Current and Future Long Baseline Neutrino Experiments

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Solar neutrino deficit

Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000

Cl
H₂O
Ga

Theory
γBe p–p, pep
³B CNO

Experiments
Atmospheric neutrino deficit

\[ R = \frac{(\mu/e)_{\text{Data}}}{(\mu/e)_{\text{MC}}} \]

\( R \sim 0.6 - 0.7 \)
The SNO experiment

- 1000 tons of D$_2$O
- 6500 tons of H$_2$O
- 10,000 PMTs
- 2km underground
The SNO experiment

**CC**
\[ \nu_e + d \rightarrow p + p + e^- \]
- \( Q = 1.445 \text{ MeV} \)
- good measurement of \( \nu_e \) energy spectrum
- some directional info \( \propto (1 - 1/3 \cos \theta) \)
- \( \nu_e \) only

**NC**
\[ \nu_x + d \rightarrow p + n + \nu_x \]
- \( Q = 2.22 \text{ MeV} \)
- measures total \( ^8\text{B} \) \( \nu \) flux from the Sun
- equal cross section for all \( \nu \) types

**ES**
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]
- low statistics
- mainly sensitive to \( \nu_e \), some \( \nu_\mu \) and \( \nu_\tau \)
- strong directional sensitivity

- Produces Cherenkov Light Cone in \( \text{D}_2\text{O} \)
- \( \nu \) captures on deuteron
  \( ^2\text{H}(n, \gamma)^3\text{H} \)
  Observe 6.25 MeV \( \gamma \)
SNO results

- $\nu_e$ to $\nu_{\mu\tau}$ oscillations confirmed!
Combined Results

Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
Re-interpretation of SK results assuming that some fraction of the CR $\nu_\mu$ have oscillated to $\nu_\tau$ (that SK is not sensitive to)
3 neutrino mixing

- Neutrino oscillations have now been unequivocally observed using atmospheric, solar, reactor and accelerator neutrinos.
- The weak and mass neutrino eigenstates are related via the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

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

where

- **Known knowns:** neutrinos have mass and oscillate between flavours; \(\theta_{12}, \theta_{23}, \theta_{13}, \Delta m_{21}^2, |\Delta m_{32}^2|\) all measured.
- **Known unknowns:** absolute masses, order of mass states (mass hierarchy), Dirac or Majorana, value of \(\delta_{CP}\), is \(\theta_{23}\) maximal / which octant, number of neutrinos.
In the above the different matrices relate to different measurements:

\[ U_{PMNS} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13} e^{i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \]

Atmospheric sector
\[ \nu_\mu \rightarrow \nu_\tau \]
\[ \theta_{e\mu} = 45.0^\circ \pm 2.4^\circ \]
\[ \Delta m_{23}^2 = |2.8 \times 10^{-3}| \text{eV}^2 \]

13 Sector
\[ \nu_e \rightarrow \nu_\mu \]
\[ \theta_{13} = 9.7^\circ \pm 2.0^\circ \]
\[ \Delta m_{23}^2 = |2.8 \times 10^{-3}| \text{eV}^2 \]

Solar sector
\[ \nu_e \rightarrow \nu_\mu \]
\[ \theta_{e\mu} = 32.5^\circ \pm 2.4^\circ \]
\[ \Delta m_{12}^2 = +7.1 \times 10^{-5} \text{eV}^2 \]
Oscillation Probabilities

• In general:

\[ P(\nu_\alpha \to \nu_\beta)_{(\alpha \neq \beta)} = -4 \left( \begin{array}{c}
U_{\alpha_1}U_{\beta_1}U_{\alpha_2}U_{\beta_2}\sin^2(1.27 \frac{\Delta m_{12}^2 L}{E}) + \\
\Delta m_{12}^2 \\
\end{array} \right) + \\
\left( \begin{array}{c}
U_{\alpha_1}U_{\beta_1}U_{\alpha_2}U_{\beta_3}\sin^2(1.27 \frac{\Delta m_{13}^2 L}{E}) + \\
\Delta m_{13}^2 \\
\end{array} \right) + \\
\left( \begin{array}{c}
U_{\alpha_2}U_{\beta_2}U_{\alpha_2}U_{\beta_3}\sin^2(1.27 \frac{\Delta m_{23}^2 L}{E}) + \\
\Delta m_{23}^2 \\
\end{array} \right) \]

\[ \Delta m^2 = \Delta m_{13}^2 \sim \Delta m_{23}^2 \text{ (solar, large)} \]

\[ \delta m^2 = \Delta m_{12}^2 \text{ (atmos, small)} \]
Long baseline accelerator neutrino physics

- Uses $\nu_\mu$ ($\overline{\nu}_\mu$) beams derived from proton-induced pion decay
- $\nu_\mu$ disappearance is sensitive to $\theta_{23}$ and (subleading) to the octant

$$
P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2(\theta_{13}) \sin^2(\theta_{23}) [1 - \cos^2(\theta_{13})] \sin^2(\theta_{23}) \sin^2(1.267 \Delta m^2 L/E_\nu)$$

- $\nu_e$ appearance is sensitive to $\theta_{13}$ and (subleading) to the CP phase $\delta$

$$
P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \frac{\Delta m^2_{31} L}{4E}$$

$$
- \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \frac{\Delta m^2_{21} L}{4E} \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E} \sin \delta_{CP}
$$
T2K (Tokai to Kamioka)

- 295km long baseline experiment
- Uses 2.5° off-axis $\nu_\mu$ ($\overline{\nu}_\mu$) beam
- Data-taking started in 2009
- UK contribution to near detector (ND280) includes:
  - Electronics
  - DAQ
  - ECAL
- SK far detector
T2K off-axis near detector

Primary Interaction Material: Carbon
Secondary Interaction Materials: Oxygen, Lead, Brass, Argon

Interaction in POD
Interaction in FGD1

Interaction in ECal

Also there is an on-axis detector (INGRID) used for beam rate and direction measurements
T2K beam operation and data taking

- **Integrated POT:**
  - Neutrino mode: \(7.0 \times 10^{20}\)
  - Anti-neutrino mode: \(4.0 \times 10^{20}\)

Total of \(11 \times 10^{20} = 13\%\) of total expected POT
T2K $\nu_\mu$ disappearance results

- Observation of a deficit of $\nu_\mu$ events in SK

World-leading measurement of $\theta_{23}$

T2K $\nu_e$ appearance results

- $4.92 \pm 0.55$ background events expected (no oscillations)
- 28 events observed
- $7.3\sigma$ significance for non-zero $\theta_{13}$
- First observation (> $5\sigma$) of an appearance channel signal

T2K joint analysis fit

- Results from a combined likelihood ratio fit to the T2K $\nu_\mu$ and $\nu_e$ CCQE samples
- Using the PDG 2013 value for $\theta_{13}$ there is a preference for $\delta_{CP} \approx -\pi/2$ and normal mass hierarchy
- Very similar results from an independent analysis based on Markov chain MC
T2K ND280 and systematic errors

Flux and cross-section systematic uncertainty on $N_{_{SK}}$ significantly reduced to $\sim 7\%$
T2K anti-neutrino mode running

- Why run with anti-neutrinos?
  - Consistency between $\nu$ and $\bar{\nu}$ behaviour, e.g. CPT requires that the disappearance probability in both cases is the same
  - Combining data taken in both modes reduces the overall uncertainties on $\delta_{CP}$
Results are consistent with T2K neutrino disappearance results (above) and with MINOS anti-neutrino results (below).
MINOS / MINOS+

Cambridge • Oxford • STFC/RAL • Sussex • UCL

- MINOS
  - 735km baseline, FNAL to Soudan
  - 1kt near detector 1km from source
  - 5.4kt far detector
  - Both ND and FD are steel-plastic scintillator calorimeters
  - UK contributions
    - DAQ, electronics, PMT testing, light injection

MINOS+

- Uses updated NUMI beamline
- Higher energy (cross-checks with different beam and cross-section systematics)
- More statistics (4000 $\nu_\mu$ CC events/year in far detector)
MINOS/MINOS+ combined fit

- MINOS+ has accumulated $6.4 \times 10^{20}$ POT from FNAL NUMI beam
- Largely focusing on exotic searches (sterile neutrinos, etc.)
- Combined MINOS/MINOS+ fit is consistent with previously reported MINOS results

Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3} \text{eV}^2$$

$$\sin^2 \theta_{23} = 0.43^{+0.19}_{-0.05}$$

$$0.36 < \sin^2 \theta_{23} < 0.65 \text{ (90\% C.L.)}$$
NOνA experiment and status

Sussex

- Precision appearance/disappearance $\nu_\mu (\bar{\nu}_\mu)$ measurements
- 810km long baseline experiment
- Off-axis narrow band FNAL NUMI neutrino beam
- 209t near detector and muon catcher
- Far detector 14kt totally active liquid scintillator

UK contribution: data driven trigger, stopping muon calibration, $\nu_\mu$ analysis

ND and FD as similar as possible to minimize systematics when using the large ND flux to predict the unoscillated FD spectrum
NOvA far detector data

5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light

Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)
NOvA candidate $\nu_\mu$ event
NOνA $\nu_\mu$ disappearance results

$\Delta m^2_{32} = +2.37^{+0.16}_{-0.15}$ (normal hierarchy)

$\Delta m^2_{32} = -2.40^{+0.14}_{-0.17}$ (inverted hierarchy)

$\sin^2 \theta_{23} = 0.51 \pm 0.10$

201 events expected, 33 observed
8% of nominal exposure
NOvA candidate $\nu_e$ event
NOvA $\nu_e$ appearance results

- Results from 2 independent analyses using different particle ID algorithms
- Commented at NuFACT: both analyses “prefer” NH and $\delta_{CP}=3\pi/2$
NOνA and T2K complementarity

• Combining NOνA and T2K data helps break degeneracies and improves coverage in the overlap regions
• Mainly due to NOνA ‘s increased sensitivity to the mass hierarchy via matter effects
Current understanding

Mixing angles and mass differences

Mass hierarchy

- Global fit data as of June 2014
- Uses LBL, SBL, reactor, solar, atm data
- Uses technique in Capozzi et al. PRD 89 (2014) 093018)
HyperK beam and detector

- 295km baseline
- Large volume water Cerenkov
- 990kT total volume
- 560kT fiducial volume (25x SK)
- 99,000 PMTs (20% coverage)
- 10 optically isolated compartments

- J-PARC $\nu_\mu$ ($\bar{\nu}_\mu$) beam upgraded to $\geq 0.75$MW
- 2.5° off-axis, narrow band 600MeV beam
In 2013 Japan granted a 5 year £2.3M R&D grant which includes provision for a prototype detector (+$1.2M)

In early 2014 the Science Council of Japan selected HyperK as one of its top 27 scientific projects in its 2014 Master Plan

Discussions with Japanese funding agency, MEXT, in progress for long-term funding

Current Collaboration>240 people

UK represents the second largest group of scientists after Japan
HyperK timeline

- **Construction**
  - 2012: JFY
  - 2018: Photo-sensor development, Prototype detector
  - 2019: Photo-sensor production
  - 2020: Cavity excavation, Tank construction
  - 2021: Sensor installation, Water filling
  - 2022-2023: T2K will accumulate approved PCT
  - 2024-2025: J-PARC Power Upgrade (~240kW), 750kW and beyond
  - 2025: Operation

- **Operation**
  - 2018: Construction begins
  - 2015: Design report
  - 2025: Operation
HyperK $\nu_e(\bar{\nu}_e)$ appearance events

- Neutrino mode: dominant background is intrinsic $\nu_e$ contamination from the beam
- Anti-neutrino mode: also large wrong-sign background

$7.5 \times 10^7$ MW sec, $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, normal MH, $\nu: \bar{\nu} = 1:3$
HyperK $\nu_\mu (\bar{\nu}_\mu)$ disappearance events

Disappearance $\nu_\mu$ events

Disappearance $\bar{\nu}_\mu$ events

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$\nu_\mu$ CC</th>
<th>$\bar{\nu}_\mu$ CC</th>
<th>$\nu_e$ CC</th>
<th>$\bar{\nu}_e$ CC</th>
<th>NC</th>
<th>$\nu_\mu \rightarrow \nu_e$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode</td>
<td>17225</td>
<td>1088</td>
<td>11</td>
<td>1</td>
<td>999</td>
<td>49</td>
<td>19372</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>10066</td>
<td>15597</td>
<td>7</td>
<td>7</td>
<td>1281</td>
<td>6</td>
<td>26964</td>
</tr>
</tbody>
</table>

- Anti-neutrino mode: significant wrong-sign $\nu_\mu$ contribution

7.5 x $10^7$ MW sec, $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP}=0$, normal MH, $\nu:\bar{\nu} = 1:3$
HyperK sensitivity to CP

Assuming $7.5 \times 10^7$ MW sec:

- CP violation can be observed at
  - $3\sigma$ for 76% values of $\delta_{CP}$
  - $5\sigma$ for 58% values of $\delta_{CP}$

- $\delta$ can be measured with
  - $8^\circ$ precision for $\delta = 0$
  - $19^\circ$ precision for $\delta = \pi/2$
# HyperK broad scientific programme

<table>
<thead>
<tr>
<th>Physics target</th>
<th>Sensitivity</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neutrino study w/ J-PARC ν</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- ( CP ) phase precision</td>
<td>(&lt; 19^\circ)</td>
<td>(7.5 \text{ MW} \times 10^7 \text{ s}) @ (\sin^2 2\theta_{13} = 0.1), mass hierarchy known</td>
</tr>
<tr>
<td>- ( CPV ) discovery coverage</td>
<td>(76% (3 \sigma), 58% (5 \sigma))</td>
<td>(\sin^2 2\theta_{13} = 0.1), mass hierarchy known</td>
</tr>
<tr>
<td>- ( \sin^2 \theta_{23} )</td>
<td>(\pm 0.015)</td>
<td>(1 \sigma ) @ (\sin^2 \theta_{23} = 0.5)</td>
</tr>
<tr>
<td><strong>Atmospheric neutrino study</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- MH determination</td>
<td>(&gt; 3 \sigma \text{ CL})</td>
<td>10 yr observation (\sin^2 \theta_{23} &gt; 0.4)</td>
</tr>
<tr>
<td>- ( \theta_{23} ) octant determination</td>
<td>(&gt; 3 \sigma \text{ CL})</td>
<td>(\sin^2 \theta_{23} &lt; 0.46) or (\sin^2 \theta_{23} &gt; 0.56)</td>
</tr>
<tr>
<td><strong>Nucleon decay searches</strong></td>
<td></td>
<td>10 yr data</td>
</tr>
<tr>
<td>- ( p \rightarrow e^+ + \pi^0 )</td>
<td>(1.3 \times 10^{35} \text{ yr (90% CL UL)})</td>
<td></td>
</tr>
<tr>
<td>- ( p \rightarrow \bar{\nu} + K^+ )</td>
<td>(5.7 \times 10^{34} \text{ yr (3\sigma discovery)})</td>
<td></td>
</tr>
<tr>
<td>- ( p \rightarrow \bar{\nu} + K^+ )</td>
<td>(3.2 \times 10^{34} \text{ yr (90% CL UL)})</td>
<td></td>
</tr>
<tr>
<td>- ( p \rightarrow \bar{\nu} + K^+ )</td>
<td>(1.2 \times 10^{34} \text{ yr (3\sigma discovery)})</td>
<td></td>
</tr>
<tr>
<td><strong>Astrophysical neutrino sources</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- (^8\text{B} \nu ) from Sun</td>
<td>(200 \nu/\text{day})</td>
<td>7.0 MeV threshold (total energy) w/ osc. @ Galactic center (10 kpc)</td>
</tr>
<tr>
<td>- Supernova burst ( \nu )</td>
<td>(170 000\text{000} \nu)</td>
<td>(\nu\text{ from M31 (Andromeda galaxy)})</td>
</tr>
<tr>
<td>- Supernova relic ( \nu )</td>
<td>(30\text{–}50 \nu)</td>
<td></td>
</tr>
<tr>
<td>- WIMP annihilation at Sun (( \sigma_{SD} ): WIMP–proton spin-dependent cross section)</td>
<td>(\sigma_{SD} = 10^{-39} \text{ cm}^2)</td>
<td>5 yr observation (M_{\text{WIMP}} = 10 \text{ GeV} ), (\chi \chi \rightarrow bb) dominant</td>
</tr>
<tr>
<td>- WIMP annihilation at Sun (( \sigma_{SD} ): WIMP–proton spin-dependent cross section)</td>
<td>(\sigma_{SD} = 10^{-40} \text{ cm}^2)</td>
<td>(M_{\text{WIMP}} = 100 \text{ GeV} ), (\chi \chi \rightarrow W^+W^-) dominant</td>
</tr>
</tbody>
</table>
## HyperK UK involvement

Edinburgh • Imperial • Lancaster • Liverpool • Oxford
QMUL • RHUL • Sheffield • STFC/RAL • Warwick

<table>
<thead>
<tr>
<th>Work Package</th>
<th>Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP1: Physics, Software and Computing</td>
<td>interface GENIE neutrino interaction generator with Hyper-K; software release and data distribution</td>
</tr>
<tr>
<td>WP2: Detector R&amp;D</td>
<td>design of TITUS, a water Cerenkov near detector TITUS; inform the decision on Gd-doping; selection of the photo-sensor technology for near and far detectors; conceptual design of HPTPC near detector.</td>
</tr>
<tr>
<td>WP3: DAQ</td>
<td>Design of a functional, flexible system that will meet the physics requirements of the experiment. A small-scale DAQ test system will be demonstrated using a prototype detector located in Japan.</td>
</tr>
<tr>
<td>WP4: Calibration</td>
<td>Delivery of a fibre-coupled pulsed light source; Fixed point diffuser; Pseudo-muon light source.</td>
</tr>
<tr>
<td>WP5: Beam</td>
<td>Identify critical materials issues for reliable beam window and target operation at multi-MW beam powers; specify materials test programs; select preferred target technology and plan the necessary research programme</td>
</tr>
</tbody>
</table>
HyperK UK WP2 Detector R&D

- **TITUS**
  - 2kt Water Cerenkov surrounded by MRD situated at 2km from beam source (sees almost identical spectrum to HK)
  - Possibly Gd doped to improve $\nu/\bar{\nu}$ and $\nu_e/\nu_\mu$ separation

- **PMT/LAPPD studies**
HyperK UK WP4 Calibration

• Pseudo light-source:
  – Short duration light pulses from LEDs
  – Light coupled into optical fibres
  – Fibre ends inject light directly into the detector
  – Illuminate multiple PMTs on other side of a tank
  – Continuous low pulse rate operation during data taking
  – Electronics (which may require intervention) is easily accessible
  – LED pulser circuit designs under consideration include modified Kapustinsky, 4 MOSFETs in H bridge

• Pseudo-muon light source:
  – Objective is to inject a Cherenkov-like cone of light into the detector
  – Can be achieved using a short, narrow transparent (acrylic) tube along with a light source which produces almost parallel light
  – Different muon momenta can be simulated by using different lengths

\[ n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \]

As \( \theta_1 \rightarrow 90^\circ \), \( \sin(\theta_2) \rightarrow 1/n_c \)

Light emitted at Cherenkov angle.
Water Č: Gd loading

- Turn a standard Water Cherenkov detector into an anti-neutrino detector by loading with ~0.2% water soluble Gd
- Use delayed (~30µs) coincidence of γ and e⁺

- The problem is that you need to completely remove the Gadolinium Sulphate when necessary → need a selective GD filtration system
- New system based on nano-filtration. Molecular band-pass filter analogous to electrical equivalent
- EGADS: 200ton Gd demonstrator close to Super-K
- Initial results show 66% Č light left at 20m with Gd c.f. 71% to 79% without
- Recent decision to run SK with Gd
• DOE CD-1 preliminary baseline approval in December 2012
  – DOE commitment of $867M to LBNE
  – Plus PIP-II for 1.2MW beam – total of $1.5B
• Funding bids in process/successful in UK, India, Brazil, Italy,…
• UK is largest non-US group represented ~10% of collaboration
• Far detector
  – Up to 40kt fiducial volume
  – Staged approach 4 x 10kt in separate caverns
  – Allows different designs to be considered (single vs double phase)
Beamline visualisation
Liquid Argon TPCs

Why Liquid Argon?
- High density, cheap
- Dense → good target
- Excellent dielectric properties support large voltages
- Free electrons from ionizing track can be drifted in long distances in LAr
- Electron cloud diffusion is small
- High scintillation light yield (at 128 nm) can be used for triggering

Why a Liquid Argon TPC?
- Combines the principles of a gaseous TPC with a LAr calorimeter
- Fine grained tracking
- High granularity dE/dX
- True 3D imaging with mm-scale spatial resolution
- Excellent PID
- Constantly sensitive
Liquid Argon TPCs: Challenges

- Technical challenges:
  - to achieve long drift distances, ultra-high purities (better than 100 ppt O₂ equivalent) are required
  - Drift field requires HV on the cathode
  - Operation of large wire chambers at cryogenic temps
  - No charge amplification in liquid → fC charges requiring sensitive preamps
  - Large number of R/O channels
  - Large cryogenic systems

[Diagram showing charge attenuation efficiency with different O₂ concentrations and drift fields.]

A Rubbia, Neutrino 2012
Liquid Argon TPCs: performance

Tracking Performance:
- Data taken in test beams with prototypes (e.g. 250l T32 experiment at J-PARC)
- Hit charge distribution fitted well with Birks Law

\[ Q = A \frac{Q_0}{1 + (k/\varepsilon) \times (dE/dx) \times (1/p)} \]

Calorimetric Performance:
- ICARUS data (2004) with Michel electrons from stopping muon decay

\[ \frac{\sigma_E}{E} \approx \frac{11\%}{\sqrt{E}} \oplus 4\% \]

- MC expectations (higher E):

\[ \frac{\sigma_{\text{EM}}^{MC}}{E} \approx \frac{3\%}{\sqrt{E}} \oplus 1\% \]
\[ \frac{\sigma_{\text{HAD}}^{MC}}{E} \approx \frac{15\%}{\sqrt{E}} \oplus 10\% \]
LAr prototyping activities

- DUNE 35 ton prototype due to take data at FNAL in late 2015
- LAr1-ND, 82t TPC for MicroBoone (2017)
- Other activities ArgoNeut, LARIAT etc.

- Plans to test full scale LBNE drift cells in 8m x 8m x 8m cryostat at CERN (WA105)
- Programmes provide short term physics and analysis opportunities
Far detector appearance probabilities

- Appearance probabilities at 1300km as a function of neutrino energy and $\delta_{CP}$ value
- Value of $\delta_{CP}$ affects both frequency and amplitude of oscillation
- Black line: probability if $\theta_{13}=0$
DUNE far detector event rates

![Graphs showing event rates for DUNE far detector in appearance and disappearance modes.](image)
DUNE MH sensitivity

- Significance for mass hierarchy determination as a function of $\delta_{CP}$ value for 300 kt.MW.years (approx 7 years of running)
- Mass hierarchy determined with a significance of 5 or higher for 100% of $\delta_{CP}$ values (optimised beam design)
DUNE $\delta_{CP}$ sensitivity

Significance for CP violation determination as a function of $\delta_{CP}$ value for 300 kt.MW.years (approx 7 years of running)
# DUNE UK involvement

Cambridge • Lancaster • Liverpool • Manchester • Oxford
Sheffield • STFC/RAL • Sussex • UCL • Warwick

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<td>Oscillation physics simulation; GENIE-LArSoft interface; Near detector design studies; Target and beam design; Beam systematics study;</td>
</tr>
<tr>
<td>WP2: Neutrino Event Reconstruction</td>
<td>Pattern recognition software (PANDORA) and interface to LArSoft; neutrino event reconstruction;</td>
</tr>
<tr>
<td>WP3: DAQ</td>
<td>DAQ for 35t prototype; data compression and event triggering; DAQ architecture design and prototyping.</td>
</tr>
<tr>
<td>WP4: 35t Prototype</td>
<td>HV monitoring cameras; operation and commissioning; simulation and data analysis; rejection of cosmic-induced backgrounds.</td>
</tr>
<tr>
<td>WP5: TPC Design and Construction</td>
<td>LAr1-ND APA and CPA frame design, wiring, cold-testing, construction and installation; LBNE APA and CPA design.</td>
</tr>
</tbody>
</table>
DUNE UK WP2 Event Reconstruction

- Neutrino events in a LAr TPC give high resolution, bubble-chamber like images
- The challenge is to go from this to reconstructed physics quantities
- PANDORA-based event reconstruction and LAr pattern recognition tools being developed
DUNE UK WP5 APA design

- UK-built 35t APA undergoing LN$_2$ cool down tests

- APA wiring frame concept design

- LAr1-ND: UK proposes to build
  - One of the two APAs
  - The CPA and HV feedthrough
Systematics

- With the promise of high statistics in the next generation long baseline experiments, systematics will play a major role.

E.g. consideration of:
- Neutrino cross-sections
- Beam flux uncertainties
Non-accelerator based oscillations - SK

Next 3 Slides from Alex Sousa’s summary talk at NuFACT’15

- **Normal** hierarchy favored at: $\chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -3.2$ (-3.0 SK only)
- **CP** Conservation ($\sin\delta_{cp} = 0$) allowed at (at least) 90% C.L. for both hierarchies

new result with 4972 days SK data
SK-III(2005-2008) SK-IV(2008-Present) → total 4972 days

- Super-K-Gd Project approved!
  - High efficiency neutron tagging by adding 0.2% $\text{Gd}_2(\text{SO}_4)_3$
  - Allows neutrino/antineutrino discrimination
Non-accelerator – IceCube + DeepCore

PRD 91, 072004 (2015) with SK result updated

This measurement is still statistics limited.

- Still working on strategy 2: relax “golden event” requirements ⇒ expected increase by an order of magnitude of number $\nu$ in sample
Non-accelerator future – PINGU/ORCA

- Can reach 3σ resolution of mass hierarchy after 3 years of running.
- Mass hierarchy sensitivity strongly dependent on value of $\theta_{23}$
- Expect to achieve similar $\theta_{23}$ and $\Delta m^2_{32}$ precision as NOvA and T2K
Conclusions

• Neutrino oscillations are now well-established and experiments are in a phase of accurately measuring the parameters of the PNMS mixing matrix
• In recent years a non-zero $\theta_{13}$ mixing angle has been observed – thus opening the door to a search for CP violation
• Current and proposed projects have excellent prospects for measuring $\delta_{\text{CP}}$ and determining the neutrino mass hierarchy
• There is a well-defined global programme of long baseline experiments reaching well into the late 2020s
T2K $\overline{\nu}_e$ appearance

Expected # of events with our data stat.

<table>
<thead>
<tr>
<th>Normal Hierarchy with actual POT (0.4x10^{21})</th>
<th>$\delta_{CP} = -\pi/2$</th>
<th>$\delta_{CP} = 0$</th>
<th>$\delta_{CP} = +\pi/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected events (NH)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>1.961</td>
<td>2.636</td>
<td>3.288</td>
</tr>
<tr>
<td>Background $\nu_\mu \rightarrow \nu_e$</td>
<td>0.592</td>
<td>0.505</td>
<td>0.389</td>
</tr>
<tr>
<td>Background NC</td>
<td>0.349</td>
<td>0.349</td>
<td>0.349</td>
</tr>
<tr>
<td>Background other</td>
<td>0.826</td>
<td>0.826</td>
<td>0.826</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.73</td>
<td>4.32</td>
<td>4.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inverted Hierarchy with actual POT (0.4x10^{21})</th>
<th>$\delta_{CP} = -\pi/2$</th>
<th>$\delta_{CP} = 0$</th>
<th>$\delta_{CP} = +\pi/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected events (IH)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>2.481</td>
<td>3.254</td>
<td>3.939</td>
</tr>
<tr>
<td>Background $\nu_\mu \rightarrow \nu_e$</td>
<td>0.531</td>
<td>0.423</td>
<td>0.341</td>
</tr>
<tr>
<td>Background NC</td>
<td>0.349</td>
<td>0.349</td>
<td>0.349</td>
</tr>
<tr>
<td>Background other</td>
<td>0.821</td>
<td>0.821</td>
<td>0.821</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4.18</td>
<td>4.85</td>
<td>5.45</td>
</tr>
</tbody>
</table>

Total number of events so far: 3!
CHIPS concept
Manchester • UCL

• CHIPS is a water Cherenkov detector which will be sunk in a flooded mine pit in the path of the NuMI beam
• Water will provide mechanical support
• Its main development goal is to chart a new path towards cost effective Megaton neutrino detectors, hoping to get to $200k/kt (presently $1M/kt)
• Complements NOvA (being more on-axis) and DUNE (more off-axis) when redeployed in the LBNF beamline
• Consists of a series of prototypes which will deliver physics results and demonstrate real costs for (O)100kt
• Proposed site is the Wentworth pit in Minnesota
• UK-led work packages include
  – Simulation and reconstruction
  – DAQ
  – In-situ calibration
CHIPS Physics Goals

• Short term:
  – Contribute to the measurement of $\delta_{CP}$ using neutrinos from the NuMI beam by measuring the sub-dominant $\nu_e$ appearance and rejecting the NC background
  – Building and instrument a 10kt prototype

• Medium term:
  • ~25kt (TBD) vessel to follow
  • Yearly increase of instrumented mass depending on funding
    – Deployment seasonal
    – Large up-front funding not necessary
    – Staging of detector(s) natural

• Long term:
  • Re-deploy CHIPS in LBNF beam off axis
  • 2nd oscillation maximum located around 0.8 GeV
    – Large quasi-elastic x-section
    – Suitable for water Cerenkov detector
      • High efficiency for QE events