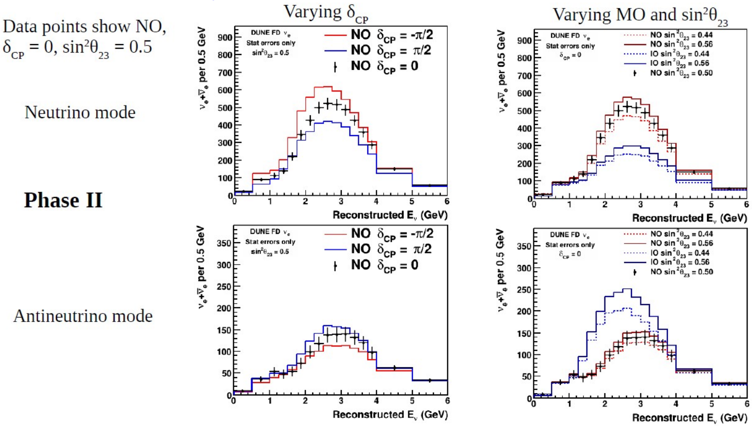
Phase I

Antineutrino mode

Rich spectral information = unmatched sensitivity to osc. parameters

DUNE Long-Baseline Oscillation Measurements

DUNE Phase II - measures δ_{cp}, θ_{23} octant



Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

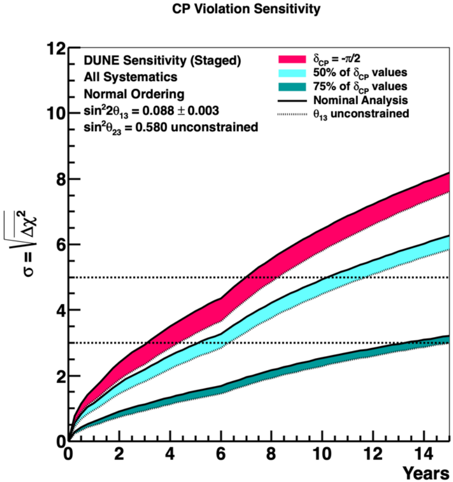
Neutrino mode

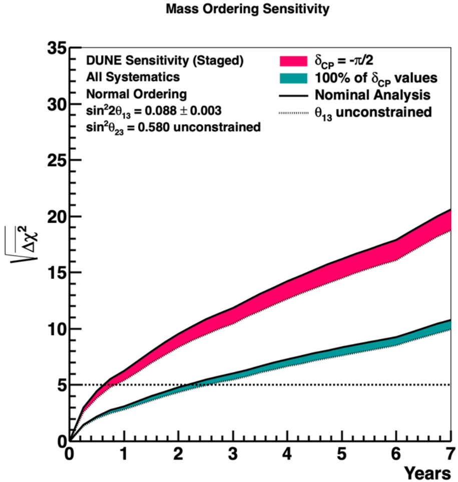
Phase II

Antineutrino mode

Rich spectral information = unmatched sensitivity to osc. parameters

DUNE Sensitivities to ν 3-flavor Oscillations (TDR staging)

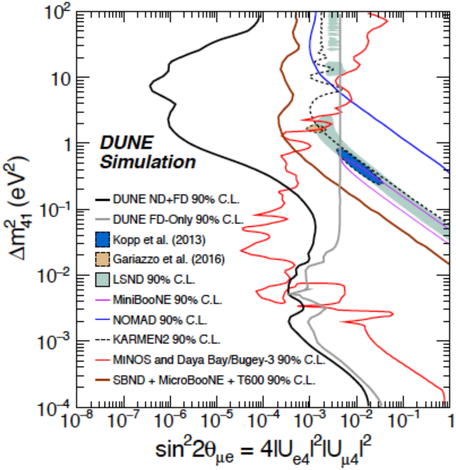

CP Violation Sensitivity


Mass Ordering Sensitivity

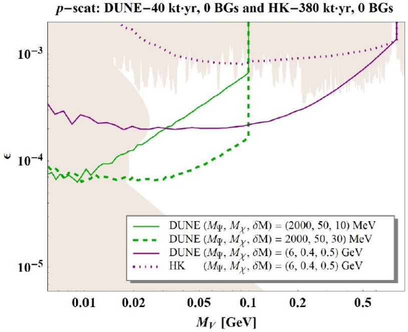
DUNE will determine MH unambigously and CPV to 5σ (50% of δ_{cp})

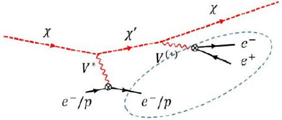
BSM Searches with DUNE

Sterile ν Searches



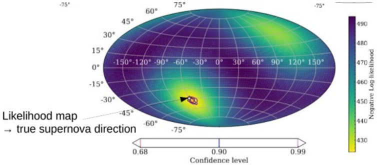
Inelastic Dark Matter Scattering





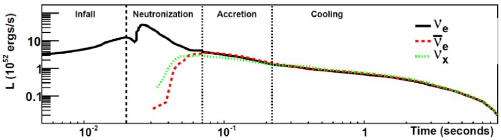
Supernova Burst Neutrinos in DUNE

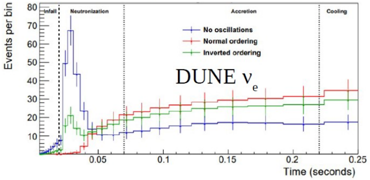
- **DUNE has unique sensitivity to the ν_e flux**
- **Studies using ν_e electron scattering indicate 5% pointing resolution**



- **Phase I: $\mathcal{O}(100)$s events per FD module for galactic SNB**
- **Phase II: Reach extends beyond Milky Way. Enhancements to LArTPC design in Phase II could signficantly improve low-energy physics.**

10 kpc supernova burst

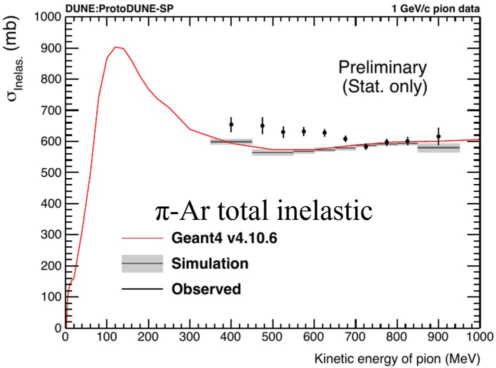


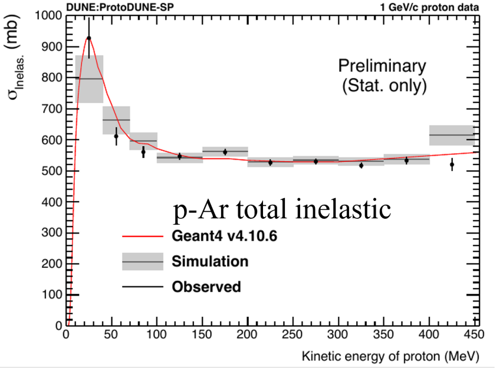


	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1] Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2] Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

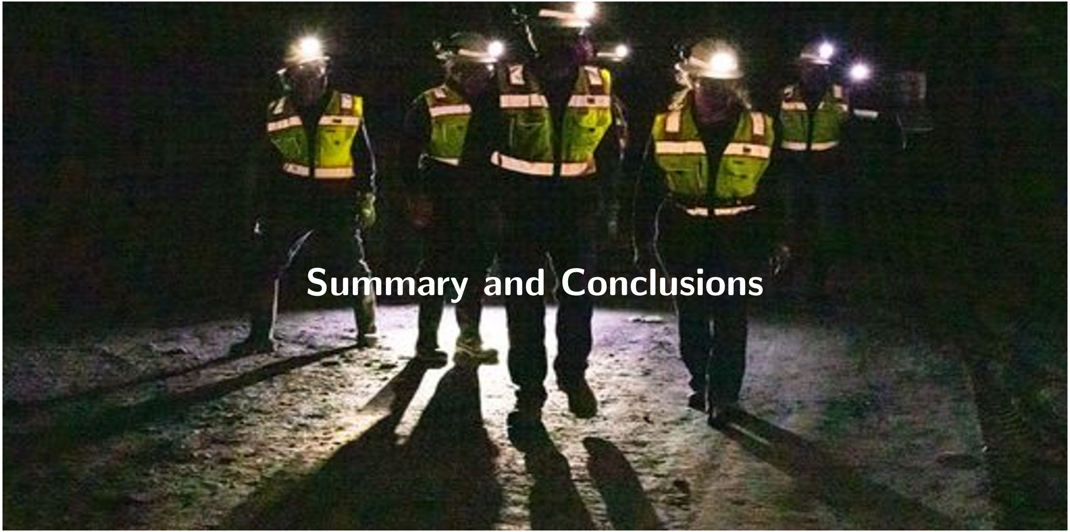
Preliminary Physics Results from ProtoDUNE Data





DUNE Publications and Conference Proceedings 2023

1. Muon energy reconstruction for applications in neutrino astronomy in the DUNE far detector **_JINST_ 18 (2023) 10, C10026**
2. The SAND detector at the DUNE near site *Nuovo Cim.C* 46 (2023) 4, 101
3. Production and testing of the large-area photon detector ArCLight **_JINST_ 18 (2023) 06, C06008**
4. Scintillation light detection performance for the DUNE ND-LAr 2 × 2 modules **_JINST_ 18 (2023) 04, C04004**
5. Impact of cross-section uncertainties on supernova neutrino spectral parameter fitting in the Deep Underground Neutrino Experiment **_Phys.Rev.D_ 107 (2023)**
6. Slicing with deep learning models at ProtoDUNE-SP *J.Phys.Conf.Ser.* 2438 (2023)
7. Sparse Convolutional Neural Networks for particle classification in ProtoDUNE-SP events *J.Phys.Conf.Ser.* 2438 (2023
8. The role of protoDUNE-SP in future oscillation physics *PoS* NOW2022 (2023) 029, *PoS* 029 (2022)
9. Sensitivity of DUNE to low energy physics searches *PoS* ICHEP2022 (2022) 621
10. Highly-parallelized simulation of a pixelated LArTPC on a GPU **_JINST_ 18 (2023) 04, P04034**
11. Detection efficiency measurement and operational tests of the X-Arapuca for the first module of DUNE far detector **_JINST_ 18 (2023) 02, C02064**
12. Light detection with power and signal transmission over fiber **_JINST_ 18 (2023) 02, C02029**
13. Identification and reconstruction of low-energy electrons in the ProtoDUNE-SP detector **_Phys.Rev.D_ 107 (2023) 9, 092012**
14. Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora **_Eur.Phys.J.C_ 83 (2023) 7, 618**



Summary and Conclusions

Summary

Neutrino long-baseline oscillations offer a unique opportunity to search for CP violation, unravel the mass ordering of neutrinos, and search for physics beyond the Standard Model.

- **LBNF/DUNE are "best-in-class" facilities/experiment for precision measurements of neutrino oscillations with unique sensitivity to Supernova burst astrophysics and beyond the Standard Model searches in both near and far detectors**
- **The LBNF far site excavation is near completion (expected early 2024), the DUNE far detector cryostats are under fabrication (CERN contract) and the detector components for FD1 and 2 are under construction. Near detectors are in final prototyping phase.**
- **DUNE collaboration now comprises $\sim$ 1400 active collaborators and 37 countries.**
- **DUNE experiment is highly internationalized with non-US contributions to the detectors exceeding 50%. The first large scale multi-lateral MOU between DOE and multiple international partners was signed on Nov 17,2023**
- **DUNE physics output continues to grow with real data analysis from prototypes as well as advances in simulation and reconstruction and pursuing new physics ideas.**
- **DUNE Phase II R&D effort is growing with large international and US effort already underway. US Phase II plans were presented to P5 - expecting report Dec 6-7,2023.**

THANK YOU