Probing lepton and baryon symmetries with DUNE

Jon Urheim, Indiana University, for the DUNE Collaboration

2017 Tamura Symposium, Austin, TX
DUNE Experimental Scope

• Starting from recommendations from many high-level studies, including:
  – European Strategy for Particle Physics Update (2013)

and subsequent work building from LBNE & LBNO/Laguna efforts

• DUNE (experiment/apparatus) & LBNF (beam line + facility) elements:
  – Optimized 1.2 MW wide-band Beam, upgradeable to 2.4 MW
  – On-axis 40-kt (fiducial) LArTPC Far Detector sited at Sanford Underground Research Facility (1300 km baseline)
    • 4 x 10-kt modules: 1\textsuperscript{st} & 2\textsuperscript{nd} modules to be commissioned in 2024/2025, not necessarily of identical design/technology

  – Highly capable Near Detector system

  – Enabling program of technical development
Establishment of DUNE in 2015 as a fully international scientific collaboration meant starting from scratch on every organizational aspect

- Now have ~950 collaborators...
  ...from ~160 institutions...in 30 countries

- Strong, inclusive, collaborative spirit driven by ambitious science

- Welcoming to the theory community
DUNE: Technical Elements
LBNF – Beam Line and Optimization

• Conventional horn-focused Beam Line
  – 60-120 GeV protons from Fermilab Main Injector
  – 101 mrad pitch to get to S. Dakota, unconventional initial upward pitch
  – ~200-m Decay pipe; Near Detector Hall at edge of Fermilab site
  – Critical contributions from international partners (UK, CERN)
LBNF – Beam Line and Optimization

• Starting point was LBNE: DUNE CDR “Reference” (green)

• Adoption of optimization procedure developed by LBNO
  – “Genetic” algorithm

• Led to DUNE CDR “optimized” configuration (blue)
  – Much longer target \( (2\lambda \rightarrow 5\lambda) \) coupled w/ long 1\(^{st}\) horn
  – Larger (radially) 2\(^{nd}\) horn

• Further optimizations \( \rightarrow \) split 1\(^{st}\) horn into two (red)
  – Note enhancement at 2\(^{nd}\) oscillation maximum

\[ \nu_e \] appearance signal example: “optimized” vs “reference”
Sanford Underground Research Facility, Lead, S. Dakota

- Site has long & storied history as home to neutrino experiments
- **LBNF scope:** 4 detector chambers, utility cavern, connecting drifts
- **Extensive preparatory work** for LBNF/DUNE already done
- **DOE approval pending** to begin excavation & surface building construction

**Future Laboratories**

- **Experiment Hall**
  Proposed third generation dark matter and/or 1 T neutrinoless double-beta decay

- **DUNE at LBNF**
  Proposed Deep Underground Neutrino Experiment at the Long-Baseline Neutrino Facility
  4850 Level—four 10kT liquid argon detectors

**4850 Level (4300 mwe)**
DUNE Single-Phase LArTPC Far Detector Design

- Based on LBNE modular drift cell design
  - Suspended Anode (APA) / Cathode (CPA) assemblies – 3.6 m spacing
  - APA’s w/ “wrapped” induction wire planes
  - Scintillation detection based on light guides embedded in APA’s, SiPM read out
Key Features:

APA’s / CPA’s suspended from ceiling like curtains

APA’s: 2 x 6 m x 2.3 m paired for top/bottom readout: induction wires at 35.7°, wrapped to enable this scheme

Photon Detectors (not shown) sit within frames
DUNE Dual-Phase LArTPC Far Detector Design

- Single TPC volume with Amplification in gas phase:
  - 12m max drift (vertical), LEM read-out
  - Features excellent S/N: ~100/1
  - Scintillation via PMT’s below cathode
DUNE Fine-Grained Tracker: 
Near Detector Reference Design

- NOMAD inspired detector
  - Magnetized straw-tube based tracking system
  - Pb-scintillator sampling ECAL
  - RPC-based muon tracker
  - Multiple Targets (incl. Argon)

- Alternative / augmented ND systems being investigated
  - High-pressure Ar Gas TPC
  - LAr TPC, a la ArgonCube
DUNE: Science Program

I. Oscillation Physics
Physics (MH, $\theta_{23}, \theta_{13}, \delta$) extracted from combined analysis of 4 samples: 
- CDR estimates, assuming: CDR optimized beam, 56% LBNF uptime, FastMC detector response 
- Physics inputs: $\delta = 0, \theta_{23} = 45^\circ$, others from NuFIT: Gonzalez-Garcia, Maltoni, Schwetz, JHEP 1411 (2014)

<table>
<thead>
<tr>
<th>$\nu$ mode / 150 kt-MW-yr</th>
<th>$\nu_e$ appearance</th>
<th>$\nu_\mu$ disappearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal events (NH / IH)</td>
<td>945 (521)</td>
<td>7929</td>
</tr>
<tr>
<td>Wrong-sign signal (NH / IH)</td>
<td>13 (26)</td>
<td>511</td>
</tr>
<tr>
<td>Beam $\nu_e$ background</td>
<td>204</td>
<td>-</td>
</tr>
<tr>
<td>NC background</td>
<td>17</td>
<td>76</td>
</tr>
<tr>
<td>Other background</td>
<td>22</td>
<td>29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anti-$\nu$ mode / 150 kt-MW-yr</th>
<th>$\bar{\nu}_e$- appearance</th>
<th>$\bar{\nu}_\mu$ disappearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal events (NH / IH)</td>
<td>168 (438)</td>
<td>2639</td>
</tr>
<tr>
<td>Wrong-sign signal (NH / IH)</td>
<td>47 (28)</td>
<td>1525</td>
</tr>
<tr>
<td>Beam $\nu_e$ background</td>
<td>105</td>
<td>-</td>
</tr>
<tr>
<td>NC background</td>
<td>9</td>
<td>41</td>
</tr>
<tr>
<td>Other background</td>
<td>13</td>
<td>18</td>
</tr>
</tbody>
</table>
• Exposure needed to reach given sensitivity or better for all 100% of $\delta_{CP}$ range vs. exposure for cases of:

CDR **Reference** Beam  
(lower edge of contour)

CDR **Optimized** Beam  
(upper edge of contour)
DUNE Physics Landscape:
CP Violation Sensitivity as a function of $\delta_{cp} / MH$

- **Note:** Software configurations (geometry, flux, detector response) used for sensitivity calculations shown here are now published: arXiv:1606.09550

Sensitivity to CP Violation, after 300 kt-MW-years (3.5+3.5 yrs x 40kt @ 1.07 MW)

(Bands represent range of beam configurations)
DUNE Physics Landscape:
CP Violation Sensitivity vs Exposure

- Sensitivities shown as function of exposure in kt-MW-yr’s.
  - 40-kt x 10 yrs x 1.2 MW
  ~ 500 kt-MW-yr
- Other factors:
  • Efficiency / Background Rejection
  • Neutrino beam flux
  • Physics: MH, $\theta_{23}$, $\theta_{13}$, $\delta$
  • Systematic Errors
  • Complications from BSM physics, for example...
    - sterile $\nu$’s – see e.g., (1) R Gandhi, B Kayser, M Masud, S Prakash, JHEP 1511 (2015); arXiv:1508.06275,
      (2) SK Agarwalla, SS Chaterjee, A Palazzo, arXiv:1603.03759
      (3) JM Berryman, A de Gouvêa, KJ Kelly, A Kobach, PRD 92 (2015); arXiv:1507.03986,
- DUNE Strengths: LArTPC technology, flexible wide-band beam, Near Detector
  • also, direction resolution for atmospheric neutrinos
• Exposure needed to reach given sensitivity or better for 50% of $\delta_{CP}$ range vs. exposure for cases

CDR Reference Beam (green)

CDR Optimized Beam (blue/shaded)

Band represents range of assumptions about systematic errors
DUNE – CP Violation Sensitivity & Systematic Errors

- Systematic Error evaluations compared with corresponding MINOS & T2K experience
  - “Goal for DUNE” column is for total errors, i.e., those correlated among samples, as well as uncorrelated ones: significant cancellation for correlated errors

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>MINOS $\nu_e$</th>
<th>T2K $\nu_e$</th>
<th>Goal for DUNE $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Flux</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>Included above</td>
<td>Included in 5% $\nu_\mu$ uncertainty</td>
</tr>
<tr>
<td>Energy Scale ($\nu_e$)</td>
<td>2.7%</td>
<td>2.5% includes all FD effects</td>
<td>2%</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>2.4%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>5.7%</td>
<td>6.8%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

**Used for DUNE sensitivity evaluations:**

5% = $\nu_\mu$ Normalization uncertainty (correlated among samples); 2% = uncorrelated $\nu_e$ error
**DUNE $\theta_{23}$ Octant Sensitivity**

- Green band shows the DUNE sensitivity for exclusion of the incorrect $\theta_{23}$ octant vs its true value.

**Assumptions / considerations:**

- 890 kt-MW-yr exposure with CDR “optimized” beam
- Plot shows case for Normal Hierarchy
- Sensitivity depends on value of $\delta_{\text{CP}}$, as well as beam line configuration, represented by the thickness of the green band

![Octant Sensitivity Diagram](image-url)
DUNE: Science Program

II. Nucleon Decay Physics
DUNE Physics Landscape: Nucleon Decay

- Imaging, $dE/dx$, calorimetric capabilities of LArTPC enable sensitive, **background-free** searches

- Many modes accessible, marquee channel: SUSY-favored $p \rightarrow K^+ \bar{\nu}$

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<table>
<thead>
<tr>
<th>Year</th>
<th>Lifetime Sensitivity (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$10^{32}$</td>
</tr>
<tr>
<td>2</td>
<td>$10^{33}$</td>
</tr>
<tr>
<td>4</td>
<td>$10^{34}$</td>
</tr>
<tr>
<td>6</td>
<td>$10^{35}$</td>
</tr>
</tbody>
</table>

- Current Super-K limit, 260 kt-yr
- DUNE 40 kton
- Hyper-K, 1900 & 5700 kt-yr (projected from SK)
- DUNE CDR

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Kaon observed entering ICARUS TPC in CNGS run
ICARUS, Pavia 2001, CR data

- $K \rightarrow \mu \rightarrow e$ decay chain
- Kaon is below Cherenkov threshold in water detectors
- But dE/dx signature of Kaon is distinctive in LArTPC !!
Just Two Sources

- Cosmic ray muon induced backgrounds:
  - CR Rate at 4850L is \( \sim 0.1 \) Hz in 40-kt DUNE LArTPC
  - 10 yr run \( \Rightarrow \sim 3 \times 10^7 \) muons. Rejection needed is “only” at \( 10^{-8} \) level !!
  - Easily met, since muons in detector volume are tracked with \( \sim 100\% \) efficiency!

- Atmospheric Neutrinos:
  - Interaction rate in 40-kt detector only at level of few \( \times 10^5 \) per Mt-yr
  - So rejection needed is ‘only’ at the \( 10^{-6} \) level !!
Atmospheric Neutrinos:

- Interaction rate in 40-kt detector only at level of few $x \times 10^5$ per Mt-yr
  - So rejection needed is ‘only’ at the $10^{-6}$ level !!

- Final state consisting of / mimicking single kaon very low probability
- Atmospheric neutrino MC’s well validated (i.e., by SK proton-decay searches – see next slide)
- Analysis by Bueno et al., JHEP 0704, 041 (2007) [arXiv:hep-ph/0701101] $\rightarrow$ 0.3 evts / 10 yrs, for 40-kt detector, based on a single simulated NC interaction passing nominal cuts.
- Studies within DUNE suggest rate of backgrounds w/ real K’s should be lower still.
- Note: considerable theoretical/phenomenological effort ongoing, toward improving simulation of exclusive neutrino interaction processes, including those with strange quark production, also understanding better $K^+$ rescattering within nucleus
- Major effort within DUNE at present: confronting reconstruction pathologies in “garden variety” CC atmospheric neutrino interactions
As a start, we believe DUNE can be background-free because:

SK has already carried out background-free searches!

- $K \rightarrow \mu \nu$, w/ prompt $\gamma$ tag
  (de-excitation of $^{15}$N):
  Plot of # of $\gamma$ hits, from
  PRD 90, 072005 (2014)
  (blue = signal, red = atmos $\nu$ BG)

- $K \rightarrow \pi^+ \pi^0$:
  Plot from Miura, NNN10

Atmospheric neutrinos are now exceptionally well-modeled!!
DUNE: Science Program

III. Supernova Neutrino Burst Physics
• In LAr, dominant process is: $\nu_e + {}^{40}\text{Ar} \to e^- + {}^{40}\text{K}^*$
  - In contrast with water, org. scintillator-based detectors: anti $\nu_e$'s dominate
  - LAr uniquely sensitivity to neutronization process at $\sim$30 ms
  - Also elastic scattering events potentially give directionality
  - Note distinct features in time (left plot) and energy (right plot) spectra
  - O(few thousand) events expected for galactic SNB
ICARUS 2003, Pavia CR Test

- Michel electron energy spectrum
- Note: sub-10 MeV threshold
- Found resolution consistent with:

\[
\frac{\sigma_E}{E} = \frac{11\%}{\sqrt{E}\,[\text{MeV}]} + 2\%
\]

20 MeV electron (LArSoft/LBNE geom)
Creating an accurate model for $\nu_e$ArCC events requires confronting several challenges.

$\nu_e$ArCC events access $\sim$25 excited levels in $^{40}K^*$.

Transition to $^{40}K$ g.s. strongly suppressed (3rd-forbidden).

$\nu_e$ energy reconstruction relies on determining accessed level.

$^{40}Ar$ 0$^+$

$^{39}K$ 0$^+$

$^{39}Ar$ 0$^+$

$J^\pi$ values and $\gamma$-decay data are missing for many relevant $^{40}K^*$ levels.

Significant loading of unbound nuclear levels occurs.

Large number of de-excitation channels complicates energy reconstruction.

Slide courtesy S. Gardiner.
Example $e^- + \gamma$s Only Event (true trajectories)

- $E_\nu = 16.1$ MeV
- $e^-$ deposited 10.2 MeV
- $\gamma$s deposited 4.3 MeV
- $^{40}$K deposited 3.7 keV
- Total visible energy: 14.5 MeV
- Visible energy sphere radius: 48.4 cm
- Electrons are nearly always easy to see
- Gammas leave “blips” plus pair production tracks at high energy
Example neutron event (true trajectories)

- $E_\nu = 16.3$ MeV
- $e^-$ deposited 4.5 MeV
- No primary $\gamma$s from vertex
- $^{39}$K deposited 68 keV
- n deposited 7.6 MeV (mostly from capture $\gamma$s)
- Total visible energy: 12.2 MeV
- Visible energy sphere radius: 1.44 m
- Neutrons bounce around for a long time!
DUNE: Strategy 2016—2019: Focus on Large-Scale Prototype Prototypes
DUNE Strategy / Implementation Plan

• Key Steps/Milestones:
  – Two ProtoDUNE Detectors (SP & DP) operational at CERN in 2018
    • Provides key risk mitigation opportunity for Far Detector modules
  – DUNE Technical Design Report to be reviewed in 2019
    • Done in context of both US DOE process and international organizations
  – Set up of Far Detector Fabrication facilities in Q1 2020
  – Start of FD installation: 1st module in Q4 2021, 2nd module in 2023
  – 20 kt operational in 2024
  – Beam operations at 1.2 MW beginning 2026
Path to DUNE: Technical Design & Large-scale Prototypes

• DUNE 10-kt LArTPC Modules represent $O(50x)$ scale-up w.r.t. largest LArTPC to date (ICARUS), 100x scale-up w.r.t. MicroBooNE

• Operation of large-scale prototypes an important ingredient of DUNE program
  – Understand production as well as operational issues
  – Provides opportunities for Test Beam data (ProtoDUNE Science Program)
  – Will say a few words about
    • 35-ton single-phase TPC test at FNAL (completed)
    • 3x1x1 m$^3$ dual-phase TPC at CERN (WA105/NP02), operating Spring 2017
    • Associated dual & single phase ProtoDUNE’s @ CERN (NP02,04), 2018
    • Each one of these is a major experimental effort on its own!
  – Will not talk about external-to-DUNE, but very relevant, efforts:
    • LArIAT, MicroBooNE, SBND, ICARUS, ArgonCube, CAPTAIN …
Phase-II of program w/ membrane cryostat
- First phase established Ar purity capability
- 2nd phase – install, operate LBNE style TPC
- operations Feb-Mar 2016
- Purity → Success!
- TPC / Scint Det. Ops → Success!
  • Incl. operation @ 250 V/cm
- Not all rosy though:
  • Noise environment not good
  • Early end due to mechanical failure leading to Ar contamination
Happening Now: WA105 Dual-Phase 3x1x1 m³ Prototype

- Pilot Detector for WA105/ProtoDUNE-DP
  - Assembled in Bldg 182 @ CERN
  - Filled & Commissioning now!
  - Important large-scale test of promising technology
  - will set the stage for ProtoDUNE-DP, and hopefully one of the initial 10-kt DUNE modules

Detector Assembly
(Top Cap visible)

Membrane Cryostat/
Detector Vessel

- J. Urheim
ProtoDUNE’s:

- EHN1 Extension newly constructed
- Beneficial Occupancy, Sept. ’16
- Cryostats complete, April ’17
- Test-Beam Operations in 2018
- H2/H4 tertiary beam lines:
  - 0.5-5 GeV/c e, μ, π, K, p +/- beams
ProtoDUNE-SP

- Single-phase TPC prototype
  - Will sit in H4 beam line @ CERN
  - Consisting of 4 full-size APA’s plus CPA’s → 2 x 3.6m drift regions
  - Will install photon detectors of different fabrication methods
  - Plan for operation in 2018

- Will be a key test of:
  - Components
  - Construction methods
  - Installation procedures
  - Commissioning
  - Detector response to particles
Dual phase protoDUNE - WA105 6x6x6m$^3$

Drift HV system

Signal feed-throughs

CRP frame + hanging system

CRP readout planes

Drift cage + cathode plane

Photon Electronics

Cold readout electronics

DAQ

Online computing

Purity monitor

Slow control

Cosmic tracker

Photon Detectors

(US contributions under discussion)
Much More to Say on Technical & Scientific Fronts…

No time to talk about interesting technical developments, including work on event reconstruction, detector optimization studies, etc…

…But will wrap up here with two points concerning…
Momentum: now, and going forward

- **DUNE firmly established as an international scientific priority**
  1) **Fermilab Program is Fully Aligned**
     → Central Role of FNAL Directorate
     → Key Synergies with Short Baseline Program
  2) **US DOE & Congress/President Embrace DUNE Vision**
     → Authorization of FY2017 LBNF construction start in appropriation bills
     → FY2017 budget just enacted (last week!) $50M for DUNE
  3) **CERN Role is Huge**
     → Rapid progress on implementation of Neutrino Platform: ProtoDUNEs !!
     → Crucial roles in LBNF, ProtoDUNEs, SBN program
  4) **International Partners are Engaged**
     → High-level engagements: governments & funding agencies

- **Young Scientists are driving innovation within DUNE (and ProtoDUNEs)**
  - Many opportunities for students and postdocs
Summary

• LBNF/DUNE program is under way!

• Fantastic Science Opportunities

• Extensive Beam & Detector Design/Construction Scope

• Beam, Detector, Data Analysis, etc... challenges abound

• Really significant level of effort required on many fronts
  – In short-term, ProtoDUNEs are major experimental / scientific efforts

• DUNE welcomes your participation!
Additional Material
Beyond LBNF: 700kW $\rightarrow$ 1.2 MW $\rightarrow$ 2.4 MW – PIP-II / III

- DUNE Program will benefit strongly from continued upgrades to the Fermilab accelerator complex

- PIP-II
  - New 800 MeV SC Linac
  - New Linac–Booster transfer line
  - Platform for extension to 2.4 MW
  - Fermilab – ANL – LBNL – SNS – India collaboration

- Status:
  - DOE statement of mission need in Nov 2015: > 1MW to LBNF
  - CDR in preparation
  - PIP-II completion targeted for 2025
DUNE Far Detector Caverns + Auxiliary Drifts @ SURF
DUNE CDR “Optimized Beam” Event Rate Comparisons

• Top:
  Event rates for DUNE CDR “Optimized” 2-horn beam line, by neutrino species (note logarithmic scale)

• Bottom:
  Event rate ratio with respect to DUNE CDR “Reference” beam line design

  Optimized design gives higher flux at energies of interest, lower flux at high energy, where backgrounds enter
PIP-II Injector: Commissioning of RFQ with Beam

- PIP-II RFQ built in collaboration with LBNL has been installed and successfully commissioned with beam
  - Beam studies are in progress to increase intensity and repetition rate.
- Indian (BARC) quadrupoles installed and working with beam
$\beta = 0.90$, 650 MHz Cavity for PIP-II

- Fermilab has processed 1$^{st}$ $\beta = 0.90$, 650 MHz Cavity fabricated by AES.
  - The preliminary result exceeds PIP-II design goals.
- Fermilab has finalized the design of an improved $\beta = 0.92$ cavity design.
  - Fabrication of dressed HB650 cavity has started under the Joint R&D collaboration with India, one of 13 major deliverables.
DUNE – Neutrino Energy Spectra After Oscillations

- Energy spectra for selected $\nu_e$ & $\nu_\mu$ samples: CDR ref & opt beams

- Top Plots
  Neutrino-beam running (150 kt-MW-yr)

- Bottom:
  Anti-neutrino beam mode (150 kt-MW-yr)

Beam:
Solid = CDR reference
Dashed = CDR optimized

Reconstructed Energy (GeV)
Events/0.25 GeV

$\nu_e$
$\bar{\nu}_e$
$\nu_\mu$
$\bar{\nu}_\mu$

CDR Reference Design
Optimized Design

$\sin^2(\theta_{23})=0.45$
$\delta_{CP}=0$
$\text{Normal MH}$
• Dependence on $\delta_{CP}$ and experiment statistical fluctuations
DUNE CPV Sensitivity assuming particular staging scenario

- 75% CPV Sensitivity from CDR
  - Assumes particular staging scenario
    - Yr 1 = 10 kt @ 1.07 MW
    - Yr 2, Yr 3, Yr 4: add successive 10kt
    - Yr 7: 40kt @ 2.14 MW

- DUNE CPV Sensitivity vs $\delta$ (NH)
  - Snapshot after 300 kt-MW-yr stated as 40 kt x 1.07 MW x (3.5+3.5 yr)
Where things stand now...
A. Marrone, from Neutrino 2016 talk on global fits.

Bounds on single oscillation parameters

(preliminary update)

- LBL Acc + Solar + KamLAND + SBL Reactors + Atmos
- \( \Delta \chi^2_{10-NO} = 3.1 \)

\[ \Delta m^2/10^{-5} \text{ eV}^2 \]

- \( \delta \sim 1.4\pi \) at best fit
- CP-conserving cases (\( \delta = 0, \pi \)) disfavored at \(-2\sigma\) level or more
- Significant fraction of the \([0,\pi]\) range disfavored at \(>3\sigma\)

\[ \Delta m^2/10^{-3} \text{ eV}^2 \]

\[ \delta/\pi \]

\[ \sin^2\theta_{12}, \sin^2\theta_{13}, \sin^2\theta_{23} \]

- \( \theta_{23} \) trend:
  - maximal mixing disfavored at about \(-2\sigma\) level
  - best-fit octant flips with mass ordering

\[ \sin^2\theta_{13} \]

\[ \sin^2\theta_{23} \]

\[ \Delta \chi^2_{10-NO} = 3.1 \]

inverted ordering slightly disfavored
Where things stand now...with current long-baseline experiments
Case study: NOvA $\nu_e$ appearance results

- **NOvA expectation for event yields at FD shown as bands.**
  - NOvA actually observed 33 events
  - Pretty consistent w/ any $\delta$ for NH

- **Schematic depiction of NOvA event yield** (from C. Backhouse W&C talk)
  - Essentially a counting exp’t at fixed L/E
  - Also true of T2K
Implications of T2K + NOvA results for CPV: will the global picture get to 3$\sigma$ on CPV within the next few years?

**Scenario I**
- T2K central values for appearance probabilities stay fixed at current ones.
- This means T2K data will become progressively less consistent with $\delta = 0, \pi$
- But, before long it will become an unlikely outcome for $\delta = 3\pi/2$ as well (!)
- This would actually be an interesting scenario for DUNE !!!

**Scenario II**
- New T2K & NOvA data will have central values within “physical range”
- This would relax the global picture toward a less constraining set of measurements.
  - i.e., it will take some time for current experiments to be constraining on CPV
- Simple projections: DUNE and/or HK are needed to get over the 3$\sigma$ hump
DUNE CPV Sensitivities as a function of Exposure

- 300 kt-MW-yr (~7 yrs)
- 875 kt-MW-yr (~14 yrs)
DUNE CDR Oscillation Sensitivity Milestones

- Note resolution milestones

<table>
<thead>
<tr>
<th>Physics milestone</th>
<th>Exposure $kt \cdot MW \cdot year$ (reference beam)</th>
<th>Exposure $kt \cdot MW \cdot year$ (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</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>
DUNE Resolution for $\delta_{cp}$ & $\theta_{23}$

- **Top:** Resolution in $\delta_{cp}$ as a function of exposure for two values of $\delta_{cp}$ (0 & $\pi/2$)

- **Bottom:** Resolution in $\theta_{23}$ as a function of exposure
DUNE CDR Oscillation Sensitivity Milestones

• Long-term context for DUNE Precision Results
Existence of light sterile neutrinos would distort spectra observed in both Far & Near Detectors:

- Showing here raw oscillation probabilities for just one example of mass ($\Delta m_{41}^2 = 0.50 \text{ eV}^2$) & mixing parameters
Theoretical Context & Current Experimental Limits

$p \rightarrow e^+ \pi^0$
- minimal SU(5)
- predictions

$p \rightarrow e^+ K^0$
- minimal SUSY SU(5)
- flipped SU(5)
- SUSY SO(10)
- non-SUSY SO(10) $G_{224D}$
- 6D SO(10)

$p \rightarrow \mu^+ K^0$

$n \rightarrow \bar{\nu} K^0$

$p \rightarrow \bar{\nu} K^+$
- minimal SUSY SU(5)
- non-minimal SUSY SU(5)
- SUSY SO(10)

$p \rightarrow \bar{\nu} K^+$ predictions

$\tau/B$ (years)

E. Kearns
DUNE 35-ton Prototype:
Argon purity measurements during Phase-II running (i.e., with TPC)
History of Dual-Phase ProtoDUNE / WA105

Project started in 2013 (CERN RB approval) following the submission of LBN0 Expression of Interest
Collaborators from 10 countries and 22 institutes

Integration in DUNE project as DP-ProtoDUNE
December 2015; EOI call for ProtoDUNEs, January 2016

TDR submitted on 31st March 2014
CERN-SPSC-2014-013
SPSC-TDR-004(2014)

2015 Annual SPSC progress report 31st March 2015
SPSC-SR-158

DUNE CDR, July 2015: WA105 and Dual-phase 10 kton design

WA105 project MOU fully signed, December 2015

2016 Annual SPSC progress report, 7th April 2016
CERN-SPSC-2016-017
SPSC-SR-184

Slide Courtesy D. Autiero

DUNE: Probing lepton & baryon symmetry - J. Urheim