# Long Baseline Neutrino Experiments

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# Long Baseline Neutrino Experiments

- Three neutrino mixing
- Where we are … projects with current UK involvement
  - T2K
  - MINOS / MINOS+
  - NO$\nu$A
- Where we're going … future projects with proposed UK involvement
  - HyperK
  - LNBE
  - LBNO
  - CHIPS

# 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

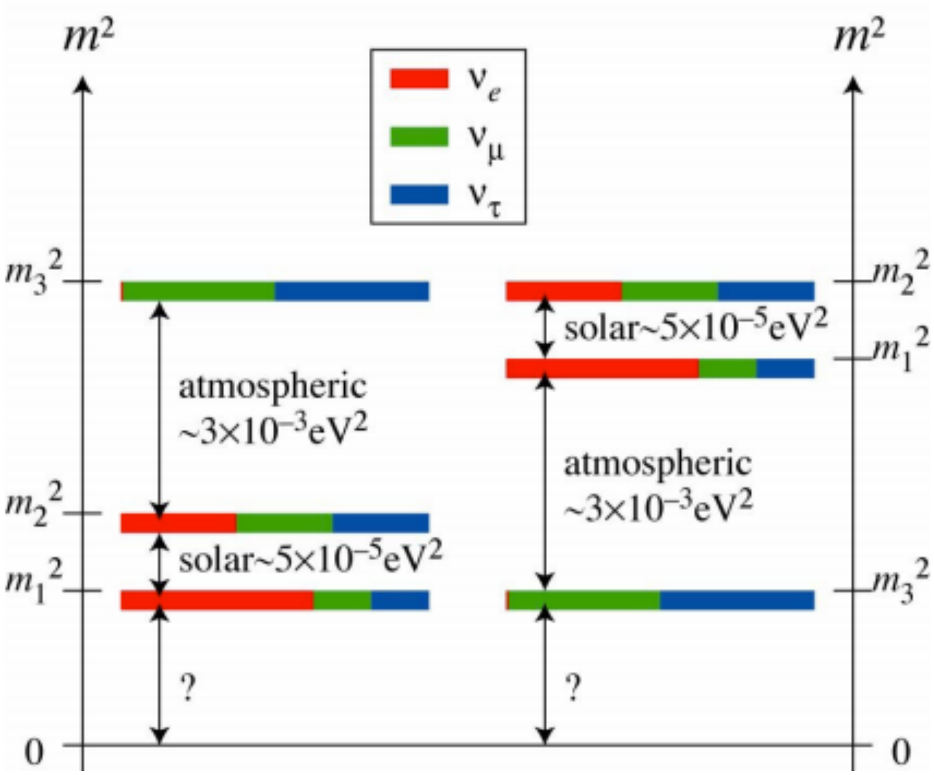
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$, $\delta$=CP violating phase

- 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

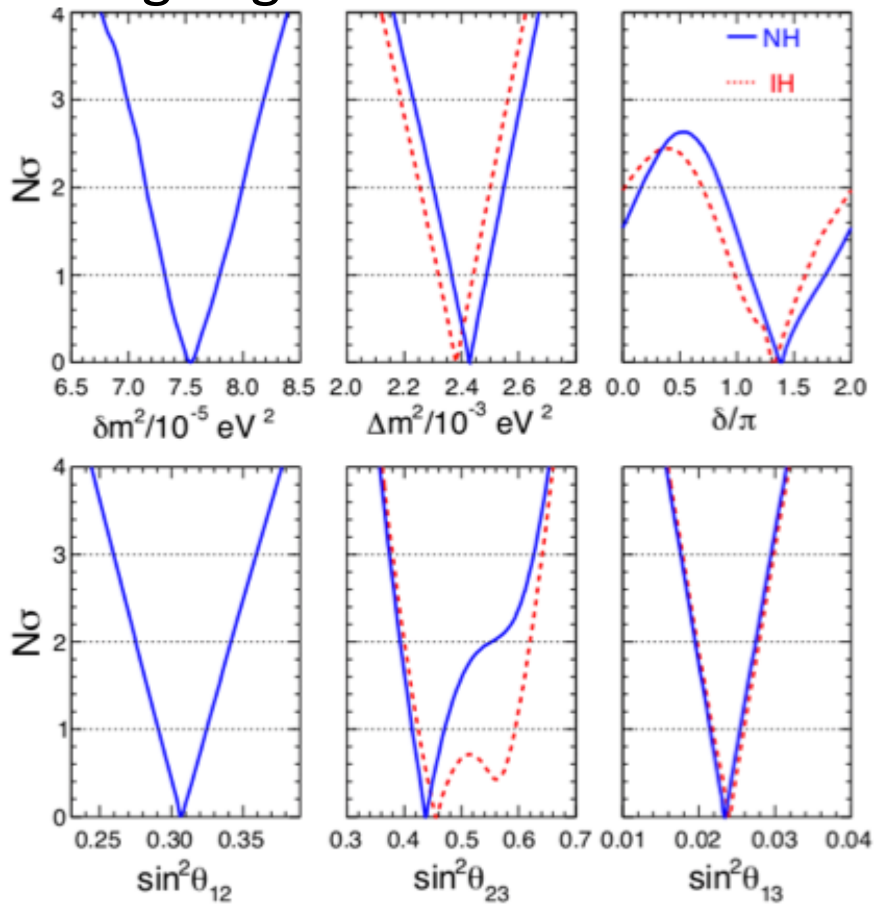
# Current understanding

## Mass hierarchy




Normal Inverted

## Mixing angles and mass differences




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

# Long baseline accelerator neutrino physics

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

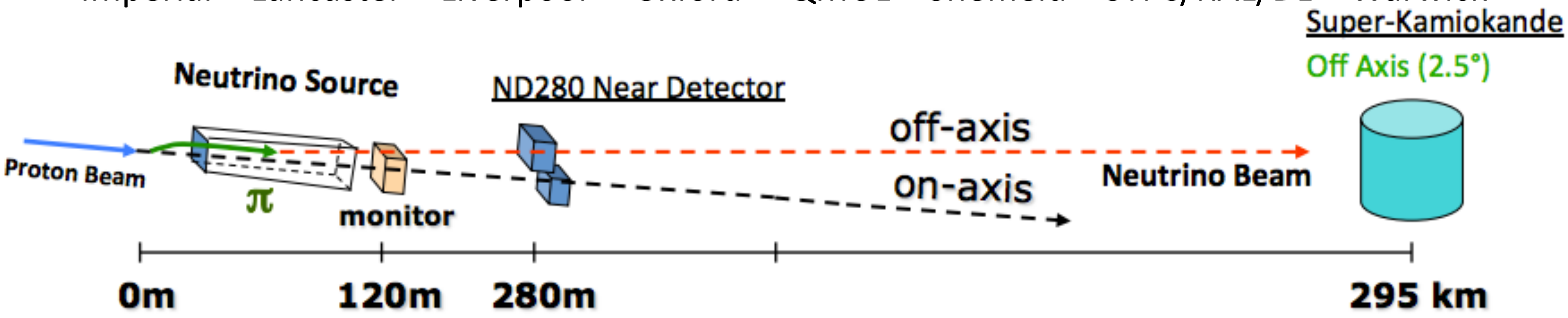
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1 - \cos^2(\theta_{13}) \times \sin^2(\theta_{23})]\sin^2(1.267\Delta m^2 L/E_\nu)$$

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

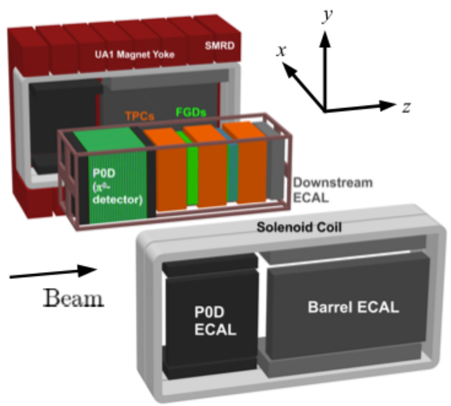
$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\sin\delta_{CP}$$

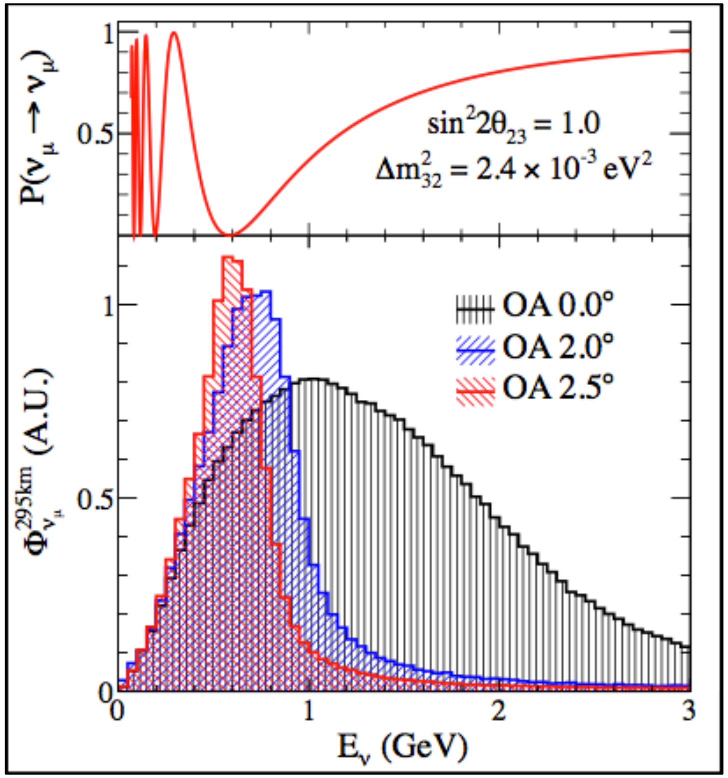
# T2K (Tokai to Kamioka)

Imperial • Lancaster • Liverpool • Oxford • QMUL • Sheffield • STFC/RAL/DL • Warwick



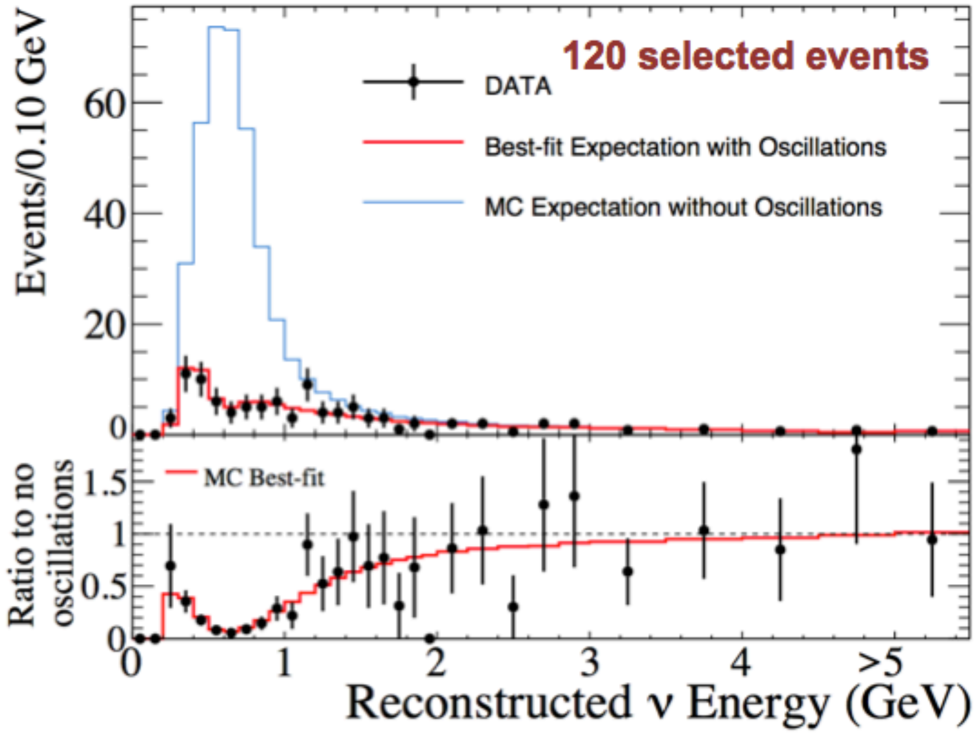

- 295km long baseline experiment
- Uses 2.5° off-axis $\nu_\mu$ ($\overline{\nu}_\mu$) beam
- Data-taking started in 2009
- UK contribution to near detector (ND280) includes:
  - Electronics
  - DAQ
  - ECAL
- SK far detector

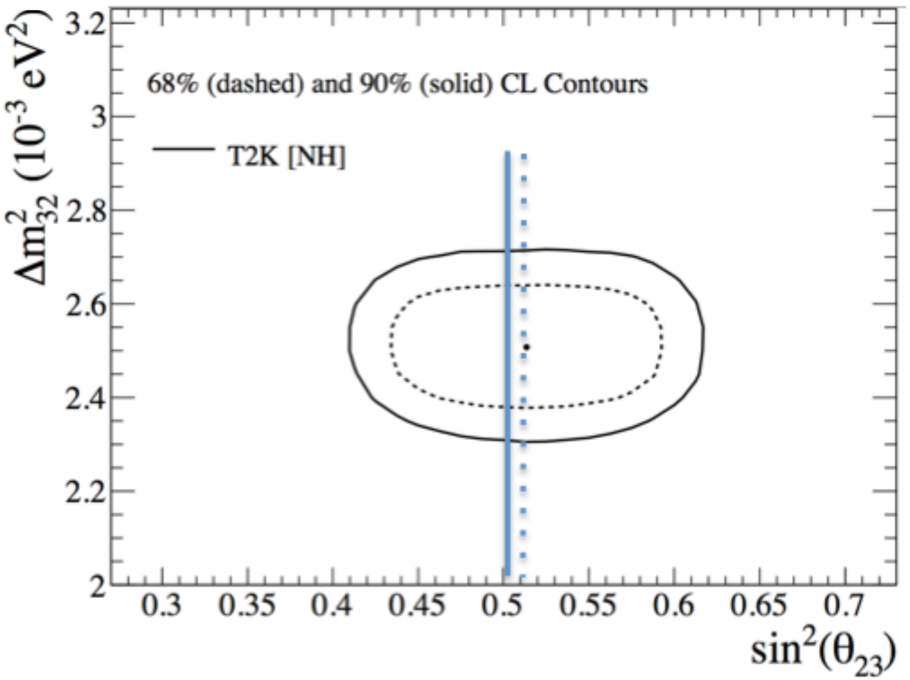


# T2K $\nu_\mu$ disappearance results

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

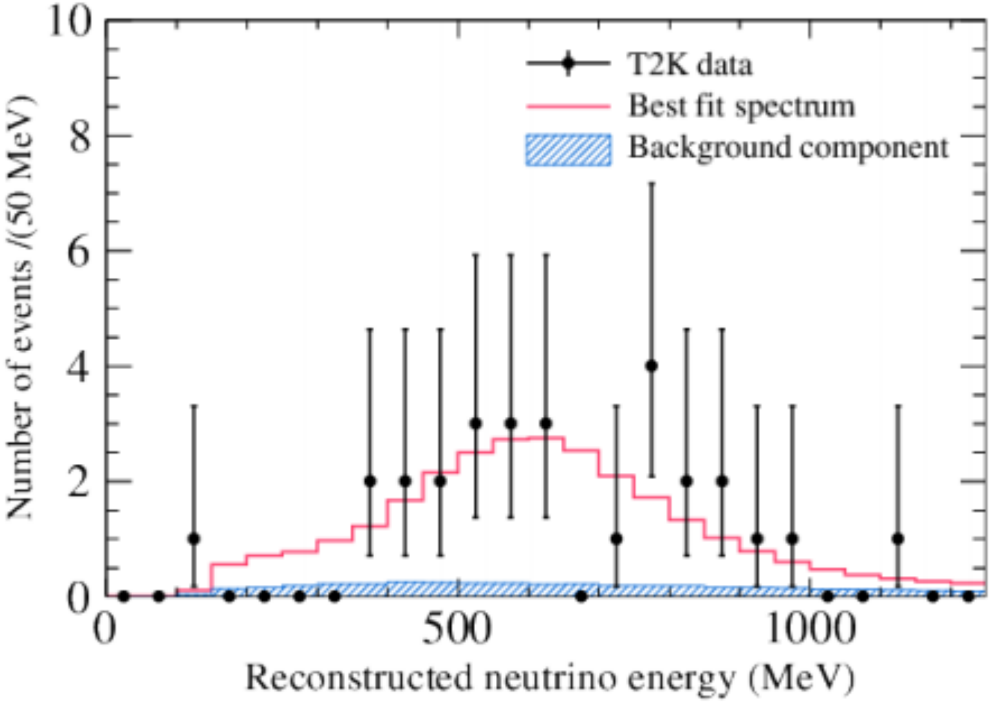


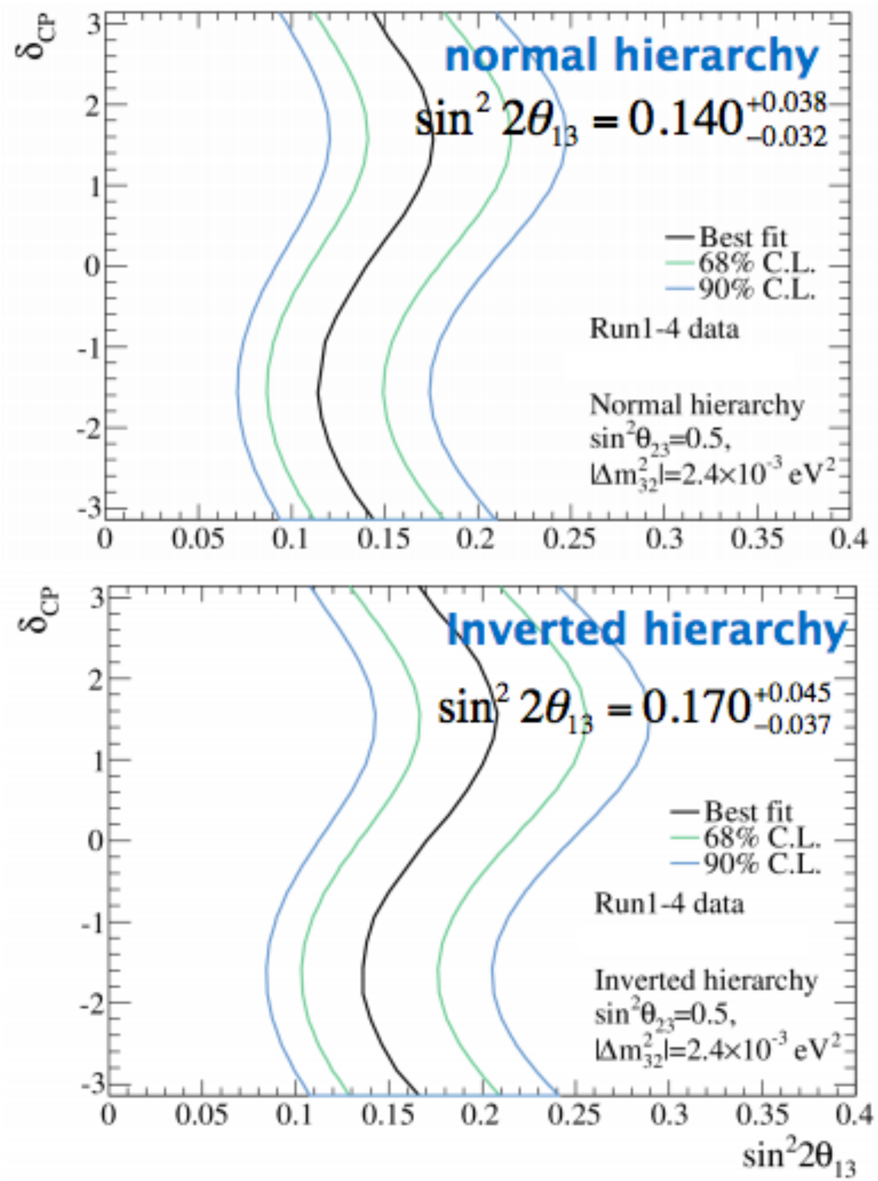




- Best fit values:
  - $\sin^2\theta_{23}$ (NH) = 0.514
  - $\Delta m^2_{32}$ (NH) = $2.51 \times 10^{-3}$ eV$^2$

Analysis published in Phys. Rev. Lett. 112, 181801 (2014)

# T2K $\nu_e$ appearance results

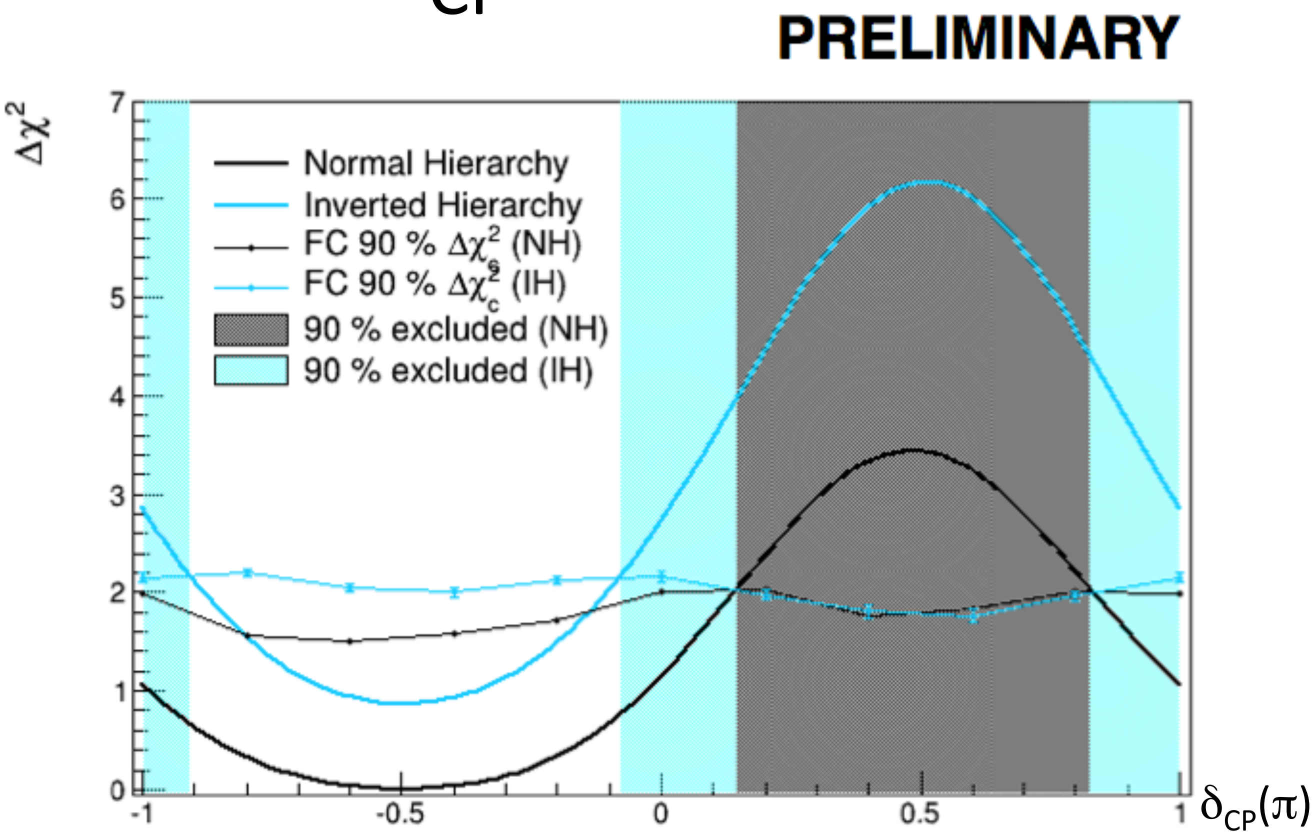



- 4.92 ± 0.55 background events expected (no oscillations)
- 28 events observed
- 7.3$\sigma$ significance for non-zero $\theta_{13}$
- First observation (> 5$\sigma$) of an appearance channel signal

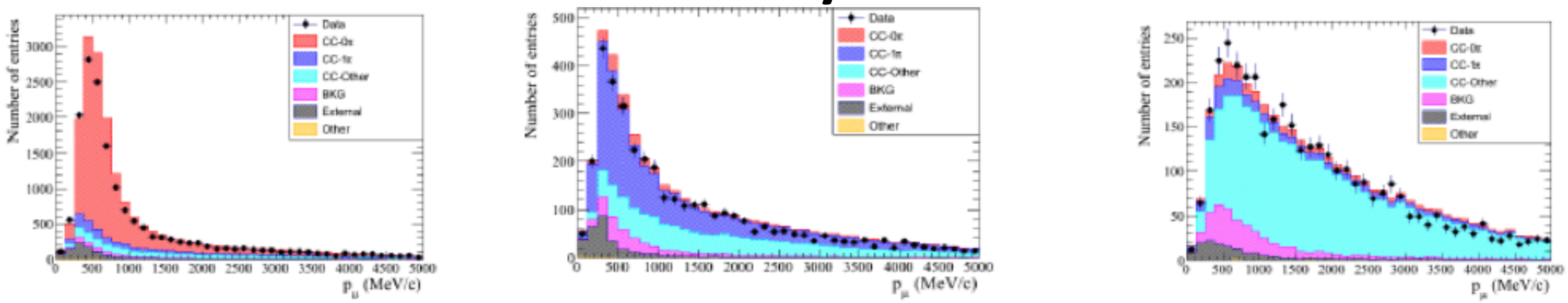
Analysis published in Phys. Rev. Lett. 112, 061802 (2014)

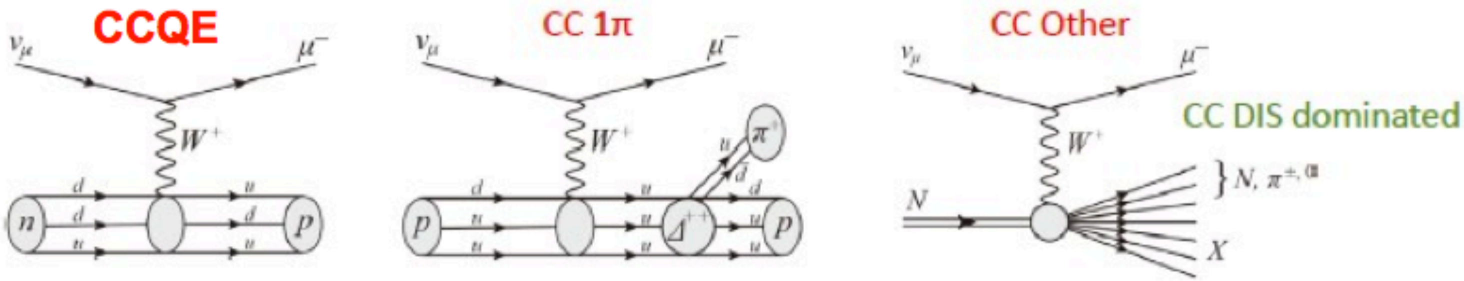
# T2K $\delta_{CP}$ constraints




- 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

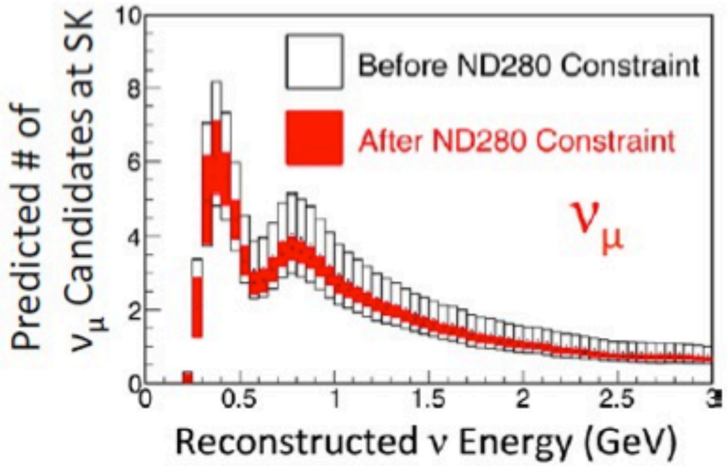
# T2K ND280 and systematic errors

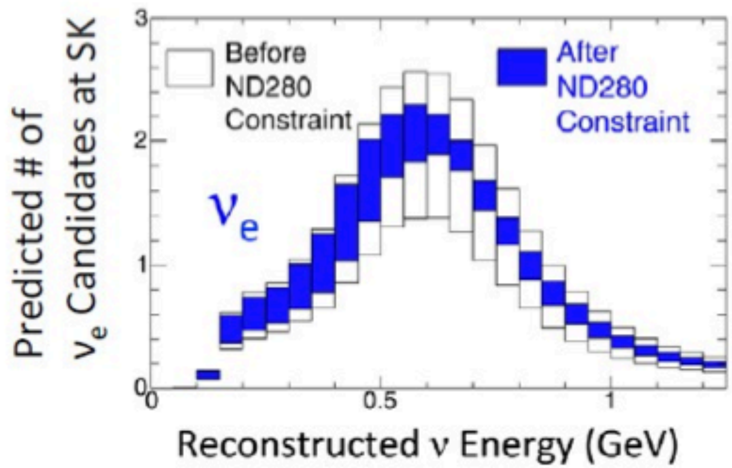



Signal channel for oscillation analysis

Flux and cross-section systematic uncertainty on $N_{SK}$ significantly reduced to ~7%

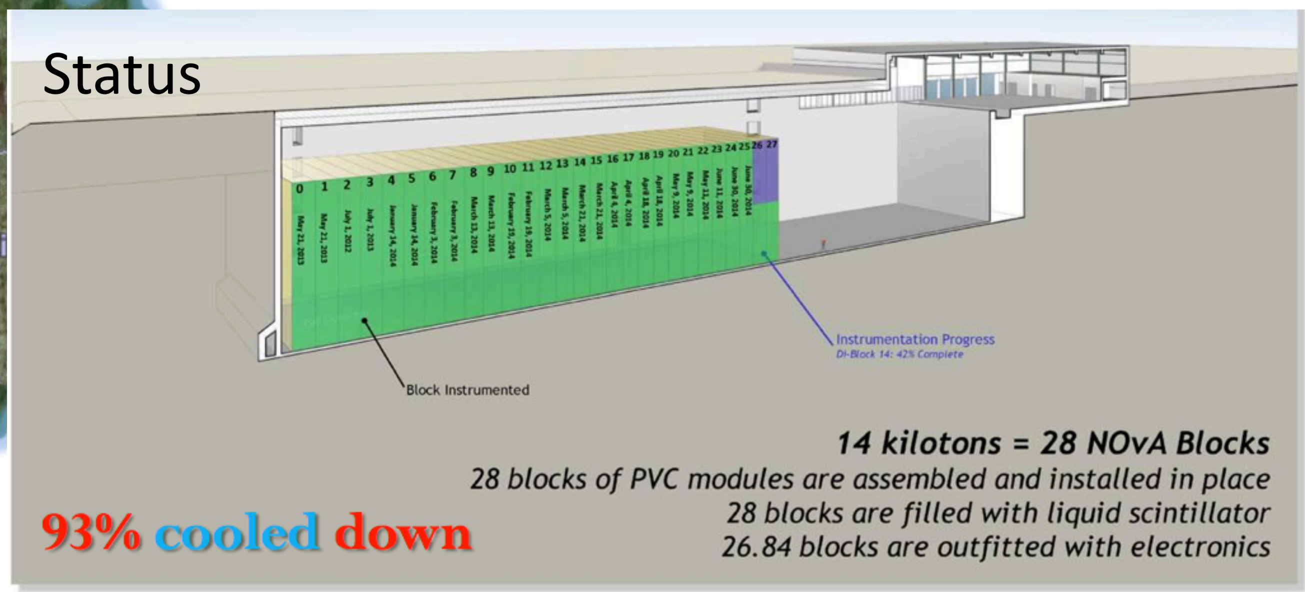


# NOνA experiment and status

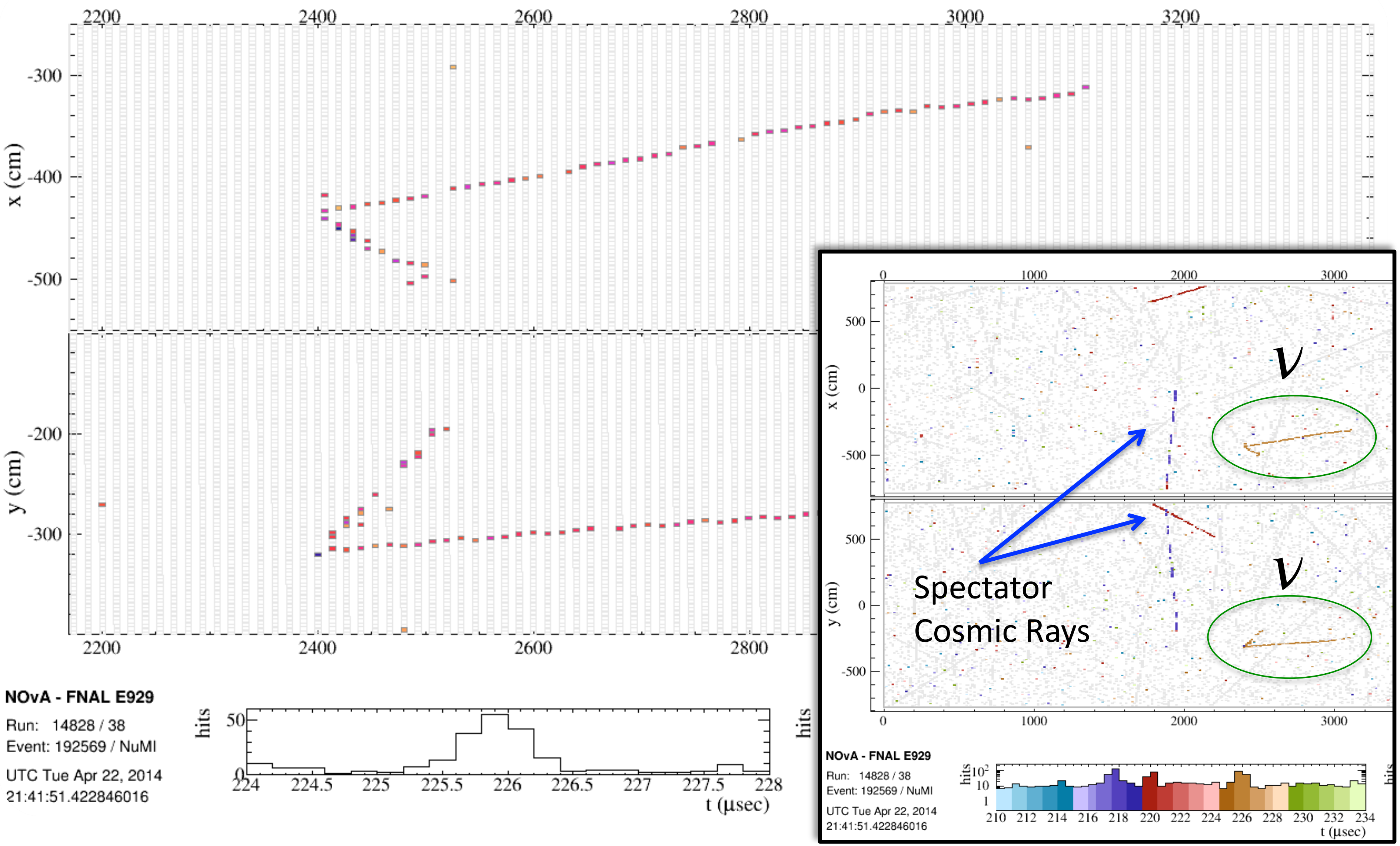

Sussex

- 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

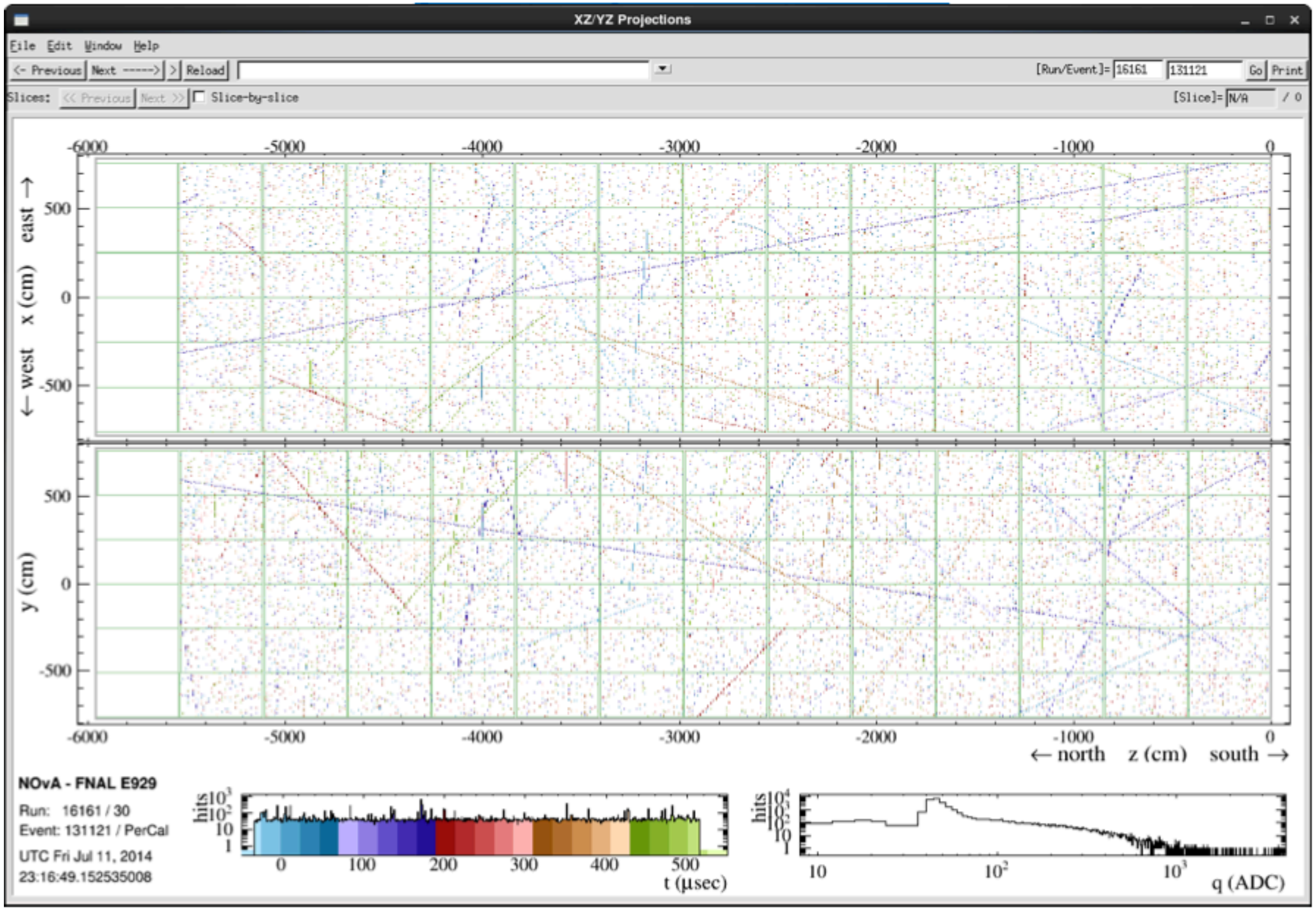



- 93% of APDs cooled down to -15C
- Final di-block (1kt) being instrumented now
- 1-2 month accelerator shutdown in October, 500kW beam expected afterwards
- UK contribution: data driven trigger, stopping muon calibration, $\nu_\mu$ analysis

# NOvA CC candidate event

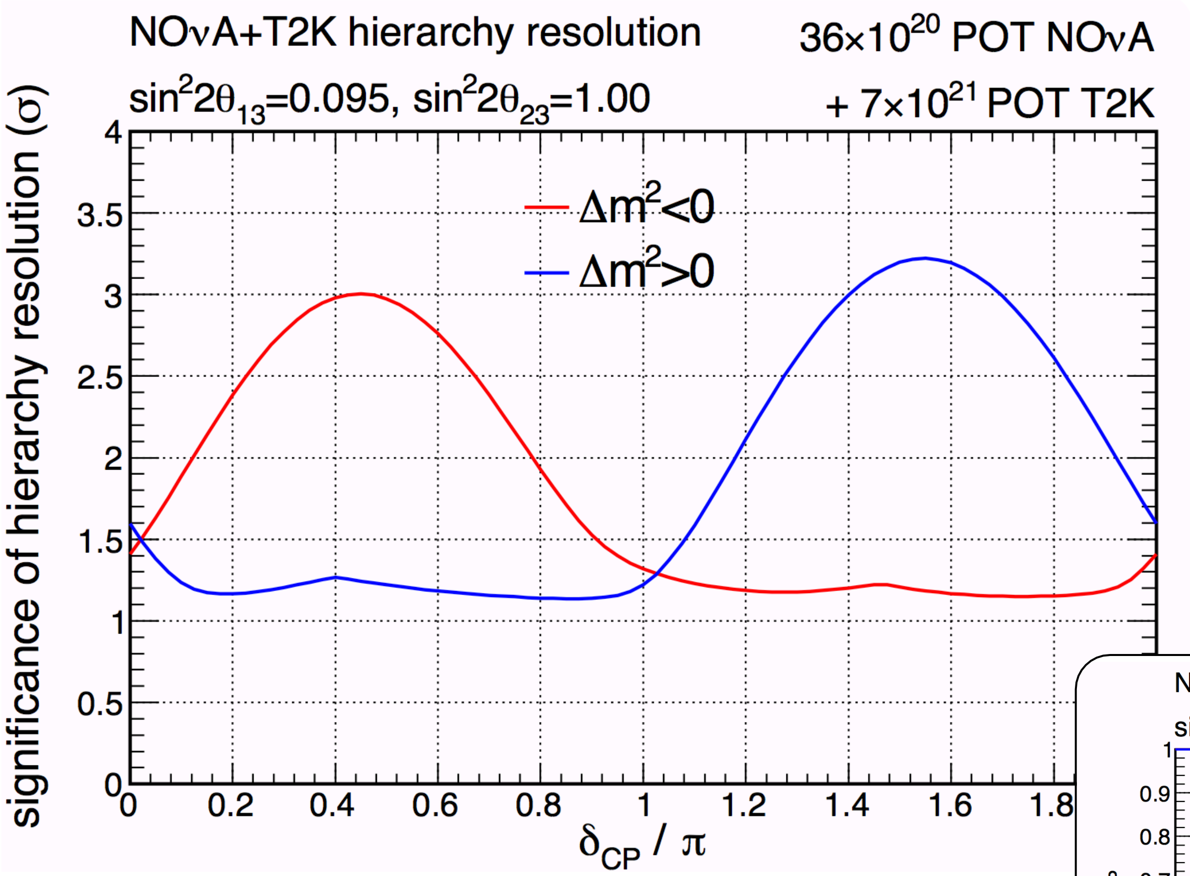


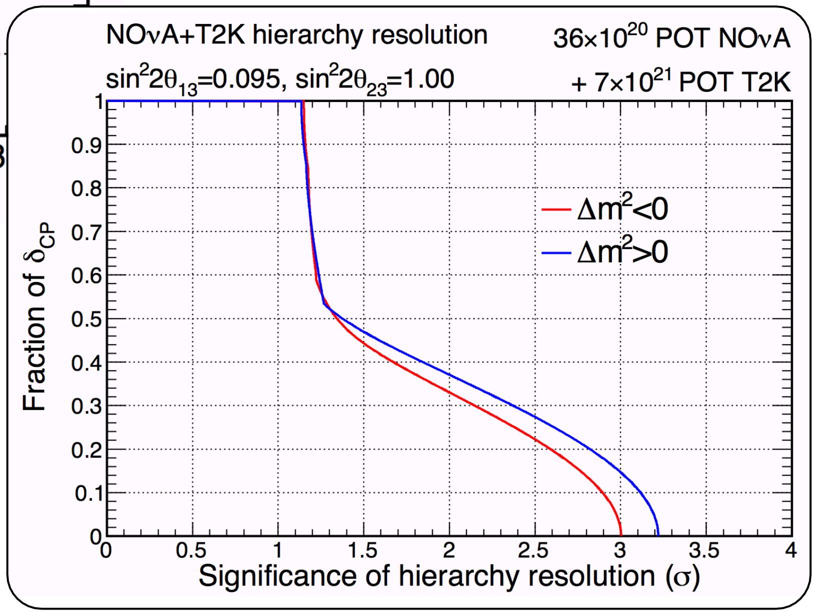
# NOvA cosmic muon event




- 55m long cosmic ray muon passing through the 13 di-block detector configuration

# NOνA and T2K complementarity



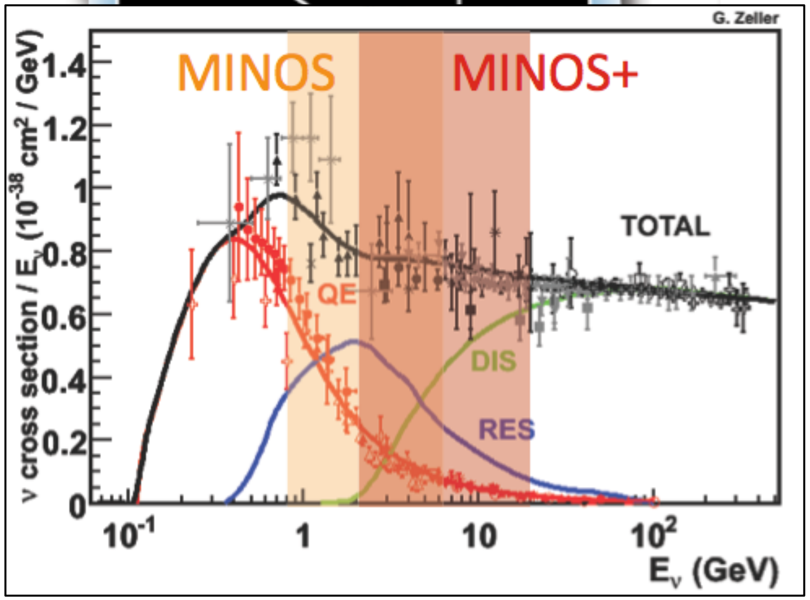




- Combining NOνA and T2K data helps break degeneracies and improves coverage in the overlap regions

# MINOS / MINOS+

Cambridge • Oxford • STFC/RAL • Sussex • UCL

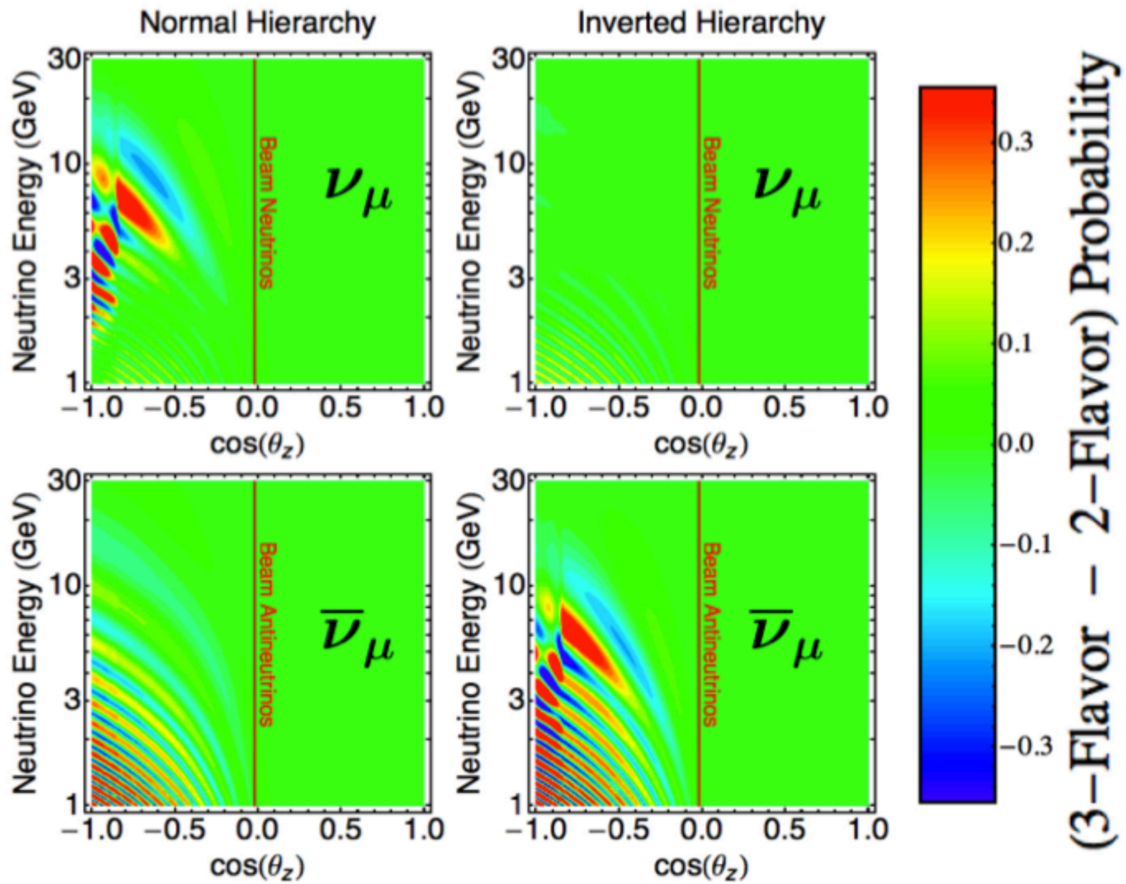

- MINOS
  - 735km baseline, FNAL to Soudan
  - 1kt near detector 1km from source
  - 5.4kt far detector
  - Both ND and FD are steel-plastic scintillator calorimeters
  - UK contributions
    - DAQ, electronics, PMT testing, light injection
- MINOS+
  - Uses updated NUMI beamline
  - Higher energy (cross-checks with different beam and cross-section systematics
  - More statistics (4000 $\nu_\mu$ CC events/ year in far detector)



# MINOS/MINOS+ 3 flavour oscillation analysis

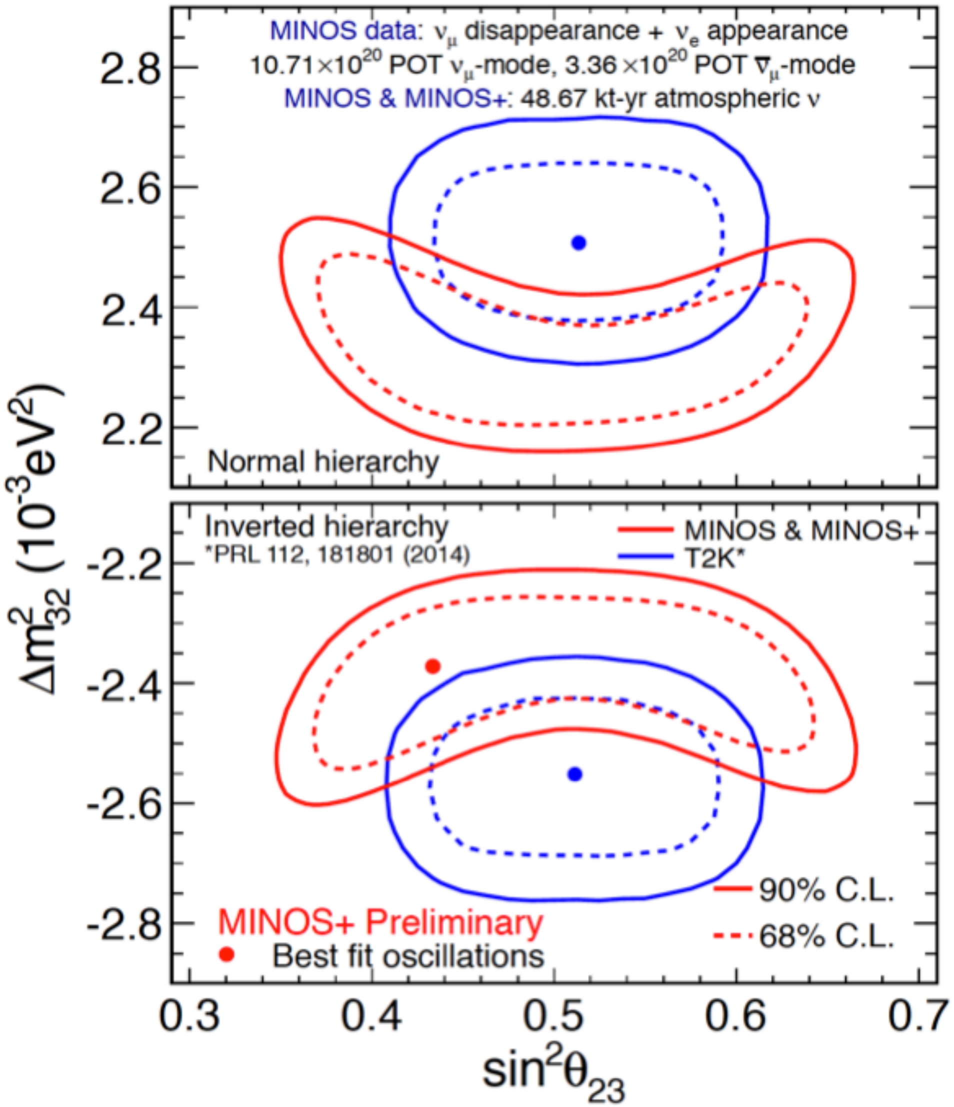
- Analysis combines:
  - Full MINOS $\nu_\mu$-CC and $\bar{\nu}_\mu$-CC disappearance sample - *PRL **112**, 191801 (2014)*
  - Full $\nu_e$-CC, $\bar{\nu}_e$-CC appearance sample, described in *PRL **110** 171801 (2013)*
  - Full MINOS and **new MINOS+ atmospheric neutrino samples**

- Sensitive to $\theta_{13}$, $\theta_{23}$ octant, mass hierarchy, and $\delta_{CP}$ from $\nu_e$ sample
- Sensitivity enhanced by atmospherics:
  - Matter effects in multi-GeV, upward-going events
  - Effect seen in neutrinos or antineutrinos, depending on hierarchy
- MINOS first to probe effect with event-by-event charge separation




Sousa, Neutrino 2014

# MINOS/MINOS+ combined fit




**Three-Flavor Oscillations Best Fit**

**Inverted Hierarchy**

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

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

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

**Normal Hierarchy**

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\mathrm{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

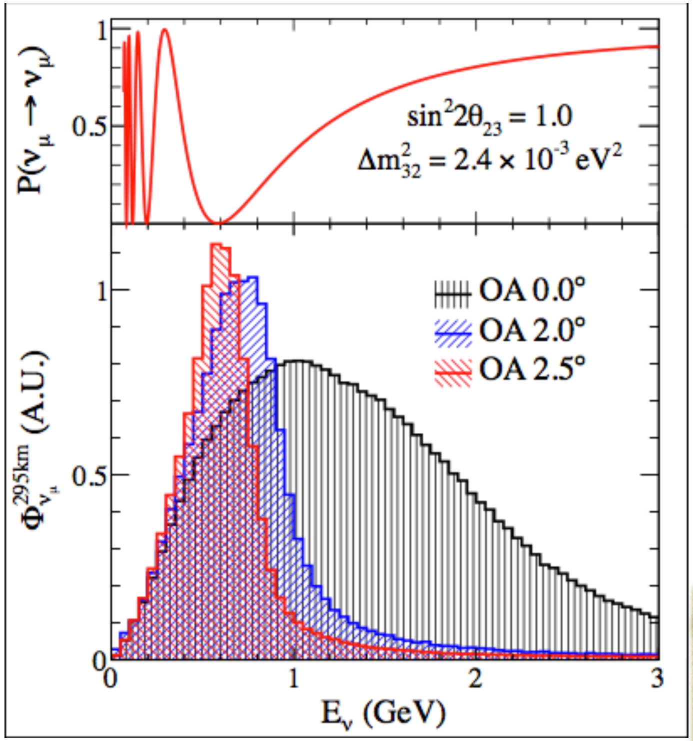
$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

- **Most precise measurement of $|\Delta m^2_{32}|$**
- Consistent with maximal mixing

Sousa, Neutrino 2014

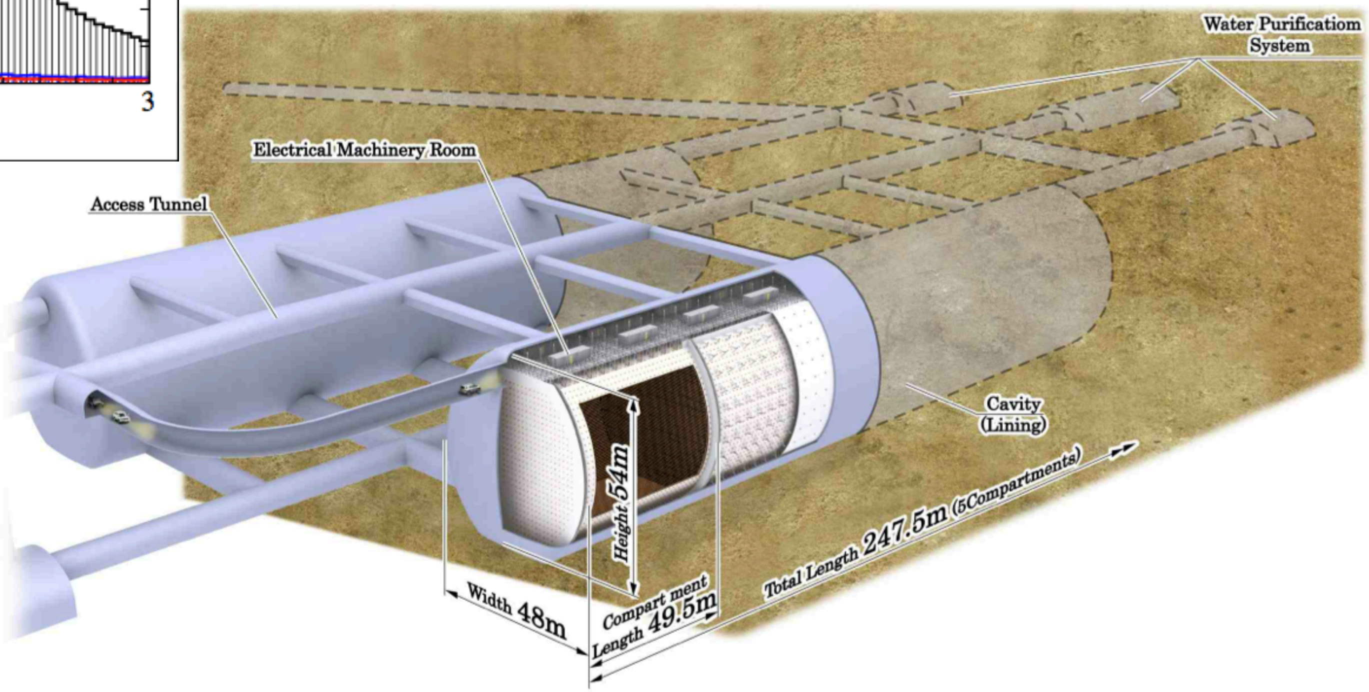
- Other interesting results on sterile neutrinos, etc.

# HyperK beam and detector

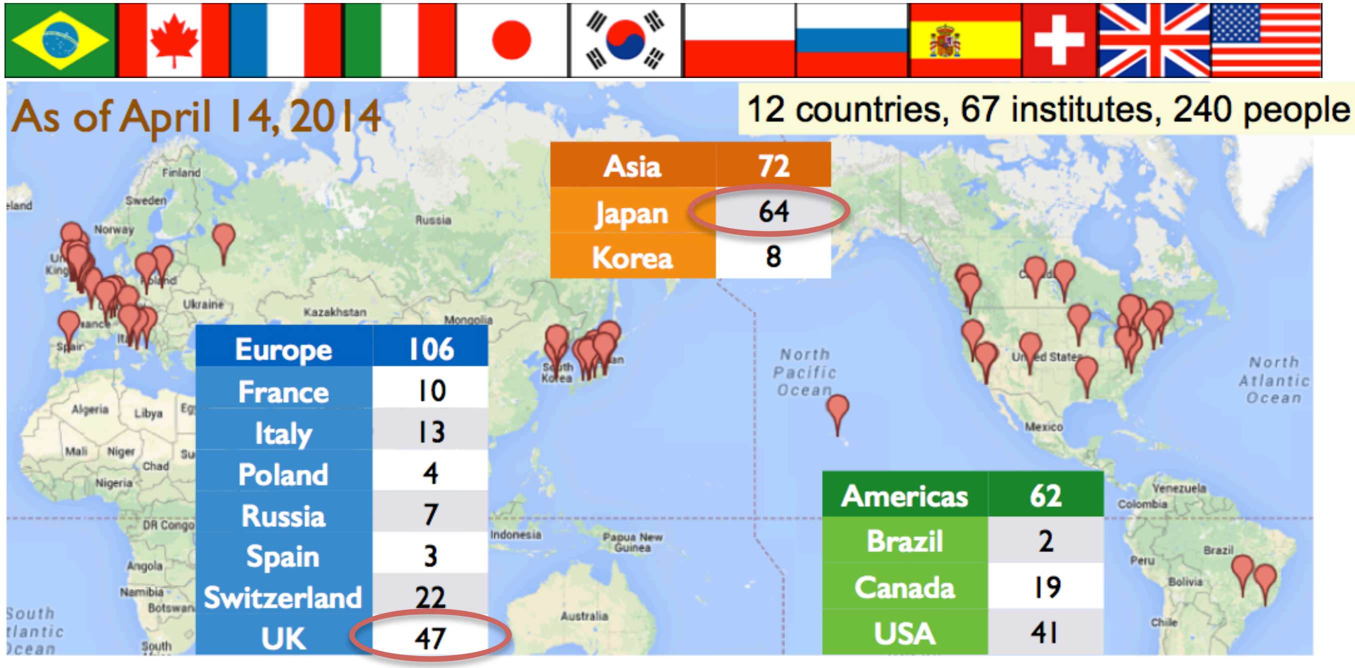



- 295km baseline
- Large volume water Cerenkov
- 990kT total volume
- 560kT fiducial volume
- 99,000 PMTs (20% coverage)
- 10 optically isolated compartments each x2 SK

- J-PARC $\nu_\mu$ ($\overline{\nu}_\mu$) beam upgraded to ≥ 0.75MW
- 2.5° off-axis, narrow band 600MeV beam

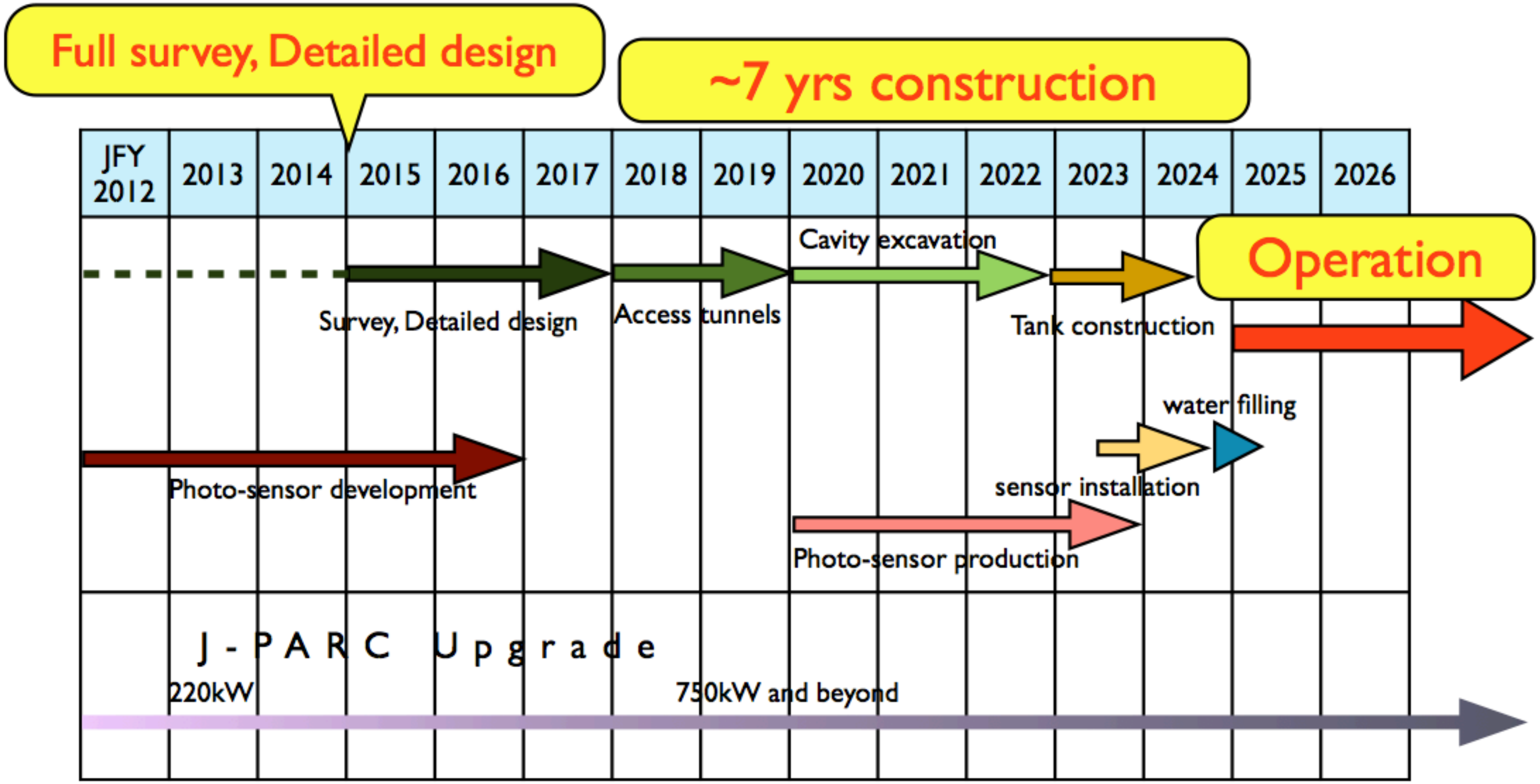


# HyperK status


- 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 International Working Group >240 people
- Funding requests submitted in UK, EU, Canada and Switzerland
- UK represents the second largest group of scientists after Japan

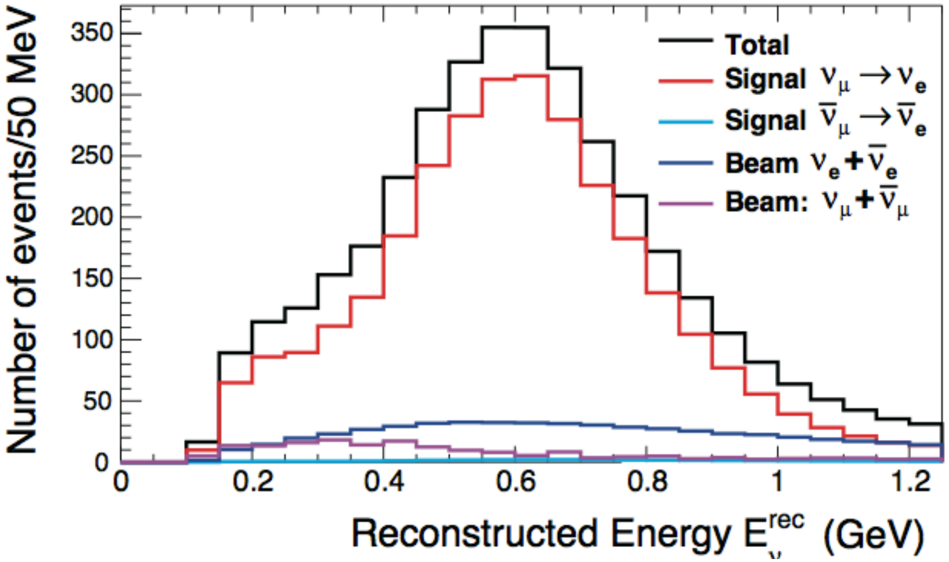
# HyperK timeline



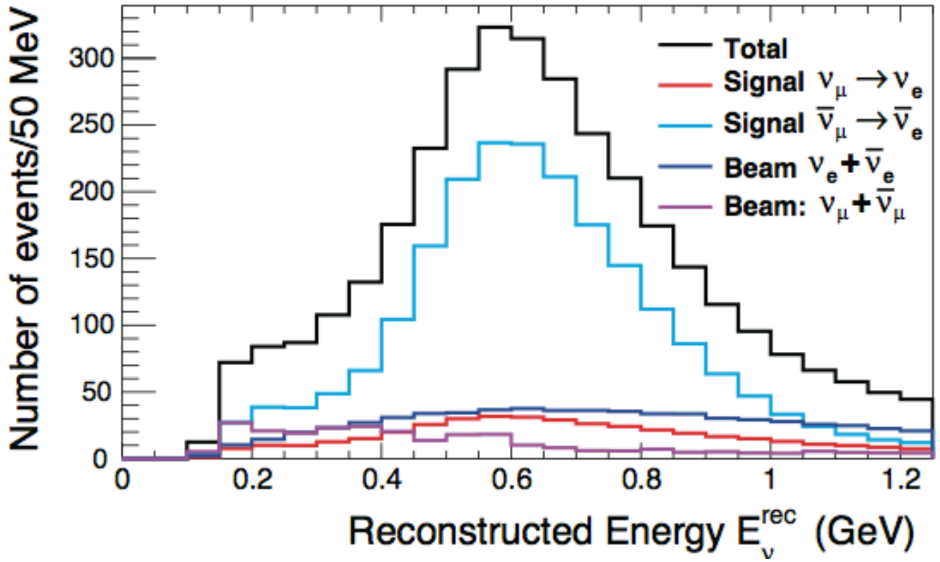

- 2015 Full survey, Detailed design (3 years)
- 2018 Excavation start (7 years)
- 2025 Start operation

# HyperK appearance and disappearance events

**Appearance $\nu_e$ events**




**Appearance $\bar{\nu}_e$ events**

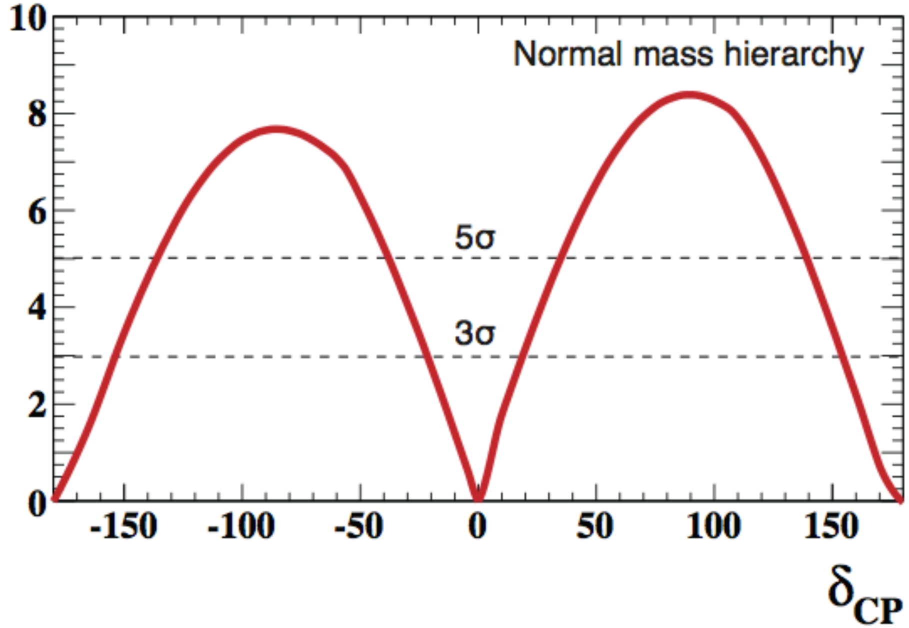


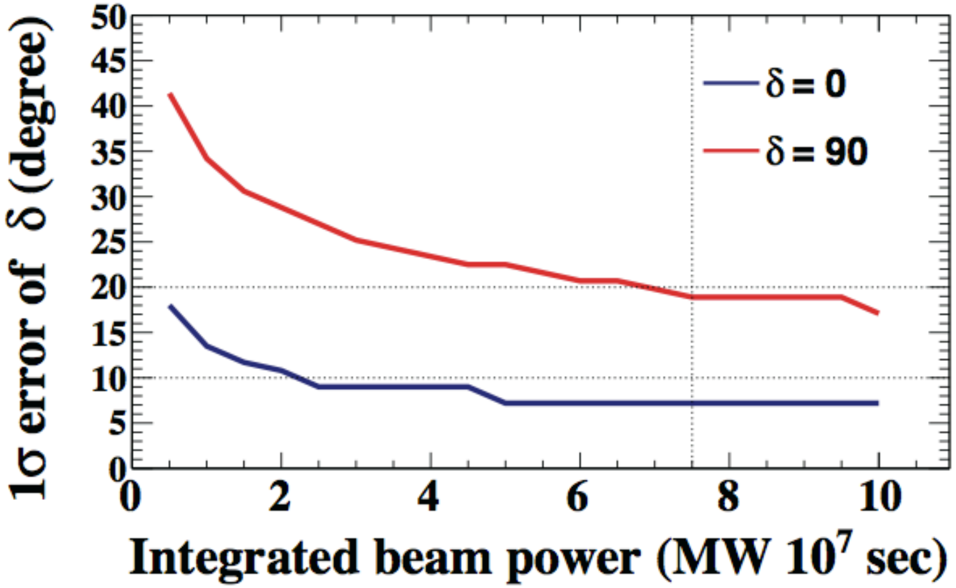

| Appearance | Signal | | Background | | | | Total |
|---|---|---|---|---|---|---|---|
| | $\nu_\mu \rightarrow \nu_e$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | $\nu_\mu$ | $\bar{\nu}_\mu$ | $\nu_e$ | $\bar{\nu}_e$ | |
| $\nu$ mode | 3016 | 28 | 168 | 9 | 508 | 21 | 3750 |
| $\bar{\nu}$ mode | 396 | 2110 | 86 | 179 | 226 | 400 | 3397 |

| Disappearance | $\nu_\mu$ | $\bar{\nu}_\mu$ | $\nu_e+\bar{\nu}_e$ | Total |
|---|---|---|---|---|
| $\nu$ mode | 18142 | 1136 | 94 | 19372 |
| $\bar{\nu}$ mode | 10640 | 16255 | 69 | 26964 |

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

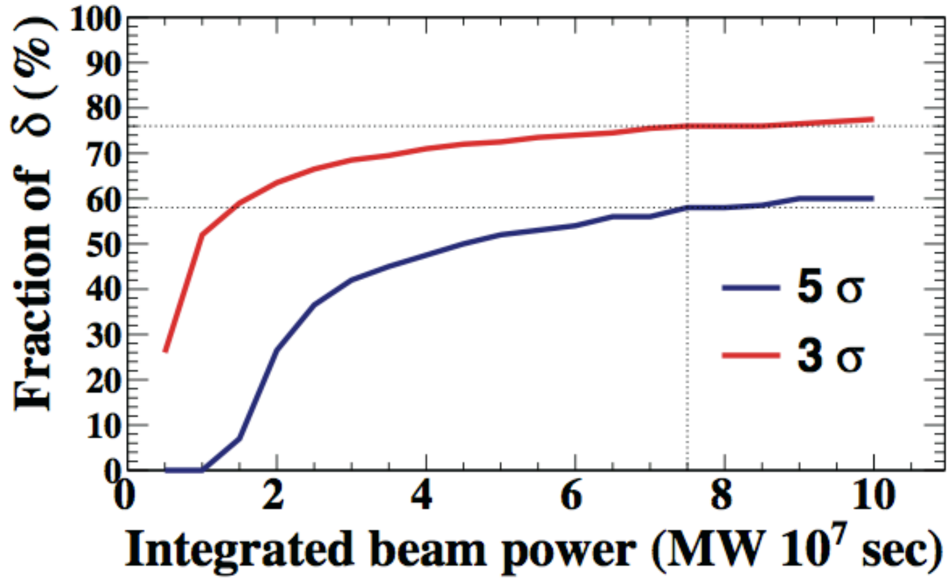
# HyperK sensitivity to CP




Assuming 7.5x$10^7$ MW sec:

- CP violation can be observed at
  - **3σ** for **76%** values of δ
  - **5σ** for **58%** values of δ
- δ can be measured with
  - 8° precision for δ = 0
  - 19° precision for δ = π/2



# HyperK UK involvement

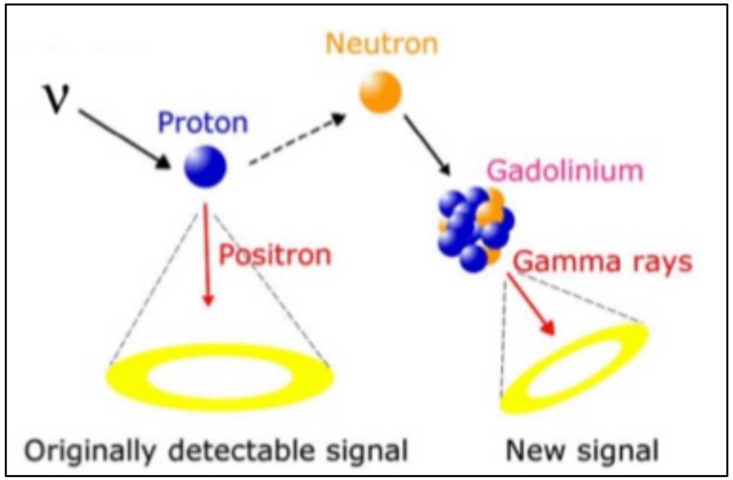
Edinburgh • Imperial • Lancaster • Liverpool • Oxford

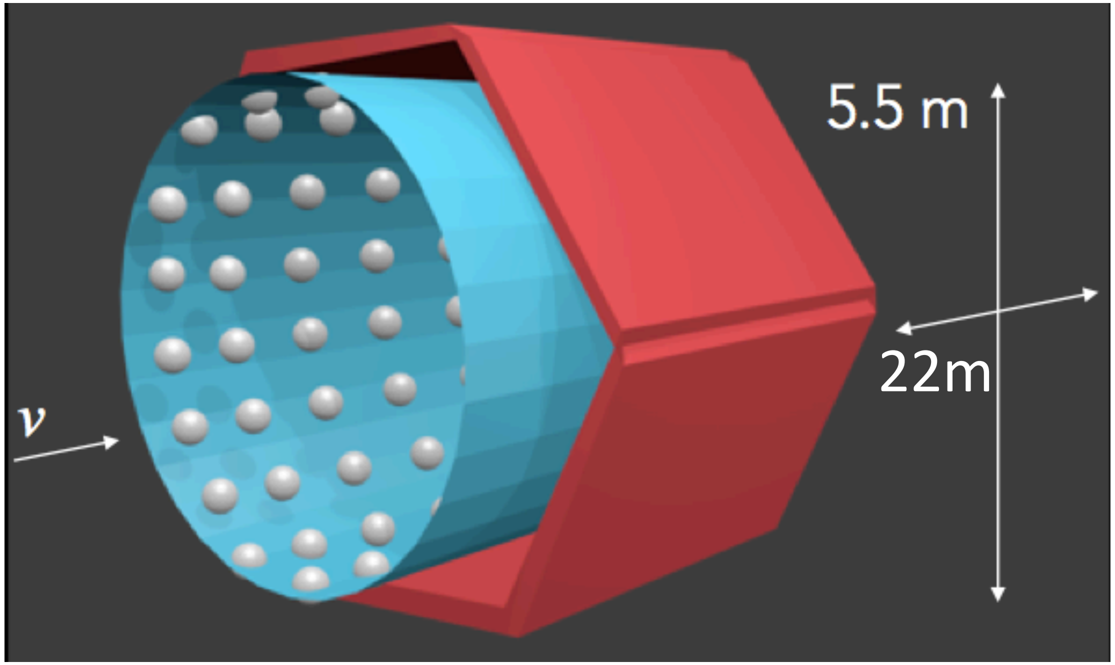
QMUL • RHUL • Sheffield • STFC/RAL • Warwick

| Work Package | Deliverables |
|---|---|
| WP1: Physics, Software and Computing | interface GENIE neutrino interaction generator with Hyper-K; software release and data distribution |
| WP2: Detector R&D | 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. |
| WP3: DAQ | 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. |
| WP4: Calibration | Delivery of a fibre-coupled pulsed light source; Fixed point diffuser; Pseudo-muon light source. |
| WP5: Beam | 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 |

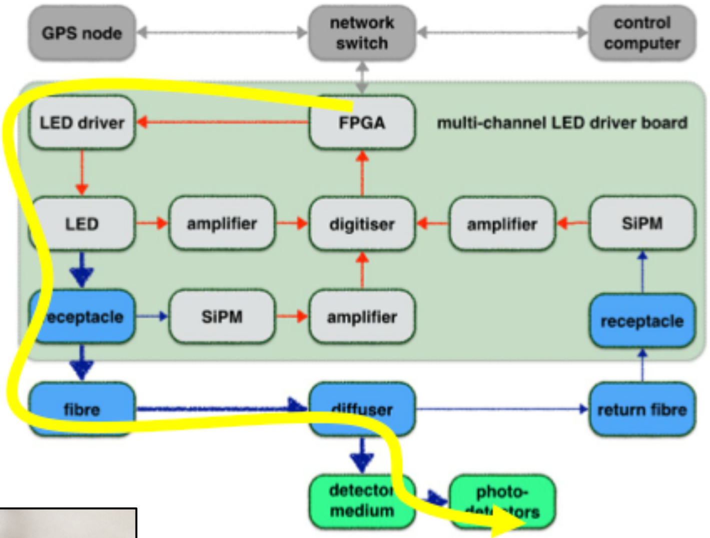
# HyperK UK WP2 Detector R&D

- TITUS
  - 2kt Water Cerenkov near detector instrumented with HPCs and LAPPDs situated at 2km from beam source
  - Possibly Gd doped to improve $\nu/\bar{\nu}$ separation and background rejection
- Design of HPTPC to reduce cross-section systematics down to ~ 2%
- PMT/LAPPD studies

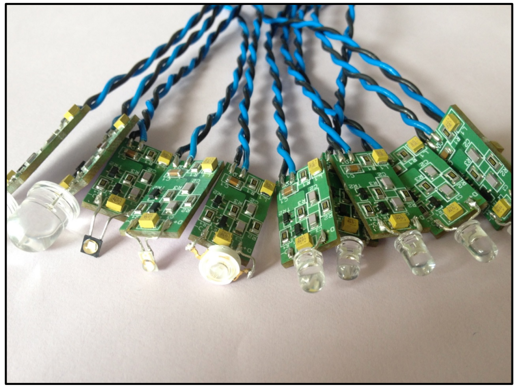


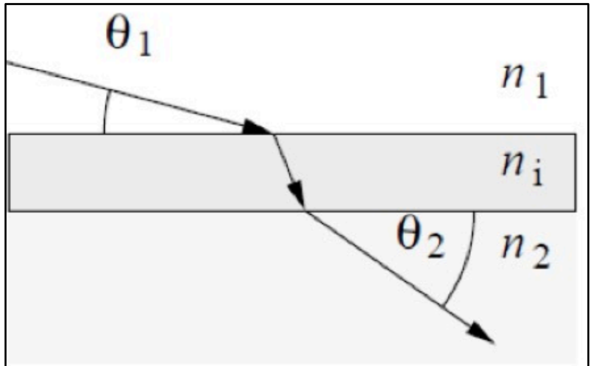
# HyperK UK WP4 Calibration




- 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



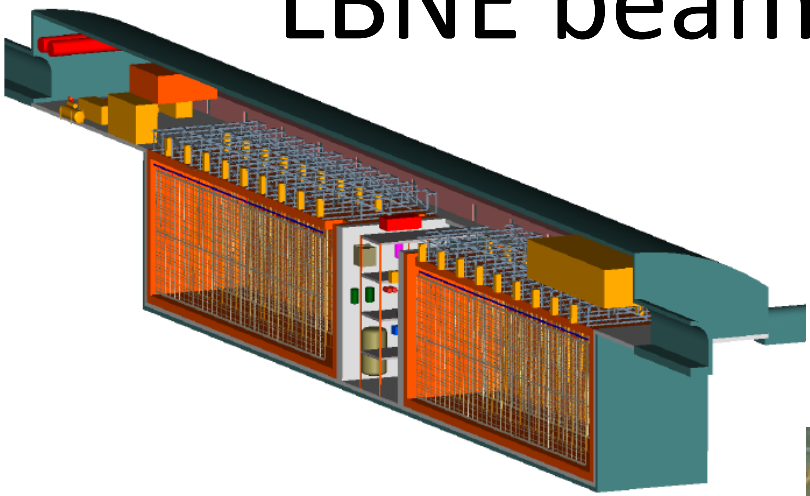

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

independent of $n_i$

As $\theta_1 \to 90^\circ$ $\sin(\theta_2) \to 1/n_c$

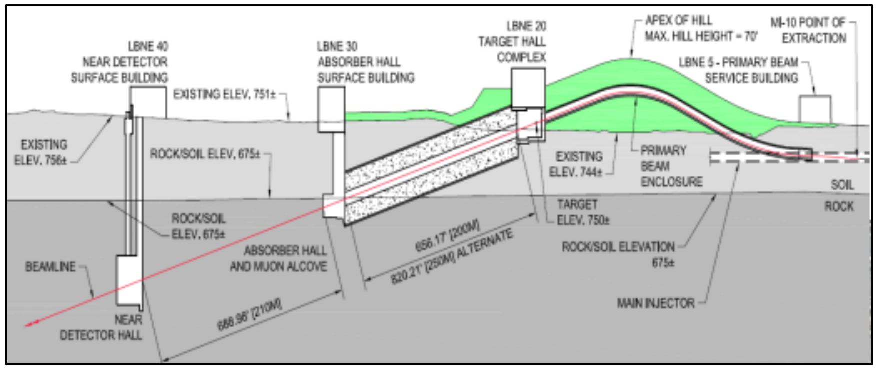
Light emitted at Cherenkov angle.

# LBNE beam and far detector

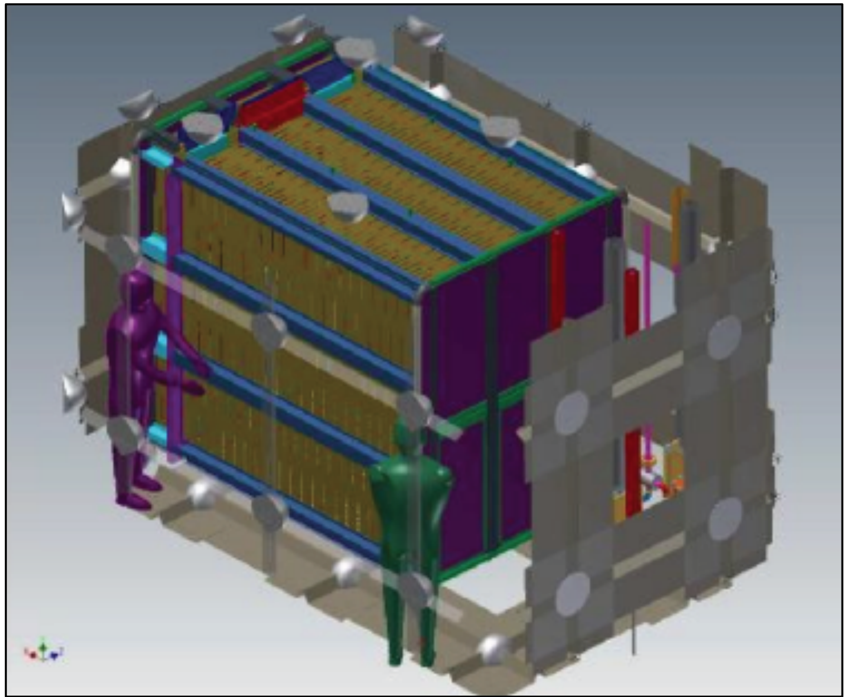


- Wide band FNAL neutrino beam
- 1.2MW upgradeable to 2.3MW
- 0.5 – 5.0 GeV sign-selected $\nu$
- Near detector design in progress

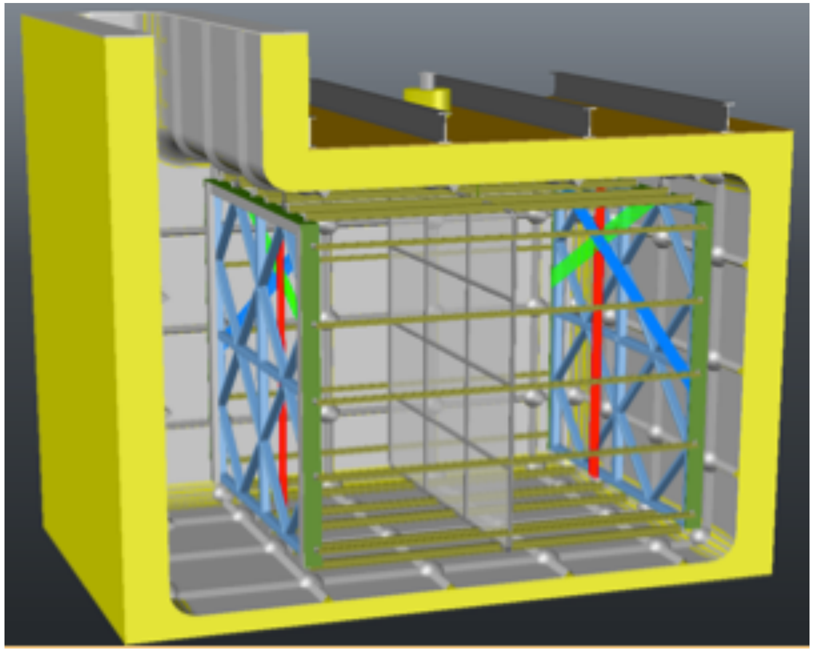

- Far detector
  - 10kt/34kt fiducial volume at 4850ft
  - 2 TPC modules each ~14m x 22m x 45m in the same cavern
  - Cosmic backgrounds ~ 0.1Hz

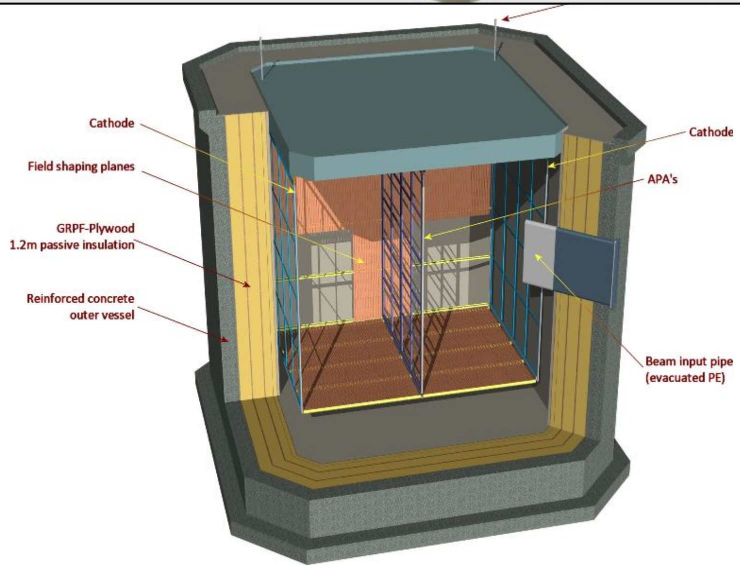


# LAr prototyping activities



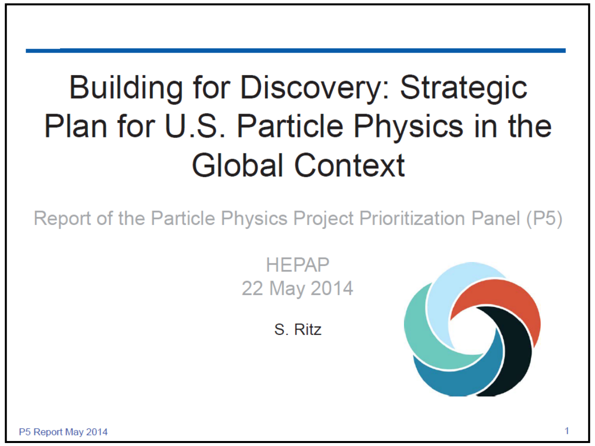
- LBNE 35 ton prototype due to take data at FNAL in early 2015
- LAr1-ND, 82t TPC for MicroBoone (2017)
- Other activities ArgoNeut, LARIAT etc.






- 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

# LBNE status

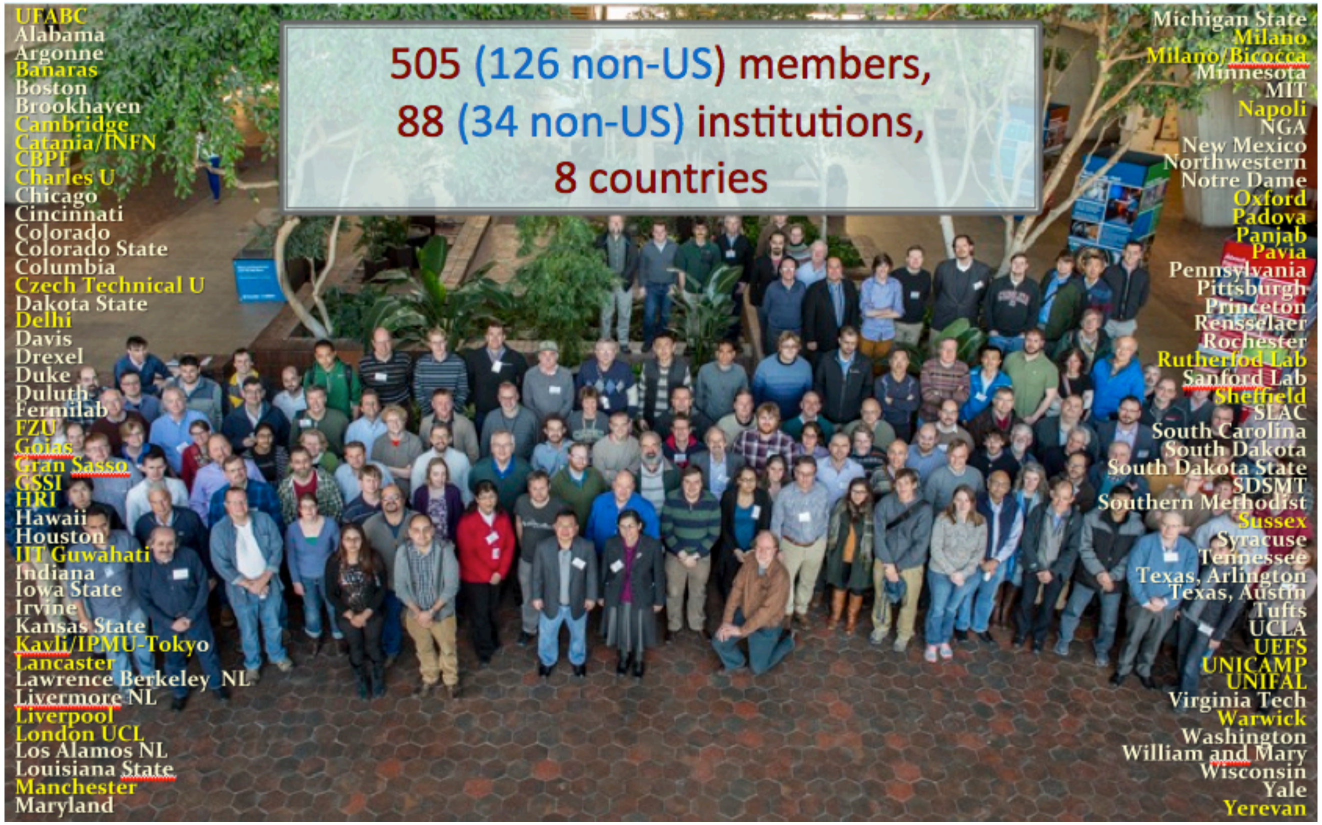

Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

HEPAP
22 May 2014

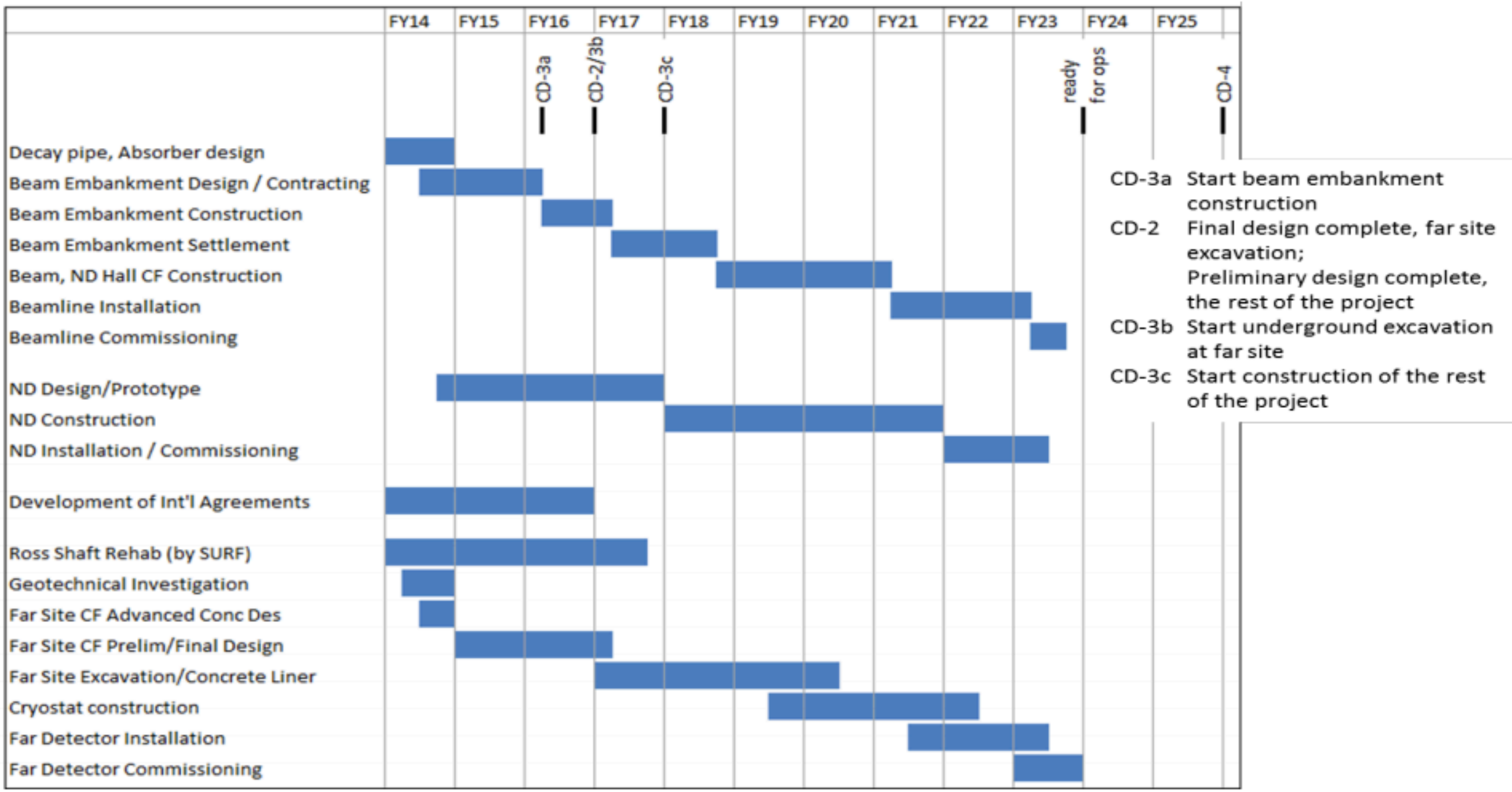
S. Ritz

P5 Report May 2014 1



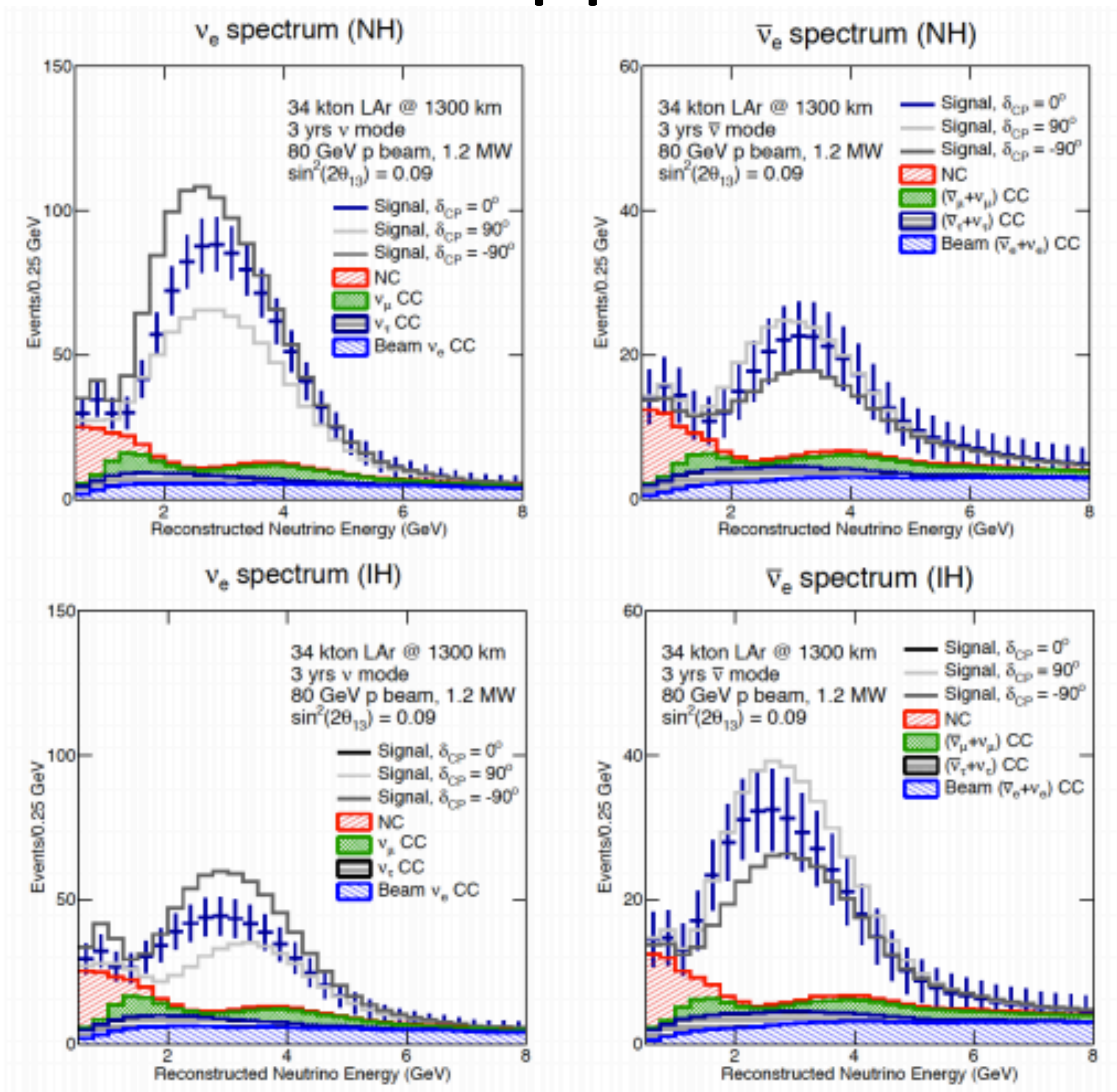

- DOE CD-1 preliminary baseline approval in December 2012
  - DOE commitment of $867M to LBNE
  - Plus PIP-II for 1.2MW beam – total of $1.5B
- Funding bids in process/successful in UK, India, Brazil, Italy
- External resources needed to support fully-scoped project
- UK is largest non-US group represented ~10% of collaboration

# LBNE Timeline




- Schedule is strongly dependant on involvement of new international partners

# LBNE far detector appearance event rates

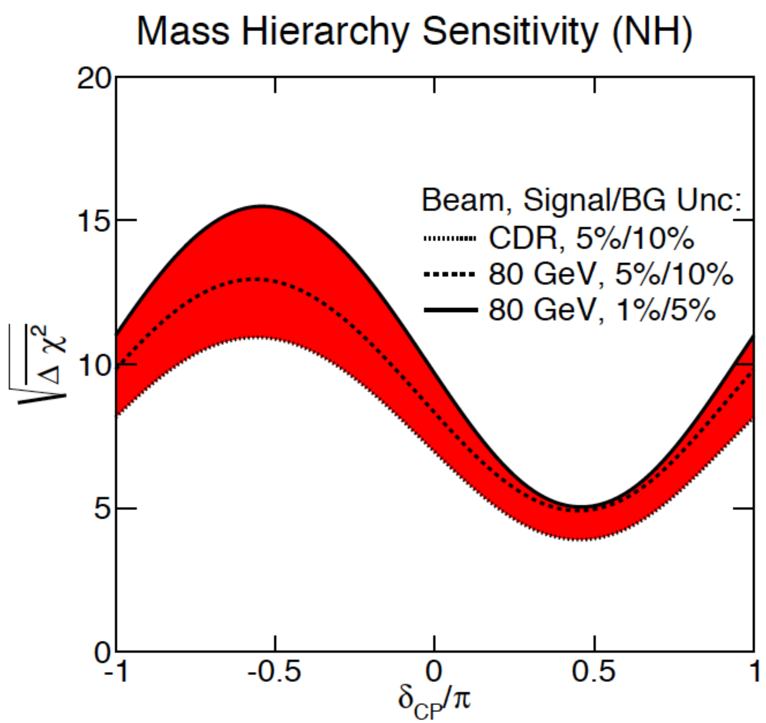


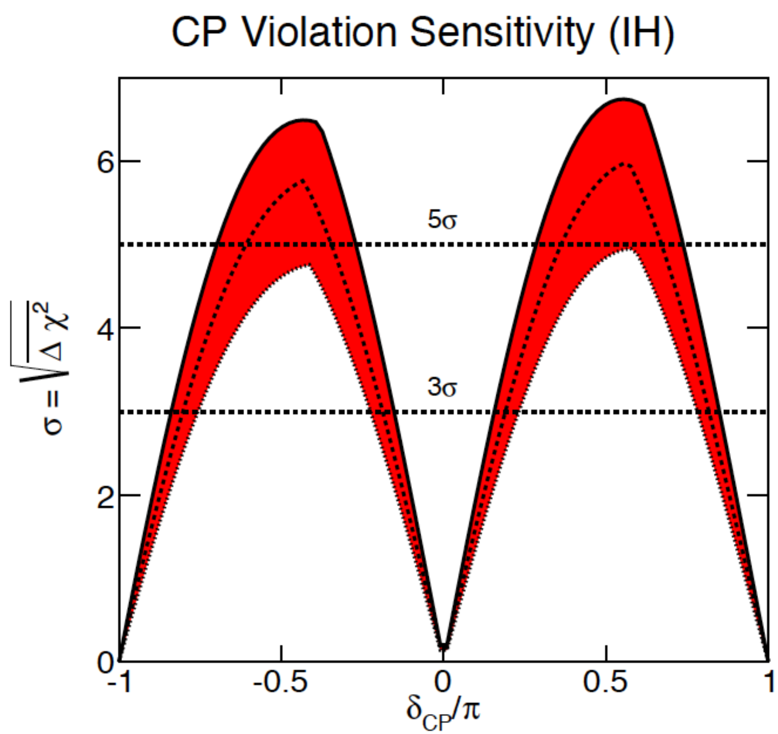

Normal hierarchy

Inverted hierarchy

- Based on 3 years $\nu$ and 3 years $\bar{\nu}$ running
- GLoBES simulation with global smearing and efficiencies based on ICARUS
- Typically 1000 events in neutrino run and 300 events in anti-neutrino run for $\nu_e$ appearance channel

# LBNE CP and MH sensitivity




- Mass hierarchy is well determined over most of $\delta_{CP}$ range
- CPV > 3σ over most of range and > 5σ for maximal CPV
- Atmospheric neutrinos in LBNE provide
  - an independent $\sim\Delta\chi^2=4$ cross-check on MH
  - ~1σ increased CPV sensitivity if combined with beam

Exposure 245 kt.MW.yr   34 kt x 1.2 MW x (3ν+3ν) yr

# LBNE UK involvement

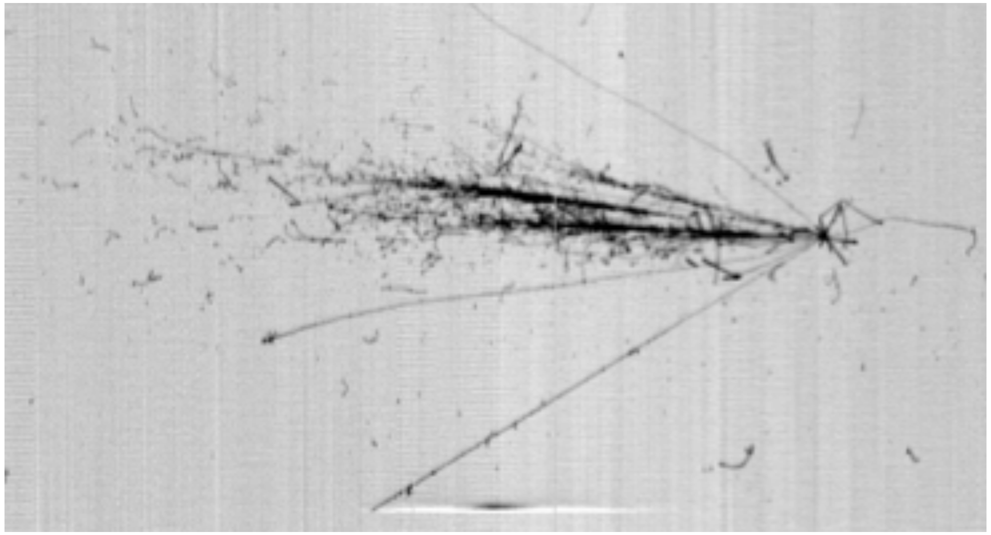
Cambridge • Lancaster • Liverpool • Manchester • Oxford

Sheffield • STFC/RAL • Sussex • UCL • Warwick

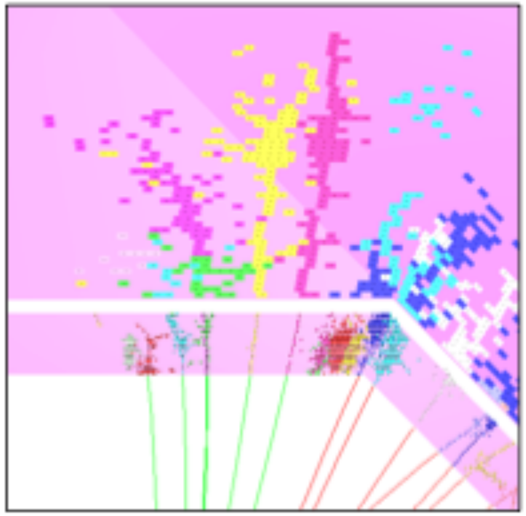
| Work Package | Deliverables |
|---|---|
| WP1: Physics Simulation and Experiment Design | Oscillation physics simulation; GENIE-LArSoft interface; Near detector design studies; Target and beam design; Beam systematics study; |
| WP2: Neutrino Event Reconstruction | Pattern recognition software (PANDORA) and interface to LArSoft; neutrino event reconstruction; |
| WP3: DAQ | DAQ for 35t prototype; data compression and event triggering; DAQ architecture design and prototyping. |
| WP4: 35t Prototype | HV monitoring cameras; operation and commissioning; simulation and data analysis; rejection of cosmic-induced backgrounds. |
| WP5: TPC Design and Construction | LAr1-ND APA and CPA frame design, wiring, cold-testing, construction and installation; LBNE APA and CPA design. |

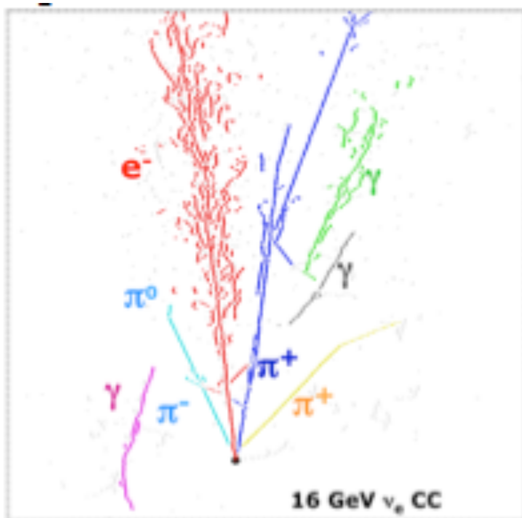
# LBNE UK WP2 Event Reconstruction

- Neutrino events in a LAr TPC give high resolution, bubble-chamber like images

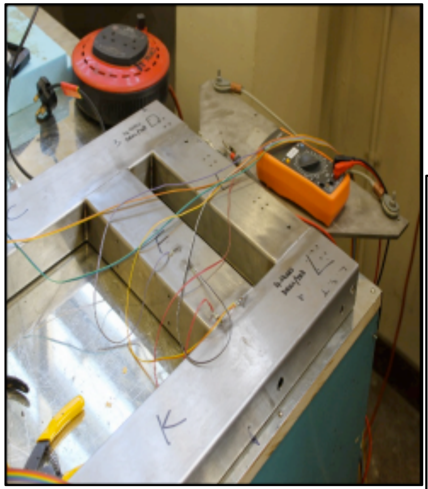


- The challenge is to go from this to reconstructed physics quantities
- PANDORA-based event reconstruction and LAr pattern recognition tools being developed

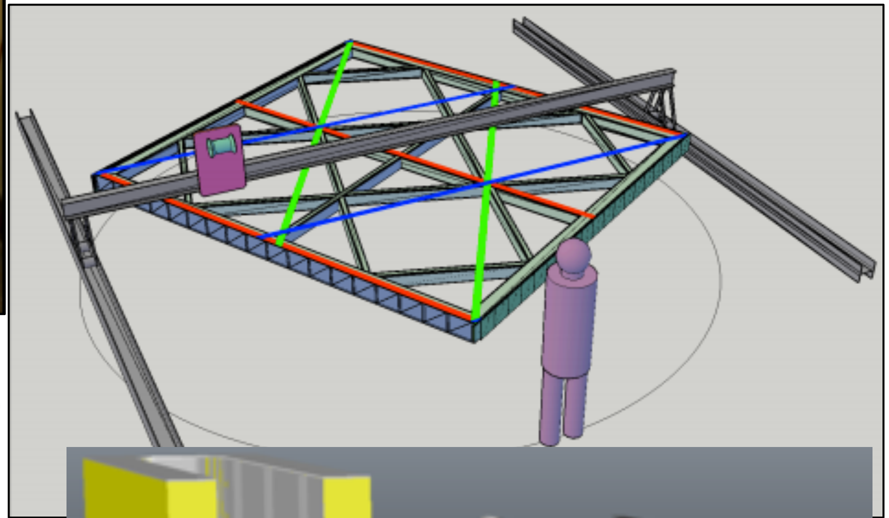




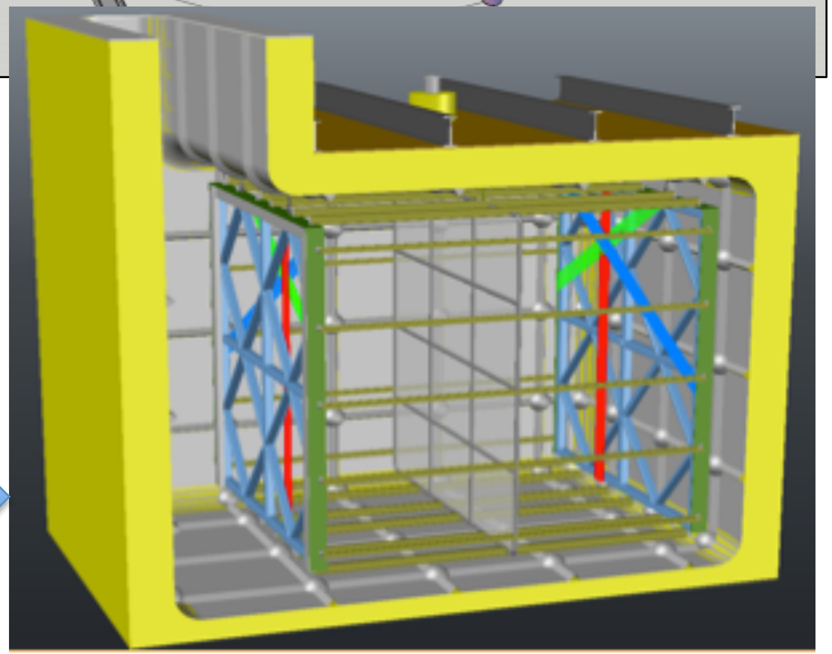
# LBNE UK WP5 APA design



- UK-built 35t APA undergoing $LN_2$ cool down tests



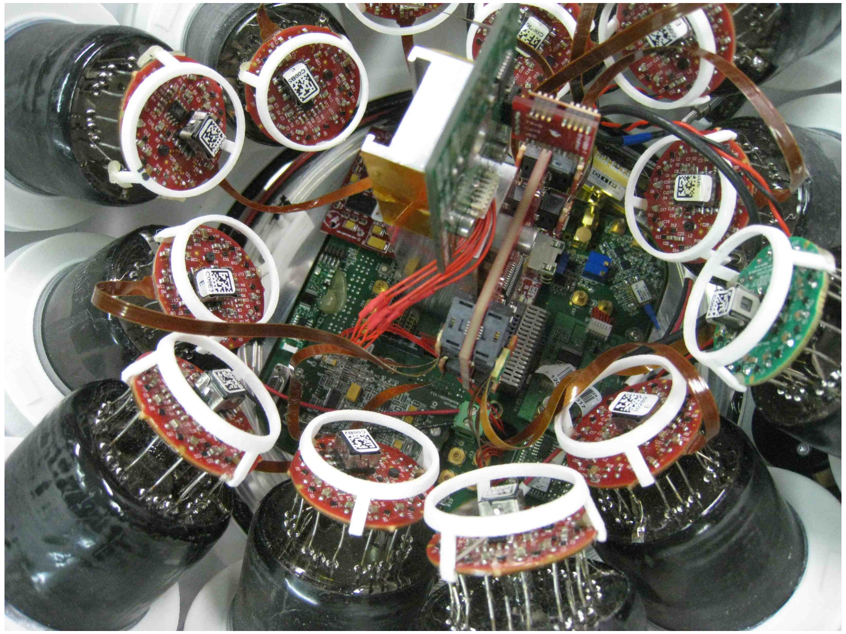
- APA wiring frame concept design
- LAr1-ND: UK proposes to build
  - One of the two APAs
  - The CPA and HV feedthrough



# CHIPS concept

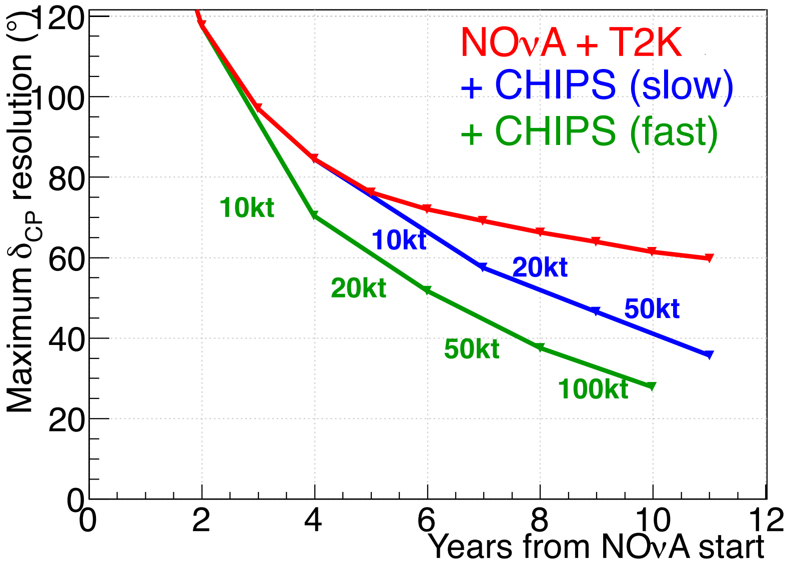
Manchester • UCL

- 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 NO$\nu$A (being more on-axis) and LBNE (more off-axis) when redeployed in the LBNE beam
- 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

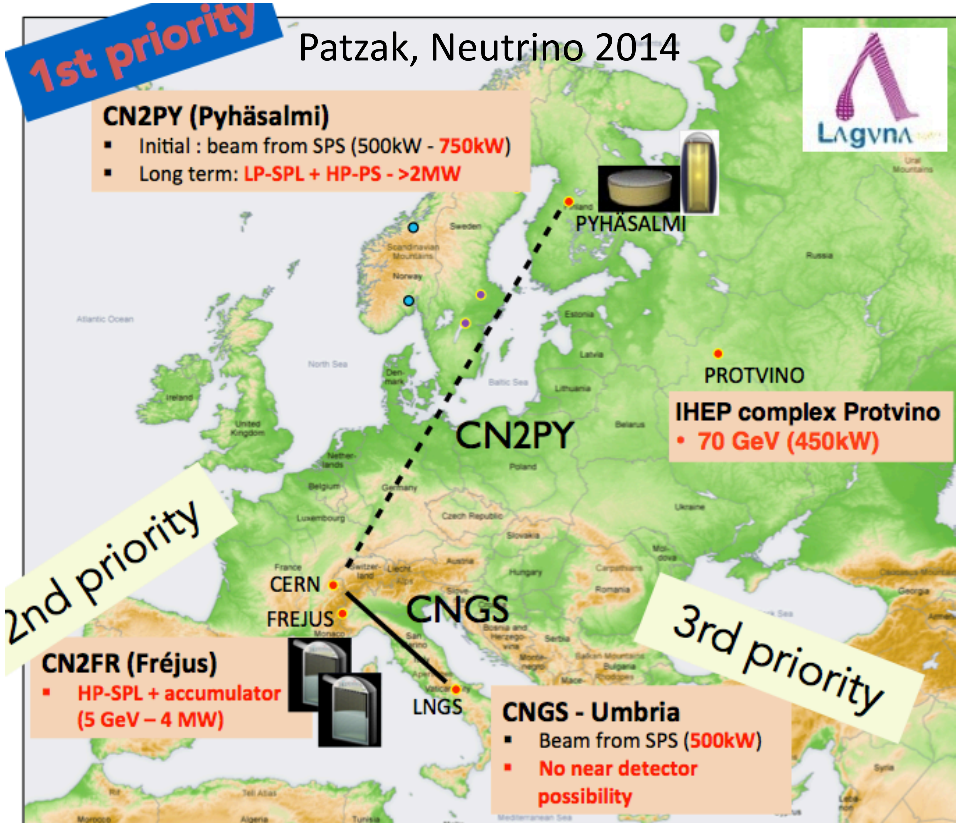



- Medium term:
- ~25kt (TBD) vessel to follow)
- Yearly increase of instrumented mass depending on funding
  - Deployment seasonal
  - Large up-front funding not necessary
  - Staging of detector(s) natural
- Long term:
- Re-deploy CHIPS in LBNE beam off axis
- 2nd oscillation maximum located around 0.8 GeV
  - Large quasi-elastic x-section
  - Suitable for water Cerenkov detector
    - High efficiency for QE events

# LAGUNA/LBNO

Durham IPPP • Lancaster • Liverpool • Oxford •QMUL • Sheffield • STFC/RAL • UCL • Warwick

- Design study phase has been supported via EU FP7 funding
- Proposed 2300km baseline from CERN to Pyhasalmi
- Phased approach
- Detailed engineering designs in place
- Far detector is dual phase argon



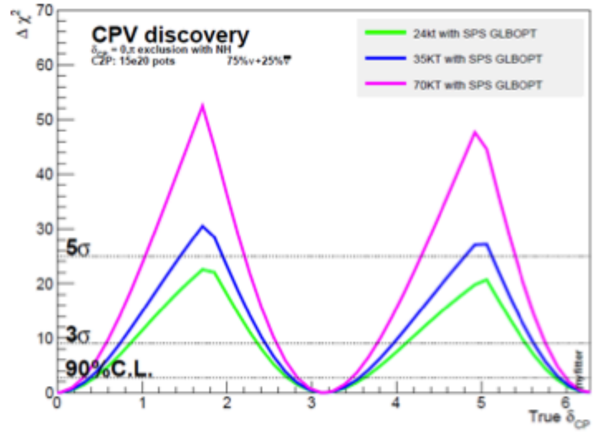

| 2014 | 2018 | 202X | 202X | 203X |
|---|---|---|---|---|
| **LAGUNA-LBNO DS** | **WA 105** | **LBNO – PILOT (2.5 – 5 kt)** | **LBNO Phase I (LBNO20)** | **LBNO Phase II (LBNO70)** |
| Site selection<br>Full assessment of physics<br>Full engineering costing | DLAr demonstrator<br>Calibration<br>Software development | Underground installation<br>Astro particle physics | MH<br>CPV 3 σ: 46%<br>Proton decay<br>Astrophysics | CPV 3 σ: 80 %<br>Proton decay<br>Astrophysics |

# LAGUNA/LBNO physics reach

The mass-hierarchy and CP-violation discovery reach of the LBNO long-baseline neutrino experiment

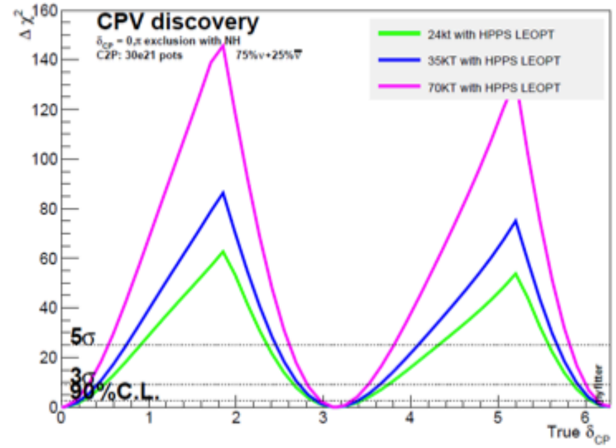
10.1007/JHEP05(2014)094

LBNO Phase I (24 kt) with Optimized SPS beam: Covers 47 % CPV space at 3 σ




Remark: Similar results are obtained with LBNO @ Garpenberg

LBNO Phase II (70kt) with Optimized HPPS beam: Covers 80 % CPV space at 3 σ




Remark: Alternatively an additional beam from Protvino instead of HPPS

Patzak, Neutrino 2014

# Conclusions

- There is a significant amount of UK activity in both current and future long baseline neutrino experiments
- In many (most) cases the UK is the biggest partner after the host country
- In recent years we have definitively measured a non-zero $\theta_{13}$ mixing angle opening the door to a search for CP violation
- Current and proposed projects have excellent prospects for measuring $\delta_{CP}$ and determining the neutrino mass hierarchy
- The above is just a small part of the rich physics programme in the reach of future LB experiments