Long Baseline Neutrino Facility (for the comprehensive exam)

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Outline

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  - Beam Production System
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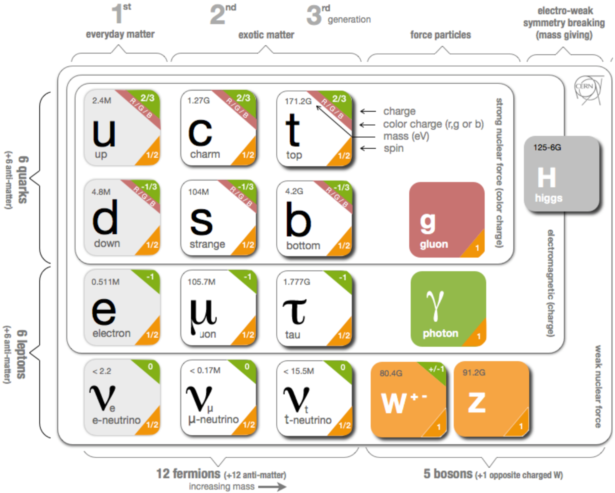
  - Comparison to the Other Facilities
- Conclusions

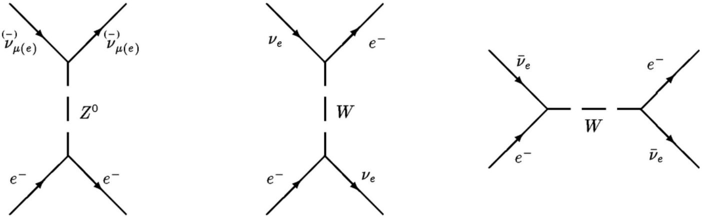
Introduction. Standard Model



All these and only these fundamental particles are discovered at the moment. Source of picture: [?]

Introduction. Neutrino Interactions

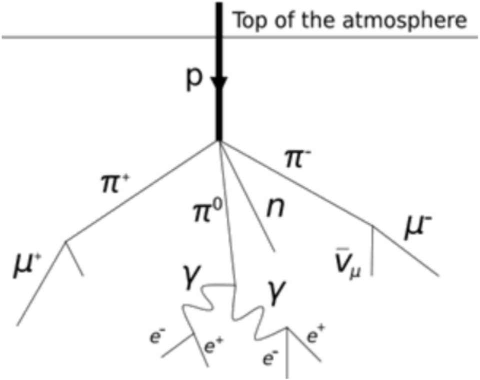
Feynmann diagrams of neutral current (NC, left), and neutral current (CC, middle and right) neutrino scattering.



Quoting [?], 11.1: "John Bahcall, who was responsible for most of the calculations of solar neutrino abundances, liked to say that 100 billion neutrinos pass through your thumbnail every second; and yet they are so ethereal that you can look forward to only one or two neutrino-induced reaction in your body during your entire lifetime".

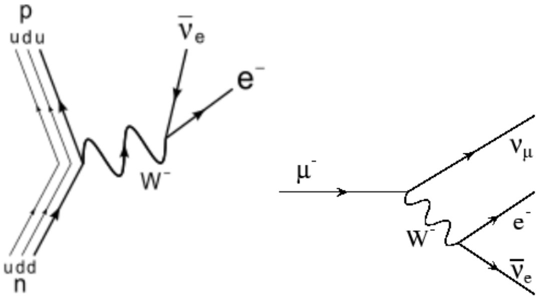
Introduction. Cosmic shower

Figure: Cosmic shower induced by scattering of the incident cosmics proton of an air molecule. Charged and neutron pions are born in the reaction and then they further decay as $\pi^0 \to \gamma\gamma$, $\pi^+ \to \mu^+ + \nu_\mu$, $\pi^- \to \mu^- + \bar{\nu_\mu}$.



Introduction. Muon and Neutron Decay

Figure: Feynmann diagrams of (left) neutron and (right) muon decays. Neutron beta decay [?](d-quark of transfers to u-quark through the W-boson with emission of electron and antineutrino). Muon decay [?](muon decays to electron, neutrino and antineutrino through W-boson



Introduction. Lepton Flavor Number

3 flavors of neutrino, one for each generation: ν_e, ν_μ, ν_τ. 3 lepton flavor numbers: L_e, L_μ and L_τ

Table: Lepton Flavor Number

particles	L_e	L_μ	L_τ
e^-, ν_e	+1	0	0
$e^+, \bar{\nu_e}$	-1	0	0
μ^-, ν_μ	0	+1	0
$\mu^+, \bar{\nu_\mu}$	0	-1	0
τ^-, ν_τ	0	0	+1
$\tau^+, \bar{\nu_\tau}$	0	0	-1

The lepton flavor numbers are conserved in almost all particle physics processes and the only violation of this law observed by this time is the neutrino oscillations - the ability of neutrino to change flavor.

Neutrino Oscillations Discovery

Theory. Two Neutrinos Case

$$\nu_1 = \nu_\mu cos\theta - \nu_e sin\theta$$
$$\nu_2 = \nu_\mu sin\theta + \nu_e cos\theta$$

$$\nu_1(t) = \nu_1(0)e^{\frac{-iE_1 t}{\hbar}}, \ \nu_2(t) = \nu_2(0)e^{\frac{-iE_2 t}{\hbar}} \leftarrow \text{from quantum mechanics}$$

Suppose, at t=0 there were $\nu_e(0) = 1$, $\nu_\mu(0) = 0$
Then: $\nu_1(0) = -sin\theta$, $\nu_2(0) = cos\theta$, $\nu_1(t) = -sin\theta e^{\frac{-iE_1 t}{\hbar}}$, $\nu_2(t) = -cos\theta e^{\frac{-iE_2 t}{\hbar}}$
Therefore, we are getting the system:

$$-sin\theta e^{-\frac{iE_1 t}{\hbar}} = \nu_\mu(t)cos\theta - \nu_e(t)sin\theta,$$
$$-sin\theta e^{-\frac{iE_2 t}{\hbar}} = \nu_\mu(t)sin\theta - \nu_e(t)cos\theta$$

By solving this sytem for ν_e and ν_μ, one would get:

$$P_{\nu_e \to \nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1 - E_2)t}{2\hbar}]^2,$$
$$P_{\nu_e \to \nu_e} = |\nu_e(t)|^2 = 1 - [sin2\theta sin\frac{(E_1 - E_2)t}{2\hbar}]^2$$

Theory. Two Neutrinos Case

$$P_{\nu_e \to \nu_\mu} = |\nu_\mu(t)|^2 = [sin 2\theta sin \frac{(E_1 - E_2)t}{2\hbar}]^2,$$
$$P_{\nu_e \to \nu_e} = |\nu_e(t)|^2 = 1 - [sin 2\theta sin \frac{(E_1 - E_2)t}{2\hbar}]^2$$

Therefore, for freely travelling neutrinos, if ν_e was emmitted, at any point there is a certain probability to register ν_e or ν_μ and those probablities change with time periodically, by $[sin(At)]^2$ law. That's why the phenomenon is called the neutrino oscillations. Suppose momenta $p_1 = p_2$. Then using $E^2 = p^2 + m^2$ and assuming $m_{1,2} << E_{1,2}$, the probablities will take forms of

$$P_{\nu_e \to \nu_\mu} = |\nu_\mu(t)|^2 = [sin 2\theta sin \frac{(E_1 - E_2)t}{2\hbar}]^2 = [sin 2\theta sin \frac{(m_1^2 - m_2^2)c^3}{4\hbar E} z]^2$$

Theory. Three Neutrinos Case

Oscillations are determined by Pontecorvo-Maki-Nakagava-Sakata (PMNS) matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The U_{PMNS} matrix depends on three neutrino mixing angles (θ_{12}, θ_{23}, θ_{13}) and CP-violating phase δ_{CP}. If define $c_{ab} = cos\theta_(ab)$, $s_{ab} = sin\theta_(ab)$, the U_{PMNS} matrix can be splitted into three multipliers, each would be responsible for mixing of one pair of neutrino flavors:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & e^{i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Theory. Three Neutrinos Case

The probability amplitudes of neutrino mixing are defined by parameters of the U_{PMNS} but, analogous to simplified two-neutrino case described above, the differences of squares of neutrino masses also contribute to the probability. There are two independent expressionce for squares of masses differences: $\Delta m_{12}^2 = m_1^2 - m_2^2$ and $\Delta m_{32}^2 = m_3^2 - m_2^2$. Mass differences were measured in other neutrino oscillation experiments but the Δm_{12}^2 and Δm_{32}^2 present in the equations evenly and therefore the signs of these expressions were not measured. If the masses order as $m_3 > m_2 > m_1$, it's called normal neutrino mass hierarchy because other fundamental particles orders in a way that later generation particles have higher masses than lower generation particles. If the masses order as $m_1 > m_2 > m_3$ it's called inverted neutrino mass hierarchy. The mixing angles θ_{12}, θ_{23}, θ_{13} and differences of squared masses $|\Delta m_{12}^2|$ and $|\Delta m_{32}^2|$ are measured and give U_{PMNS} matrix form of

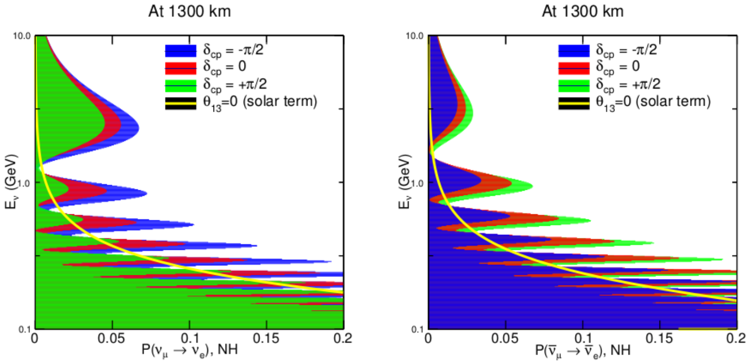
$$|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.5 & 0.6 & 0.6 \\ 0.2 & 0.6 & 0.8 \end{pmatrix}$$

The CP-violating phase δ_{CP} is unknown.
The analogous matrix for quark mixing, Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{CKM}, is much more diagonal:

$$|V_{CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

One of the important questions in modern particle physics is why the quark mixing angles are so much smaller than neutrino mixing angles and the other important

$P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km

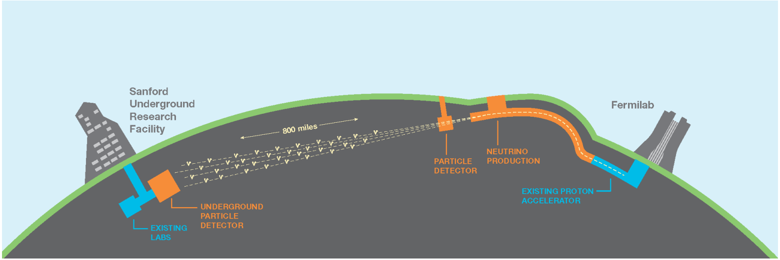


$P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km, as a function of neutrino energy. Left - neutrinos, right - antineutrinos. Figure is taken from the LBNF CDR draft, volume physics[?]

Available Experimental Results [?]

- $sin^2(2\theta_{12})$=0.846 ± 0.021
- $sin^2(2\theta_{23})$=$0.999^{+0.001}_{-0.018}$
- $sin^2(2\theta_{23})$=$1.000^{+0.000}_{-0.017}$
- Δm^2_{21}=$(7.53 \pm 0.18) \cdot 10^{-5} eV^2$
- Δm^2_{32}=$(2.44 \pm 0.06) \cdot 10^{-3} eV^2 \leftarrow$ if $m_3 > m_2 > m_1$
- Δm^2_{32}=$(2.52 \pm 0.07) \cdot 10^{-3} eV^2 \leftarrow$ if $m_1 > m_2 > m_3$
- CP-violation phase δ_{CP} - not measured
- mass hierarchy - not determined

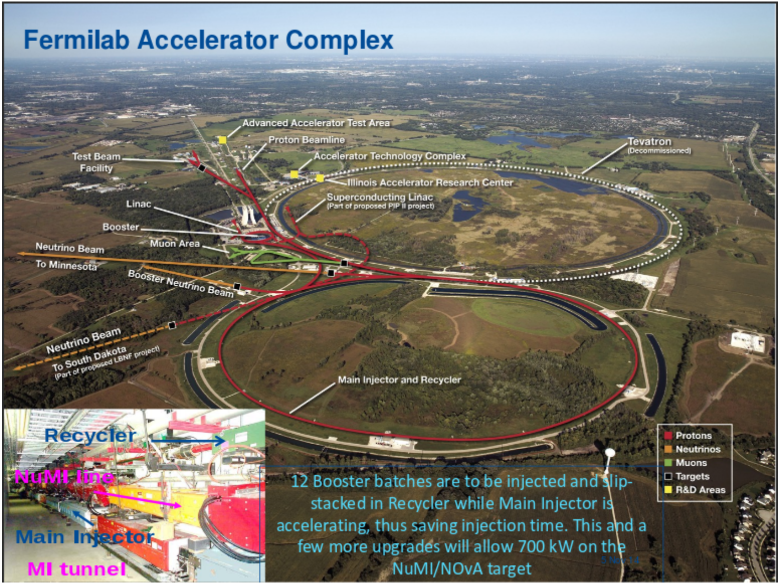
Long Baseline Neutrino Facility (LBNF) Experimental Setup



- neutrino beam production system at FNAL, Illinois
- near detector at FNAL, Illinois
- far detector at SURF, South Dakota

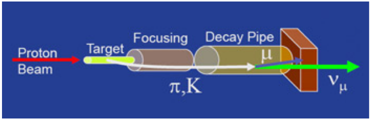
FNAL - Fermilab National Accelerator Laboratory, SURF - Sanford Underground Research Facility

Source of figure: [?]



12 Booster batches are to be injected and slip-stacked in Recycler while Main Injector is accelerating, thus saving injection time. This and a few more upgrades will allow 700 kW on the NuMI/NOvA target

LBNF. Beam Production System



The neutrino beam production at the LBNF. Source of figure: [?]
Pions (or kaons) are created: $p + p \to p + n + \pi^+$, $p + p \to p + \Delta^{++} + \pi^-$,
$p + n \to p + p + \pi^-$, $p + n \to n + n + \pi^+$, $p + n \to p + \Delta^- + \pi^+$
And then decay: $\pi^+ \to \mu^+\nu_\mu$, $\pi^- \to \mu^-\bar{\nu_\mu}$, $K^+ \to \mu^+\nu_\mu$, $K^- \to \mu^-\bar{\nu_\mu}$

(Feynmann diagrams of these reactions are shown at the next slide)

LBNF. Pions and kaon creation and decay

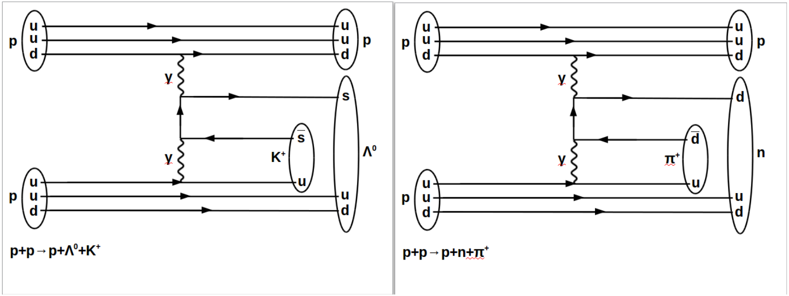
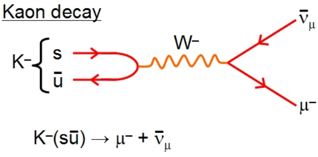
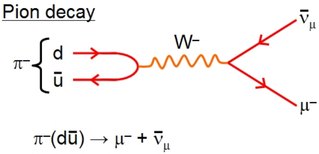
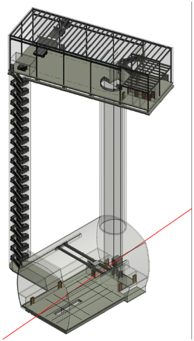


Figure: Feynmann diagrams of charged pion and kaon decays to muon and muon antineutrino weakly through W-boson. Figures taken from [?].



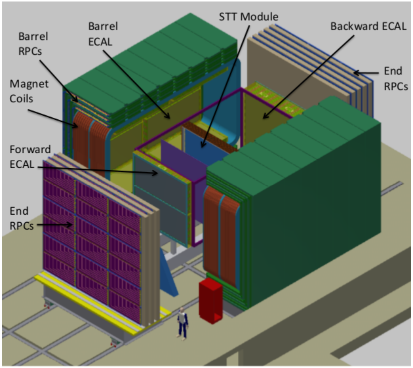


LBNF. Near Detector



Quoting the LBNF website [?], "The DUNE near detector will require LBNF to excavate and provision a cavern 200 ft (60 m) below grade on the Fermilab site and to construct a surface building directly above it. An elevator will provide the primary access between the two spaces; the stairway shown is planned for emergency egress. This complex will be constructed a minimum of 690 feet (210 m) downstream of the beamline target."

LBNF. Near Detector



The scheme of the near detector is shown at the fig. **??**. The detector will consist of central Straw-Tube Tracker (STT) modules, electromagnetic calorimeter (ECAL), magnet coils of 0.4T and muon identification system consisting of Resistive Plate Chamber (RPC) modules. The neutrinos would come from the bottom left corner of the picture, to the End RPCs.

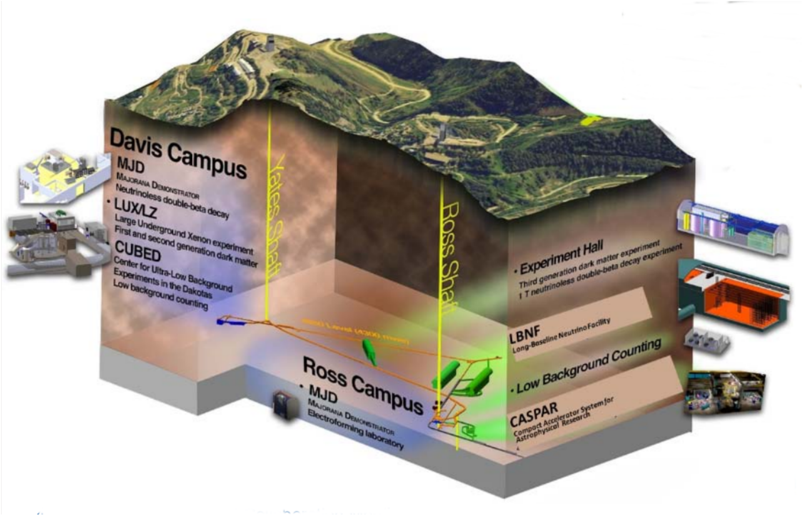
LBNF. Near Detector Physics

- absolute flux measurement
- relative neutrino and antineutrino flux measurements
- flavor content of the neutrino source
- determination of the E_ν-scale of neutrinos versus antineutrinos
- event-by-event measurements of NC interactions
- measurement of π^0, $\pi^\pm$, $K^\pm$, p, K_S^0 and Λ in the NC and CC
- nucleon structure, parton distribution functions and QCD studies
- precision measurements of electroweak physics

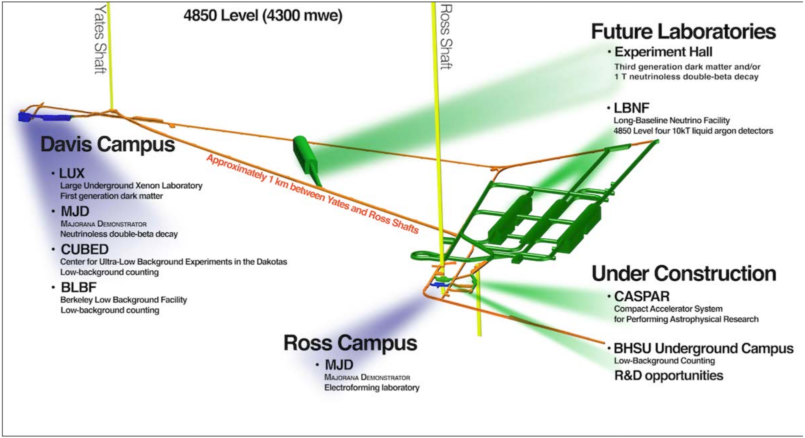
More specifically, the list of the physics measurements related to the neutrino oscillations to be performed by the Near Detector includes:

- fluxes of ν_μ, $\bar{\nu_\mu}$, ν_e and $\bar{\nu_e}$. To distinguish between flavors, the measurement should rely on charged current interaction (fig. **??**, middle and right) and measure the products of these interactions μ^-, μ^+, e^-, and e^+. (While the beam production system has the highest probability to produce muon neutrinos, the production of certain number electron neutrinos is also possible, for example, from charged kaon decays)
- ν_e-$\bar{\nu_e}$ assymetries. For that, it's important not only distinguish between $\mu^\pm$ and $e^\pm$ but also between e^- and e^+.
- the absolute ν_μ and $\bar{\nu_\mu}$ fluxes need to be measured with $\simeq$ 3% precision in the neutrino energy range 0.5-8 GeV
- cross section of NC versus CC processes as a function of hadronic energy. NC is one of major backrounds which contribute to neutrino oscillation measurement
- yields of π_0 and photons. These particles are the most significant background to ν_e and $\bar{\nu_e}$ contamination
- fractions of the $\pi^\pm$ into the CC and the NC hadronic jets.

LBNF. SURF (Far Detector Site)

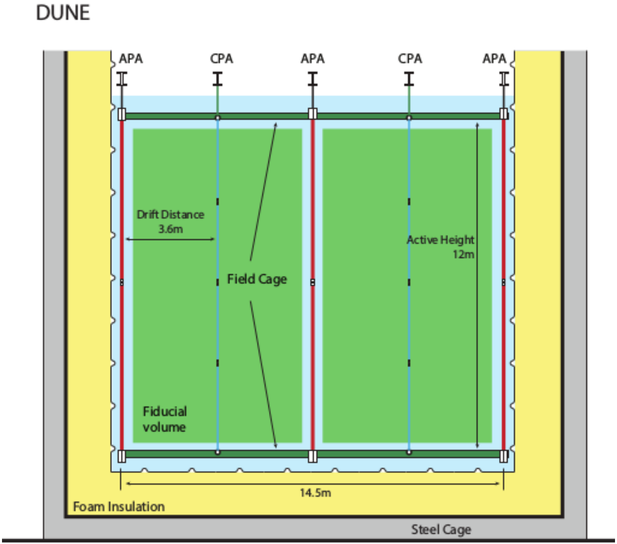


LBNF. SURF (Far Detector Site)



4 modules (15m x 12m x 58m, 10,000 tonnes of liquid argon each) placed into 4 caverns 1500 m underground. 5th cavern between two pairs - cryogenic equipment

LBNF. Far Detector. Liquid Argon Time Projection Chamber



LBNF Compared to the Other Experiments

	KEK (K2K)	NuMI	CNGS	T2K	LBNF (DUNE)
location	Japan	Illinois - Minnesota	Switzerland - Italy	Japan	Illinois - South Dakota
accelerator	KEK PS	FNAL	CERN's SPS	J-PARC	FNAL
time of oper.	1999-2004	2005-2012	2006-2012	2010-	future
beam power	5 kW	300-350 kW	300 kW	750 kW	2000 kW
E_p	12 GeV	120 GeV	400 GeV	30 GeV	60-120 GeV
baseline	250 km	735 km	730 km	295 km	1300 km
near detector(s)	(water ChD) (FGD)	MINOS (track. and scint.)	(muon detector)	ND280 INGRID	DUNE (FGD)
ND mass	1 kt (ChD)	0.98 kt			
far detector(s)	SuperK (water ChD)	MINOS track. and scint.	ICARUS (LAr) OPERA (FGD)	SuperK (water ChD)	DUNE (LAr)
FD mass	50 kt	5.4 kt	0.76 kt (ICARUS) 1.25 kt (OPERA)	50 kt	40 kt

LBNF. Status

- Experiment is under development
- Conceptual Design Report (CDR) drafts are partially available
- First collaboration meeting took place on April 16th-18th, 2015
- Fermilab accelerator is available
- Cavern for the near detector to be excavated
- Caverns for the far detector exist (former Homestake mine)
- far detector installation planned on 2021-2022

Conclusions

- LBNF - long baseline neutrino oscillations experiment under development to be hosted by FNAL and SURF
- Collaboration of > 750 people (~ 200 attended the 1st meeting on April 16th-18th of 2015)
- Expected parameters: baseline - 1300 km, beam power - 2 MW, far detector - 40kt of liquid argon
- plan: far detector installation in 2021-2022
- plan on precise measuments of θ_{12}, θ_{23}, θ_{13}, $|\Delta m_{12}{}^2|$, $|\Delta m_{31}{}^2|$
- expected: to measure CP-violation phase δ_{CP} and ν mass hierarchy which never was measured before
- not expected: to measure absolute values of ν masses (different type of experiment would be needed)