An Experimental Programme at the DUNE

Jarek Nowak
on behalf of the DUNE Collaboration

ICNFP2015
August 28, 2015
DUNE Primary Science Program

• **Neutrino Oscillation Physics**
  - CP symmetry violation in the leptonic sector
    - Is Leptogenesis the answer to matter dominance?
  - Mass Hierarchy
  - Precision Oscillation Physics & testing the 3-flavor paradigm

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

• **Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to \( \nu_e \)
    - Time information on neutron star or even black-hole formation

• **Precision neutrino interactions studies (Near Det.)**
DUNE collaboration

782 Collaborators
144 institutions

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
Main 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
- Highly capable ND to constrain systematic errors in DUNE
- 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 to be installed 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
- Good coverage 1 to 5 GeV
Far Detector – Cryostat / Cryogenic Systems Layout

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
Nominal 10 kt Detector Configuration – Single phase readout

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 non-accelerator based physics

Liquid Argon Time projection chamber with both charge and scint. light readout.

First 10kt detector will be single phase
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
Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program.
Oscillation Probability

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \left( \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \right) \]
\[ + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta_{\text{CP}}) \]
\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2, \]

where \( \Delta_{ij} = \Delta m_{ij}^2 L / 4 E_\nu \)

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

\[ \nu_e \text{ appearance amplitude depends on } \theta_{13}, \theta_{23}, \delta_{\text{CP}}, \text{ and mass hierarchy} \]

Large value of \( \sin^2(2\theta_{13}) \) allows significant \( \nu_e \) appearance sample.

\( \delta_{\text{CP}} \) and a switch signs in going from the \( \nu_\mu \rightarrow \nu_e \) to the \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \).
Event Spectra

The full power of the experiment comes from a simultaneous fit to these spectra.
DUNE will definitively determine the neutrino mass hierarchy
For a favorable CP phase this could be achieved in a few years!
Optimization of the neutrino beam profile can greatly improve the sensitivity thus reducing the time needed for a definitive measurement.
<3 % $\nu_e$ systematics important after ~200 kt.MW.yr

Optimization of the neutrino beam profile have significant impact

5 $\sigma$ discovery of CP violation in half the possible phase space in ~10 years

Atmospheric neutrinos provide ~1$\sigma$ increased sensitivity if combined with beam
θ_{23} Resolution and Octant Sensitivity

“Maximal mixing” (θ_{23} = 45°) would indicate equal contributions to ν_μ and ν_τ from ν_3 from 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>
**Supernova vs**

When a star’s core collapses \(~99\%\) of the gravitational binding energy of the proto-neutron star goes into \(\nu\)'s

SN at galactic core (10 kpc) \(\Rightarrow\) several thousand interactions in 40kt LArTPC in tens of seconds – reconstructed with sub-millisec precision

- Trigger on and measure energy of neutrinos from galactic SNB
  - To date only observed \(\bar{\nu}_e\) from single SN
  - In argon, the largest sensitivity is to \(\nu_e\)
    - CC interaction: \(\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*\)

\[ E \sim O(10 \text{ MeV}) \]
Signal for SN at 10 kpc

Neutronization peak

- uniquely among neutrino observatories,

$$\nu_e + ^{40}Ar \rightarrow e^- + ^{40}K^*$$

- large LAr detectors provide a direct probe of this stage of the supernova process
Nucleon Decay

- Best limit from SK (1.3x10^{34} yr, 206kt-yr);
- Water has high-efficiency, clean signal;
- LAr should be even cleaner but can’t compete easily with no. of free protons in water.

The strength of LAr

- Image particles from nucleon decay
  - target sensitivity to kaons (from dE/dx)
  - from SUSY-inspired GUT p-decay modes

\[ E \sim O(200 \text{ MeV}) \]
Baryon Number Violation

Efficiency and background in water and agron (events per Mton-yr)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Water Efficiency</th>
<th>Cherenkov Background</th>
<th>Liquid Argon Efficiency</th>
<th>TPC Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow K^+\bar{\nu}$</td>
<td>19%</td>
<td>4</td>
<td>97%</td>
<td>1</td>
</tr>
<tr>
<td>$p \rightarrow K^0\mu^+$</td>
<td>10%</td>
<td>8</td>
<td>47%</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>$p \rightarrow K^+\mu^-\pi^+$</td>
<td>97%</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n \rightarrow K^+e^-$</td>
<td>10%</td>
<td>3</td>
<td>96%</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>$n \rightarrow e^+\pi^-$</td>
<td>19%</td>
<td>2</td>
<td>44%</td>
<td>0.8</td>
</tr>
</tbody>
</table>

High efficiency and low background in LAr for these modes

$\rho \rightarrow K^-\nu$
DUNE/LBNF Timeline

- Dec. 2015 CD-3a CF Far Site. Needed to authorize far site conventional facilities work including underground excavation and outfitting.
- 2017 Ongoing shaft renovation at SURF complete
- 2017 Start of far site conventional facilities.
- 2018 Testing of “full-scale” far detector elements at CERN
- 2019 Technical Design review
- 2021 Ready for start of installation of the first far detector module
- 2024 start of physics with one detector module
  - Additional far detector modules every ~2 years.
- 2026 Beam available
- 2026 Near detector available
- 2028 DUNE construction finished
Summary

• The long-baseline DUNE experiment will perform measurements of CP violation, mass hierarchy, non-standard interaction, proton decay and supernova burst neutrino from intra-galactic distances.

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

• Many opportunities for early discoveries

• DUNE will be the definitive experiment for neutrino oscillations
DUNE Sensitivity Calculations
Oscillation Probability

\( P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \left( \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + \right. \)

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

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

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

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

- \(\nu_e\) appearance amplitude depends on \(\theta_{13}, \theta_{23}, \delta_{\text{CP}},\) and matter effects.
- Large value of \(\sin^2(2\theta_{13})\) allows significant \(\nu_e\) appearance sample.
- \(\delta_{\text{CP}}\) and a switch signs in going from the \(\nu_\mu \rightarrow \nu_e\) to the \(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\)
South Dakota Ross Shaft Rehabilitation

- Experimental Facilities at 4850 ft level
- Two vertical access shafts for safety
- Ross shaft refurbishment in process and is ~55% complete
- Over $100M invested from private and state funds
- Facility donated to the State of South Dakota for science in perpetuity
- Working two 12 hour shifts/day in order to be done by 2017
- Will allow large excavations at SURF in 2017!
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

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

$E \sim$ few GeV
Cryostats
Cryostats

Steel-supported membrane cryostat

- **Today:**
  - WA105
  - 3 x 3 x 2 m³ at CERN

- **Next steps ~2018**
  - SBND single-phase detector at Fermilab
  - WA105 & single-phase prototypes (8 x 8 x 8 m³) at CERN

- **DUNE 10-kt Far Detector ~2021**
  - Inner dimensions:
    - 15.1 (W) x 14.0 (H) x 62 (L) m³
  - Assume common design for all 4 FD cryostats
Reconstruction
LAr-TPC Reconstruction

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

- Full DUNE simulation/reconstruction now in reach
Physics
Parameter Resolutions

\( \delta_{CP} & \theta_{23} \)

- As a function of exposure
SNB

- Energy and timing sensitive to particle & astrophysics

- Event Rates:
Beam Optimization
Beam Optimization

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

Unoscillated $\nu_\mu$ Flux, $\nu$ Mode

- Optimized, 241x4 m DP
- Optimized, 195x4 m DP
- Enhanced Reference, 250x4 m DP
- Enhanced Reference, 204x6 m DP
- Reference, 204x4 m DP

Horn 1

$r_1$, $r_2$, $r_3$, $r_4$, $r_{OC}$, $L_1$, $L_2$, $L_3$, $L_4$, $L_5$, $L_6$, $L_7$
Resource Loaded Schedule

Oct-15 CD-1 Refresh Approval
Jan-16 CD-3a Approval
Dec-19 CD-2/3c Project Baseline & Construction Approval

- Preliminary Design
- CERN Test
- Final Design and Production Set-up
- Construction of APAs, Detector #1
  - Install TPC, Detector #1
    - Fill & Commission Detector #1
- Construction of APAs, Detector #2
  - Install TPC, Detector #2
    - Fill & Commission Detector #2
- Construction of APAs, Detector #3
  - Install TPC, Detector #3
    - Fill & Commission Detector #3
- Install TPC, Detector #4
  - Fill & Commission Detector #4

FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
FY23
FY24
FY25
FY26
FY27
FY28

DOE Activity
- Start Full Scale Mock-up
- Cryostat #1 Ready for Detector Installation
- Cryostat #2 Ready for Detector Installation
- Detector #2 Commissioned

DOE and Non-DOE Activity
- Cryostat #4 Ready for Detector Installation
- Detector #1 Commissioned

Non-DOE Activity
**Indicative Far Detector Decision Dates**

- **FY15**
  - Oct-15 CD-1 Refresh Approval
  - Jan-16 CD-3a Approval

- **FY16**
  - Dec-19 CD-2/3c Project Baseline & Construction Approval

- **FY17**
  - Preliminary Design
  - CERN Test

- **FY18**
  - Final Design and Production Set-up
  - Construction of APAs, Detector #1
  - Install TPC, Detector #1
  - Fill & Commission Detector #1

- **FY19**
  - Construction of APAs, Detector #2
  - Install TPC, Detector #2
  - Fill & Commission Detector #2

- **FY20**
  - Construction of APAs, Detector #3
  - Install TPC, Detector #3
  - Fill & Commission Detector #3

- **FY21**
  - Install TPC, Detector #4
  - Fill & Commission Detector #4

- **FY22**

- **FY23**

- **FY24**

- **FY25**

- **FY26**

- **FY27**
  - Feb-27 CD-4b (early completion)

- **FY28**

**DOE Activity**
- Start Full Scale Mock-up
- Cryostat #1 Ready for Detector Installation

**DOE and Non-DOE Activity**
- Cryostat #1 Ready for Detector Installation

**Non-DOE Activity**
- Cryostat #2 Ready for Detector Installation
- Cryostat #4 Ready for Detector Installation
- Detector #2 Commissioned
- Detector #1 Commissioned
Far Detector Technology Timeline

- DOE scope is for ~50% of two 10-kt FD modules
  - Remaining ~50% from international partners
  - Gives scope for two single-phase detectors
  - Timescale for CD-2 is 2019/2020 sets timescale for baseline design
  - Matches the decision time for second 10-kt module

- Currently, the funding for other two 10-kt FD modules 100% from non-DOE sources
  - Opportunity for to attract new international partners with desire to contribute to enhanced designs, e.g. dual phase
  - Flexibility is required: will take 3 – 4 years for international agreements

- Given schedule – first 10-kt will be single phase (see CDR)

- Second and subsequent 10-kt modules:
  - Details will depend on timescale of demonstration and performance of alternative technologies
  - CERN neutrino platform critical here
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

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**Diagram:**
- **CC $\nu_e$**
- **$\nu_e$ appearance**
Evaluating DUNE Sensitivities III

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

50% CP Violation Sensitivity

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

- 5% \(\oplus\) 1%
- 5% \(\oplus\) 2%
- 5% \(\oplus\) 3%

- <3% \(\nu_e\) systematics important after \(\sim\)200 kt.MW.yr
Systematics & Performance
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°</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>100 MeV</td>
<td>MIP-like: from track length Contained $\pi^\pm$-like track: 5% Showering/Exiting: 30 %</td>
<td>1°</td>
</tr>
<tr>
<td>$e^\pm/\gamma$</td>
<td>30 MeV</td>
<td>2% $\oplus$ 15%/√(E/GeV)</td>
<td>1°</td>
</tr>
<tr>
<td>$p$</td>
<td>50 MeV</td>
<td>$p &lt; 400$ MeV: 10 % $p &gt; 400$ MeV: 5% $\oplus$ 30%/√(E/GeV)</td>
<td>5°</td>
</tr>
<tr>
<td>$n$</td>
<td>50 MeV</td>
<td>440%/√(E/GeV)</td>
<td>5°</td>
</tr>
<tr>
<td>other</td>
<td>50 MeV</td>
<td>5% $\oplus$ 30%/√(E/GeV)</td>
<td>5°</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
Muon momentum as a function of track length (GEANT4):

Momentum resolution using track length method:

\[ \sigma \approx 5\% \]
Neutrino Resolution

Neutrino signal resolution from Fast MC based on preceding single particle resolutions

$\nu_e$ Appearance Signal:

$\nu_\mu$ Disappearance Signal:
Sensitivity Calculations: $\nu_e$ Efficiency

Low-energy efficiency reduced to match early hand-scan studies of LArSoft simulations (3 mm pitch)

Did not use $dE/dx$ e/$\gamma$ separation based on $dE/dx$ applied using LArSoft simulations (3 mm pitch)

95% efficiency/50% purity for $E_\gamma = 250$ MeV

95% efficiency/92% purity for $E_\gamma > 1.5$ GeV

Effect of pitch next slide

NC/$\nu_e$ background reduction applied using kNN algorithm (based primarily on $p_T$)
Effect of Wire Pitch on $e/\gamma$ PID

ICARUS MC:

Effect of:
- 3mm vs 6mm wire pitch — since large projects are considering different pitch values (=N* channels)
- cascade energy $>100\text{MeV}$ and $>300\text{MeV}$
The DUNE Collaboration

As of today:

776 Collaborators

from

144 Institutes

- USA
- UK
- Italy
- India
- Other
- Switzerland
- Spain
- France
- Brazil
- Americas
- Poland
- Czech Republic

- USA
- India
- Other
- UK
- Italy
- Brazil
- France
- Americas
- Poland
- Switzerland
- Spain
- Czech Republic
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
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.
LBNF/DUNE Neutrino Beam

- FNAL proton improvement program will increase the beam power before the start of DUNE to 1.2 MW!
- Beam upgradable to 2.4 MW
## LBNF/DUNE Projects estimate in CORE Accounting

<table>
<thead>
<tr>
<th></th>
<th>M &amp; S K $</th>
<th>Labor K Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LBNF</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project Office - LBNF</td>
<td>$15,569</td>
<td></td>
</tr>
<tr>
<td>Far Site Facilities</td>
<td>$545,421</td>
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<td>Far Site CF</td>
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<td>Cryogenics Infrastructure</td>
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<td>Near Site Facilities</td>
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<td>Near Site CF</td>
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<tr>
<td>Beamline</td>
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<td><strong>LBNF Total</strong></td>
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<td><strong>DUNE Total</strong></td>
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<tr>
<td>Near Detector</td>
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<td><strong>DUNE Total</strong></td>
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<td><strong>GRAND TOTAL</strong></td>
<td><strong>$987,558</strong></td>
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