The Deep Underground Neutrino Experiment (DUNE):

An Experimental Program in Neutrinos, Nucleon Decay and Astroparticle Physics Enabled by the Fermilab Long-Baseline Neutrino Facility

Jim Stewart
Brookhaven National Laboratory

Yale
September 2015
Outline

• Introduction
• DUNE Experiment Overview
• Neutrino Oscillation Physics at DUNE
• Supernova and Proton Decay
Questions Addressed By DUNE

• What is the origin of the matter-antimatter asymmetry in the Universe?
  - Where did the antimatter go?
  - CPV if it exists if the best candidate to explain a baryon dominated universe.
• Is there a Grand Unified Theory of the Universe?
  - Do protons decay? Baryon number violation!
• How do supernova explode and what new physics will we learn from a neutrino burst?
  - The heavy elements are generated by supernova. Neutrinos are fundamental to supernova evolution.
Leading up to DUNE

For over a decade groups around the world have been designing/planning very long baseline neutrino experiments for CP and mass hierarchy measurements: eg. US LBNE, Europe LBNO, Japan T2HK.

2012: Daya Bay measured $\theta_{13}$ is non-zero! (CP can be measured!)

2013: European Strategy for Particle Physics updated
Endorsed high priority of neutrino physics
Bottom line: CERN should help the European neutrino community participate in a long-baseline program outside of Europe.

2014: The US particle physics strategy updated

Particle Physics Project Prioritization Panel (P5)

P5 Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest priority large project in its timeframe.
The international community has come together very quickly to form the new DUNE collaboration.

DUNE will be the first mega-science project on US soil

- Governance modeled on the CERN LHC experiments

DUNE is moving forward rapidly (first collaboration meeting in April)

- 776 collaborators from 144 institutions and 26 nations
- Separate facilities from the experiment → LBNF

http://www.dunescience.org
DUNE Primary Science Program

Fundamental open questions in particle and astroparticle physics:

• 1) Neutrino Oscillation Physics
  - CPV in the leptonic sector
    • Our best bet for explaining why matter dominates over antimatter
  - Mass Hierarchy
  - Precision oscillation physics to test the 3-flavor paradigm

• 2) Nucleon Decay
  - Predicted in beyond the Standard Model theories [but not yet seen]
    • e.g. the SUSY-favored mode, $p \rightarrow K^+\bar{\nu}$

• 3) Supernova burst physics & astrophysics
  - Galactic core collapse supernova, unique sensitivity to $\nu_e$
    • Time information of neutron star or even black-hole formation
Flavor composition of neutrinos change as they propagate.

Two-neutrino case:

\[ \nu_i = \sum_\alpha U_{\alpha i}^\ast \nu_\alpha \]

\[ U = \begin{pmatrix} 
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} 
\end{pmatrix} \]

\[ P_{i \rightarrow i} = \sin^2 2\theta \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right) \]

Amplitude depends on $\theta$.

Oscillation frequency depends on $\Delta m^2$, baseline, and energy.
### 3 Neutrino Model: PMNS Matrix

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]

Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

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

- \(\theta_{23} \approx 45^\circ\)
- Atmospheric, Accelerator
- Octant unknown
- \(\theta_{13} \approx 10^\circ\)
- Short-Baseline Reactor, Accelerator
- \(\delta_{CP}\) unknown
- \(\theta_{12} \approx 35^\circ\)
- Solar, Long-Baseline Reactor
Oscillation Probability

\[ \Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4 E_{\nu}} \]

\[ a = \frac{G_F N_e}{\sqrt{2}} \]

\[ P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 \theta_{23} \sin^2 2 \theta_{13} \Delta_{31} \Delta_{33}^2 \]

\[ + \sin 2 \theta_{23} \sin 2 \theta_{13} \sin 2 \theta_{12} \left( \frac{\sin \left( \frac{\Delta_{31} - a L}{2} \right)}{\left( \frac{\Delta_{31} - a L}{2} \right)} \right) \Delta_{31} \sin \left( \frac{\Delta_{31} - a L}{2} \right) \Delta_{21} \cos \left( \frac{\Delta_{31} + \delta_{\text{CP}}}{2} \right) \Delta_{21}^2 \]

\[ + \cos^2 \theta_{23} \sin^2 2 \theta_{12} \left( \frac{\sin \left( a L \right)}{a L} \right) \Delta_{21}^2, \]

- \( \nu_e \) appearance amplitude depends on \( \theta_{13}, \theta_{23}, \delta_{\text{CP}}, \) and mass hierarchy.
- Large value of \( \sin^2(2 \theta_{13}) \) allows significant \( \nu_e \) appearance sample.
- \( \delta_{\text{CP}} \) and the term \( a \) switch signs in going from the \( \nu_\mu \rightarrow \nu_e \) to the \( \nu_\mu \rightarrow \bar{\nu}_e \)
CP and Matter Asymmetries vs. Baselines for fixed L/E

The charge-parity (CP) asymmetry is defined as

\[ A_{cp} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \]

\[ A_{cp} \sim \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta}{\sin \theta_{23} \sin \theta_{13}} \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right) \]

For CP, mass hierarchy, and \( \theta_{13} \) one measures the electron appearance asymmetry

Matter and CP have very different effects at the first and second oscillation Max.

Max oscillation asymmetry with no matter

For CP, mass hierarchy, and \( \theta_{13} \) one measures the electron appearance asymmetry

Z. Parsa, W. Marciano, BNL
Key DUNE features:

• High-intensity wide-band neutrino beam originating at FNAL
  - 1.2 MW proton beam upgradable to 2.4 MW

• Highly capable near detector to measure the neutrino flux

• A ∼40 kt fiducial mass liquid argon far detector
  - Located 1300 km baseline at SURF’s 4850 ft level (2,300 mwe)
  - Staged construction of four ∼10 kt detector modules. First module installation starting in 2021.
Major features of the DUNE experiment are:

- A high-intensity wide-band neutrino beam originating at FNAL – 1.2 MW proton beam upgradable to 2.4 MW
- A highly capable near detector to measure the neutrino flux
- A ~40 kt fiducial volume liquid argon far detector – Located 1300 km baseline at SURF’s 4850 ft level (2,300 mwe)
- Staged construction of four ~10 kt detector modules. First module installation starting in 2021.
LBNF/DUNE Neutrino Beam

- 60 – 120 GeV Proton beam energy
- Initial power 1.2 MW upgradable to 2.4 MW
  - PIP II complete before start of data taking
- $10^{21}$ protons on target per year
- Large $\nu$ flux 1 to 5 GeV
NuMI style Target & Horns, viable for 1.2 MW
- Focusing system will be studied to improve neutrino flux
- Space set aside for improved targets and horns
Highest power beams for neutrinos

Lab objectives:

- PIP (700 kW), Booster (15 Hz) $\rightarrow$ fully exploit the science of NOvA and SBN
- PIP-II (1.2 MW), PIP-III (2.4 MW) $\rightarrow$ fully exploit the science of DUNE
DUNE Near Detector reference design

Precisely measure the neutrino fluxes $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, and $\bar{\nu}_\mu$

- Magnetic Spectrometer (0.4 T)
  - Central straw-tube tracking system
    - 215,040 channels
  - Lead-scintillator sampling ECAL
- Integrated nuclear targets: $\text{Ar}$, $(\text{C}_3\text{H}_6)_n$, Ca, C, Fe, etc.
  - Sufficient for 10 times the un-oscillated far detector neutrino rate from the high pressure argon targets
- RPC-based muon tracking systems

Percent level neutrino flux determination
Precision neutrino cross section measurements
Design still being optimized
Discussion of LArTPC or high pressure Ar Gas TPC
The Sanford Underground Research Facility (Far Detector Home)
Sanford Underground Research Facility (Homestake) Facilities at 4300 mwe depth
• Facility donated to the State of South Dakota for science in perpetuity
• Experimental Facilities at 4850 ft level
• Two vertical access shafts
• Ross shaft refurbishment is ~55% complete
• Over $100M invested from private and state funds
• Working two 12 hour shifts/day in order to be done by June 2017
• Will allow large excavations at SURF in 2017!
4850L Facilities Design
Four 10kt detector pits, central utility cavern, and connecting drifts

- **Future Laboratories**
  - Experiment Hall
    - Third generation dark matter and/or 1 T neutrinoless double-beta decay
  - **LBNF**
    - Long-Baseline Neutrino Facility
    - 4850 Level four 10KT liquid argon detectors

- **Under Construction**
  - **CASPAR**
    - Compact Accelerator System for Performing Astrophysical Research
  - **BHSU Underground Campus**
    - Low-Background Counting
    - R&D opportunities

- **Davis Campus**
  - **LUX**
    - Large Underground Xenon Laboratory
    - First generation dark matter
  - **MJD**
    - Majorana Demonstrator
    - Neutrinoless double-beta decay
  - **CUBED**
    - Center for Ultra-Low Background Experiments in the Dakotas
    - Low-background counting
  - **BLBF**
    - Berkeley Low Background Facility
    - Low-background counting
  - **LZ (future)**
    - LUX-ZEPLIN
    - Second generation dark matter

- **Ross Campus**
  - **MJD**
    - Majorana Demonstrator
    - Electroforming laboratory

Approximately 1 km between Yates and Ross Shafts
4850L LBNF Excavation Design
(~800,000 tons of excavated material to be removed)
Each Cryostat holds 17.1kt LAr

Free standing steel supported membrane cryostat design
- CERN-FNAL design team

Central Utility Cavern holds Cold boxes, LN2 dewars, booster compressors, LAr/GAr filters
Membrane Cryostat Design

- Stainless steel primary membrane
- Plywood board
- Reinforced polyurethane foam
- Secondary barrier
- Reinforced polyurethane foam
- Plywood board
- Bearing mastic
- Steel structure with moisture barrier

Standard in LNG industry
Free-Standing Steel Cryostat Design

External (Internal) Dimensions
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L
Time Projection Chamber (TPC) Operation

MIP $dE/dx = 2.2 \text{ MeV/cm}$
$\rightarrow \sim 1 \text{fC/mm @ 500 V/cm}$
$\rightarrow \sim 1 \text{ MeV/wire}$
LAr Capabilities

- Bubble chamber like imaging capabilities.
- Excellent e-γ separation.
- PID through energy loss.

Figure 6–3: Examples of neutrino beam interactions in an LArTPC obtained from a GEANT4 simulation [12]. A CC $\nu_e$ interaction with a stopped $\mu$ followed by a decay Michel electron (top), a QE $\nu_e$ interaction with a single electron and a proton (middle), an NC interaction which produced a $\pi^0$ that then decayed into two $\gamma$’s with separate conversion vertices (bottom).
Nominal 10 kt Detector Configuration – Single phase readout

Liquid Argon Time projection chamber with both charge and optical readout.

First 10kt detector will be single phase

LAr Detector Module Characteristics

- 17.1/13.8/11.6 Total/Active/Fiducial mass
- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  - 3.6 m max drift length
- Photon detection for event interaction time determination for underground physics
Alternative Far Detector Design

DUNE collaboration recognizes the potential of the dual-phase technology

- A dual-phase implementation of the DUNE far detector is presented as an alternative design in the CDR
- If demonstrated, could form basis of second or subsequent 10-kt far detector modules
LArTPC Development Path
Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program

**Single-Phase**
- ICARUS
- LBL
- SBL
- ArgoNueT
- LarIAT

**Dual-Phase**
- WA105: 1x1x3 m³

**DUNE Alternative Design**
- WA105
- DUNE SP PT @ CERN
- DUNE Reference Design

**Timeline**
- 2015: MicroBooNE
- 2016: ICARUS
- 2018: DUNE SP PT @ CERN
- 2018: DUNE Reference Design

**DUNE Experiment**
Jim Stewart | 09/18/15
Oscillation Probability

\[ \Delta_{ij} = \Delta m_{ij}^2 L / 4 E_\nu \]

\[ a = G_F N_e / \sqrt{2} \]

\[ P(\nu_\mu \to \nu_e) \sim \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \]

\[ + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta_{\text{CP}}) \]

\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2, \]

- \( \nu_e \) appearance amplitude depends on \( \theta_{13}, \theta_{23}, \delta_{\text{CP}}, \) and mass hierarchy.
- Large value of \( \sin^2(2\theta_{13}) \) allows significant \( \nu_e \) appearance sample.
- \( \delta_{\text{CP}} \) and the term \( a \) switch signs in going from the \( \nu_\mu \to \overline{\nu}_e \) to the \( \nu_\mu \to \overline{\nu}_e \)
Event Spectra

Pre-Oscillation

$\nu_\mu / \overline{\nu_\mu}$ disappearance

$\nu_e / \overline{\nu_e}$ appearance
DUNE Sensitivity Calculations

GEANT4

GLoBES

GENIE

Fast MC

SENSITIVITIES

Fast MC
DUNE will definitively determine the neutrino mass hierarchy
• For a favorable CP phase this could be achieved in a few years!
• Improvements in beam design can greatly improve the sensitivity thus reducing the time needed for a definitive measurement
DUNE CP Violation Sensitivity

50% CP Violation Sensitivity

\[ \frac{\sigma}{\sqrt{\Delta \chi^2}} \]

DUNE Sensitivity
Normal Hierarchy
\( \sin^2 \theta_{13} = 0.085 \)
\( \sin^2 \theta_{23} = 0.45 \)

CDR Reference Design
Optimized Design

\[ \begin{align*}
\text{5}\% & : 1
\text{5}\% & : 2
\text{5}\% & : 3
\end{align*} \]

\[ \begin{align*}
\text{4}\% & : 1
\text{4}\% & : 2
\text{4}\% & : 3
\end{align*} \]

\[ \begin{align*}
\text{3}\% & : 1
\text{3}\% & : 2
\text{3}\% & : 3
\end{align*} \]

\[ \begin{align*}
\text{2}\% & : 1
\text{2}\% & : 2
\text{2}\% & : 3
\end{align*} \]

\[ \begin{align*}
\text{1}\% & : 1
\text{1}\% & : 2
\text{1}\% & : 3
\end{align*} \]

\[ \begin{align*}
\text{<3}\% & : 1
\text{<3}\% & : 2
\text{<3}\% & : 3
\end{align*} \]

- <3 % \( \nu_e \) systematics important after \( \sim 200 \text{ kt.MW.yr} \)
- Improvements in the beam have significant impact
- 5 \( \sigma \) discovery of CP violation in half the possible phase space in \( \sim 10 \) years

Assumes staging and 2MW beam after 6 years
Octant Sensitivity

• “Maximal mixing” ($\theta_{23} = 45^\circ$) would indicate equal contributions to $\nu_\mu$ and $\nu_\tau$ from $\nu_3$
  • Unknown symmetry?
• Current global neutrino fit prefers either IH & upper octant or NH & lower octant
Physics Milestones

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$):
  - with 60 – 70 kt.MW.year reach 3$\sigma$ CPV sensitivity
- e.g. in best-case scenario for MH:
  - with 20 – 30 kt.MW.year reach 5$\sigma$ MH sensitivity

<table>
<thead>
<tr>
<th>Physics milestone</th>
<th>Exposure kt · MW · year (reference beam)</th>
<th>Exposure kt · MW · year (optimized beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^\circ \theta_{23}$ resolution ($\theta_{23} = 42^\circ$)</td>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td>CPV at 3$\sigma$ ($\delta_{CP} = +\pi/2$)</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>CPV at 3$\sigma$ ($\delta_{CP} = -\pi/2$)</td>
<td>160</td>
<td>100</td>
</tr>
<tr>
<td>CPV at 5$\sigma$ ($\delta_{CP} = +\pi/2$)</td>
<td>280</td>
<td>210</td>
</tr>
<tr>
<td>MH at 5$\sigma$ (worst point)</td>
<td>400</td>
<td>230</td>
</tr>
<tr>
<td>$10^\circ$ resolution ($\delta_{CP} = 0$)</td>
<td>450</td>
<td>290</td>
</tr>
<tr>
<td>CPV at 5$\sigma$ ($\delta_{CP} = -\pi/2$)</td>
<td>525</td>
<td>320</td>
</tr>
<tr>
<td>CPV at 5$\sigma$ 50% of $\delta_{CP}$</td>
<td>810</td>
<td>550</td>
</tr>
<tr>
<td>Reactor $\theta_{13}$ resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)</td>
<td>1200</td>
<td>850</td>
</tr>
<tr>
<td>CPV at 3$\sigma$ 75% of $\delta_{CP}$</td>
<td>1320</td>
<td>850</td>
</tr>
</tbody>
</table>

★ Genuine potential for early physics results!

P5 Goal
Cosmic rays are another source of neutrinos

- Neutrinos of all types are produced with a wide range in energies.
- Depending on the zenith angle the neutrinos have a range in path lengths to the detector.
  - Matter effect through the earth modifies the oscillation probability and the earth density is well known.
- LAr detectors have excellent resolution (energy and angle)
Atmospheric Neutrino Oscillation probability

Measure $\nu_\mu$, $\nu_e$, $\bar{\nu}_\mu$, and $\bar{\nu}_e$ event rate as a function of energy and zenith angle. Determine the likelihood based on the hierarchy hypothesis.
Dune Atmospheric Neutrino Sensitivity to Mass Hierarchy

- Provides an additional measure of the mass hierarchy independent of the beam.
- Precision comparable to other proposed experiments.
- 20 years at 40 kt mass to reach 5 sigma.
Supernova Burst Neutrinos

• When a star's core collapses ~99% of the gravitational binding energy of the proto-neutron star goes into ν’s
• SN at galactic core (10 kpc) ⇒ few thousand interactions in 40 kt LArTPC in tens of seconds ($\nu_e$ detection complementary to WCD)
• SN 1987A observation of ~20 events → ~800 publications!
Why No Prompt Explosion?

• 0.1 M$_\text{sun}$ of iron has a nuclear binding energy
  $\approx 1.7 \times 10^{51}$ erg
• Comparable to explosion energy

• Shock wave forms within the iron core
• Dissipates its energy by dissociating the remaining layer of iron
• Energy from neutrinos needed to re-generate shock wave
• Neutrinos play a critical role in supernova
Supernova Evolution in Time


- SN at galactic core (10 kpc) – 1000s interactions in DUNE in 10s of seconds
  - Can watch a star collapse in real time!
- Time scale matches will to the LAr TPC response.
- LAr TPCs are sensitive to $\nu_e$ $\nu_e + ^{40}Ar \rightarrow e^- + ^{40}K^*$
Supernova Burst Neutrinos in DUNE

Galactic Supernova rate is about once every 30 years
Proton Decay

**General Remarks**

Discovery of proton decay would provide unambiguous evidence for Baryon Number ($B$) violation

$B$ violation is essential for creation of matter in the Universe

Proton decay controls the ultimate fate of the Universe

Proton decay is the missing link of Grand Unified Theories for which strong circumstantial evidence exists

Discovery of proton decay would be a monumental scientific achievement for mankind

**Large Underground Detectors are absolutely essential in achieving this goal**

K. Babu
Proton Decay Limits

DUNE has the potential to discover proton decay especially in the Kaon decay modes favored by supersymmetry.
Proton Decay Sensitivity

\[ p \rightarrow K \nu \]

\[ K \rightarrow \mu \nu \]

\[ \mu \rightarrow e\nu e\nu_{\mu} \]

ICARUS collection plane view
DUNE/LBNF Timeline

- April 2015 First collaboration meeting
- May 2015 CERN-DOE-NSF agreement signed (includes Neutrinos)
- **Dec. 2015** CD-3a CF Far Site. Initiate far site excavation and outfitting.
- 2017 Ongoing shaft renovation at SURF complete
- 2017 Start of far site excavation.
- 2018 Testing of “full-scale” far detector elements at CERN
- 2019 Technical Design review (Start Detector Construction)
- 2021 Ready for start of installation of the first far detector module
- **2024** start of physics with one detector module
- 2026 Beam and near detector available
- 2028 DUNE construction finished
Summary

• The DUNE collaboration has formed and will be the first truly international mega science project on US soil.
  – The scope of LBNF/DUNE is a high power beam, high precision near detector, and four far detector liquid argon detectors each with over 10 kt fiducial mass.
  – The baseline will be 1,300 km and the detector will be at SURF 4850 ft
  – CD-1 Refresh review recommended approval of the DUNE scope.
    • International governance was accepted.
    • CORE costing and international management was accepted.

• Expect to start far site construction in 2017

• ProtoDUNE will test “full-scale” detector elements at CERN in 2018

• MicroBooNE, WA105, LArIAT, SNB, and Captain will provide great opportunities for involvement

• Start of physics in 2024 (beam avail. 2026)

• Many opportunities for early results

• DUNE will be the definitive neutrino oscillation experiment
Backup Slides
Cryostat Design

Each LBNE cryostat is 7,100 m³.
Oscillation Probability

$\nu_{\mu}$ oscillation probability

$$P(\nu_\mu \to \nu_e) \approx \frac{\sin^2 2\theta_{13} \sin^2 \theta_{23}}{(\Delta_{31} - aL)^2} \frac{\sin^2 (\Delta_{31} - aL)}{(\Delta_{31} - aL)} \frac{\Delta_{31}^2}{(\Delta_{31} - aL)^2} +$$

$$\alpha \sin 2\theta_{13} \cos \delta \frac{\sin (aL)}{(aL)} \frac{\sin (\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos \Delta_{32} -$$

$$\alpha \sin 2\theta_{13} \sin \delta \frac{\sin (aL)}{(aL)} \frac{\sin (\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin \Delta_{32}$$

- $\nu_e$ appearance amplitude depends on $\theta_{13}$, $\theta_{23}$, $\delta_{CP}$, and matter effects.
- Large value of $\sin^2(2\theta_{13})$ allows significant $\nu_e$ appearance sample.
- $\delta_{CP}$ and a switch signs in going from the $\nu_{\mu} \to \nu_e$ to the $\bar{\nu}_{\mu} \to \bar{\nu}_e$
Fermilab-CERN partnership
New DOE-CERN-NSF agreement signed May 7, 2015 at “White House”

“This agreement is also historic since it formalizes CERN’s participation in U.S.-based programs such as prospective future neutrino facilities for the first time.” Rolf Heuer DG CERN

“a model for the kinds of international scientific collaboration that can enable breakthrough insights and innovations.”... John Holdren, President’s Science Advisor

Our research programs...... are now deeply intertwined.”...Jim Siegrist
Neutrino Oscillation Strategy

Measure neutrino spectra at 1300 km in a wide-band beam

- Determine MH and $\theta_{23}$ octant, probe CPV, test 3-flavor paradigm and search for $\nu$ NSI in a **single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure $\nu_e$ appearance and $\nu_\mu$ disappearance over range of energies
    - MH & CPV effects are separable

$E \sim \text{few GeV}$
Cryostats
Steel-supported membrane cryostat

- **Today:**
  - WA105
  - 3 x 3 x 2 m$^3$ at CERN

- **Next steps ~2018**
  - SBND single-phase detector at Fermilab
  - WA105 & single-phase prototypes (8 x 8 x 8 m$^3$) at CERN

- **DUNE 10-kt Far Detector ~2021**
  - Inner dimensions:
    - 15.1 (W) x 14.0 (H) x 62 (L) m$^3$
  - Assume common design for all 4 FD cryostats
LAr-TPC Reconstruction

Real progress in last year – driven by 35-t & MicroBooNE

- Full DUNE simulation/reconstruction now in reach
Beam Optimization

Following LBNO approach, genetic algorithm used to optimize horn design – increase neutrino flux at lower energies
Evaluating DUNE Sensitivities II

- **Efficiencies & Energy Reconstruction from “Fast MC”**
  - Generate neutrino interactions in LAr using GENIE
  - **Fast MC** smears response at generated final-state particle level
    - “Reconstructed” neutrino energy
    - kNN-based MV technique used for $\nu_e$ “event selection”:
      parameterized efficiencies
  - Used as inputs to GLoBES
Evaluating DUNE Sensitivities III

Propagate to Oscillation Sensitivities using assumptions for systematics (from the ND)

50 % CP Violation Sensitivity

\[ \chi^2 = \sigma \]

DUNE Sensitivity

- Normal Hierarchy
  - \( \sin^2 \theta_{13} = 0.085 \)
  - \( \sin^2 \theta_{23} = 0.45 \)

5 % \( \oplus \) 1 %

5 % \( \oplus \) 2 %

5 % \( \oplus \) 3 %

- \(<3 \% \nu_e\) systematics important after \( \sim 200 \) kt.MW.yr
Evaluating DUNE Sensitivities

**Systematic Uncertainties**
- Anticipated uncertainties based on MINOS/T2K experience
- Supported by preliminary fast simulation studies of ND

<table>
<thead>
<tr>
<th>Source</th>
<th>MINOS $\nu_e$</th>
<th>T2K $\nu_e$</th>
<th>DUNE $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux after N/F extrapolation</td>
<td>0.3 %</td>
<td>3.2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Interaction Model</td>
<td>2.7 %</td>
<td>5.3 %</td>
<td>~ 2 %</td>
</tr>
<tr>
<td>Energy Scale ($\nu_\mu$)</td>
<td>3.5 %</td>
<td>Inc. above</td>
<td>(2 %)</td>
</tr>
<tr>
<td>Energy Scale ($\nu_e$)</td>
<td>2.7 %</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>2.4 %</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.7 %</strong></td>
<td><strong>6.8 %</strong></td>
<td><strong>3.6 %</strong></td>
</tr>
</tbody>
</table>

**DUNE goal for $\nu_e$ appearance < 4 %**
- For sensitivities used: 5 % $\oplus$ 2 %
  - where 5 % is correlated with $\nu_\mu$ & 2 % is uncorrelated $\nu_e$ only
Evaluating DUNE Sensitivities

- Assumed* Particle response/thresholds
  - Parameterized detector response for individual final-state particles

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Threshold (KE)</th>
<th>Energy/momentum Resolution</th>
<th>Angular Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^\pm$</td>
<td>30 MeV</td>
<td>Contained: from track length Exiting: 30 %</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>100 MeV</td>
<td>MIP-like: from track length Contained $\pi$-like track: 5% Showering/Exiting: 30 %</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>$e^\pm/\gamma$</td>
<td>30 MeV</td>
<td>2% $\oplus$ 15 %/$\sqrt{(E/\text{GeV})}$</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>$p$</td>
<td>50 MeV</td>
<td>$p &lt; 400$ MeV: 10 % $p &gt; 400$ MeV: 5% $\oplus$ 30%/$\sqrt{(E/\text{GeV})}$</td>
<td>$5^\circ$</td>
</tr>
<tr>
<td>$n$</td>
<td>50 MeV</td>
<td>$440%/$\sqrt{(E/\text{GeV})}$</td>
<td>$5^\circ$</td>
</tr>
<tr>
<td>other</td>
<td>50 MeV</td>
<td>5% $\oplus$ 30%/$\sqrt{(E/\text{GeV})}$</td>
<td>$5^\circ$</td>
</tr>
</tbody>
</table>

*current assumptions to be addressed by FD Task Force
## Sensitivity Calculations: FD Resolution

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Energy/Momentum Resolution in DUNE Fast Monte Carlo</th>
<th>Achieved Resolution/Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^\pm$</td>
<td>Contained track: track length Exiting track: 30%</td>
<td>See next slide 10-15% (1)</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>$\mu$-like contained track: track length $\pi$-like contained track: 5% Showering or exiting: 30%</td>
<td>See next slide Similar to contained $\mu$ 30%/\sqrt{E}$ [GeV] (2)</td>
</tr>
<tr>
<td>$e^\pm/\gamma$</td>
<td>2% $\oplus$ 15%/\sqrt{E}$ [GeV]</td>
<td>1% $\oplus$ 3%/\sqrt{E}$ [GeV] (3)</td>
</tr>
<tr>
<td>$p$</td>
<td>$p &lt; 400$ MeV/c: 10% $p &gt; 400$ MeV/c: 5% $\oplus$ 30%/\sqrt{E}$ [GeV]</td>
<td>6% (4) 30%/\sqrt{E}$ [GeV] (3)</td>
</tr>
<tr>
<td>$n$</td>
<td>40%/\sqrt{E}$ [GeV]</td>
<td>Also assume 40% bias from missing energy</td>
</tr>
<tr>
<td>Other</td>
<td>5% $\oplus$ 30%/\sqrt{E}$ [GeV]</td>
<td>Similar to protons</td>
</tr>
</tbody>
</table>

(2) ICARUS Collaboration, ICARUS at FNAL, arXiv:1312.7252
The DUNE Collaboration

As of today:

776 Collaborators

from

144 Institutes
The DUNE Collaboration

As of today:

776 Collaborators from 26 Nations

Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, France, Germany, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, Spain, Switzerland, Turkey, UK, USA, Ukraine

DUNE already has broad international support
Hadron Absorber Design

- Careful design of the absorber is needed to prevent overheating.
- Shower modeling well advanced.
Neutrino Oscillations

Flavor composition of neutrinos change as they propagate.

Two-neutrino case:

\[ |\nu_i\rangle = \sum_{\alpha} U_{\alpha i} ^* |\nu_\alpha\rangle \]

\[ U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} \]

- Amplitude depends on $\theta$.
- Oscillation frequency depends on $\Delta m^2$, baseline, and energy.
Stellar Collapse and Supernova Explosion

Newborn Neutron Star

Gravitational binding energy

\[ E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% M_{\text{SUN}} c^2 \]

This shows up as

- 99% Neutrinos
- 1% Kinetic energy of explosion
- 0.01% Photons, outshine host galaxy

Neutrino luminosity

\[ L_\nu \sim 3 \times 10^{53} \text{ erg / 3 sec} \]
\[ \sim 3 \times 10^{19} L_{\text{SUN}} \]

While it lasts, outshines the entire visible universe

Neutrino cooling by diffusion

Proto-Neutron Star

\[ \rho \sim \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3} \]
\[ T \sim 10 \text{ MeV} \]