Long baseline neutrino experiments

Helen O'Keeffe, Lancaster University
STFC PPAP meeting, Imperial College, 25th September 2015

Overview

Neutrino physics

Current experiments

- T2K
- NOνA
- MINOS/MINOS+

Future experiments

- DUNE
- Hyper-Kamiokande
- CHIPS
- PINGU

Summary and prospects

Three neutrino mixing

Lancaster University

Flavour and mass eigenstates related via mixing matrix

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

Flavour states

Mass states

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
δ = CP phase

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

"Oscillation parameters"

Describe flavour changes and matter effects

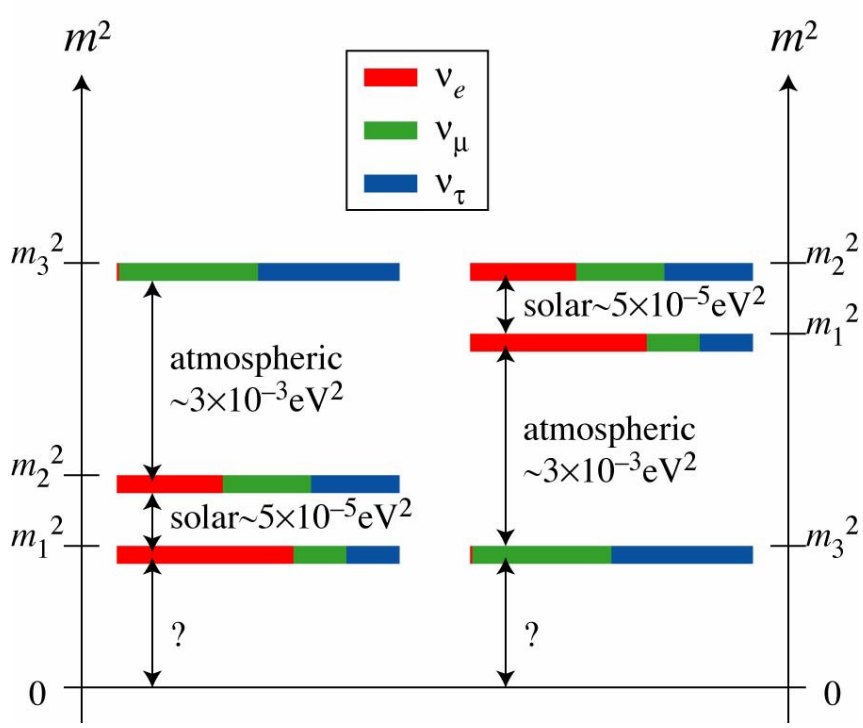
Three neutrino mixing

Known:

- Neutrinos have mass
- Oscillate between flavours
- Measured values for
  - θ_{12}, θ_{23}, θ_{13}
  - Δm_{21}^2, $|\Delta m_{32}^2|$

Unknown:

- Order of the mass states
- Absolute mass of the neutrino
- Is θ_{23} maximal?
- Are there more types?
- Majorana or Dirac?
- The value of δ_{CP}



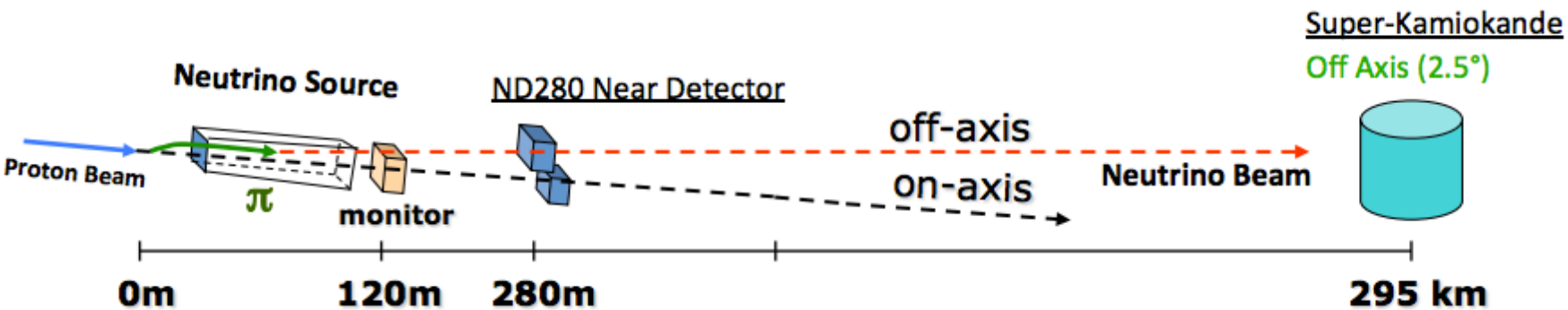
Normal hierarchy (NH)

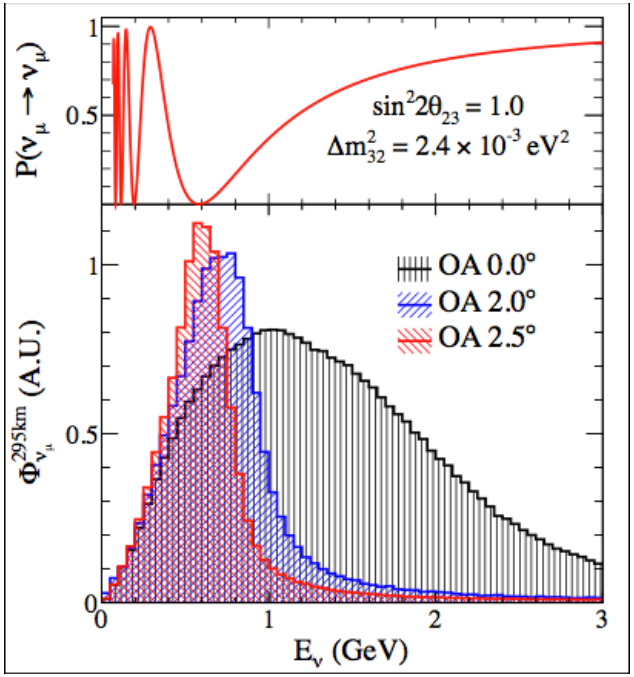
Inverted hierarchy (IH)

Tokai to Kamioka (T2K) experiment

Lancaster University

UK: Imperial, Lancaster, Liverpool, Oxford, QMUL, Sheffield, STFC RAL/DL, Warwick





295 km baseline from J-PARC to Super-K
2.5 degrees off-axis

First Neutrino beam: 2009
First anti-neutrino beam: 2014

T2K UK Leadership

Lancaster University

Significant UK leadership in collaboration

International co-spokesperson (Wascko)

ND280 analysis:

π^0, ν_e, exotics, cross-sections, calibration(x2), ND280 near detector steering committee(x2)

ND280 hardware:

DAQ, electronics, ECal, Run coordination

Others

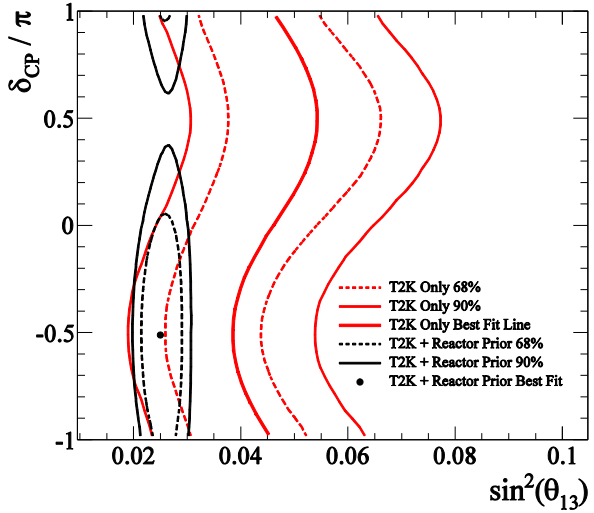
Oscillation

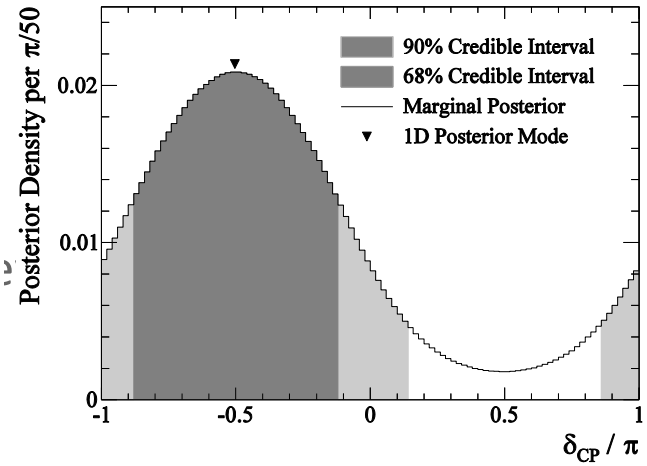
Neutrino Interactions Working group

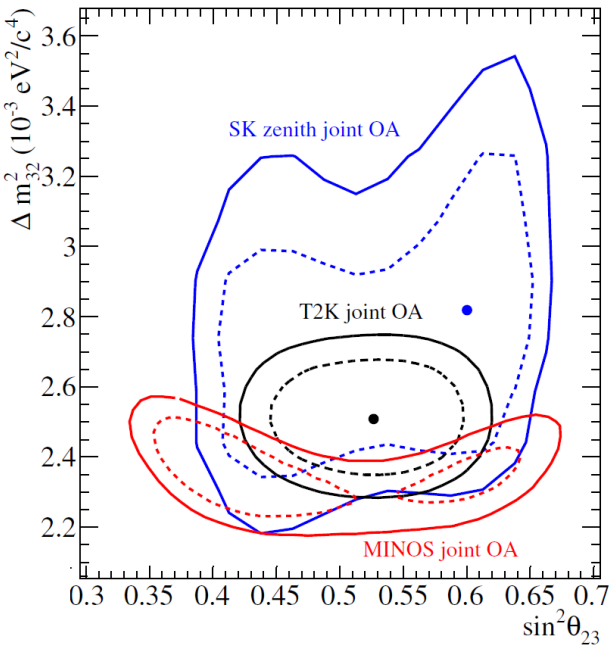
UK holds more ND280 leadership posts than any other member country!

2nd largest member of collaboration (after Japan)

T2K: Previous measurements







First measurement ν_e appearance (7.3 σ)

now have 6% more ν_μ data

Measurement of θ_{13}

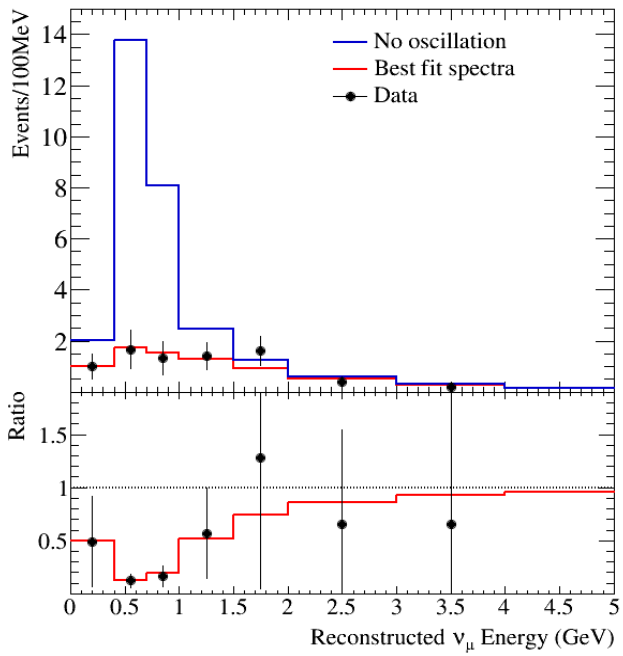
$\sin^2\theta_{13}$= 0.095±0.001

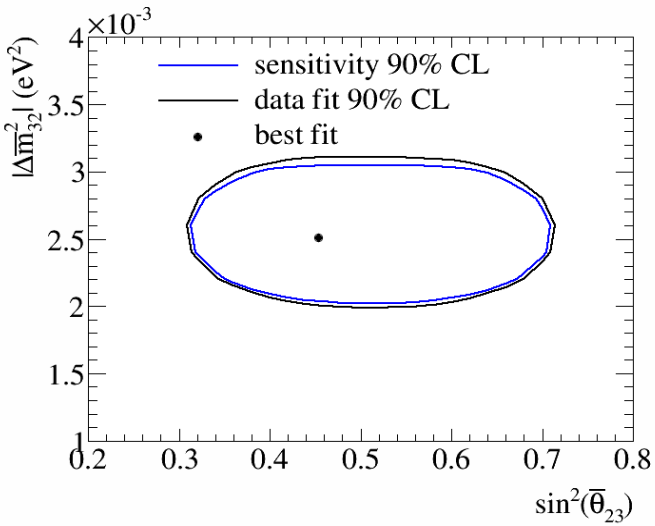
World-leading measurement of θ_{23}

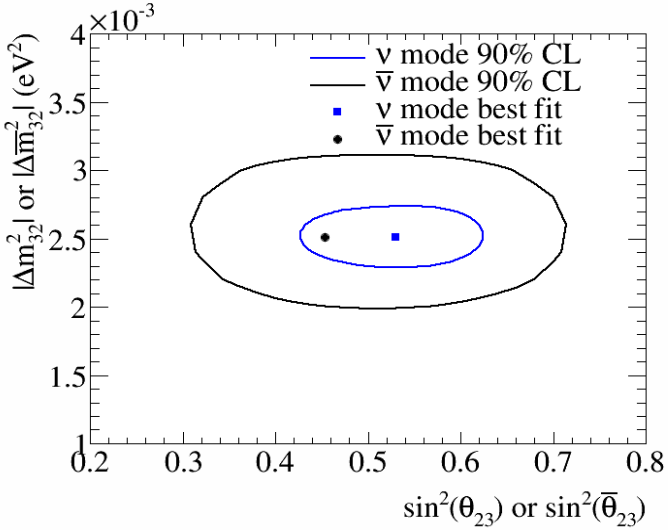
Significant measurement of Δm^2_{23}

Abe, K. et al, Physical Review D 91.7 (2015): 072010

T2K: anti ν_μ disappearance





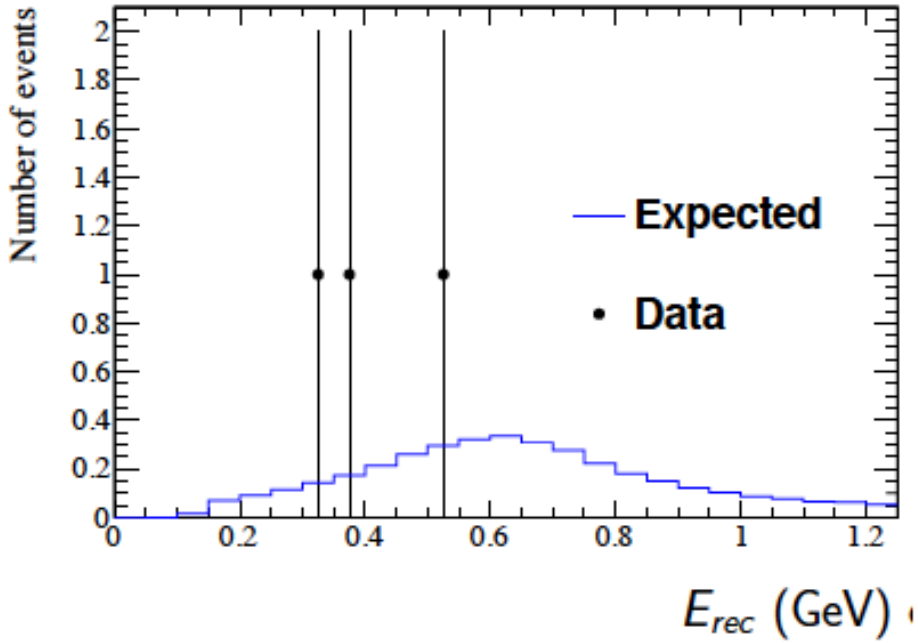


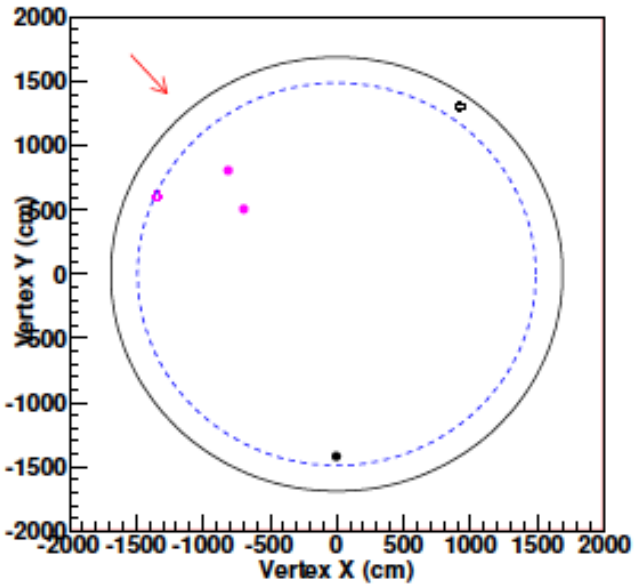
34 events observed

103.6 expected (with no oscillation)

World leading measurement of θ_{23} for anti ν_μ

T2K: Anti-ν_e appearance





- Jun. 2014
- Dec. 2014 - Jun. 2015
- Out of fiducial volume

Expect to double the data set in 2016

T2K: Other results

Selection of recent T2K results…

Several important UK-led cross section measurements

- ν_e CC cross section on carbon
- ν_μ CC quasi elastic cross section on carbon
- Coherent π^+ production on carbon
- CC1π production on water

Search for short baseline ν_e disappearance with the T2K near detector

- UK involvement

ν_μ disappearance measurement

- UK-led analysis

T2K Future

Phase I: 750 kW and 7.8x10^{21} POT

Super-Kamiokande with Gd

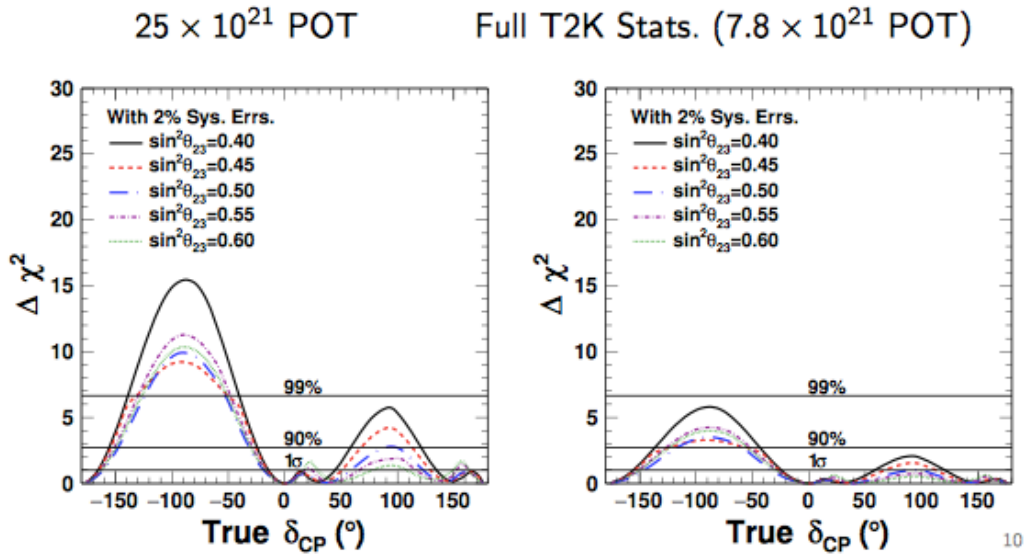
SK and T2K collaborations will negotiate the timeline for starting the process in a mutually beneficial way

Extension (2020-2025) is under discussion

Possible 1.3 MW beam

POT could reach 21x10^{21}

~3 times approved T2K POT



At 25 × 10^{21} POT, 2% systematic errors, T2K can achieve >3σ measurement of non-zero δ_{CP} (at true δ_{CP} = −90◦ , NH)

Most of this will happen before future experiments e.g. DUNE, HK

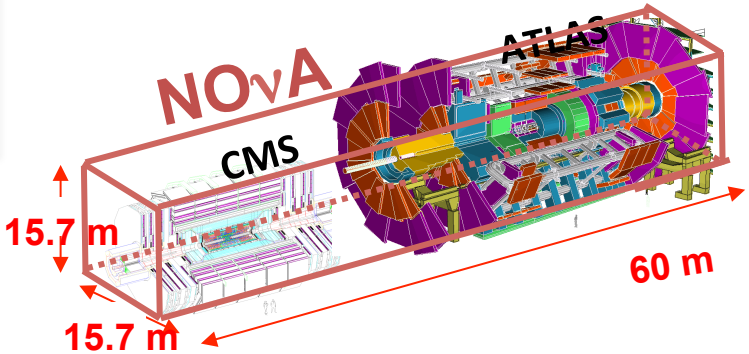
NOvA experiment

UK: Sussex, UCL

Ash River
Far detector
14,000 tons
ν_μ, ν_e,

Fermilab
Near detector
330 tons
ν_μ

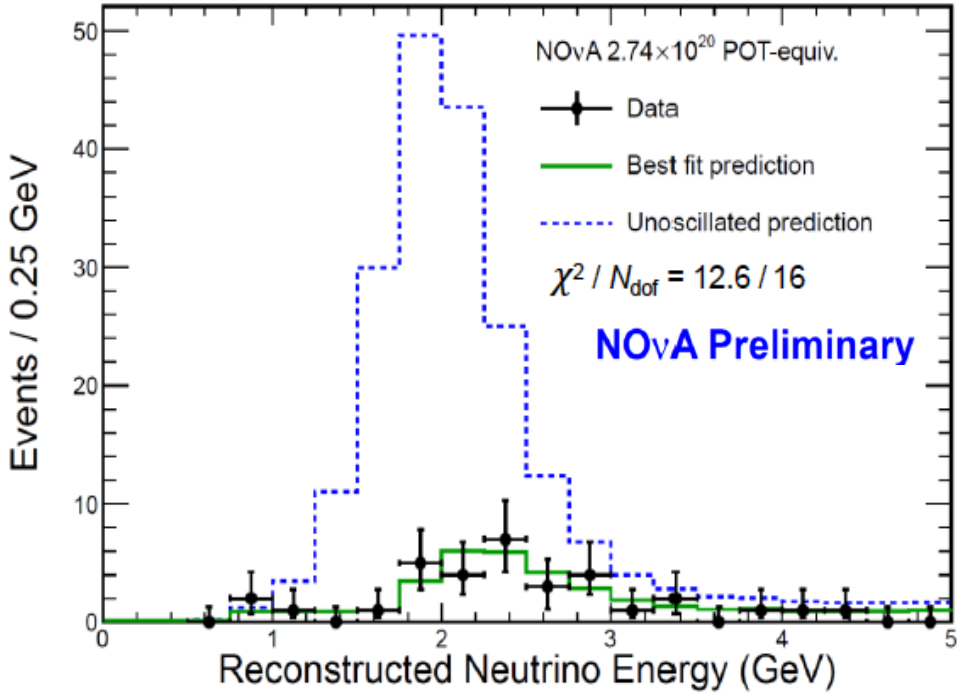
NOvA = NuMI Off-Axis ν_e Appearance

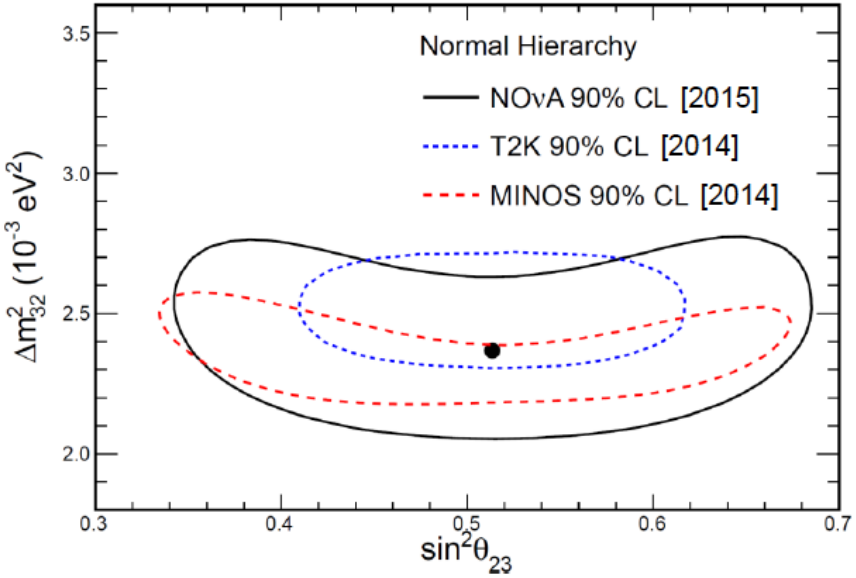


Goals:

- Neutrino mass hierarchy
- δ_{CP}
- θ_{13}

NOνA: ν_μ disappearance





Expect 201 events in FD if no oscillation
Observe 33 events

Clear observation of nu mu disappearance with 7.6 % of nominal exposure

NOvA: ν_e appearance

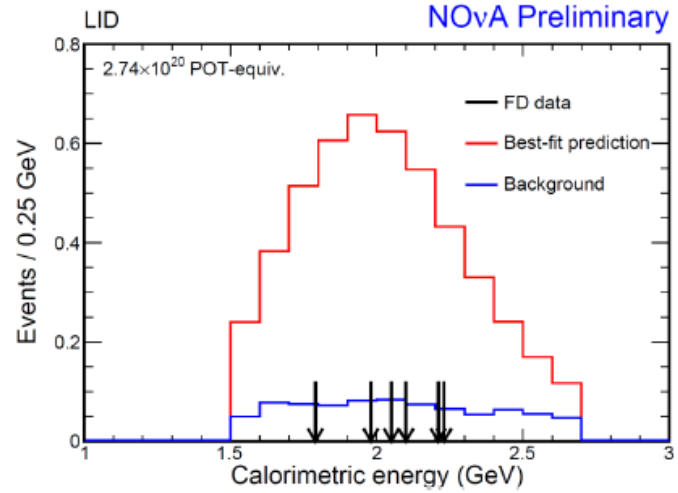
Lancaster University

LID: 6 ν_e candidates

3.3σ significance for ν_e appearance

At right:

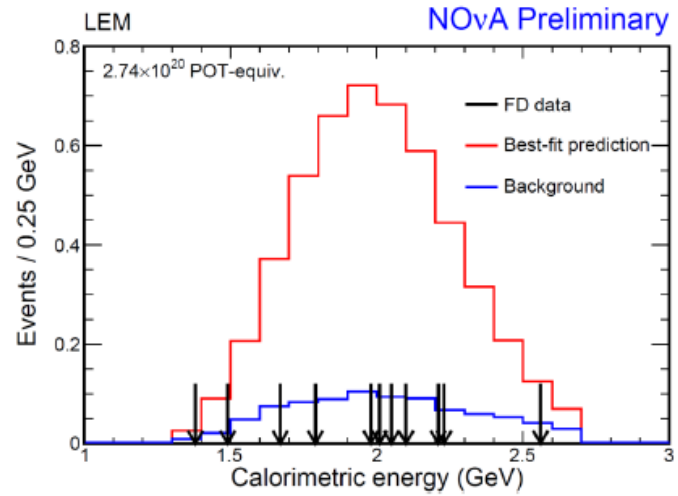
Calorimetric energy



LEM: 11 ν_e candidates

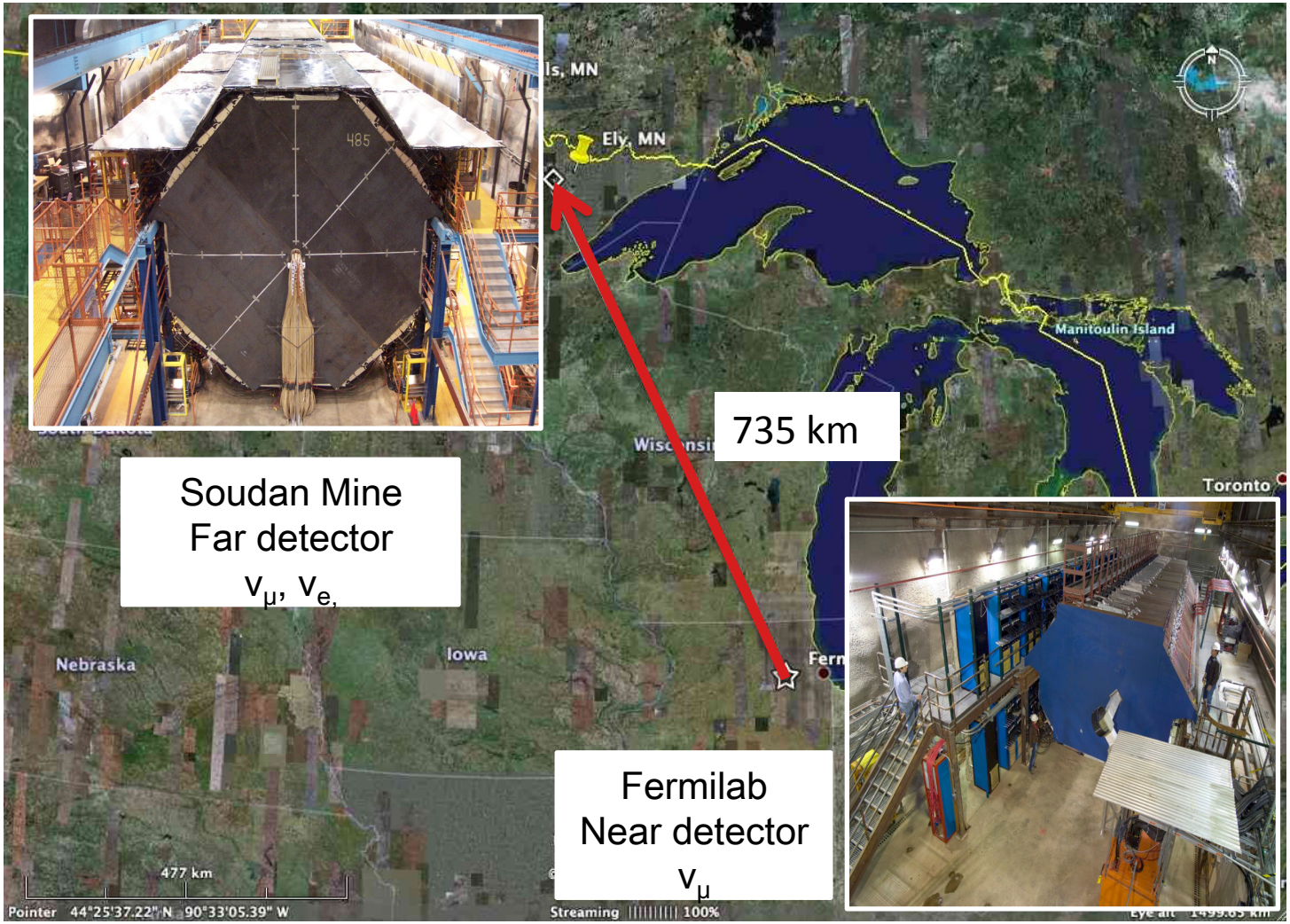
5.5σ significance for ν_e appearance

(All 6 LID events present in LEM set)



MINOS+

UK: Cambridge, Lancaster, Manchester, Oxford, Sussex, UCL



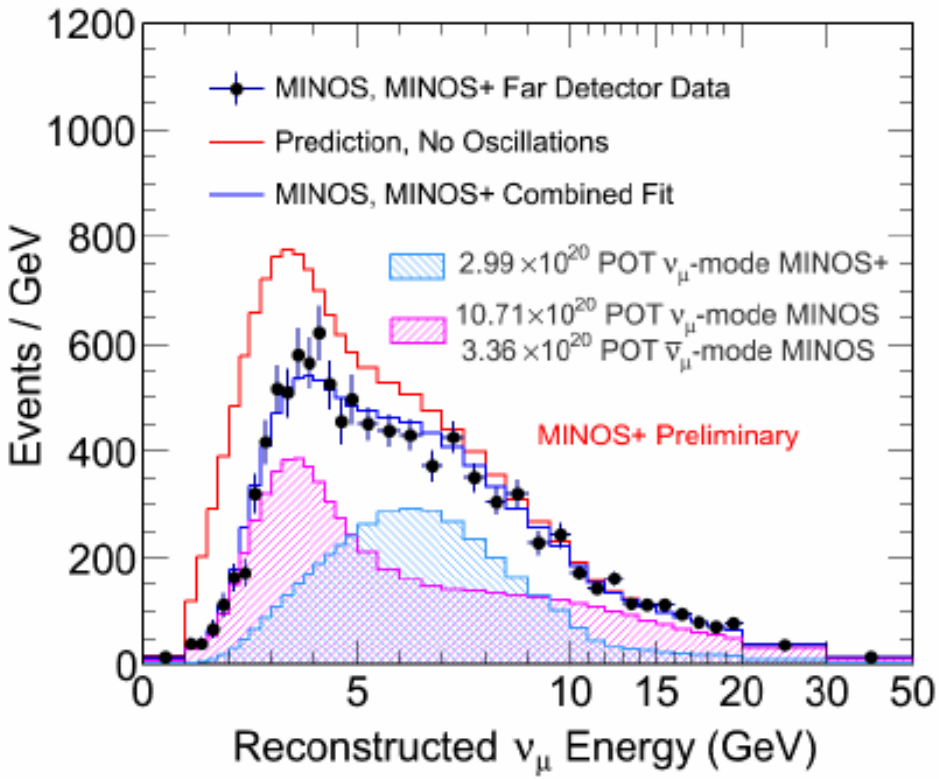
UK leadership

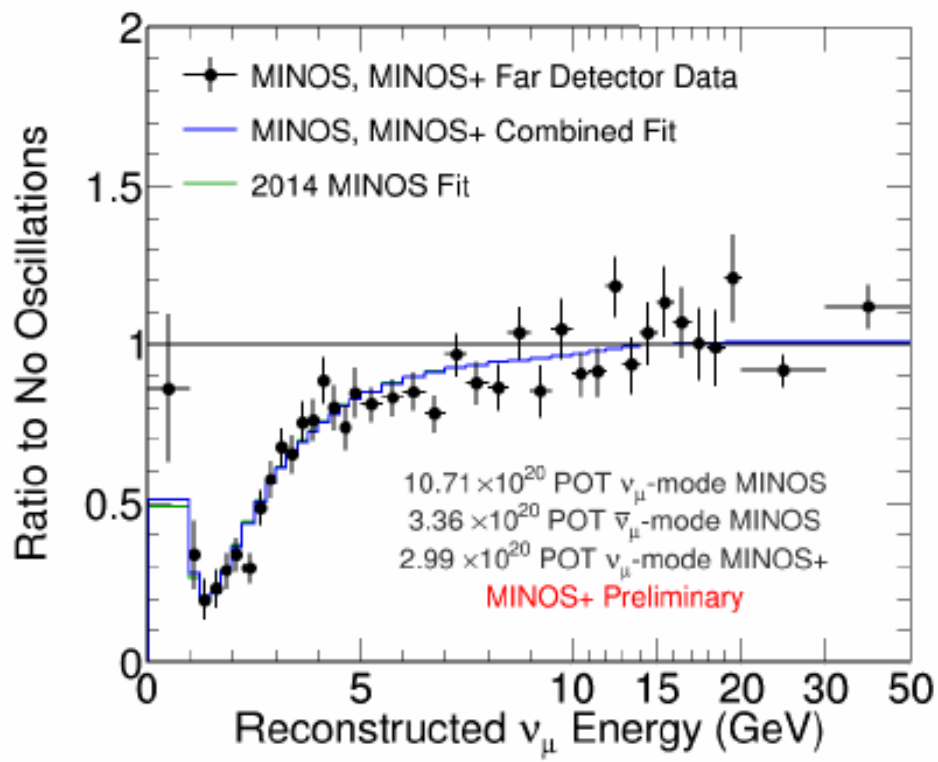
Spokesperson (Thomas)

Conveners

Analysis, steriles, beam systematics, Publication committee

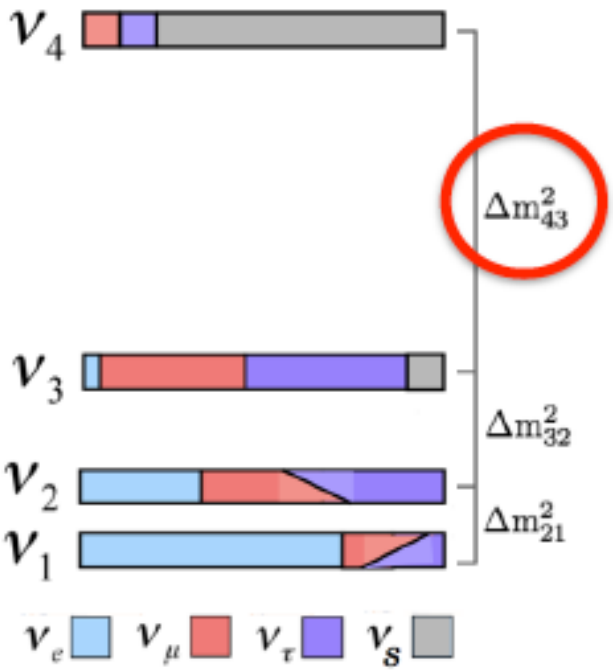
MINOS+: ν_μ disappearance

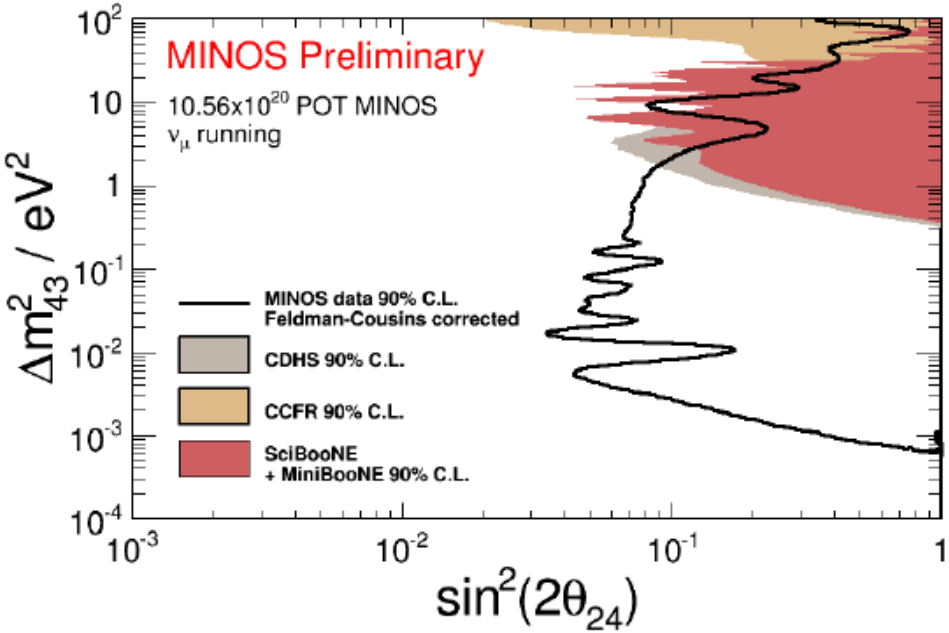




	IH	NH
$\lvert\Delta m^2_{23}\rvert$	2.37 (+0.11,-0.07) x 10^{-3} eV^2	2.34 (+0.09,-0.09) x 10^{-3} eV^2
$\sin^2\theta_{23}$	0.43 (+0.19,-0.05)	0.43 (+0.16,-0.04)
90% C.L.	$0.36 < \sin^2\theta_{23} < 0.65$	$0.37 < \sin^2\theta_{23} < 0.64$

MINOS+: Sterile analysis





Results based on 3+1 mixing model

Strongest ever constraints on ν_μ to ν_s disappearance for sterile neutrino mass splittings below 1 GeV.

CHIPS

UK: UCL

UK Leadership: Spokesperson (Thomas)

Towards a very cheap and large water Cherenkov detector

- Complementary measurement of ν_e to DUNE in LBNF
- Off-axis to study 2nd oscillation maximum
- Small PMTs with good time and position resolution
- Non-uniform PMT distribution to reflect event population

Prototype deployed in NuMI beam

- 1 year of successful cosmic data
- Winter defense system worked well
- Detector survived underwater environment
- Experimental details settled simply and cheaply

Re-instrumented for another deployment this year

CHIPS: Other activities

Simulation

Geant4 simulation of Cherenkov detector. Updates to code used for LBNE WC option

Reconstruction

Framework is being designed

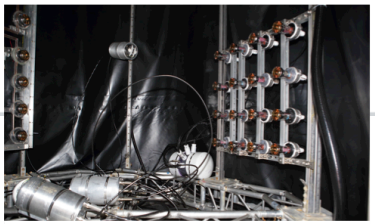
Use likelihood-based method from MiniBooNE

Prototype water will be monitored over winter

Small-scale model recirculation to understand impact of filtration

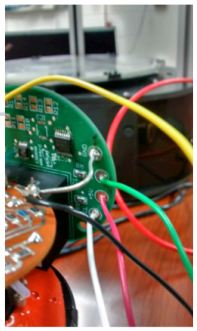
Future work

Design of 30 m diameter detector (1.5 kt volume for 2 m height)

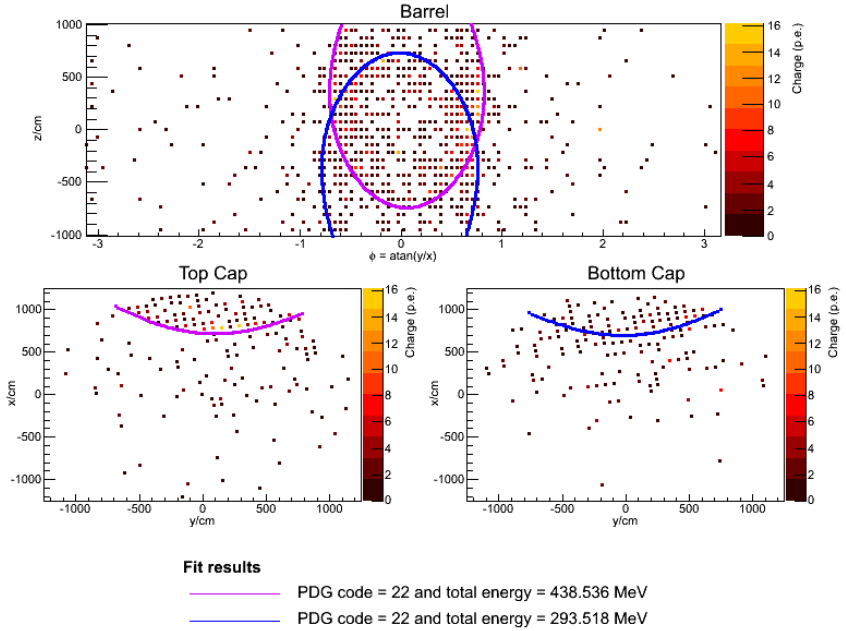


16 PMT plane with ParisROC readout (UCL involvement)

31 PMT Nikhef built using KM3NET electronics

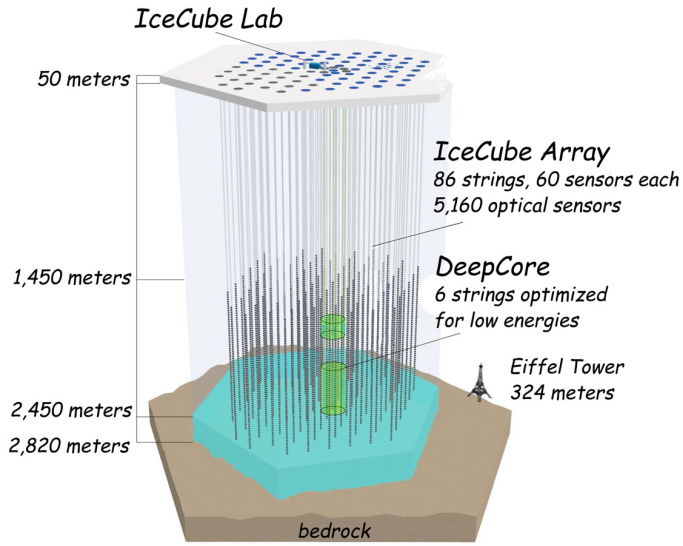


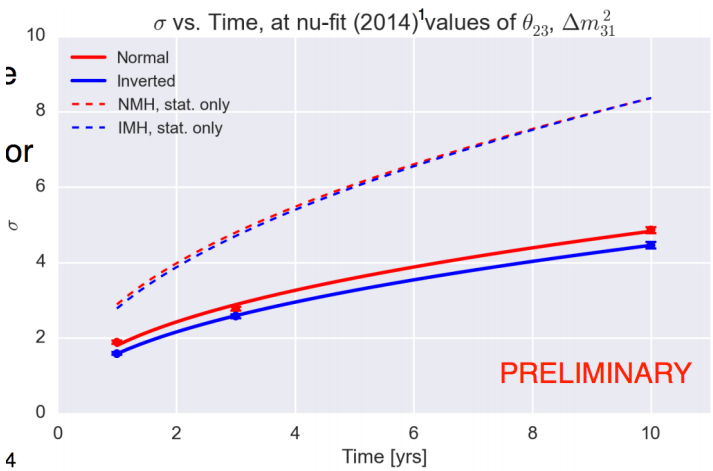
Autonomous control board (Madison)



PINGU

UK: Manchester, QMUL





Proposed upgrade of IceCube detector

Main aim: Neutrino mass hierarchy

UK involvement

Prepare physics case

Central role in analysis of DeepCore data

Understanding of atmospheric neutrino flux

Explore possibility of cross section measurements

Studies of PMT noise

UK leadership: Convener of main analysis group

Other physics:

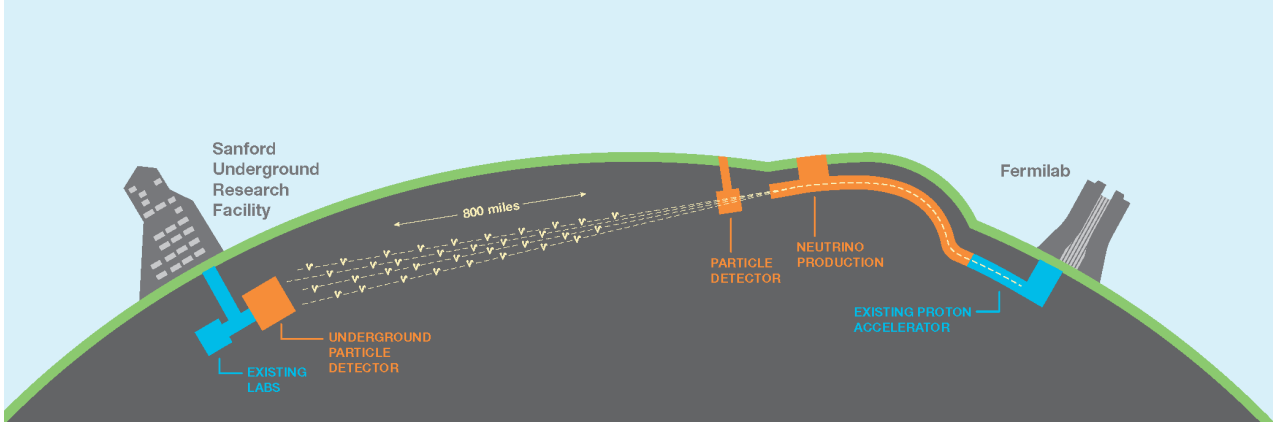
ν_τ appearance

Precision measurement of θ_{23}

Supernova neutrinos

DUNE

UK: Cambridge, Durham, Huddersfield, Imperial, Lancaster, Liverpool, Manchester, Oxford, Sheffield, STFC/RAL, Sussex, UCL, Warwick



40 kT liquid argon Far detector

Near detector: Multi-purpose high-resolution detector

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

Determine: Mass hierarchy, θ_{23} octant, probe CP violation, test 3-flavour paradigm and search for nu NSI

Long baseline

Matter effects are large

Wide-band beam

Measure ν_e appearance and ν_μ disappearance over range of energies.

Mass Hierarchy and CP effects are separable

DUNE

First "mega-science" project hosted by U.S.

- International organisation being set along lines of LHC.
- International collaboration of almost 800

DUNE/LBNF is highest priority for U.S. domestic particle physics

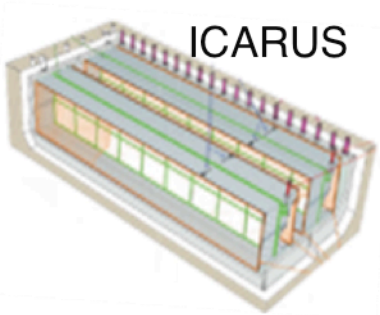
- It is the flagship project for Fermilab
- High-level CERN - U.S. agreement
- Historic CERN contribute to LBNF
- CD3a review to commit resources for far site excavation

DUNE: LArTPC development

Lancaster University

protoDUNE@CERN: first full scale engineering prototype (~ 1 kton of LAr)

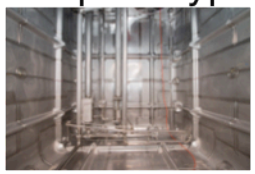
Single-Phase



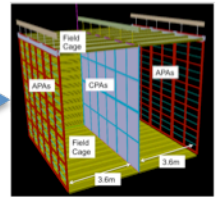
ICARUS

LBL

35-t prototype



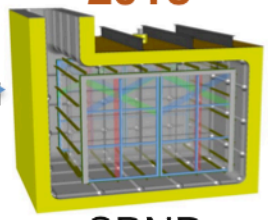
2015



2018

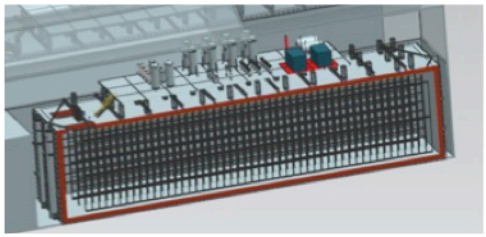
SBL

MicroBooNE



SBND

DUNE Reference Design

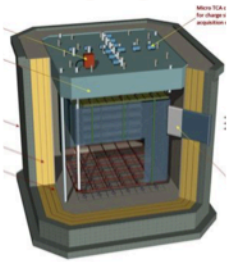


Dual-Phase

2016

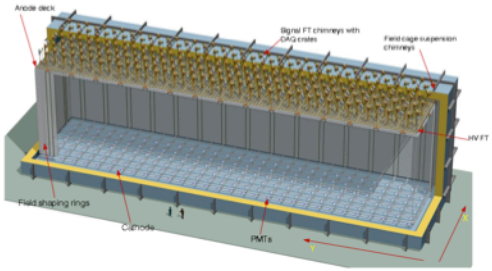
WA105: 1x1x3 m^3

2018



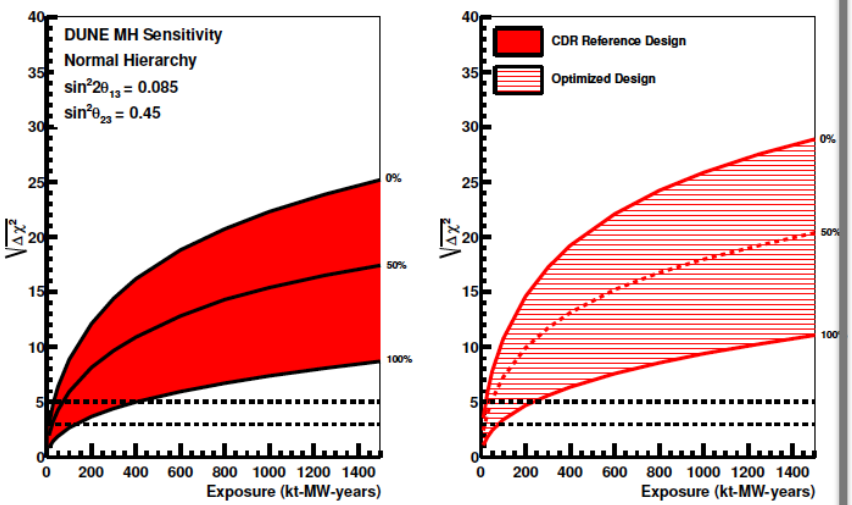
WA105

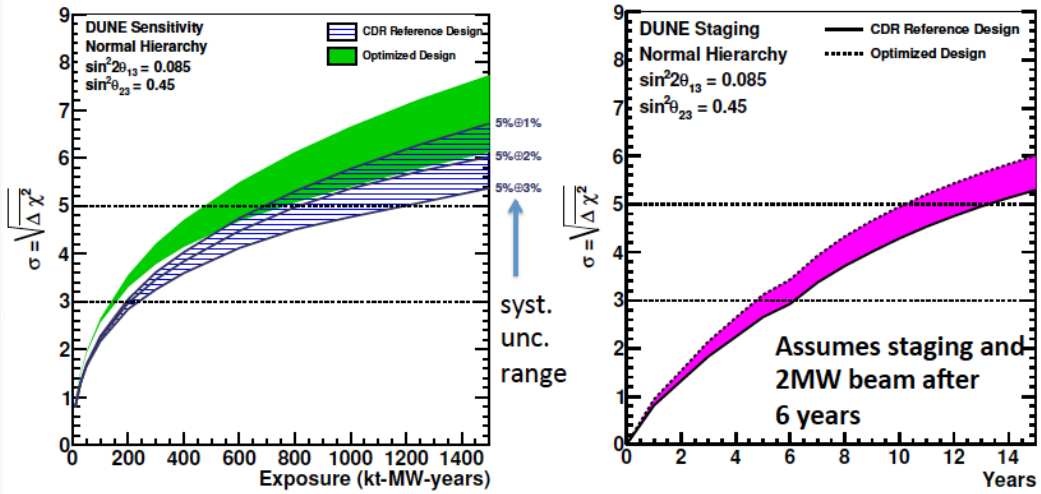
DUNE Alternative Design



35 t prototype operational later this year!

DUNE: Sensitivities





Mass Hierarchy (MH) sensitivity

- Definitively determine neutrino MH
- If CP favorable, could be in few years
- Sensitivity can be improved by beam profile optimization

CP violation sensitivity

- <3% nu e systematics important after 200 kt.MW.yr
- 5 sigma discovery of CP violation for 50% of phase space
- Optimization of beam profile is important

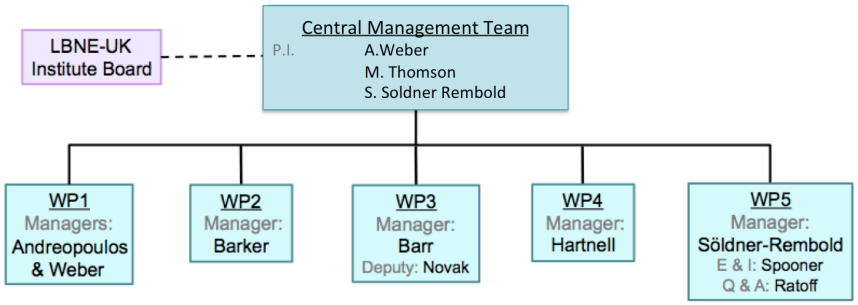
DUNE: Other physics

Other measurements

- Octant of θ_{23} i.e. is θ_{23} maximal
- Supernova neutrinos SN at 10 kpc would result in several thousand interactions in 40 kt in tens of seconds.
  - uniquely DUNE will measure electron neutrino component in time and energy - “see" formation of neutron star in real time.
- Searches for nucleon decay, particularly p to K+ anti-ν mode
- Neutrino interaction physics
- Studies of atmospheric neutrinos
- Baryon number violation searches
- Test the three-flavour paradigm in wide-band beam

DUNE in the UK

UK is 2nd largest group in the collaboration, after US



UK leadership in collaboration:
DUNE co-spokesperson *(Thomson)*
Convenerships: beam optimisation task force, speaker's board, FD installation coordinator, TPC,DAQ, FD DAQ, cosmogenics, Beam, Purity, FD optimisation, protoDUNE physics, target/horn

UK efforts are interlinked with SB LAr programme at Fermilab.
Plan to play a major role in protoDUNE at CERN

Work Package	Deliverables
WP1: Physics Simulation and Experiment Design	Calculation of full sensitivities and optimisation of the near detector
WP 2: Event Reconstruction	Implementation of PANDORA for 35 t prototype. LAr particle identification algorithms.
WP 3: DAQ	Design and construction of DAQ for the DUNE 35 t prototype. Design of system for the far detector
WP4:DUNE 35t prototype	Operation of the 35 t prototype. Analysis of data from the 35 t prototype.
WP5: LAr-TPC design	Design and construction of a LAr-TPC. Design and construction of the SBND experiment.

DUNE timeline

July 2015: CD-1 Refresh review. Conceptual design review

Dec 2015: CD-3a CF Far site. Commit resources for excavation" that will start in 2017.

2017: Ongoing shaft renovation at SURF complete

2017 Start of far site conventional facilities

2018: Testing of full scale far detector elements at CCERN

2019: Technical design review

2021: Start of underground installation.

2024: Start of physics with one detector module

Additional far detector modules every ~1 year

2025/206: Beam available

2026: Near detector available

2028: DUNE construction finished

Hyper-Kamiokande

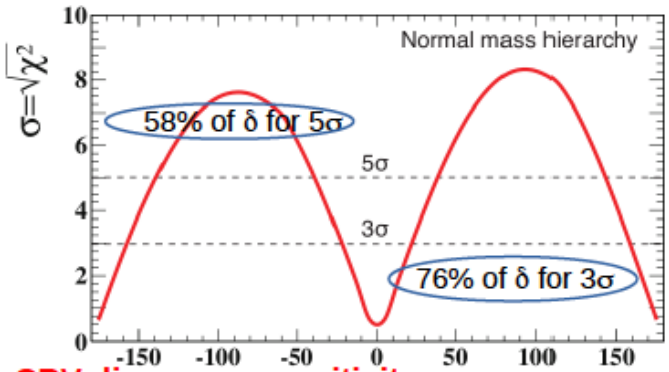
UK: Edinburgh, Imperial, Lancaster, Liverpool, Oxford, QMUL, RHUL, Sheffield, STFC/ RAL, Warwick

Narrow-band beam at ~600 MeV at 2.5°off-axis

Pure ν_μ beam with 1% ν_e contamination

Hyper-K: CP sensitivity

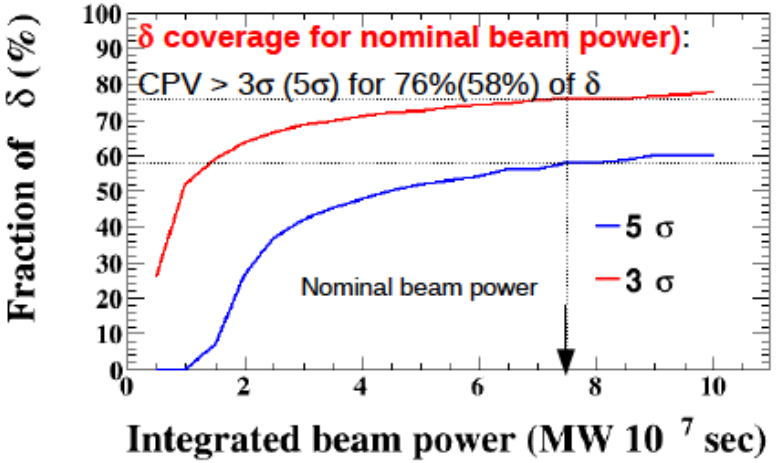
Prog. Theor. Exp. Phys. 2015, 053C02



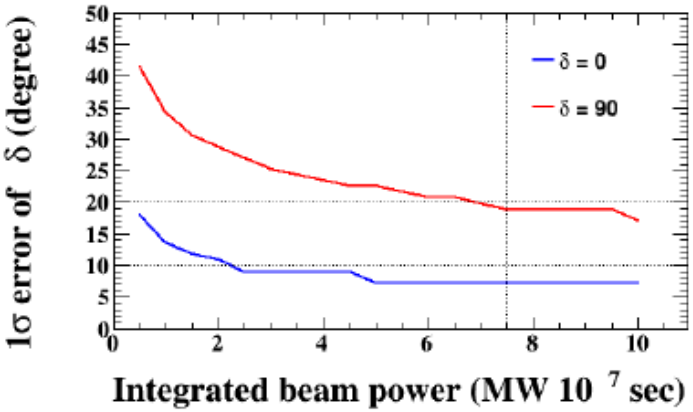
CPV discovery sensitivity to δ_{CP}=0,π w/ MH known

Errors (%) on the expected number of events				
	ν mode		$\bar{\nu}$ mode	
	ν_e	ν_μ	ν_e	ν_μ
Flux & ND	3.0	2.8	5.6	4.2
ND-independ. xsect	1.2	1.5	2.0	1.4
Far Detector	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

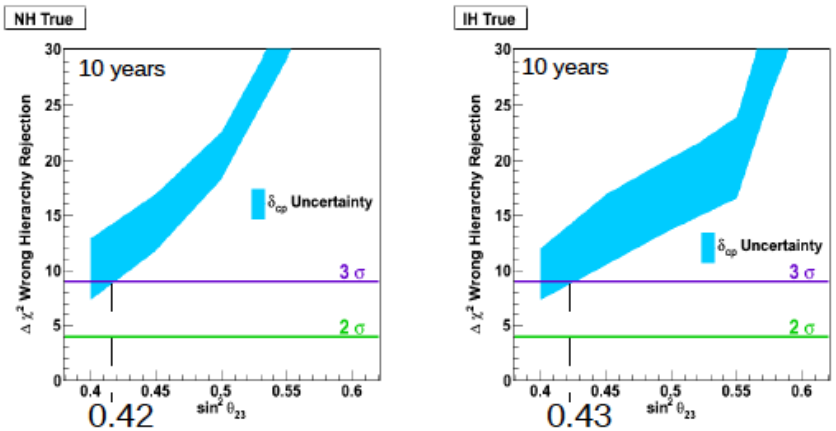
Fractional region of δ(%) for CPV (sin δ≠0) > 3,5 σ

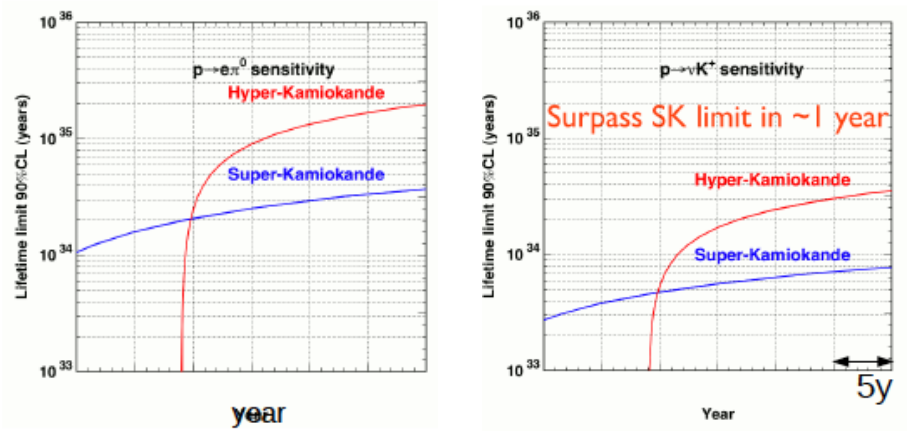


1σ uncertainty of δ as a function of the beam power: < 19°(6°) for δ = 90°(0°)



Hyper-K: Physics





Mass Hierarchy (MH) sensitivity

- Use atmospheric neutrinos for 3σ MH determination
- 3σ MH determination for $\sin^2\theta_{23}$ > 0.42 (0.42) for NH(IH) for 10 yr data
- Combine with beam data for enhanced sensitivity

Proton decay sensitivity

- 10 times better sensitivity c.f. Super-K
- Hyper-K sensitive to every single mode

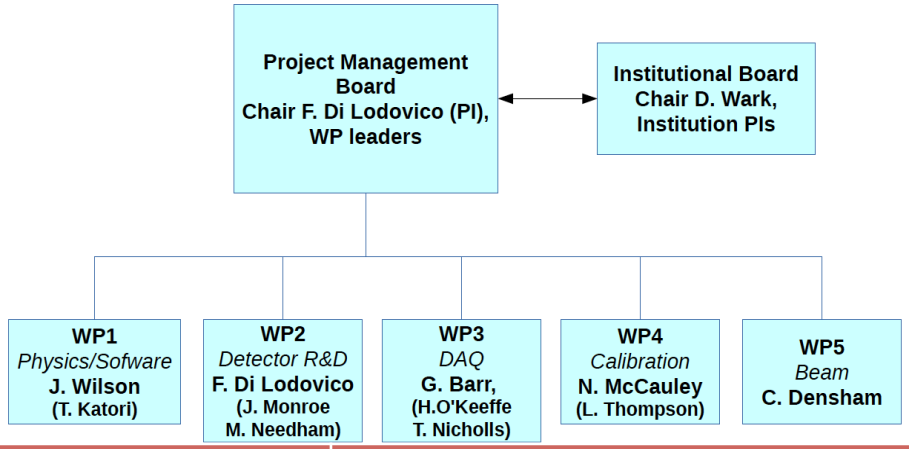
Hyper-K other physics

Other measurements

- Supernova burst neutrinos: 200,000 neutrinos from 10 kpc supernova
- Supernova relic neutrino search: 830 events in 10 years in 10-30 MeV range
- Solar neutrinos: 200 ^{8}B neutrinos per day
- Octant of θ_{23} i.e. is θ_{23} maximal
- Indirect dark matter searches
- Atmospheric neutrinos
- Cross sections and neutrino nucleus interactions (mainly at ND)
- Over-constraining the PMNS Unitarity with HyperK
- Search for transient astrophysical phenomena: solar flares, GRBs, etc.

Hyper-K in the UK

UK is 2nd largest group in the collaboration, after Japan



UK leadership in collaboration:

Co-Project leader (Di Lodovico)

IBR chair and Steering committee co-chair

Convenerships:

Calibration, near detectors, software.

Work Package	Deliverables
WP1: Physics and computing	Sensitivity studies with integrated near detectors. Computing infrastructure for managing software and simulated data production chain. Mock data challenge.
WP 2: Detector R&D	Design of TITUS Gd-doped WC intermediate detector. Design of HPTPC near detector.
WP 3: DAQ	Design of functional, flexible system that will meet physics requirements of experiment
WP4: Calibration	Delivery of fibre-coupled pulsed light source and pseudo muon source
WP5: Beam	Identify critical material issue for reliable beam window and target operation at multi-MW beam power.

PRD request made from joint DUNE/HK HPTPC working group

Super-K/Hyper-K in the UK

Lancaster University

Sub-set of UK groups in discussion with Super-K management to join collaboration. Synergy with UK Hyper-K work.

(decision expected Nov. 2015)

Beneficial to Hyper-K -> would provide environment for testing

Expansion of current T2K activities

Considered part of UK Hyper-K effort

Physics and Software (WP1): Work on systematics method to help oscillation analysis, analysis/software w/ and w/o gadolinium.

Detector R&D (WP2): Gain familiarity with Gd-doped detectors (Super-K and EGADS)

Calibration (WP4): Implement and test hardware develop calibration strategies

ANNIE/Hyper-K in the UK

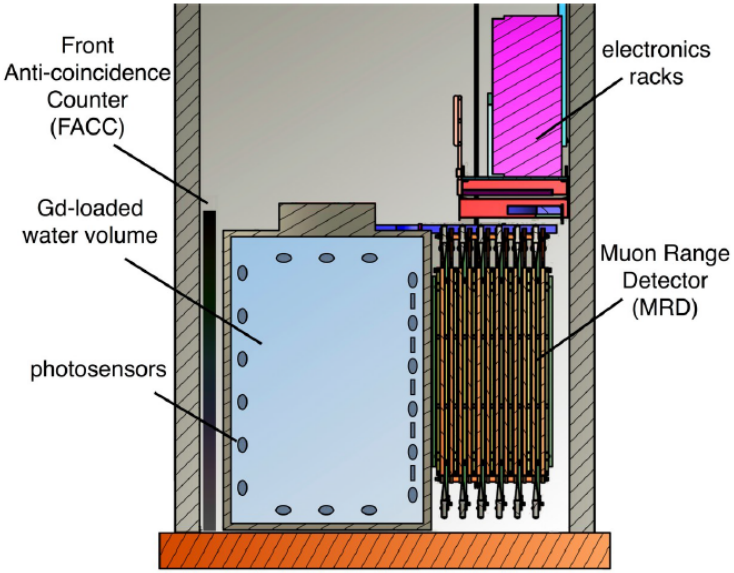
Sub-set of UK group joining ANNIE due to synergy with Hyper-K work

Gd-doped water Cherenkov detector with downstream MRD in the SciBooNE hall

(Fermilab)

Test Large Area Picosecond Photodetectors (LAPPDs)

Measure neutron multiplicity in ν_μ interactions



5 year project

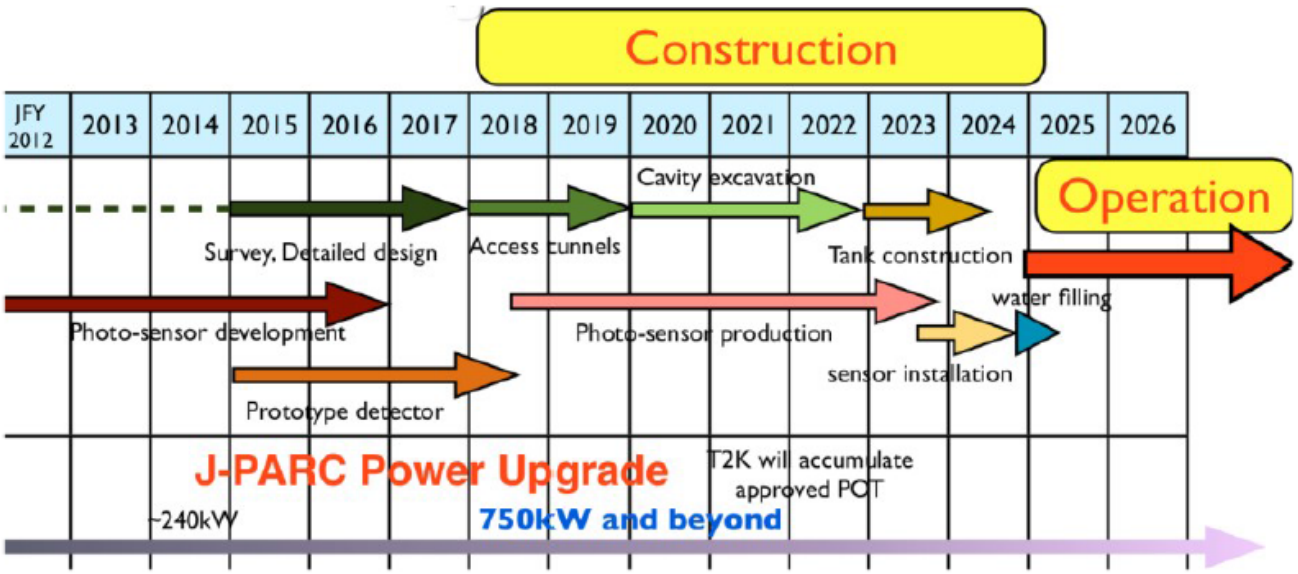
Test as many LAPPDs as available

Measure neutron multiplicity

UK leadership in Software and DAQ design and construction

Phase I approved by Fermilab, bid to DoE for consideration in intermediate Neutrino Research Programme in HEP for phases II and III (Sept. 2015)

Hyper-K timeline



Writing design report

- Detailed description of the experiment and physics potential
- Internationally reviewed

Strong support from Japan

- KEK-IPNS and UTokyo-ICRR signed an MoU for cooperation on the Hyper-Kamiokande project
- Hamamatsu getting ready for PMT mass production

Conclusions

Lancaster University

Significant amount of UK activity in LBL neutrino experiments

UK is often largest contributor after host country

UK holds major leadership positions in most experiments

Definitive measurement of most mixing parameters

Still unanswered questions

Measurement of δ_{CP} is next major goal

Current experiments should provide hints

Discovery in next generation of experiments

Physics from future experiments HK or DUNE until 2025/2026

T2K, NOvA and MINOS+ represent the only LBL physics this country has for the next decade

Lots of interesting physics for LBL experiments

Oscillations, cross sections. Critical for next generation