DUNE: The Deep Underground Neutrino Experiment

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Prague, November 5, 2015
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1: Context
The 2012 Revolution

★ Two major discoveries in particle physics

- A SM-like Higgs boson (ATLAS, CMS)
  - The key to EWSB and a possible window to the BSM world
- \( \theta_{13} \sim 10^\circ \) (T2K, MINOS, Daya Bay, RENO)
  - about as large as it could have been!
  - The door to CP Violation in the leptonic sector
The 2012 Revolution

★ Two major discoveries in particle physics

- A SM-like Higgs boson (ATLAS, CMS)
  - The key to EWSB and a possible window to the BSM world
- $\theta_{13} \sim 10^o$ (T2K, MINOS, Daya Bay, RENO)
  - about as large as it could have been!
  - The door to CP Violation in the leptonic sector

★ Now textbook physics*

- next steps: discovery CPV with a conventional $\nu$ beam

*apologies for gratuitous plug
2: How to Detect CPV with $\nu s$
In principle, it is straightforward

**★ CPV ➔ different oscillation rates for $\nu$s and $\bar{\nu}$s**

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4s_{12}s_{13}c^2_{13} s_{23}c_{23} \sin \delta$$

$$\times \left[ \sin \left( \frac{\Delta m^2_{21}}{2E} \right) + \sin \left( \frac{\Delta m^2_{23}}{2E} \right) + \sin \left( \frac{\Delta m^2_{31}}{2E} \right) \right]$$

**★ Requires $\{\theta_{12}, \theta_{13}, \theta_{23}\} \neq \{0, \pi\}$**

- now know that this is true, $\theta_{13} \approx 9^\circ$
- but, despite hints, don’t yet know “much” about $\delta$

**★ So “just” measure $P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?**

**★ Not quite, throw in matter effects**
Neutrino Oscillations in Matter

Accounting for matter effects, gives a Hamiltonian that is no longer diagonal in the basis of the mass eigenstates

\[
\mathcal{H} \left( \begin{array}{c} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{array} \right) = i \frac{d}{dt} \left( \begin{array}{c} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{array} \right) = \left( \begin{array}{ccc} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{array} \right) \left( \begin{array}{c} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{array} \right) + V|\nu_e\rangle
\]

Complicates the simple picture !!!!

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

\[
\begin{align*}
\text{ME} & \quad \frac{16A}{\Delta m^2_{31}} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \\
\text{ME} & \quad - \frac{2AL}{E} \sin \left( \frac{\Delta m^2_{31} L}{4E} \right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \\
\text{CPV} & \quad - \frac{\Delta m^2_{21} L}{2E} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) \sin \delta \quad s_{13} c_{13}^2 c_{23} s_{23} c_{12} s_{12}
\end{align*}
\]

\[
\text{with} \quad A = 2 \sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \text{eV}^2 \cdot \frac{\rho}{\text{g cm}^{-3}} \cdot \frac{E}{\text{GeV}}
\]
Neutrino Oscillations in Matter

★ Accounting for matter effects, gives a Hamiltonian that is no longer diagonal in the basis of the mass eigenstates

\[
\mathcal{H} \left( \begin{array}{c} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{array} \right) = i \frac{d}{dt} \left( \begin{array}{c} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{array} \right) = \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} \left( \begin{array}{c} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{array} \right) + V|\nu_e\rangle
\]

★ Complicates the simple picture !!!!

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

**ME**

\[
\frac{16A}{\Delta m^2_{31}} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) c^2_{13} s^2_{13} s^2_{23} (1 - 2s^2_{13})
\]

What we measure

Small

**ME**

\[
- \frac{2AL}{E} \sin \left( \frac{\Delta m^2_{31} L}{4E} \right) c^2_{13} s^2_{13} s^2_{23} (1 - 2s^2_{13})
\]

Proportional to L

**CPV**

\[
- \frac{\Delta m^2_{21} L}{2E} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) \sin \delta \cdot s_{13} c_{13} c_{23} s_{23} c_{12} s_{12}
\]

What we want

With

\[
A = 2 \sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \text{eV}^2 \cdot \frac{\rho}{\text{g cm}^{-3}} \cdot \frac{E}{\text{GeV}}
\]
Experimental Strategy

EITHER:
★ Keep L small (~200 km): so that matter effects are insignificant
  ▪ Still want oscillations:
    \[
    \frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \quad \Rightarrow \quad E_\nu < 1 \text{ GeV}
    \]
  ▪ Since \( \sigma \propto E_\nu \) need a high flux at oscillation maximum
    ➡️ Off-axis beam: narrow range of neutrino energies

OR:
★ Make L large (>1000 km): measure the matter effects (i.e. MH)
  ▪ Still want oscillations:
    \[
    \frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \quad \Rightarrow \quad E_\nu > 2 \text{ GeV}
    \]
  ▪ Unfold CPV from Matter Effects through E dependence
    ➡️ On-axis beam: wide range of neutrino energies
Experimental Strategy

EITHER:

★ Keep L small (~200 km): so that matter effects are insignificant
  • Still want oscillations:
    \[ \frac{\Delta m_{31}^2 L}{4E} \sim \frac{2\pi}{3} \]
  • Since need a high flux at oscillation maximum
    ➢ Off-axis beam: narrow range of neutrino energies

OR:

★ Make L large (>1000 km): measure the matter effects (i.e. MH)
  • Still want oscillations:
    \[ \frac{\Delta m_{31}^2 L}{4E} \sim \frac{2\pi}{2} \]
  • Unfold CPV from Matter effects through E dependence
    ➢ On-axis beam: wide range of neutrino energies
3: DUNE – the Deep Underground Neutrino Experiment

Yates Complex

Ross Complex
LBNF/DUNE in a Nutshell

- Intense beam of $\nu_\mu$ or $\bar{\nu}_\mu$ fired 1300 km at a large detector
- Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations: CPV?
LBNF/DUNE in a Larger Nutshell

★ LBNF/DUNE

- Muon neutrinos/anti-antineutrinos from high-power proton beam
  - 1.2 MW from day one
  - upgradable to 2.3 MW

- Large underground LAr detector at Sanford Underground Research Facility (SURF) in South Dakota
  - 4 Cavern(s) for ≥ 40 kt total fiducial far detector mass
  - 10 - 20 kt fiducial LAr Far Detector (from day one)
  - 40 kt as early as possible

- Highly-capable Near Detector system
  - Using one or more technologies
Origins of DUNE

Paraphrasing 2014 P5 strategic review of US HEP

- Called for the formation of **LBNF**: 
  - as an international collaboration bringing together the LBL community
  - ambitious scientific goals with discovery potential for:
    - Leptonic CP violation
    - Proton decay
    - Supernova burst neutrinos

Resulted in the formation of the **DUNE** collaboration with strong representation from:

- LBNE (mostly US)
- LBNO (mostly Europe)
- Other interested institutes
DUNE

Is a rapidly evolving scientific collaboration...

• First formal collaboration meeting April 16th - 18th 2015
• Passed DOE CD-1 Review in July
• Second collaboration meeting September 2nd - 5th 2015
  - Over 220 people attended in person
• Successful Director’s CD-3a Review last week
Is a rapidly evolving scientific collaboration...

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- **Successful Director’s CD-3a Review last week**

DUNE is on the real axis! See later
The DUNE Collaboration

As of today:

790 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:

790 Collaborators

26 Nations

from

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

+ soon to add Finland and Greece

DUNE already has broad international support
3.1: DUNE Science Strategy

A neutrino interaction in the ArgoNEUT detector at Fermilab
Focus on fundamental open questions in particle physics and astro-particle physics:

- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
  - Definitive determination of the Mass Hierarchy
  - Precision Oscillation Physics ($\theta_{23}$ octant, …) & testing the 3-flavor paradigm

- **2) Nucleon Decay**
  - Targeting SUSY-favored modes, e.g. $p \rightarrow K^+ \bar{\nu}$

- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to $\nu_e$
DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astro-particle physics:

• 1) Neutrino Oscillation Physics
  - CPV in the leptonic sector
  - Definitive determination of the Mass Hierarchy
  - Precision Oscillation Physics (θ23 octant, …) & testing the 3-flavor paradigm

• 2) Nucleon Decay
  - Targeting SUSY-favored modes, e.g. \( p \rightarrow K^+ \bar{\nu} \)

• 3) Supernova burst physics & astrophysics
  - Galactic core collapse supernova, sensitivity to \( \nu_e \)
DUNE 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

• Near Detector at Fermilab: measurements of unoscillated beam
• 40 kt LAr Far Detector at SURF: measure oscillated $\nu$ spectra
DUNE 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 ~ few GeV
Separating MH & CPV

DUNE: Determine MH and probe CPV in a single experiment

Recall:

\[ \mathcal{A} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter} \]

with

\[ \mathcal{A}_{CP} \propto L/E ; \quad \mathcal{A}_{Matter} \propto L \times E \]
Separating MH & CPV

**DUNE:** Determine MH and probe CPV in a single experiment

Recall:
\[
\mathcal{A} = P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter}
\]

with
\[
\mathcal{A}_{CP} \propto L/E ; \quad \mathcal{A}_{Matter} \propto L \times E
\]
Nucleon Decay & SuperNova vs

Nucleon decay

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

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

SNB neutrinos

• Trigger on and measure energy
  of neutrinos from galactic SNB
  - In argon, the largest sensitivity is to \( \nu_e \)
  - CC \( \nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^* \) interaction

\[ E \sim O(10 \text{ MeV}) \]
DUNE Far Detector

Far detector design optimized for:

- Pattern recognition
- Energy measurement

in energy range: few MeV – few GeV

LAr-TPC Far Detector technology gives:

- Exquisite imaging capability in 3D
  - ~ few mm scale
- Excellent energy measurement capability:
  - totally active calorimeter

Near detector designed to:

- Constrain systematic uncertainties in LBL oscillation analysis
  - Near detector must be able to constrain ν cross sections & ν flux
DUNE CDR Design =

Far detector: 40-kt LArTPC

Near detector: Multi-purpose high-resolution detector
3.2: LBNF – a MW-scale facility
LBNF and PIP-II

★ In beam-based long-baseline neutrino physics:
  ▪ beam power drives the sensitivity
★ LBNF will be the world’s most intense high-energy ν beam
  ▪ Build on strong Fermilab track record (BNB & NuMI)
  ▪ 1.2 MW from day one
    • NuMI (MINOS) <400 kW
    • NuMI (NOVA) ultimately ~700 kW
  ▪ upgradable to 2.4 MW

★ Requires PIP-II (proton-improvement plan)
  ▪ $0.5B upgrade of FNAL accelerator infrastructure
  ▪ Replace existing 400 MeV LINAC with 800 MeV SC LINAC
The LBNF Neutrino Beam

- i) Start with an intense (MW) proton beam from PIP-II
- ii) Point towards South Dakota
- iii) Smash high-energy (~80 GeV) protons into a target
- iv) Focus positive pions/kaons
- v) Allow them to decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
- vi) Absorb remaining charged particles in rock
- vii) left with a “collimated” $\nu_\mu$ beam

hadrons
3.3: The DUNE Far Detector
The Far Site

DUNE Far Detector site

- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~1 mile underground)
The Far Site

DUNE Far Detector site

- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~1 mile underground)

Plan is to commence excavation in 2017
Staged Approach to 40 kt

Cavern Layout at the Sanford Underground Research Facility based on four independent caverns

- Four identical caverns hosting four independent 10-kt FD modules
  - Allows for staged construction of FD
  - Gives flexibility for evolution of LArTPC technology design
    - Assume four identical cryostats
    - But, assume that the four 10-kt modules will be similar but not identical
LAr TPC Technologies

LArTPC technology has been demonstrated by ICARUS

DUNE is considering two options for readout of ionization signals:

• Single-phase wire-plane readout
  - Ionization signals (collection + induction) read out in liquid volume
  - As used in ICARUS, ArgoNEUT/LArIAT, MicroBooNE
  - Long-term operation/stability demonstrated by ICARUS T600

• Dual-phase readout
  - Ionization signals amplified and detected in gaseous argon above the liquid surface
  - Being pioneered by the WA105 collaboration
  - If demonstrated, potential advantages over single-phase approach
Liquid Argon TPC Basics

A modular implementation of Single-Phase TPC

- Record ionization in LAr volume $\rightarrow$ 3D image

![Anode planes and Cathode planes diagram with dimensions and voltage](image)

- Steel Cryostat
- Fiducial volume
- Foam Insulation

14.4 m
3.6 m
12 m

$-180 \text{ kV}$
Liquid Argon TPC Basics

A modular implementation of Single-Phase TPC

- Record ionization in LAr volume ➔ 3D image

Anode planes
Cathode planes

12 m
3.6 m
14.4 m

Fiducial volume
Foam Insulation
Steel Cryostat

E
e^−
−180 kV

A
C
Steel Cryostat
First 10 kt detector

Modular implementation of Single-Phase TPC

- Each 10 kt FD module:
  - Active volume: 12m x 14m x 58m
  - 150 Anode Plane Assemblies
    - 6.3m high x 2.3m wide
  - 200 Cathode Plane Assemblies
    - 3m high x 2.3m wide
  - A:C:A:C:A arrangement
  - Cathodes at -180 kV for 3.5m drift
  - APAs have wrapped wires – read out both sides
  - Each side has one collection wire plane & two induction planes
3.4: The DUNE Near Detector
DUNE ND (in brief)

The NOMAD-inspired Fine-Grained Tracker (FGT)

- It consists of:
  - Central straw-tube tracking system
  - Lead-scintillator sampling ECAL
  - Large-bore warm dipole magnet
  - RPC-based muon tracking systems

- It provides:
  - Constraints on cross sections and the neutrino flux
  - A rich self-contained non-oscillation neutrino physics program

Will result in unprecedented samples of $\nu$ interactions

- >100 million interactions over a wide range of energies:
  - strong constraints on systematics
  - the ND samples will represent a huge scientific opportunity
50% CP Violation Sensitivity

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

CDR Reference Design
Optimized Design

Exposure (kt-MW-years)
Sensitivities and Timescales

DUNE physics:

• **Game-change program in Neutrino Physics**
  - Definitive $5\sigma$ determination of MH
  - Probe leptonic CPV
  - Precisely test 3-flavor oscillation paradigm

• **Potential for major discoveries in astro-particle physics**
  - Extend sensitivity to nucleon decay
  - Unique measurements of supernova neutrinos (if one should occur in lifetime of experiment)
**MH Sensitivity**

- Sensitivities depend on multiple factors:
  - Other parameters, e.g. $\delta$
  - Beam spectrum, systematics, ...

\[
\sin^2 \theta_{13} = 0.085 \\
\sin^2 \theta_{23} = 0.45
\]
CPV Sensitivity

★ Sensitivities depend on multiple factors:
  - CPV parameter $\delta$
  - Beam spectrum, …

\[ \chi^2 = \sigma^2 \]

$\sin^2 \theta_{13} = 0.085$
$\sin^2 \theta_{23} = 0.45$

Exposure (kt-MW-years)

0 200 400 600 800 1000 1200 1400
Timescales

★ To understand how sensitivity evolves with time, fold in
- Staging of four FD modules
- Beam power and upgrades

Based on guideline funding profile

50 % CPV Sensitivity

- $\sigma = \sqrt{\Delta \chi^2}$
- $\sin^2 \theta_{13} = 0.085$
- $\sin^2 \theta_{23} = 0.45$

• **Comments**
  - Year zero = 2025
  - With additional (international) support, could go faster
Measurement of $\delta$

- CPV “coverage” is just one way of looking at sensitivity…
- Can also express in terms of the uncertainty on $\delta$

Start to approach current level of precision on quark-sector CPV Phase (although takes time)
Rapidly reach scientifically interesting sensitivities:

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

<table>
<thead>
<tr>
<th>Physics milestone</th>
<th>Exposure kt · MW · year (reference beam)</th>
<th>Exposure kt · MW · year (optimized beam)</th>
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<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</td>
<td>1200</td>
<td>850</td>
</tr>
<tr>
<td>($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPV at $3\sigma$ 75% of $\delta_{CP}$</td>
<td>1320</td>
<td>850</td>
</tr>
</tbody>
</table>

$5\sigma$ CPV Discovery

★ Genuine potential for early physics discovery
Super Nova Neutrinos I

- For a core-collapse Super Nova in the galaxy:
  - Expect a few thousand $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$ interactions
  - Complementary to other experiments (e.g. water/scintillator) which are mostly sensitive to anti-neutrino component
Super Nova Neutrinos II

- Energy and timing of neutrino burst are sensitive to particle physics & astrophysics

★ Highlights include:
  - Possibility to “see” neutron star formation stage
  - Even the potential to see black hole formation!
5. LAr-TPC Development
5. LAr-TPC Development

DUNE Far Detector will consist of 4 x 10 kton LAr-TPCs

- Basic technology demonstrated by
  - ICARUS, ArgoNEUT, LArIAT, MicroBooNE, ...

- But DUNE scale is very different...
  - Each module is ~40x larger than ICARUS T300 module

- DUNE design has wrapped wire planes
  - Readout ionization on both sides of wire plans

Need strong R&D and Prototyping programmes
Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program.

**Single-Phase**

- ICARUS
- LBL
- SBL
- 35-t prototype 2015
- MicroBooNE

**Dual-Phase**

- 2016
- WA105: 1x1x3 m³
- WA105

**DUNE SP PT @ CERN**

- 2018
- SBND
- DUNE Reference Design

**DUNE Alternative Design**
The single-phase APA/CPA LArTPC design is the reference design for the CDR

- Design is already well advanced for CDR stage
- Supported by strong development program at Fermilab
  - 35-t prototype (operational in 2015)
    almost ready to fill with LAr
  - MicroBooNE (operational in 2015)
  - SBND (operational in 2018)
- “Full-scale prototype” with ProtoDUNE at the CERN Neutrino Platform (see M. Nessi’s talk)
  - Engineering prototype of DUNE reference design
    - 6 full-sized drift cells c.f. 150 in the far detector
    - Approved by CERN SPSC (October 2015)
    - Aiming for operation in 2018

35-t wire planes (10.23.2015)
ProtoDUNE at CERN (more later)

Engineering prototype of DUNE single-phase TPC

- **DUNE PT @ CERN ~ 2018**
  - Active volume: 6m x 7m x 7m
  - 6 Anode Plane Assemblies
    - 6.3m high x 2.3m wide
  - 6 Cathode Plane Assemblies
    - 3m high x 2.3m wide
  - A:C:A arrangement
  - Cathode at -180 kV for 3.5m drift

Prototyping of FD drift cell + setting up module factories

- **Science: Charged-particle test-beam campaign**
ProtoDUNE at CERN (more later)

Engineering prototype of DUNE single-phase TPC

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  - A:C:A arrangement
    - Cathode at -180 kV for 3.5m drift

- Prototyping of FD drift cell + setting up module factories
- Science: Charged-particle test-beam campaign

Major opportunity for European groups happening very soon!
A now for something (not) completely different...
6. Fermilab Short Baseline Neutrino (SBN) Programme
SBN at Fermilab

Utilize existing Booster Neutrino Beam (SBN):

- **Low-energy (< 1 GeV) neutrino beam**
  - as deployed for MiniBooNE

**Two main aims:**

- **Address LSND and MiniBooNE anomalies**
  - eV-scale sterile neutrinos?
- **Platform for developing LAr-TPC technology**
  - MicroBooNE (now operational)
  - SBND (~2018) as a near detector
  - ICARUS (~2018) as a far detector
LSND & MiniBooNE “anomalies”

★ LSND
- Excess of electron-like events
  - $32.2 \pm 9.4 \pm 2.3$ (3.8$\sigma$)
- Neutrino energies: $20 < E$(MeV) < 50
- $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation interpretation $\Rightarrow \Delta m^2 > 0.1$ eV$^2$
- Not confirmed (or ruled out by Karmen)

★ MiniBooNE
- Excess of low-E electron-like events
  - 3.8$\sigma$
- Seen in $\overline{\nu}_\mu$ and $\nu_\mu$ data
- Possible Interpretations:
  - EM-like background (photons)
  - Neutrino oscillations via $\nu_\xi$
SBN layout at Fermilab

ICARUS: 760 t Far Det
MicroBooNE: 170 t
SBND: 180 t Near Det
MicroBooNE

★ Physics goals

- Address MiniBooNE excess
- Utilize LArTPC technology
  - If excess is seen can distinguish whether electrons (e.g. from sterile-induced oscillations) or photon-induced

★ Technology goals

- Development of single phase LAr-TPC
- Second large-scale LAr-TPC detector
- Developments for DUNE:
  - e.g. cold electronics
  - Automated computerized LAr-TPC image reconstruction?
  + $\nu \rightarrow \text{Ar}$ cross sections
MicroBooNE Status

Constructed – Moved – Installed – Filled
MicroBooNE Status

Commissioned ...
MicroBooNE Status

Commissioned ...

Nova cell

Beautiful high-resolution images
MicroBooNE Status

First BNB neutrinos in October 2015

- Selected using automated reconstruction
MicroBooNE Status

First BNB neutrinos in October 2015

- Selected using automated reconstruction
- Big step forward:
  - A first for a LAr-TPC detector
  - Challenging environment – MicroBooNE is on surface
7. DUNE: Politics and Prospects
Many reasons to be very optimistic about LBNF/DUNE

- **Fermilab**
  - LBNF/DUNE is *the* future flagship project for Fermilab
  - Fermilab is highly focused to achieve success

- **CERN**
  - CERN – US collaboration is significant
  - Investment in CERN neutrino platform (see Marzio’s talk tomorrow)
  - first time CERN will contribute to overseas facility

- **US Department of Energy**
  - DOE HEP strongly behind project
  - Support goes high up the US DOE chain

- **Large and Growing International Support**
  - Discussions within various FAs are ongoing
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DUNE: Next Steps

Rate of progress has been rapid

- **CD-3a**
  - CD-3a approval being sought in December 2015
  - By Spring 2016, could have approval for far site excavation
  - Excavation would then commence in 2017
  - Ready for start of FD installation in 2021

- **ProtoDUNE at CERN**
  - Recommended for approval by SPSC in October 2015
  - Construction starts in 2016
  - Major opportunity for Europe to contribute to DUNE at CERN
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  - Construction starts in 2016
  - Major opportunity for Europe to contribute to DUNE at CERN
    - Actively seeking contributions from existing and new collaborators
In 1965 Dr. Raymond Davis Jr. built his Nobel Prize winning solar experiment on the 4,550 Level at the Homestake Gold Mine.
8. Summary

- Progress with LBNF/DUNE has been rapid

- Ground-breaking scientific programme

- Timescales are relatively short...
  - Excavation of underground far detector cavern starting 2017 *(CD-3a in December 2015)*
  - ProtoDUNE operating in 2018
  - Far detector installation starts in 2021

- Many exciting opportunities on DUNE
  - new collaborators are very welcome
Thank you for your attention
Backup Slides
Science
Parameter Resolutions

$\delta_{CP}$ & $\theta_{23}$

- As a function of exposure
PDK

\[ p \rightarrow K \nu \]

- DUNE for various staging assumptions
Beam Optimization
Beam Optimization

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

![Graph showing neutrino flux vs. energy](image)

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

Unoscillated \( \nu_\mu \) Flux, \( \nu \) Mode

**Horn 1**

- \( r_1 \)
- \( r_2 \)
- \( r_3 \)
- \( r_4 \)
- \( L_1 \)
- \( L_2 \)
- \( L_3 \)
- \( L_4 \)
- \( L_5 \)
- \( L_6 \)
- \( L_7 \)
Reconstruction
LAr-TPC Reconstruction

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

- Full DUNE simulation/reconstruction now in reach

![Diagram of particle interactions](image)

<table>
<thead>
<tr>
<th>True muon momentum (GeV)</th>
<th>Efficiency of pattern recognition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
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<tr>
<td>2</td>
<td>0.4</td>
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<tr>
<td>3</td>
<td>0.6</td>
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<tr>
<td>4</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
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</table>

5 GeV $\nu_\mu$ CC

<table>
<thead>
<tr>
<th>True electron energy (GeV)</th>
<th>Efficiency of pattern recognition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
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<td>0.8</td>
</tr>
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<td>5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

5 GeV $\nu_e$ CC
Schedule
Calculating Sensitivities
Determining Physics Sensitivities

For Conceptual Design Report

- **Full detector simulation/reconstruction not available**
  - See later in talk for plans

- **For Far Detector response**
  - Use parameterized single-particle response based on achieved/expected performance (with ICARUS and elsewhere)

- **Systematic constraints from Near Detector + …**
  - Based on current understanding of cross section/hadro-production uncertainties
  + Expected constraints from near detector
    - in part, evaluated using fast Monte Carlo
Evaluating DUNE Sensitivities I

Many inputs calculation (implemented in GLoBeS):

- **Reference Beam Flux**
  - 80 GeV protons
  - 204m x 4m He-filled decay pipe
  - 1.07 MW
  - NuMI-style two horn system

- **Optimized Beam Flux**
  - Horn system optimized for lower energies

- **Expected Detector Performance**
  - Based on previous experience (ICARUS, ArgoNEUT, …)

- **Cross sections**
  - GENIE 2.8.4
  - CC & NC
  - all (anti)neutrino flavors

Exclusive $\nu$-nucleon cross sections
Evaluating DUNE Sensitivities II

- **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 $\pi$-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 %/$\sqrt{(E/GeV)}$</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%/$\sqrt{(E/GeV)}$</td>
<td>5°</td>
</tr>
<tr>
<td>$n$</td>
<td>50 MeV</td>
<td>440%/$\sqrt{(E/GeV)}$</td>
<td>5°</td>
</tr>
<tr>
<td>other</td>
<td>50 MeV</td>
<td>5% $\oplus$ 30%/$\sqrt{(E/GeV)}$</td>
<td>5°</td>
</tr>
</tbody>
</table>

*current assumptions to be addressed by FD Task Force*
Evaluating DUNE Sensitivities III

- **Efficiencies & Energy Reconstruction**
  - Generate neutrino interactions 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 as efficiencies
  - Used as inputs to GLoBES
Evaluating DUNE Sensitivities IV

- **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
MicroBooNE:
- Will have (most likely) either:
  - confirmed the MiniBooNE low-energy anomaly or
  - isolated its origin

The SBN $\nu_\mu \rightarrow \nu_e$ Appearance search
- Will have either:
  - confirmed the LSND anomaly is due to neutrino oscillations
    - a major discovery -
  - ruled out light sterile neutrinos over the entire LSND mass range

Loopholes:
- LSND excess was in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- OscSNS, ...?