Current and Future Long Baseline Neutrino Experiments

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29th October 2014

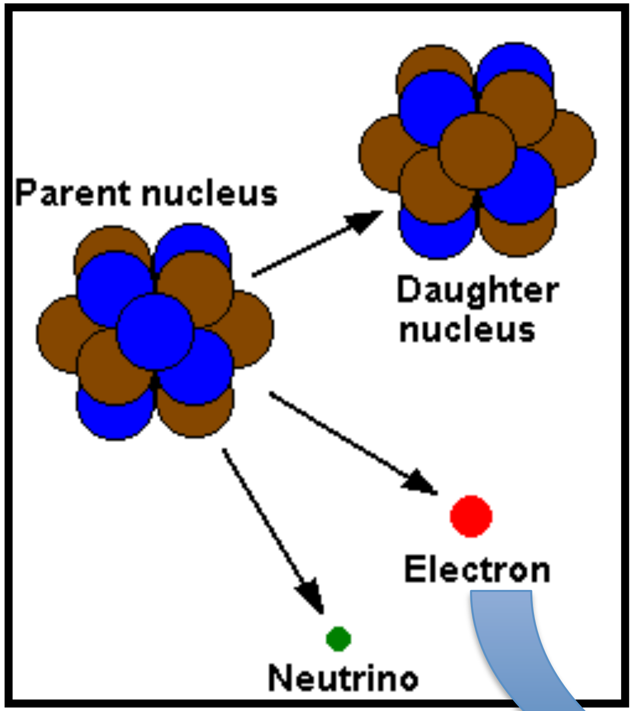
I ragazzi di Via Panisperna (The birth of the neutrino)

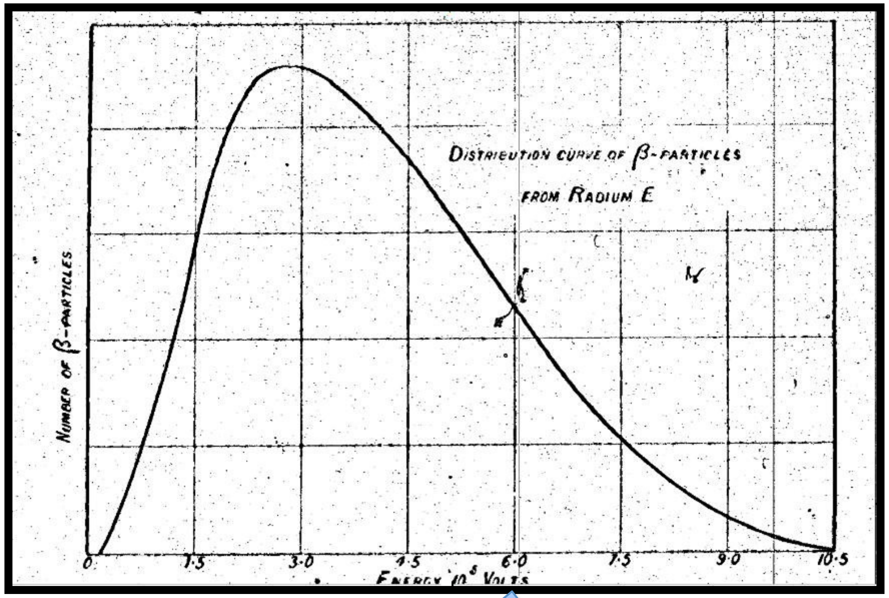
Edoardo Amaldi, Emilio Segrè, Franco Rasetti, Ettore Majorana, Enrico Fermi, Bruno Pontecorvo

- Fermi: 1939 Nobel Prize for Physics: "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"

- Segrè: 1959 Nobel Prize for Physics: discovery of the anti-proton

The birth of the neutrino





$E = \Delta mc^2$

- Pauli: postulated the existence of the neutrino in 1930 to explain the conservation of energy and momentum in beta decay a third particle must be produced, electrically neutral and with very low mass, so not observed
- Fermi: named the particle ‘neutrino’ in 1933
- Pauli: “I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do.”

Can we see them?

- 1934: Pauli predicts

$\sigma(\nu p) \sim 10^{-44}$ cm^2 for 2MeV ν

- 1934: Bethe and Peiels calculate

$$\lambda_{lead} \sim \frac{1}{N_A \rho \sigma} = \frac{1}{6.10^{23}(nuc/g) \times 7.9(g/cm^2) \times 10^{-44}(cm^2)}$$

➡ at these neutrino energies the interaction length in Lead is ~ 22 light years

tiny cross-sections means huge detectors

Experimental Discovery

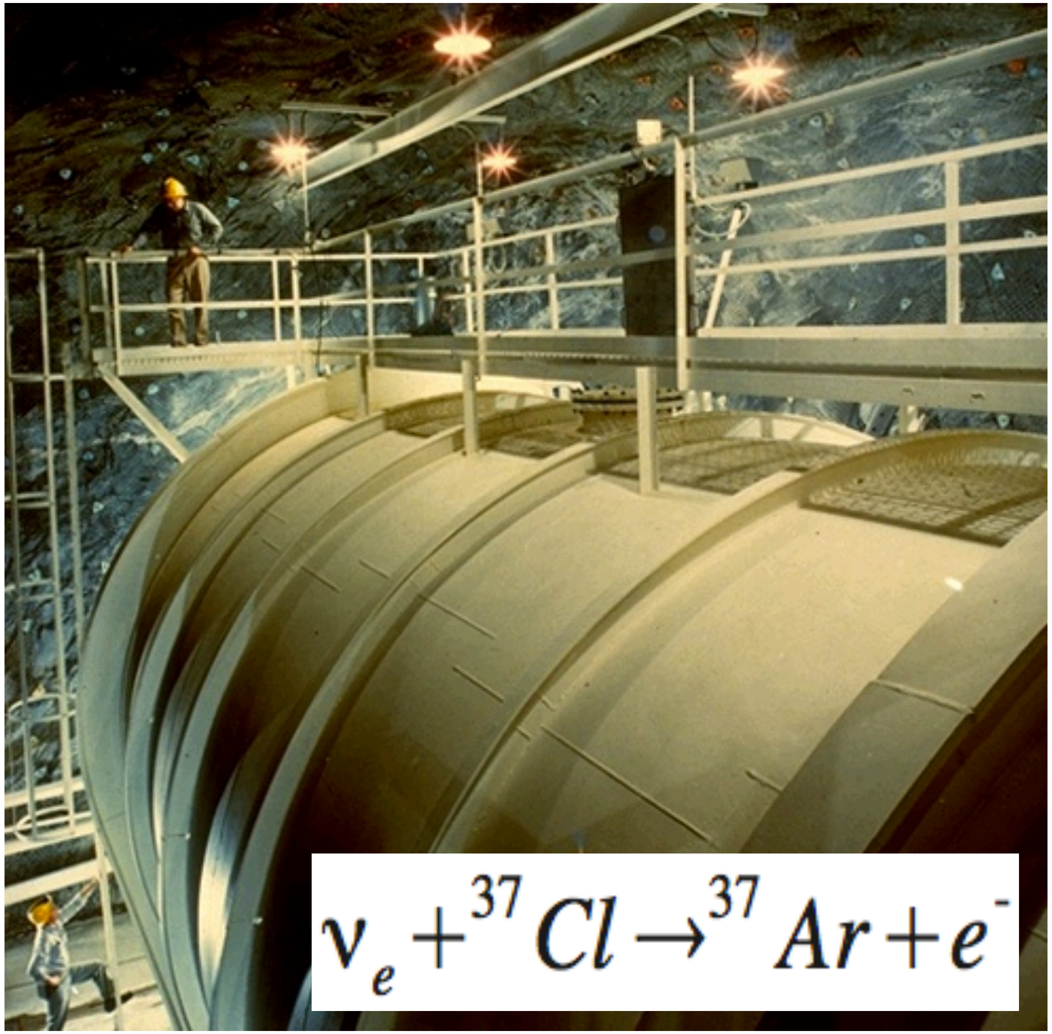
- Use a huge flux (of order 10^{13} cm^{-2} s^{-1})of (anti-)neutrinos from a nuclear reactor
- Observe the reaction $\overline{\nu}_e + p \rightarrow e^+ + n$

  in 200l water tanks loaded with ~40kg of $CdCl_3$

  $$^{108}Cd + n \rightarrow {}^{109m}Cd \rightarrow {}^{109}Cd + \gamma$$
- Unique co-incidence of 2 gamma rays from the e^+e^- annihilation and neutron capture and subsequent photon signal 5μs later. Gammas observed in liquid scintillator
- Devised by Cowan and Reines in 1956/9 (latter Nobel Prize in 1995)

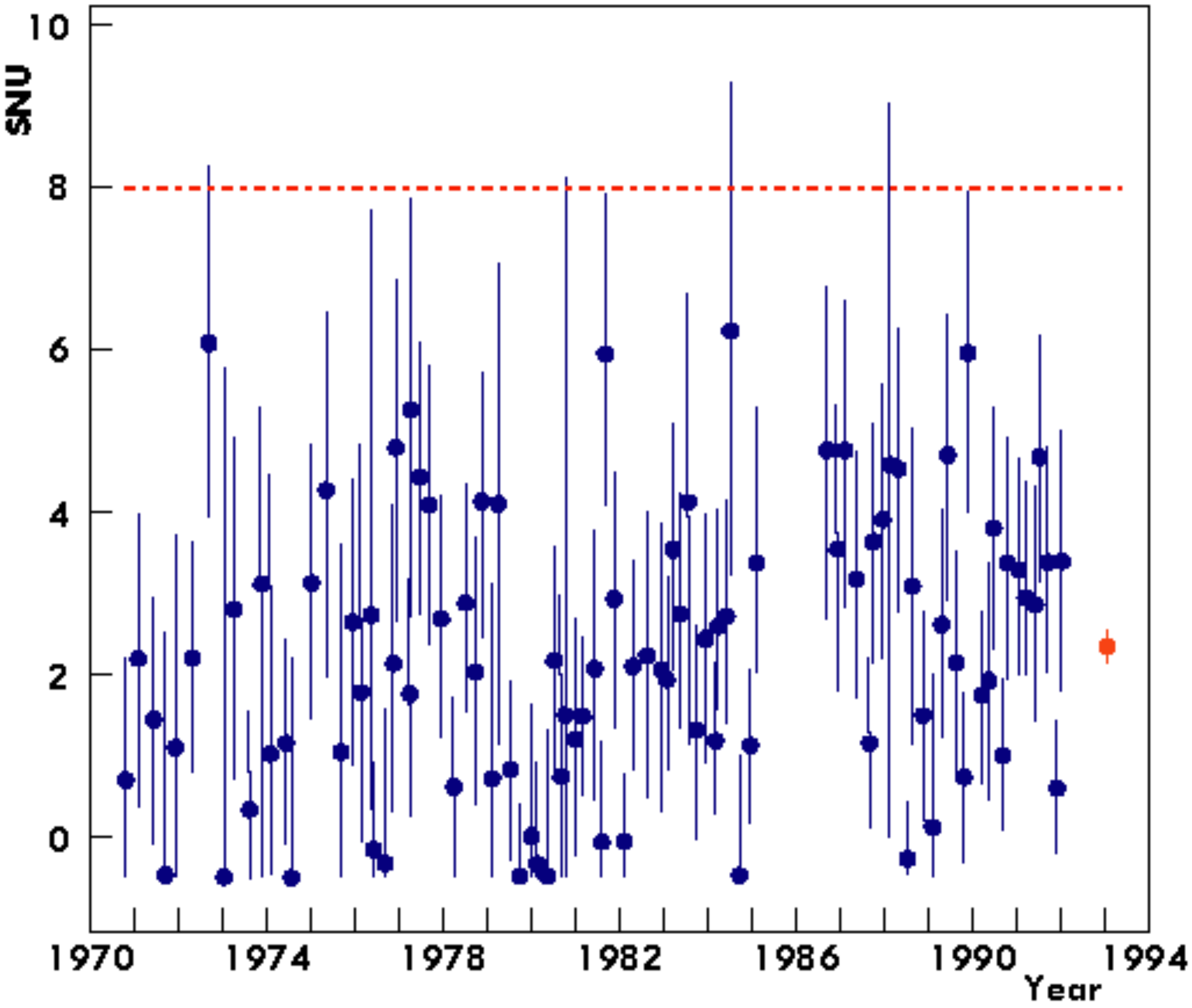
Solar neutrino experiments

- Either radiochemical (Cl or Ga) or Cerenkov radiation
- Homestake neutrino experiment
- 100,000 gal of dry cleaning fluid
- Neutrino threshold 800 keV
- Number of ^{37}Ar atoms counted



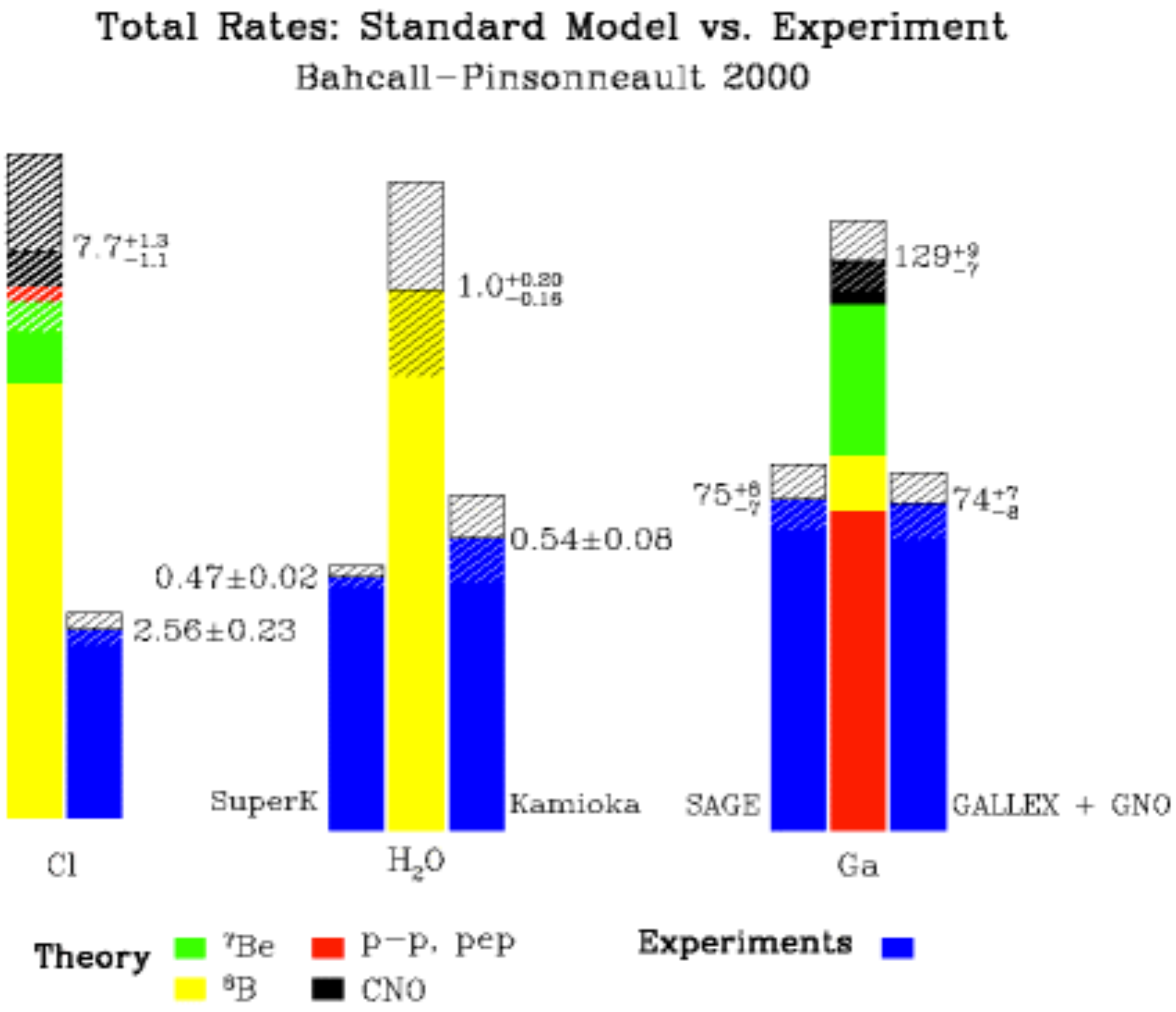
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Homestake results



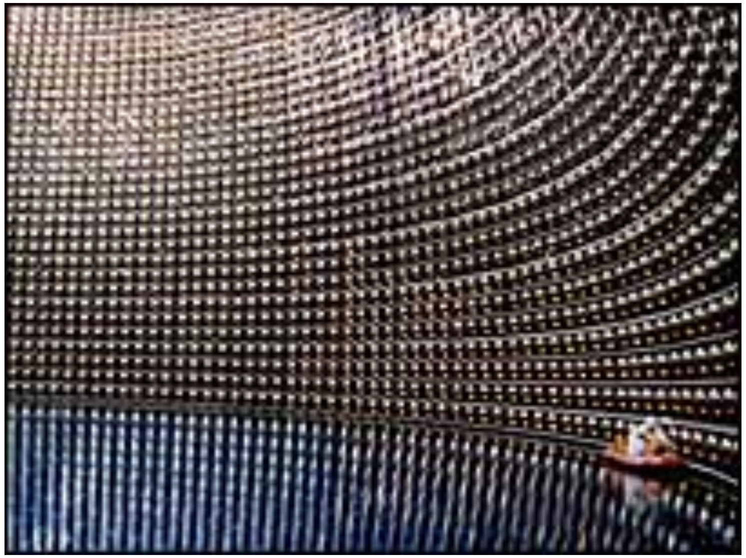
1 SNU =
10^{-36} captures
/atom/second

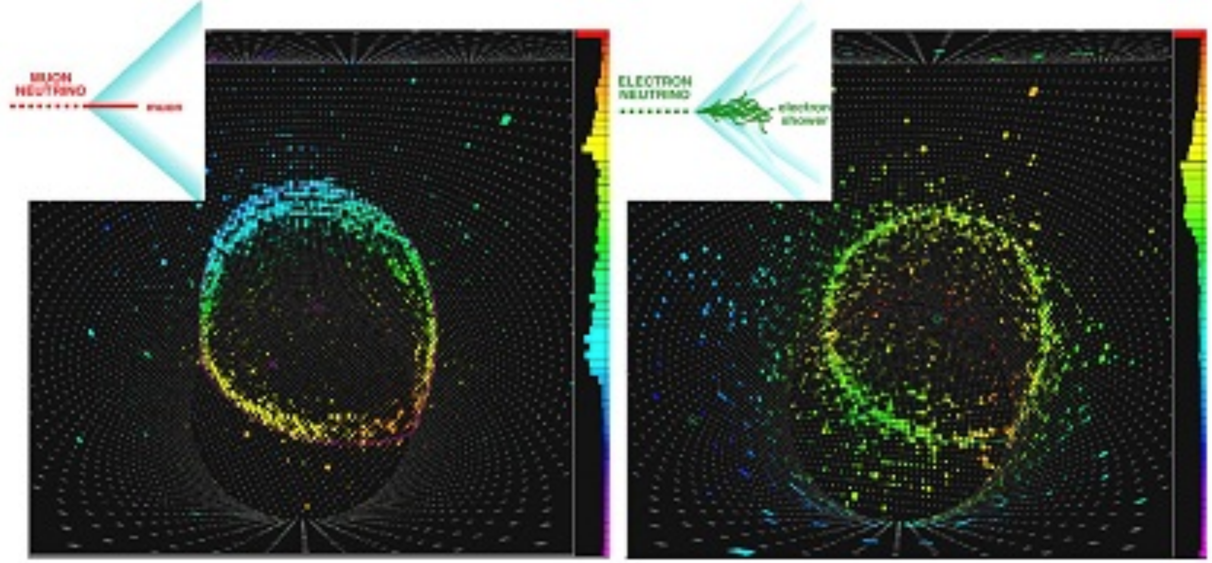
Solar neutrino results



Atmospheric Neutrino Experiment

- “SuperK”
- A water Cerenkov detector
- 50,000 tons of water under a mountain in Japan
- Higher neutrino thresholds (~5 MeV)

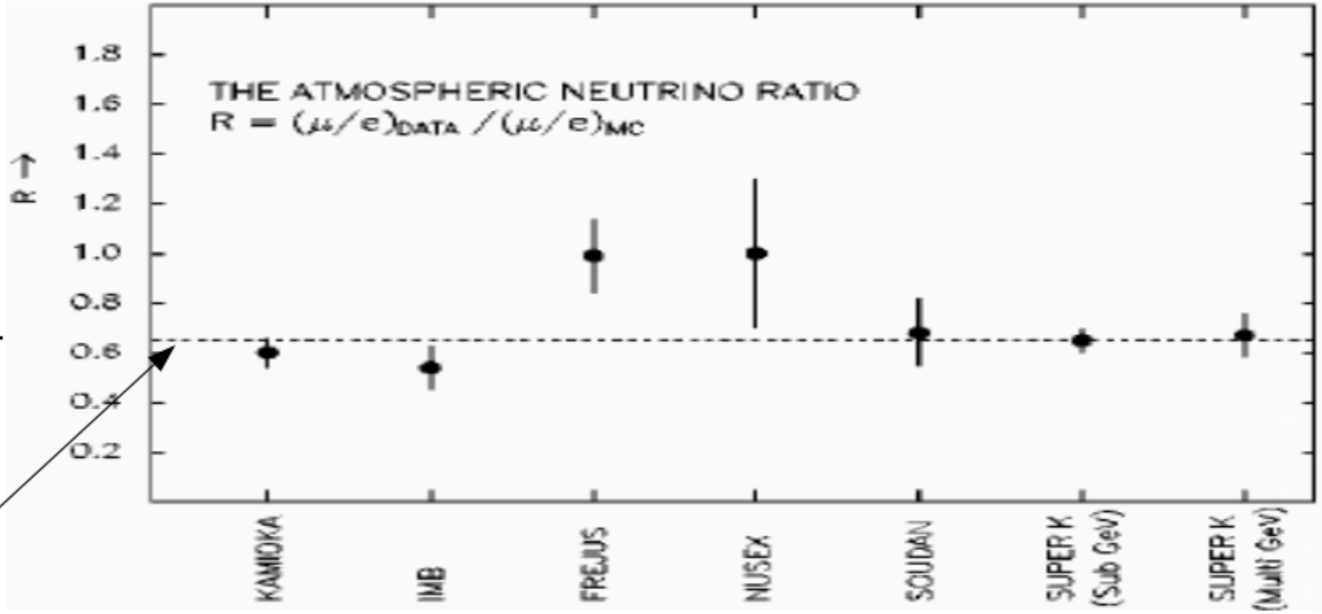


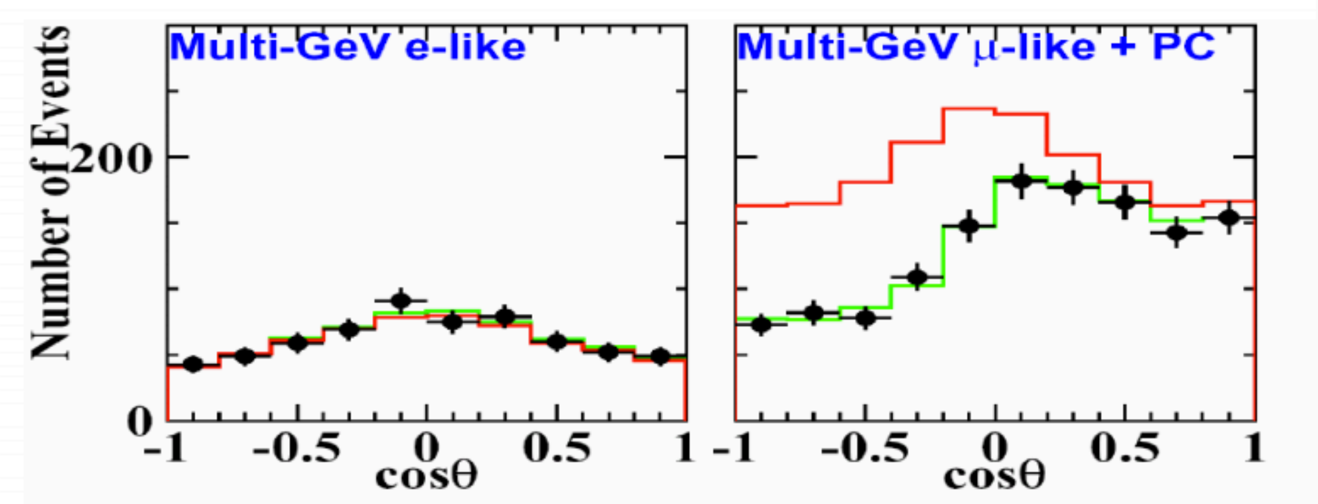


SuperKamiokande Results

$$R = \frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$$

R ~ 0.6 - 0.7

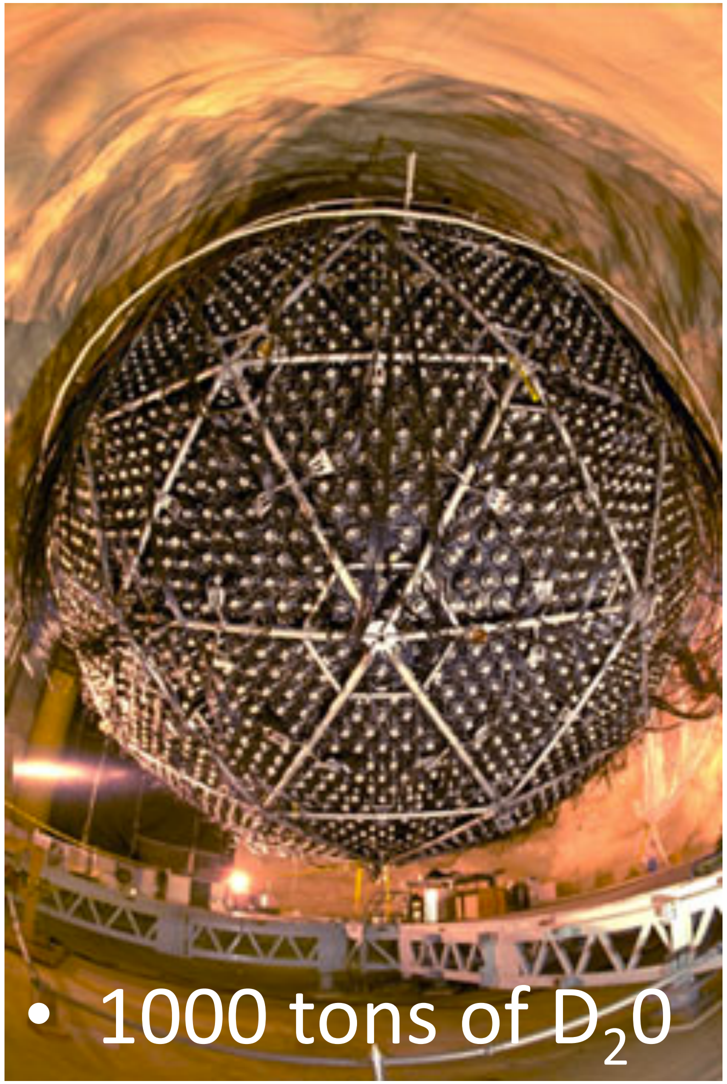




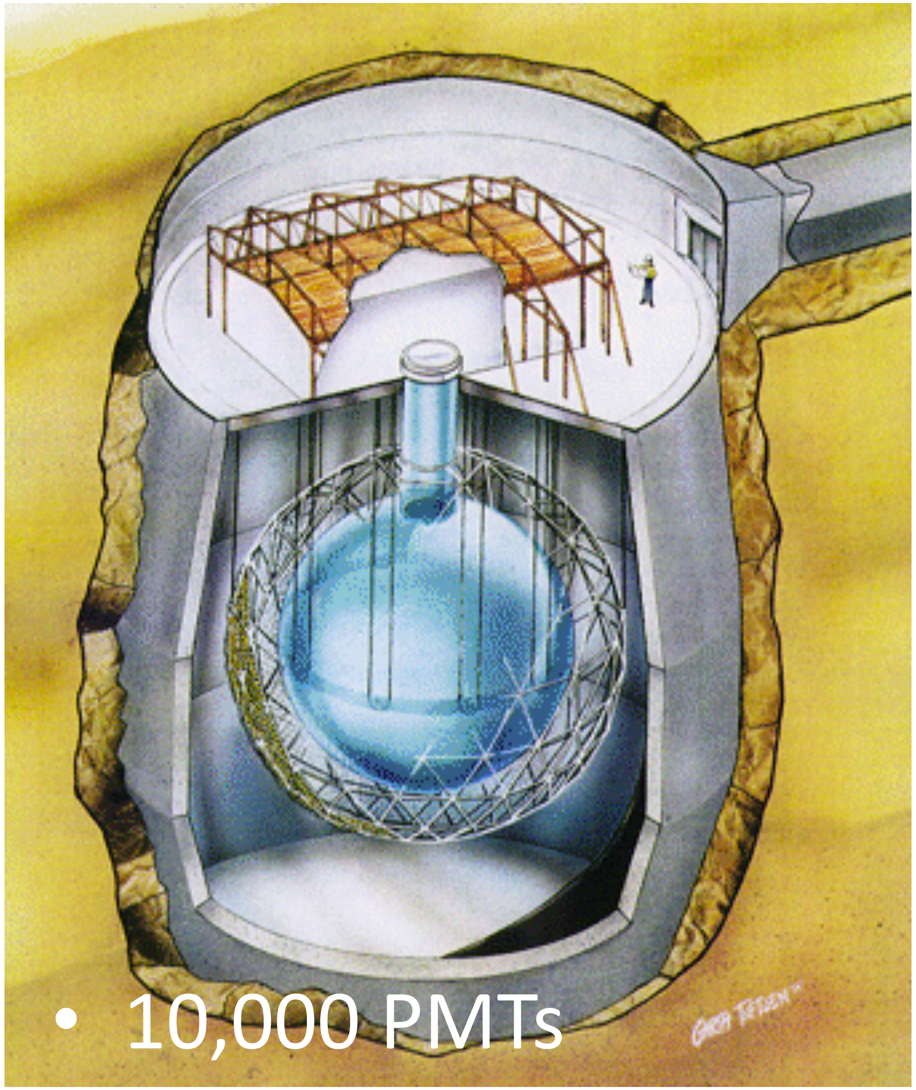
A possible explanation

- Solar neutrino anomaly
  - Solar neutrino experiments on sensitive to electron neutrino charged current interactions
  - Experiments are OK, theory is OK
  - What if the neutrinos change to a different neutrino flavour as they propagate from the source to the detector?
  - So, e.g. if some of the $\nu_e \rightarrow \nu_\mu$ or ν_τ then the observed ν_e flux would be less than expected
  - Can we devise an experiment that is sensitive to neutral current interactions instead?
  - Time for the Sudbury Neutrino Observatory (SNO)

The SNO experiment

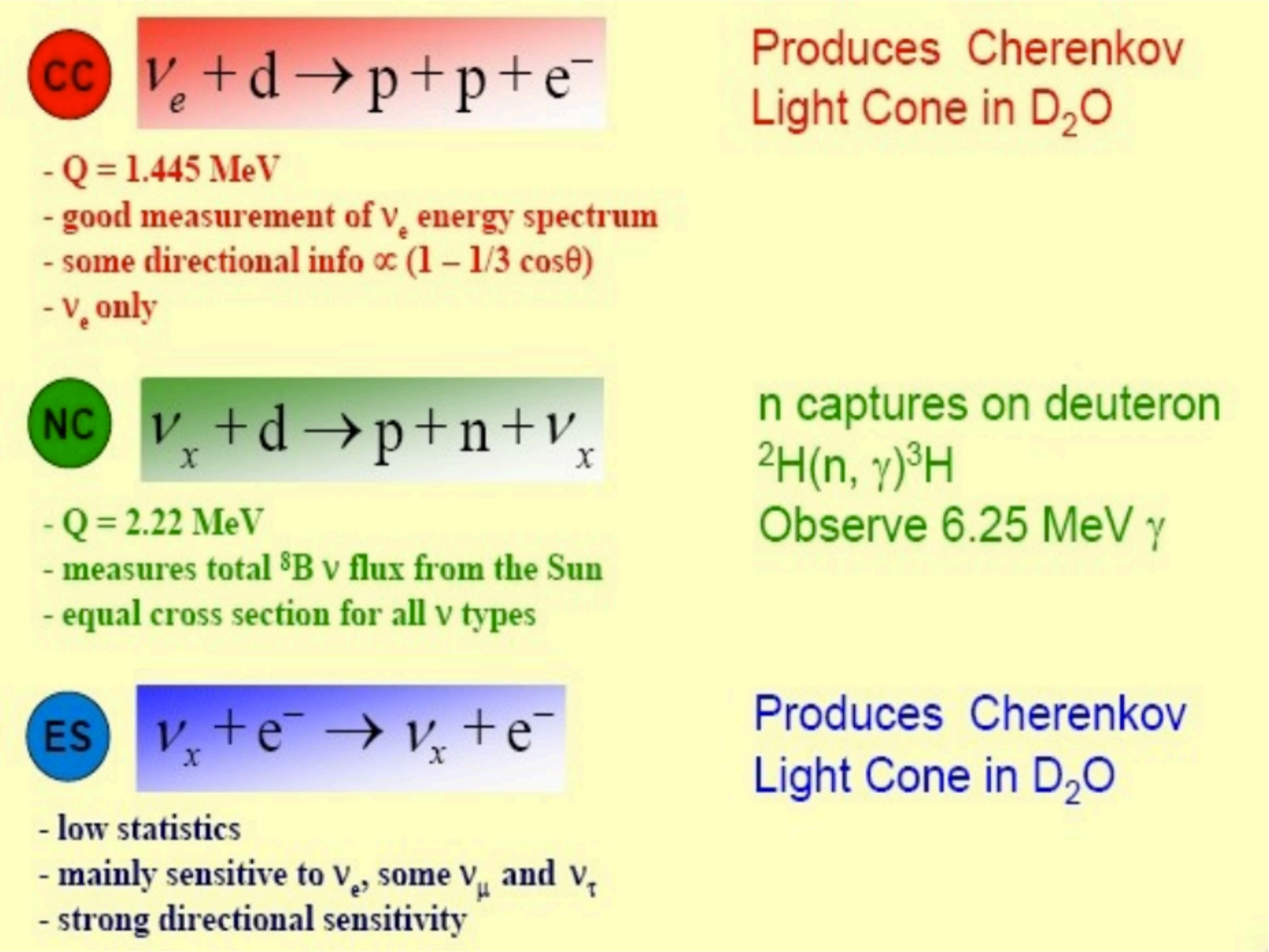


- 1000 tons of D_20
- 6500 tons of H_20



- 10,000 PMTs
- 2km underground

The SNO experiment



CC $\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$

Produces Cherenkov Light Cone in D_2O

- $Q = 1.445$ MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

NC $\nu_x + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x$

n captures on deuteron

$^2H(n, \gamma)^3H$

Observe 6.25 MeV γ

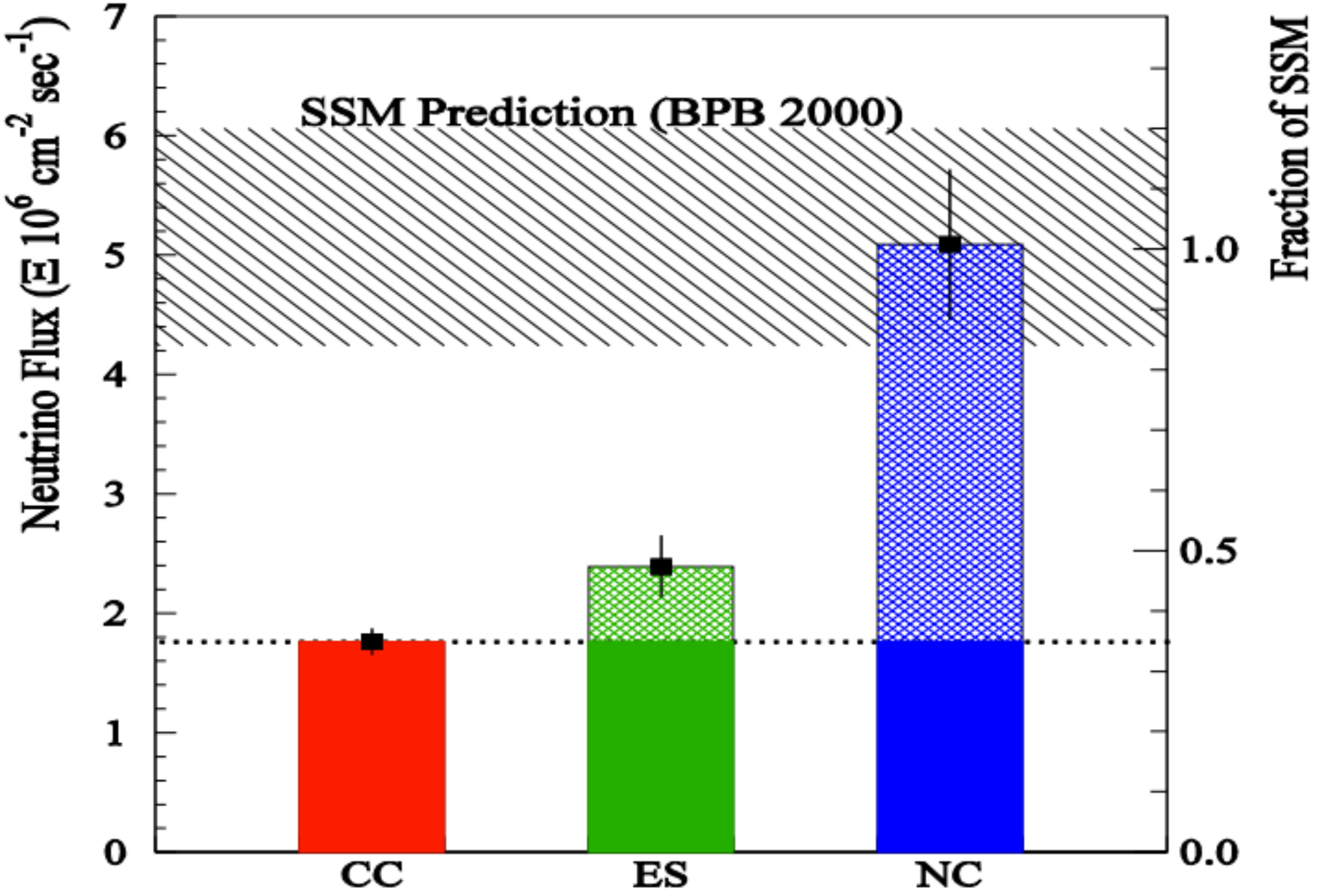
- $Q = 2.22$ MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

ES $\nu_x + \mathrm{e}^- \rightarrow \nu_x + \mathrm{e}^-$

Produces Cherenkov Light Cone in D_2O

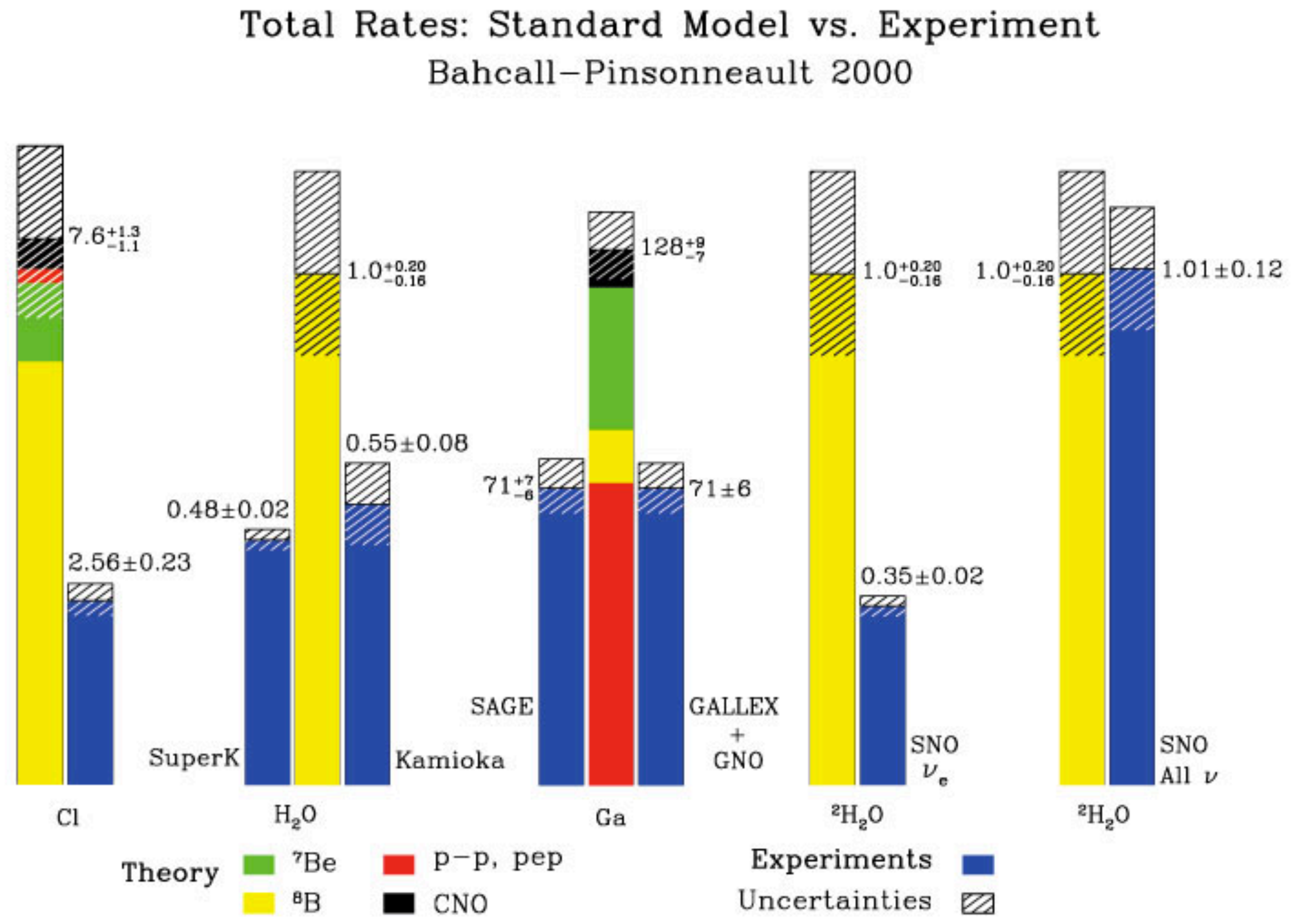
- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

SNO results



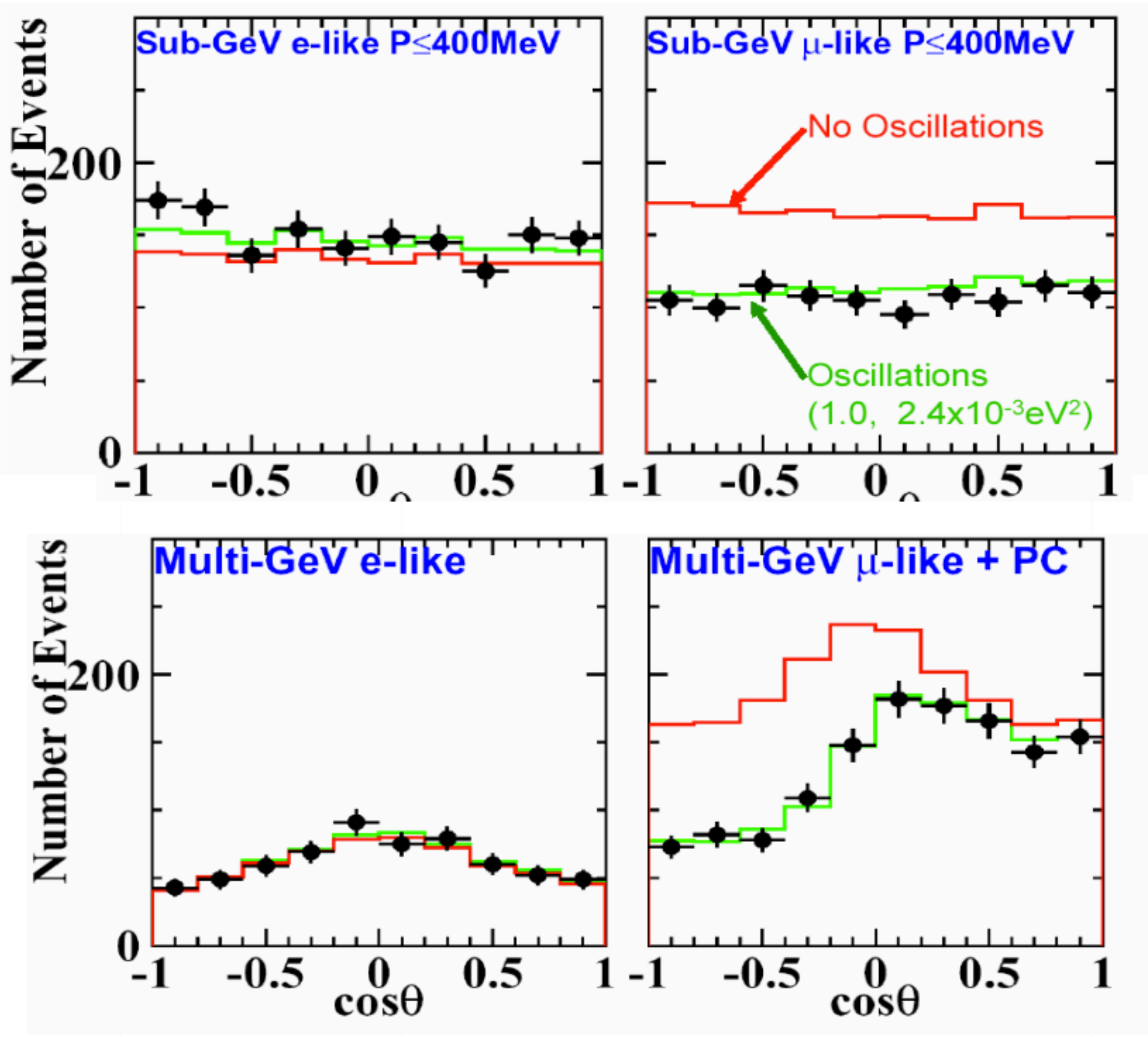
- ν_e to $\nu_{\mu\tau}$ oscillations confirmed!

Combined Results



SuperK results (assuming oscillations)

- Re-interpretation of SK results assuming that some fraction of the CR ν_μ have oscillated to ν_τ (that SK is not sensitive to)



Interpretation

- As a neutrino propagates from source to detection point then the neutrino flavour at the source and at the detection point some time/distance later are not the same
- This is known as neutrino oscillation or mixing
- Neutrino oscillation is a quantum mechanical effect
- The neutrino weak eigenstates and mass eigenstates are not the same (are not ‘aligned’)
- The neutrino propagates in the mass eigenstate but interacts in the weak eigenstate
- NB this can only happen if neutrinos have mass
- “Beyond Standard Model” physics

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

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

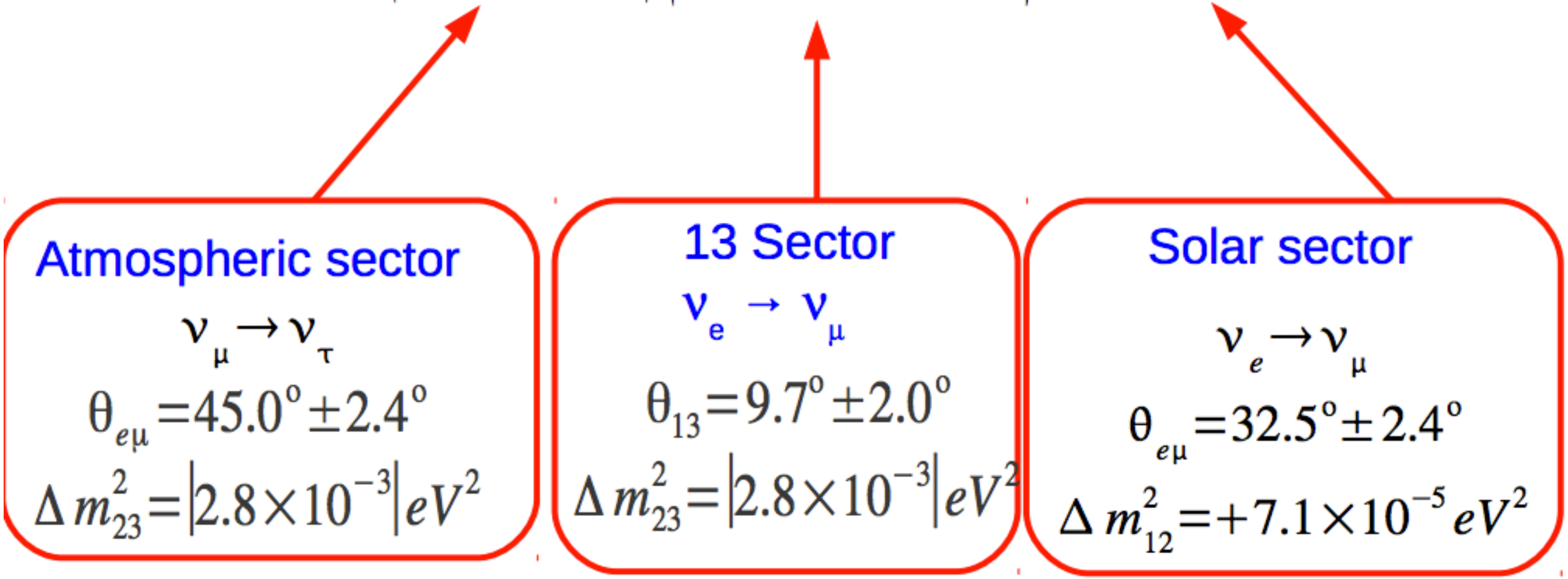
$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$, δ=CP violating phase

- Known knowns: neutrinos have mass and oscillate between flavours; θ_{12}, θ_{23}, θ_{13}, Δm_{21}^2, $|\Delta m_{32}^2|$ all measured
- Known unknowns: absolute masses, order of mass states (mass hierarchy), Dirac or Majorana, value of δ_{CP}, is θ_{23} maximal / which octant, number of neutrinos

3 flavour mixing

- 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

$\nu_\mu \rightarrow \nu_\tau$

$\theta_{e\mu}=45.0^\circ \pm 2.4^\circ$

$\Delta m^2_{23}=|2.8\times 10^{-3}|\, eV^2$

13 Sector

$\nu_e \rightarrow \nu_\mu$

$\theta_{13}=9.7^\circ \pm 2.0^\circ$

$\Delta m^2_{23}=|2.8\times 10^{-3}|\, eV^2$

Solar sector

$\nu_e \rightarrow \nu_\mu$

$\theta_{e\mu}=32.5^\circ \pm 2.4^\circ$

$\Delta m^2_{12}=+7.1\times 10^{-5}\, eV^2$

Oscillation Probabilities

- In general:

$$P(\nu_\alpha \rightarrow \nu_\beta)_{(\alpha \neq \beta)} = -4 \left(\begin{array}{l} \underbrace{U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\beta 2}}_{C_{12}} \sin^2(1.27 \frac{\Delta m_{12}^2 L}{E}) + \\ \underbrace{U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\beta 3}}_{C_{13}} \sin^2(1.27 \frac{\Delta m_{13}^2 L}{E}) + \\ \underbrace{U_{\alpha 2} U_{\beta 2} U_{\alpha 2} U_{\beta 3}}_{C_{23}} \sin^2(1.27 \frac{\Delta m_{23}^2 L}{E}) \end{array} \right)$$

$$P(\nu_\alpha \rightarrow \nu_\beta)_{(\alpha \neq \beta)} = -4 [c_{12} \sin^2(1.27\, \delta m^2 L/E)$$

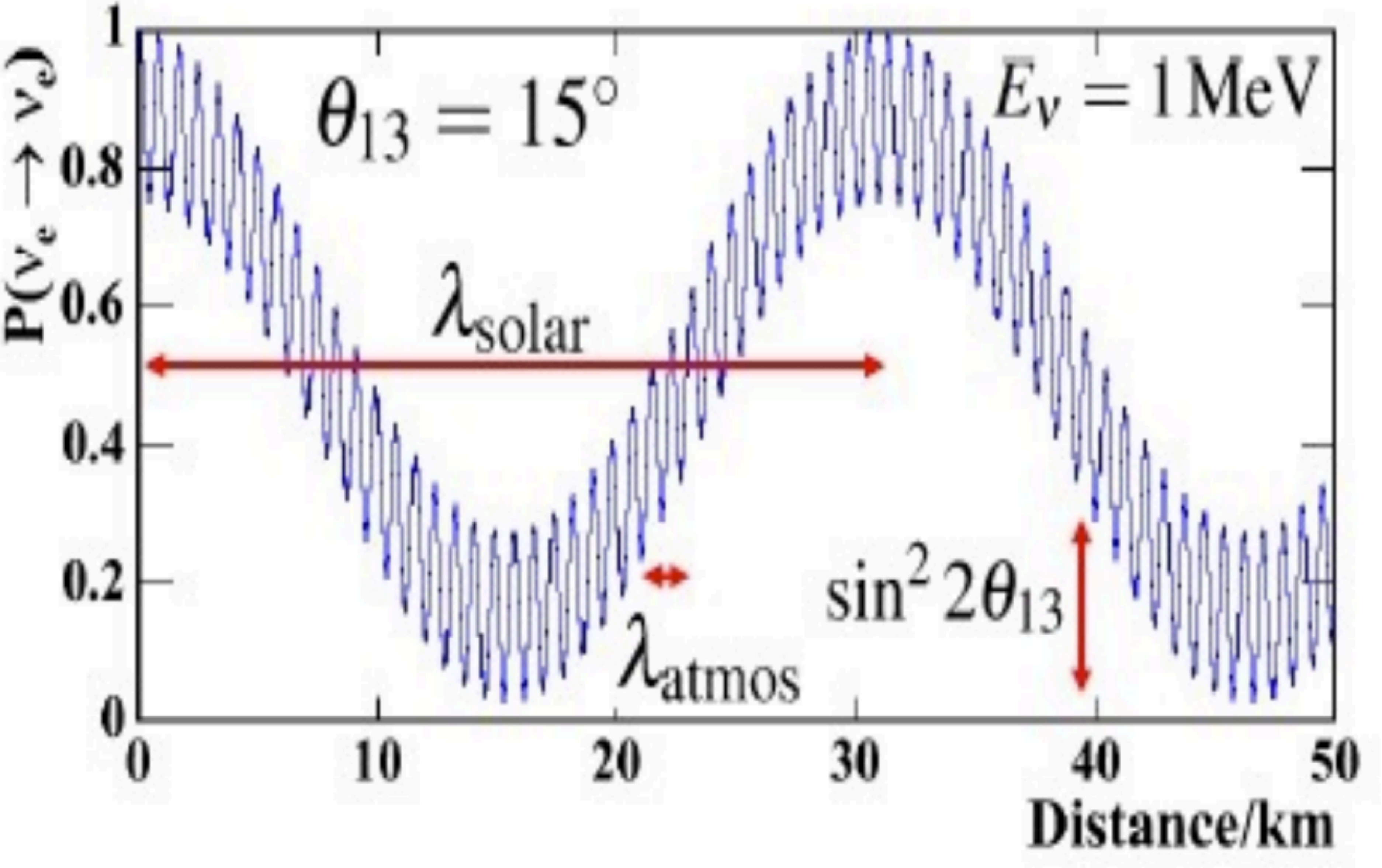
$$+ c_{13} \sin^2(1.27\, \Delta m^2 L/E)$$

$$+ c_{23} \sin^2(1.27\, \Delta m^2 L/E)]$$

$\Delta m^2 = \Delta m^2_{13} \sim \Delta m^2_{23}$ (solar, large)

$\delta m^2 = \Delta m^2_{12}$ (atmos, small)

Oscillation vs L/E



Long baseline accelerator neutrino physics

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

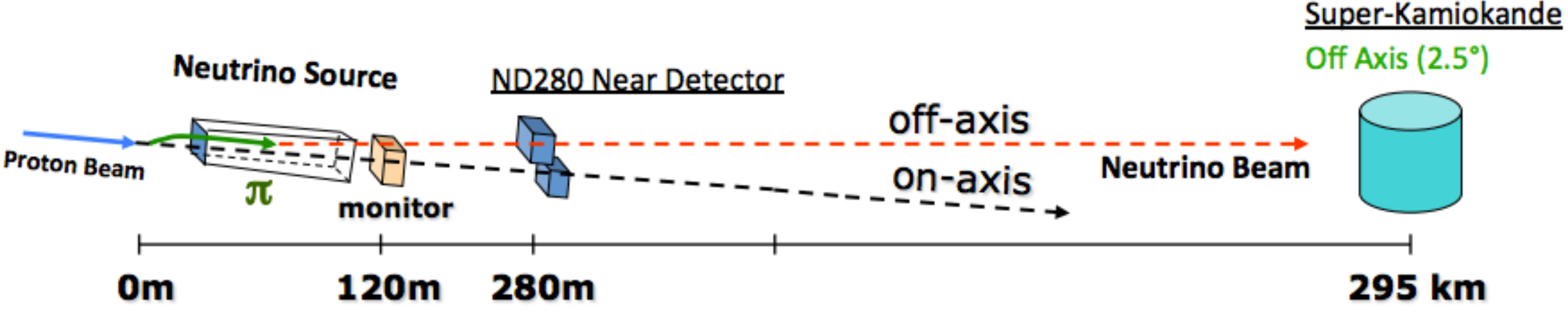
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\boxed{\sin^2(\theta_{23})}[1 - \cos^2(\theta_{13}) \times \sin^2(\theta_{23})]\sin^2(1.267\Delta m^2 L/E_\nu)$$

- ν_e appearance is sensitive to θ_{13} and (subleading) to the CP phase δ

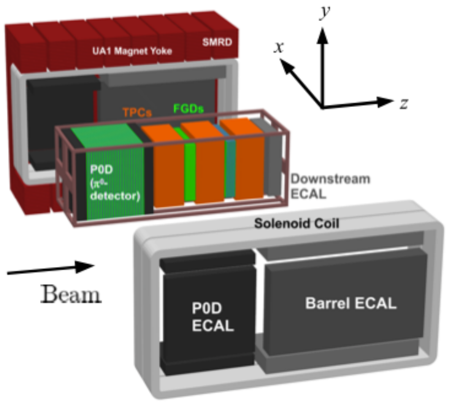
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\boxed{\sin^2 2\theta_{13}}\sin^2\frac{\Delta m^2_{31}L}{4E} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\boxed{\sin\delta_{CP}}$$

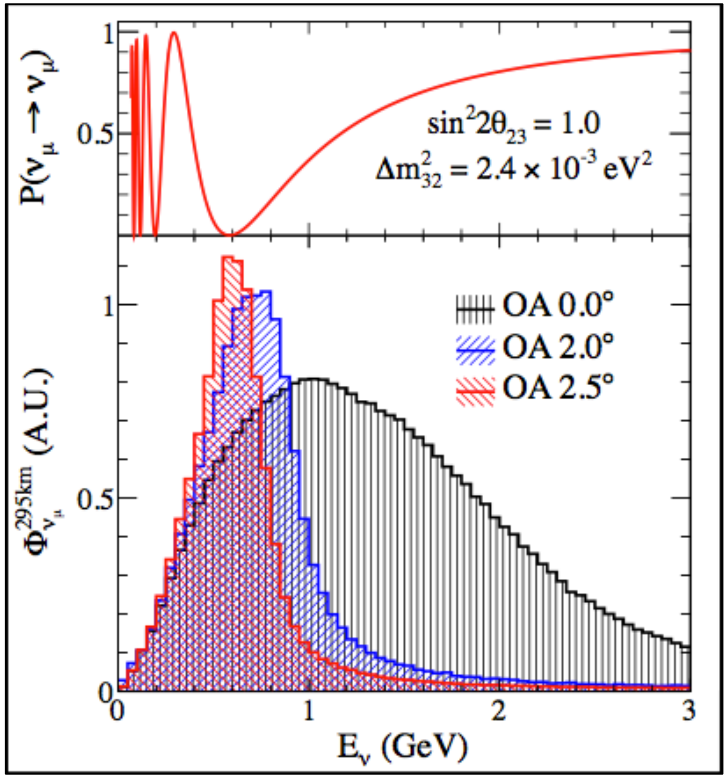
T2K (Tokai to Kamioka)

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



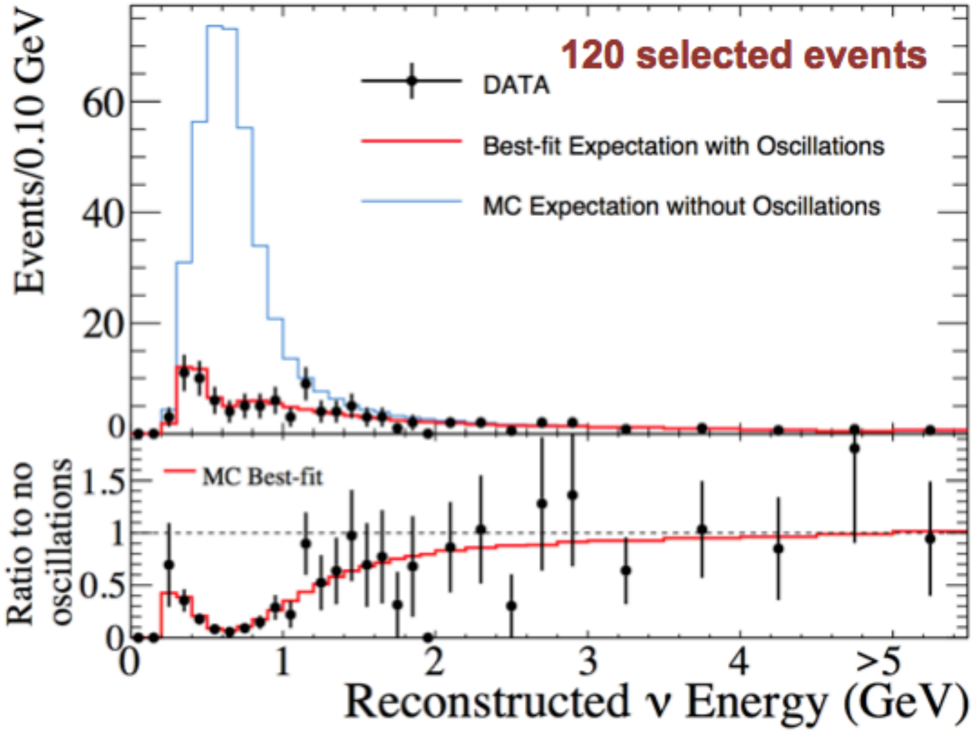
- 295km long baseline experiment
- Uses 2.5° off-axis ν_μ ($\bar{\nu}_\mu$) beam
- Data-taking started in 2009
- UK contribution to near detector (ND280) includes:
  - Electronics
  - DAQ
  - ECAL
- SK far detector

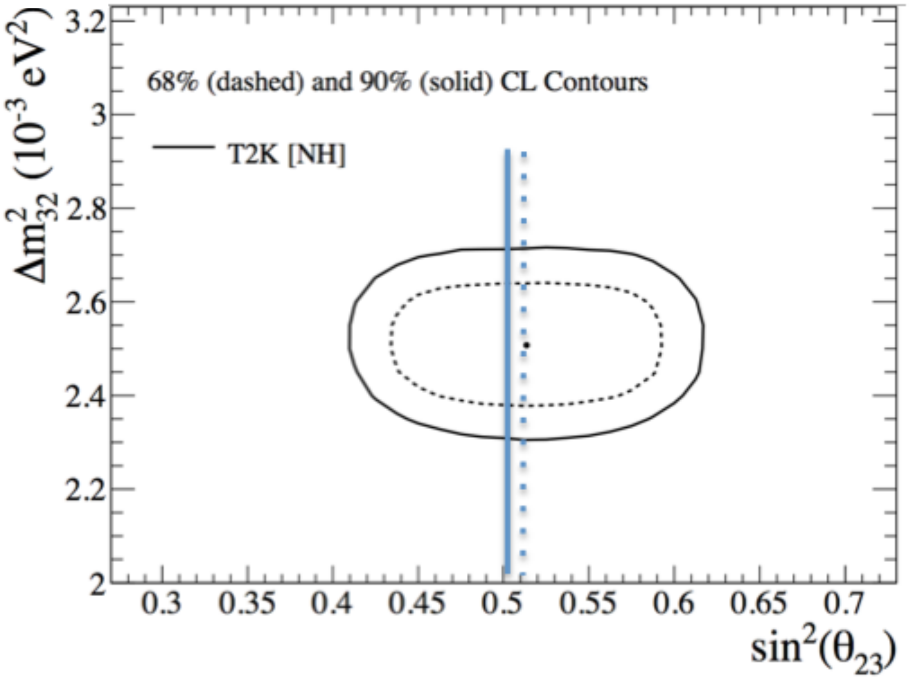




T2K ν_μ disappearance results

- Observation of a deficit of ν_μ events in SK

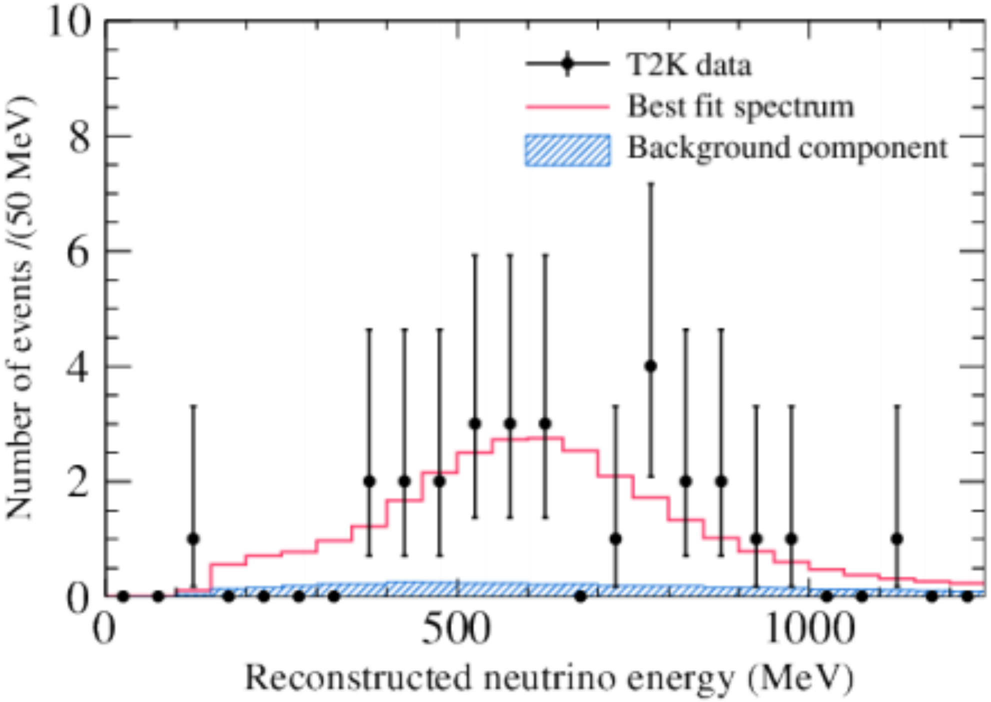


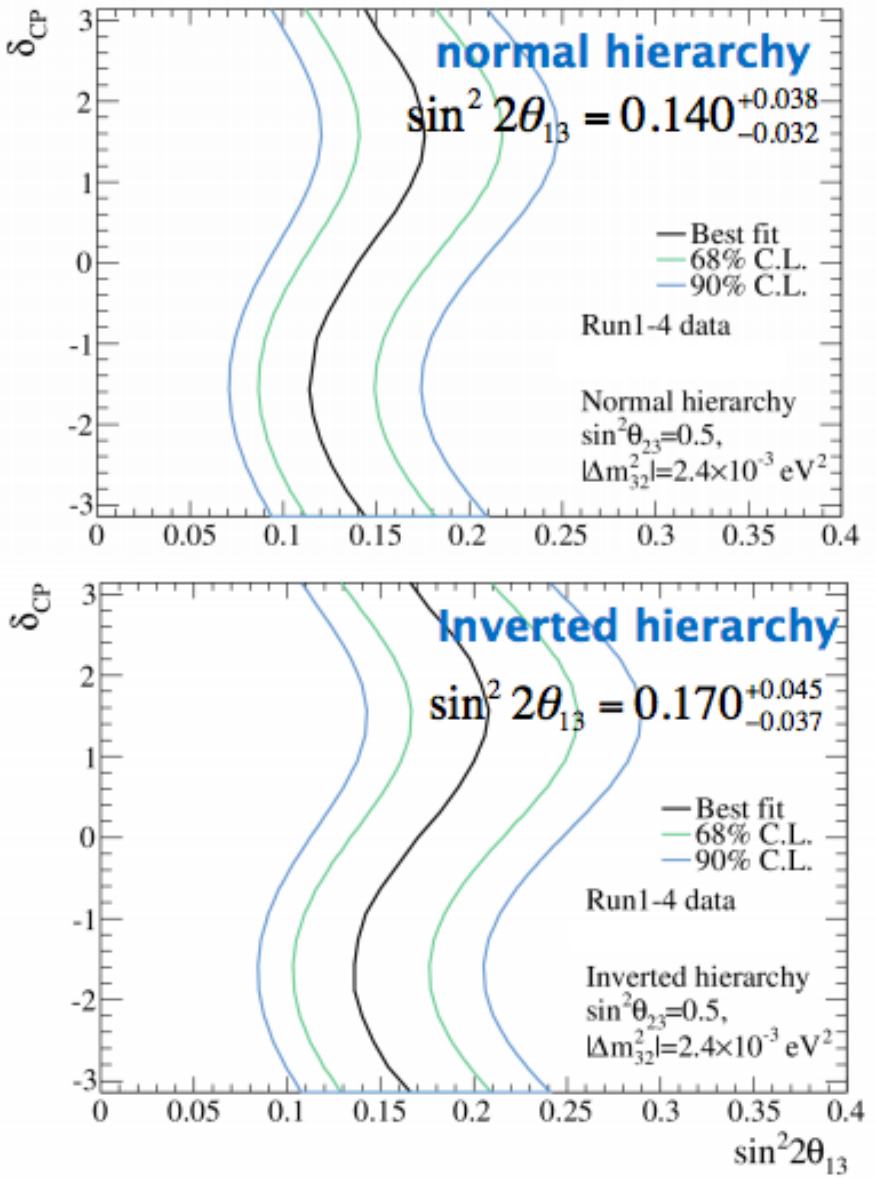


- Best fit values:
  - $\sin^2\theta_{23}$ (NH) = 0.514
  - Δm^2_{32} (NH) = 2.51×10^{-3} eV^2

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

T2K ν_e appearance results



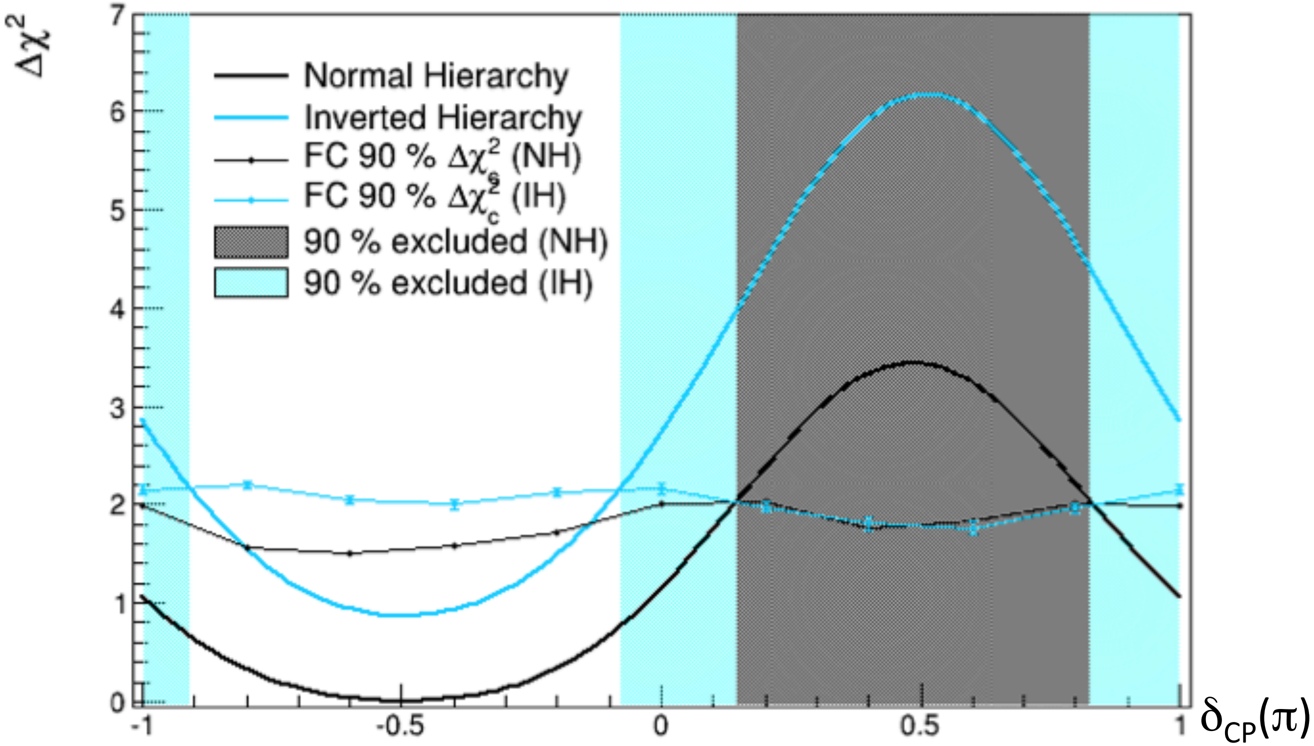


- 4.92 ± 0.55 background events expected (no oscillations)
- 28 events observed
- 7.3σ significance for non-zero θ_{13}
- First observation (> 5σ) of an appearance channel signal

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

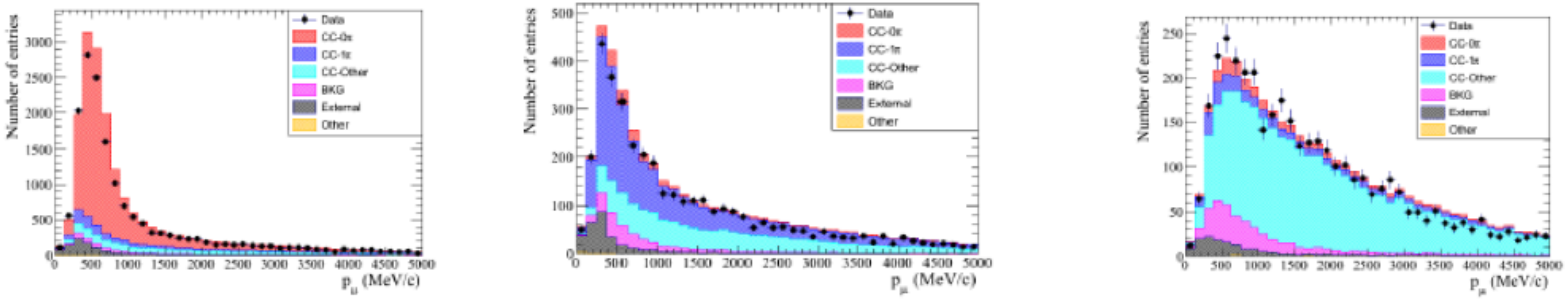
T2K δ_{CP} constraints

PRELIMINARY

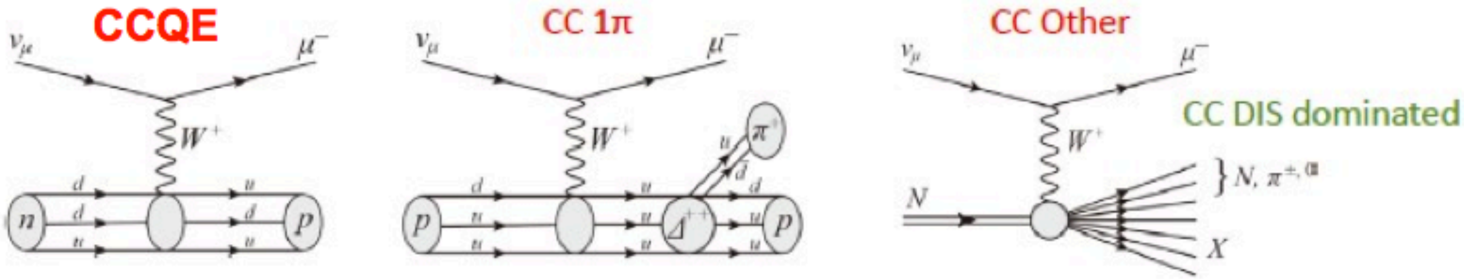


- Results from a combined likelihood ratio fit to the T2K ν_μ and ν_e CCQE samples
- Using the PDG 2013 value for θ_{13} there is a preference for $\delta_{CP} \approx -\pi/2$ and normal mass hierarchy
- Very similar results from an independent analysis based on Markov chain MC

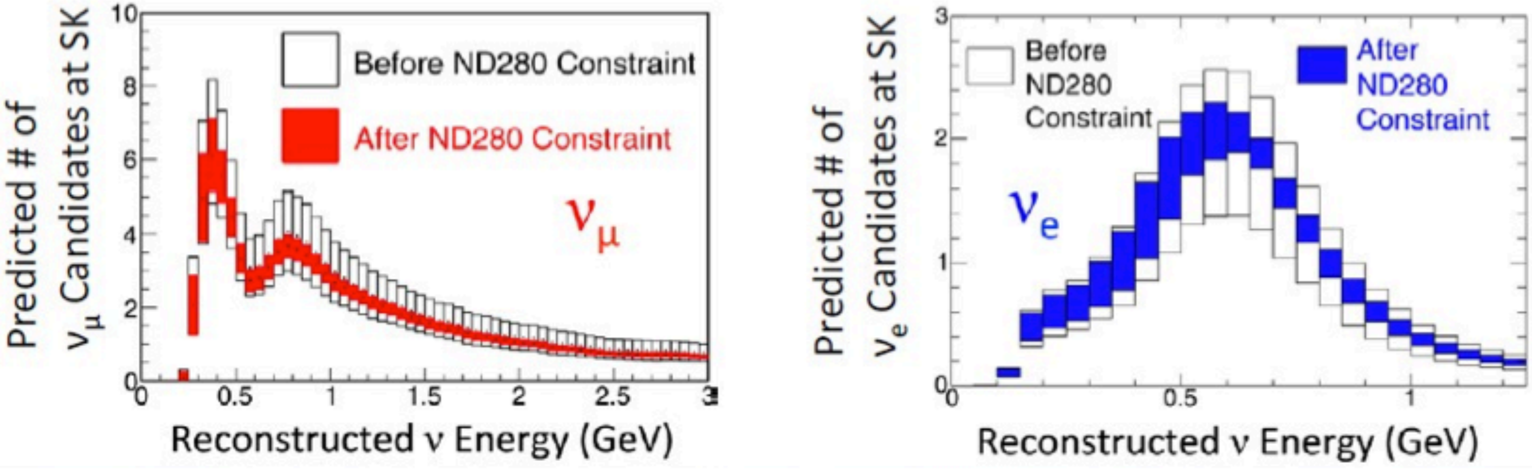
T2K ND280 and systematic errors



Signal channel
for oscillation
analysis

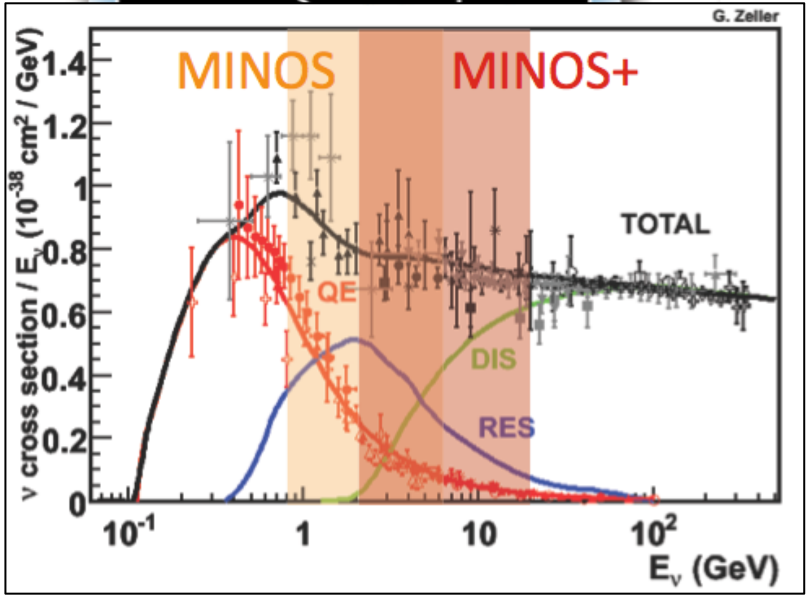


Flux and cross-section systematic uncertainty on N_{SK} significantly reduced to ~7%



MINOS / MINOS+

Cambridge • Oxford • STFC/RAL • Sussex • UCL

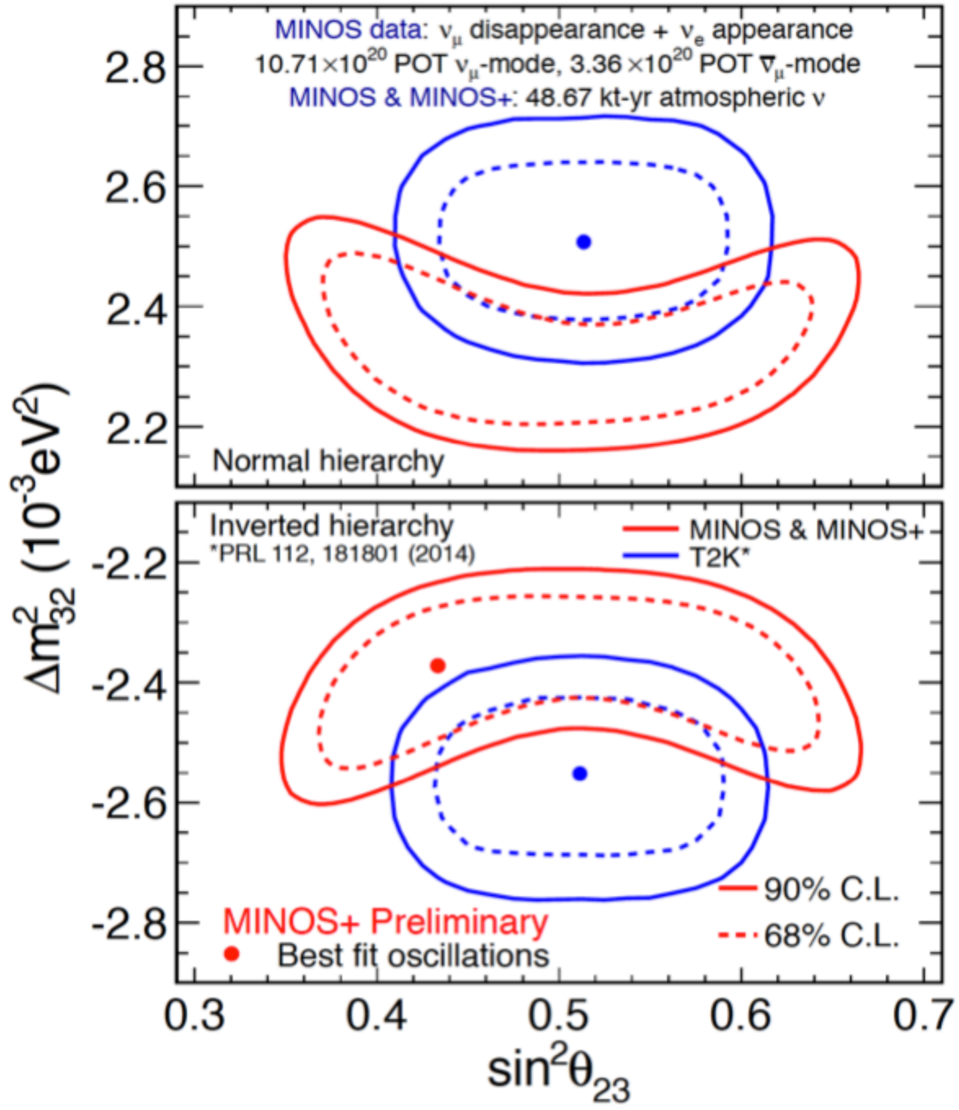


- MINOS
  - 735km baseline, FNAL to Soudan
  - 1kt near detector 1km from source
  - 5.4kt far detector
  - Both ND and FD are steel-plastic scintillator calorimeters
  - UK contributions
    - DAQ, electronics, PMT testing, light injection

MINOS+

  - Uses updated NUMI beamline
  - Higher energy (cross-checks with different beam and cross-section systematics
  - More statistics (4000 ν_μ CC events/ year in far detector)

MINOS/MINOS+ combined fit



Three-Flavor Oscillations Best Fit

Inverted Hierarchy

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

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

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

Normal Hierarchy

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

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

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

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

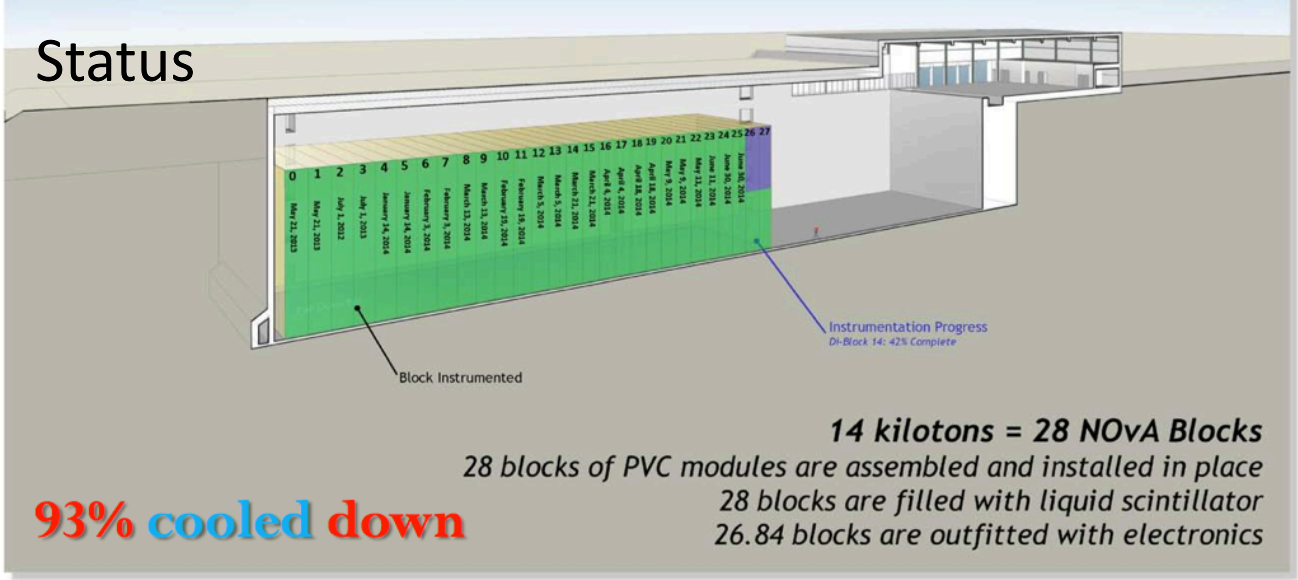
Sousa, Neutrino 2014

- Other interesting results on sterile neutrinos, etc.

NOνA experiment and status

Sussex

- Precision appearance/disappearance ν_μ ($\bar{\nu}_\mu$) 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



Status

14 kilotons = 28 NOvA Blocks

28 blocks of PVC modules are assembled and installed in place

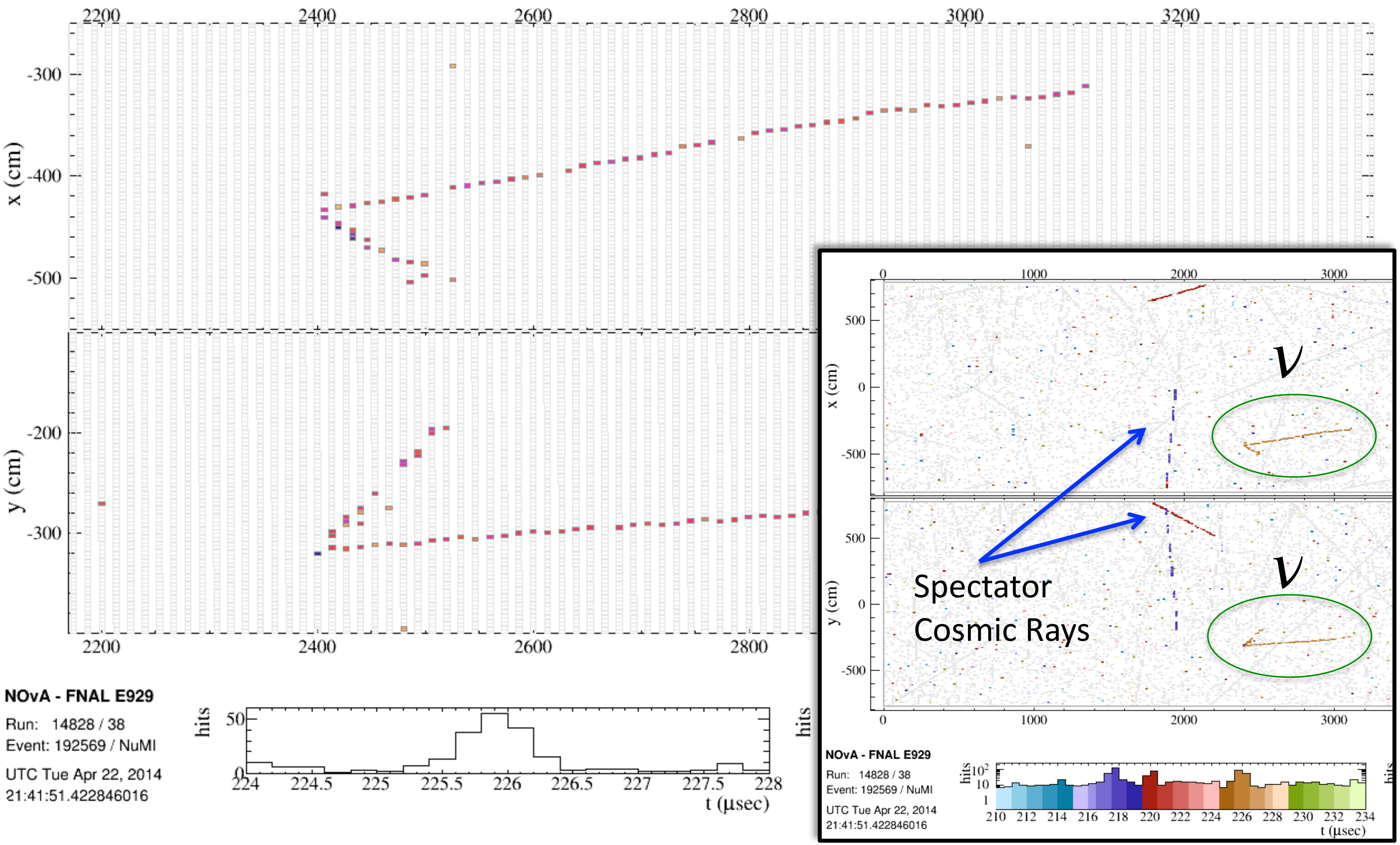
28 blocks are filled with liquid scintillator

26.84 blocks are outfitted with electronics

93% cooled down

- 93% of APDs cooled down to -15C
- Now fully instrumented
- 1-2 month accelerator shutdown now, 500kW beam expected afterwards
- UK contribution: data driven trigger, stopping muon calibration, ν_μ analysis

NOvA CC candidate event

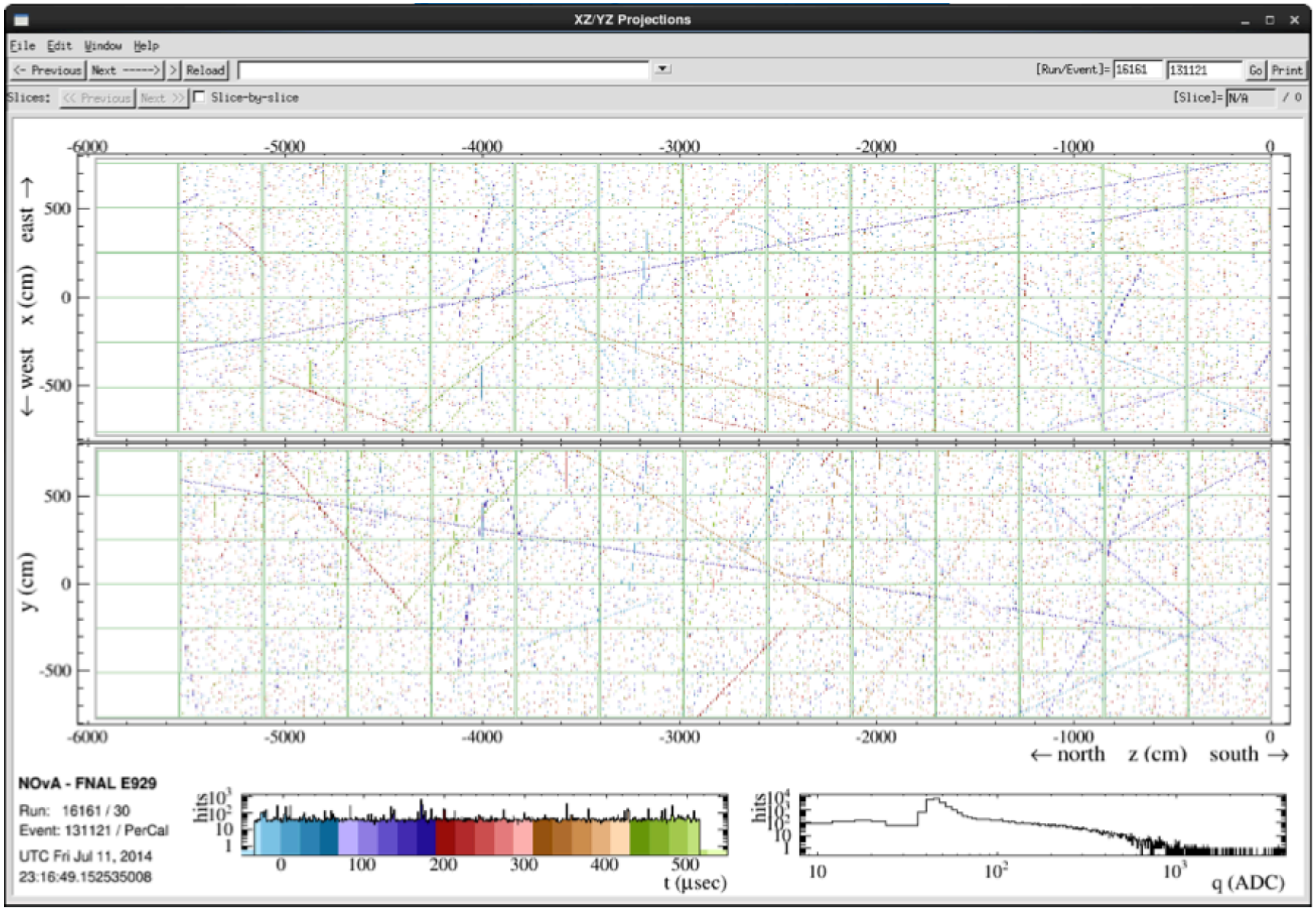


ν

ν

Spectator
Cosmic Rays

NOνA cosmic muon event



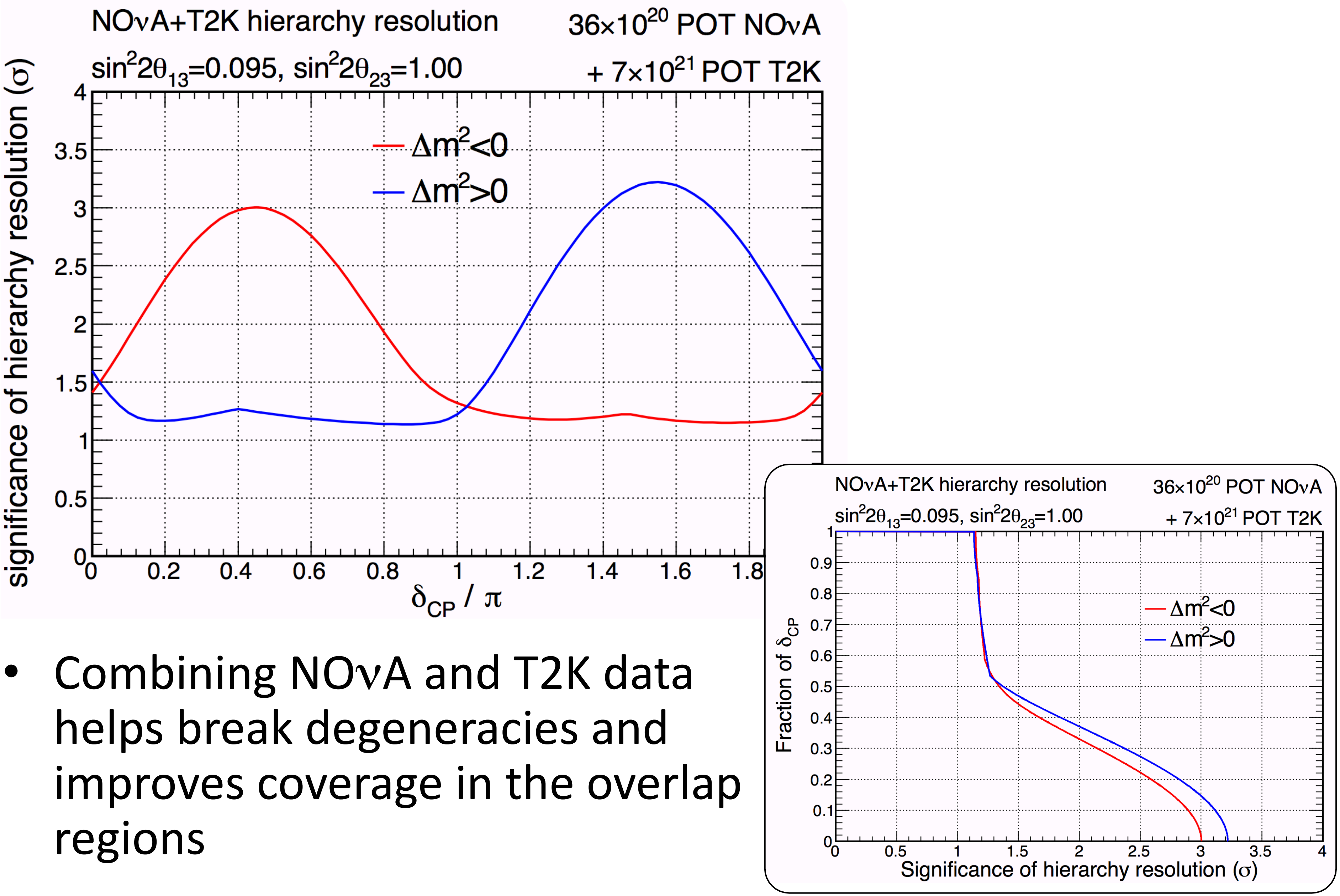
[Run/Event]= 16161 131121

[Slice]= N/A / 0

NOvA - FNAL E929
Run: 16161 / 30
Event: 131121 / PerCal
UTC Fri Jul 11, 2014
23:16:49.152535008

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

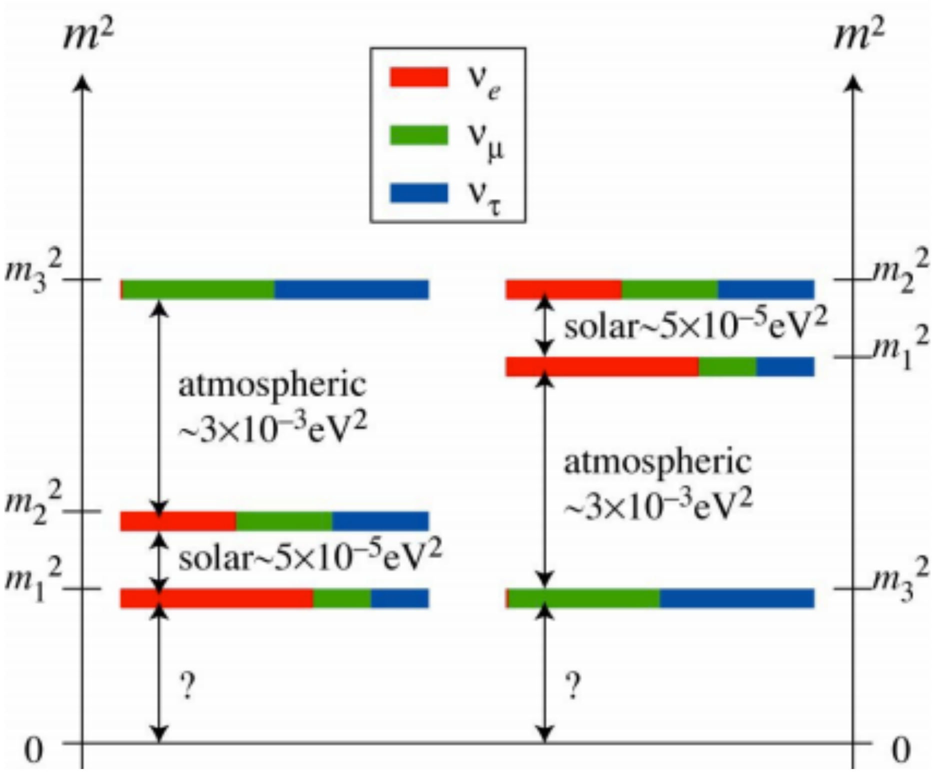
NOνA and T2K complementarity



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

Current understanding

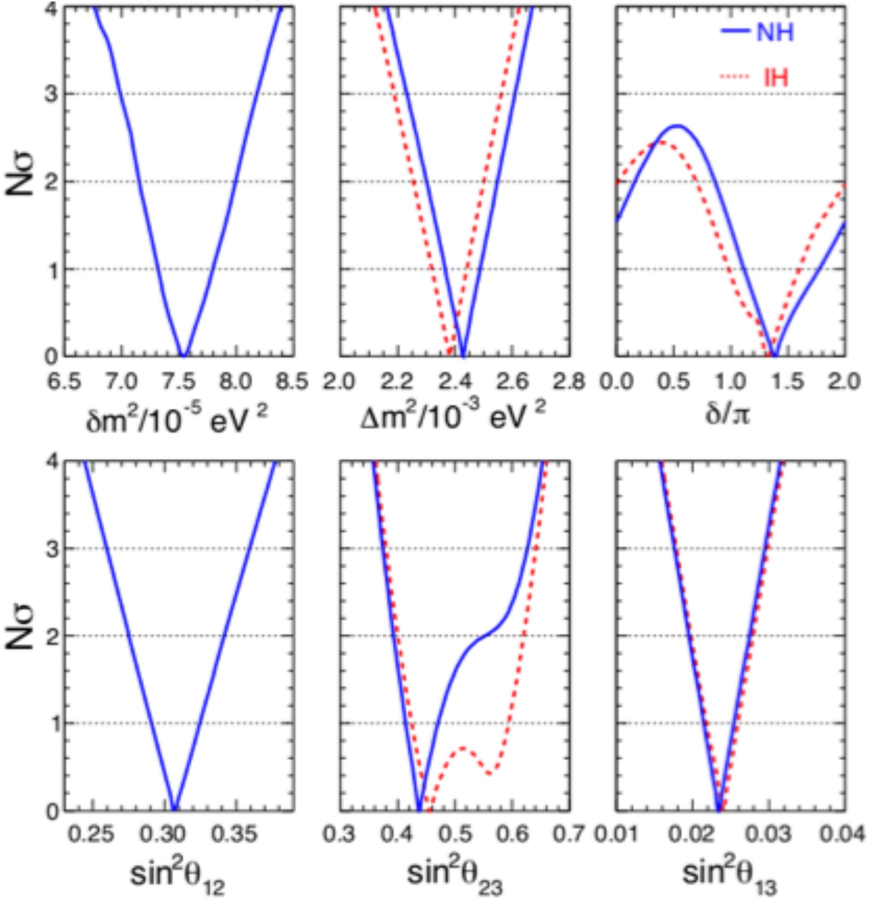
Mass hierarchy



Normal

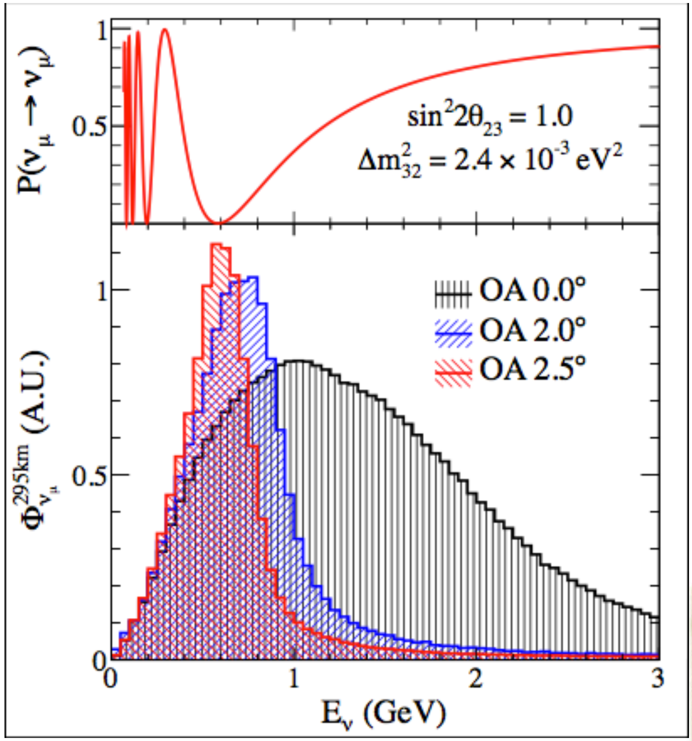
Inverted

Mixing angles and mass differences



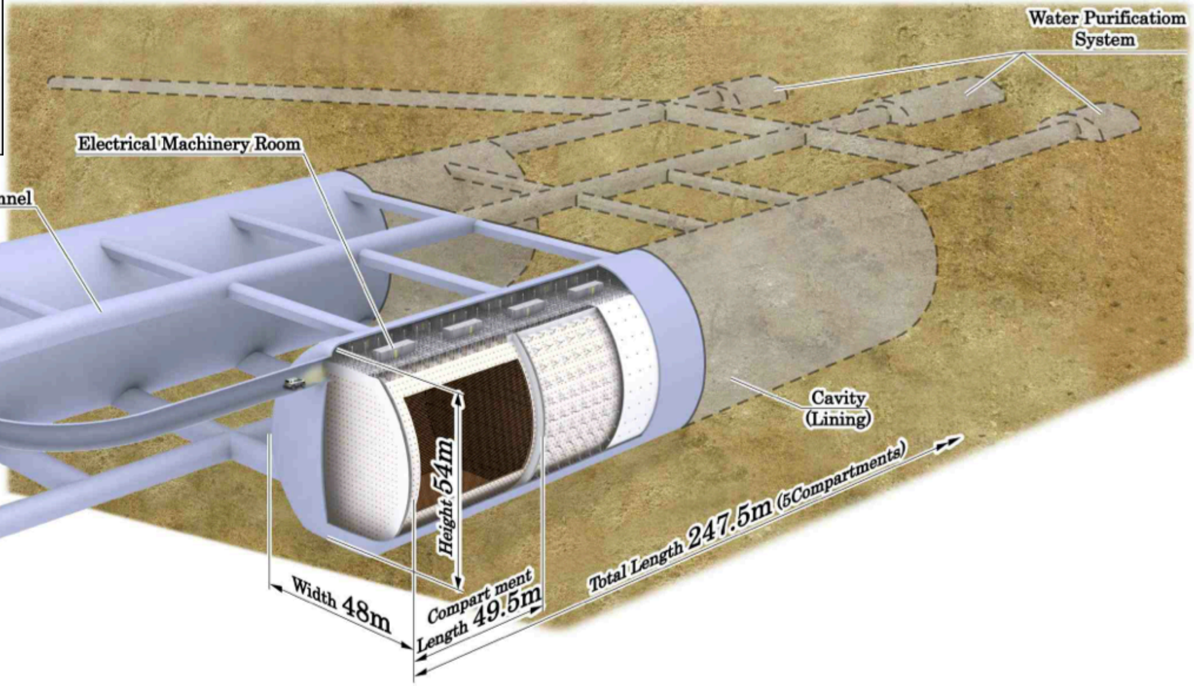
- Global fit data as of June 2014
- Uses LBL, SBL, reactor, solar, atm data
- Uses technique in Capozzi et al. PRD 89 (2014) 093018)

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

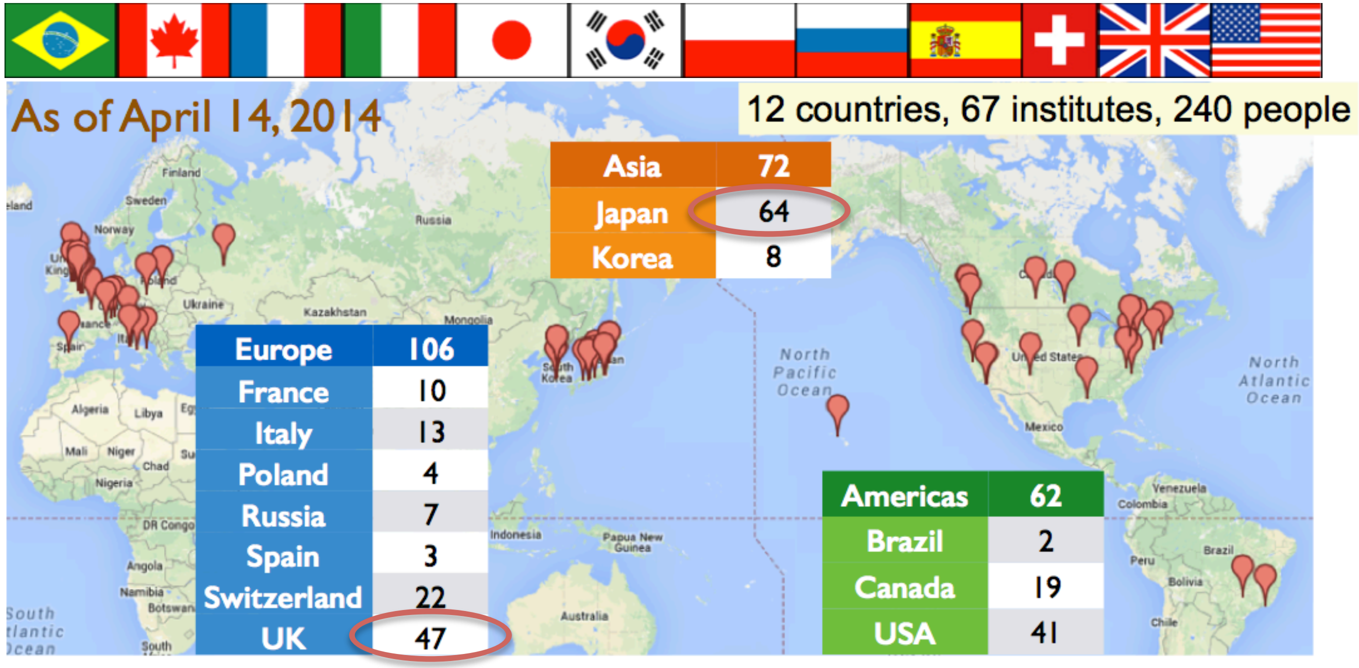
- J-PARC ν_μ ($\overline{\nu}_\mu$) beam upgraded to ≥ 0.75MW
- 2.5° off-axis, narrow band 600MeV beam



HyperK status

第 22 期学術の大型研究計画に関する
マスタープラン
（マスタープラン 2014）

平成２６年（２０１４年）２月２８日
日本学術会議
科学者委員会
学術の大型研究計画検討分科会



As of April 14, 2014

12 countries, 67 institutes, 240 people

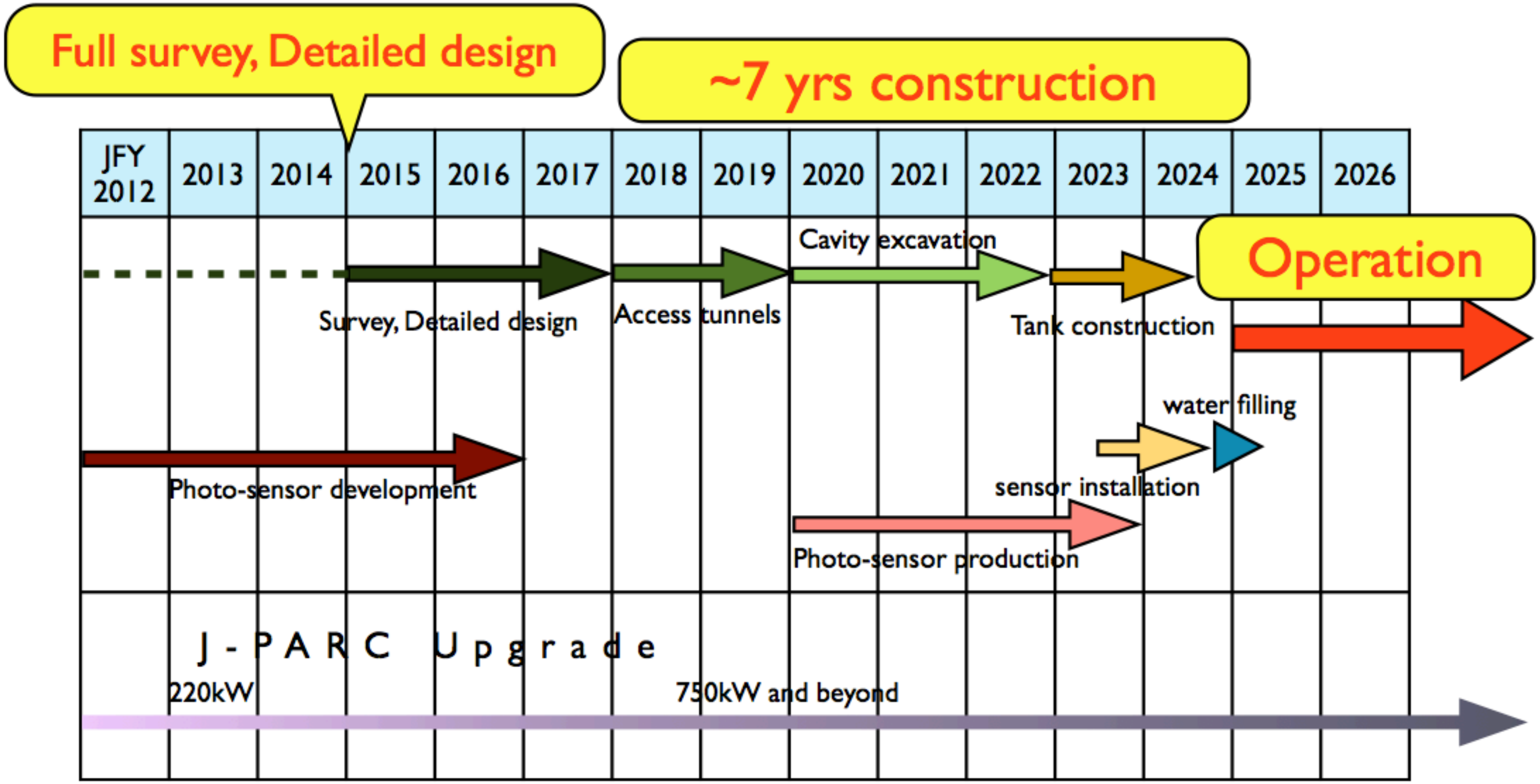
Asia	72
Japan	64
Korea	8

Europe	106
France	10
Italy	13
Poland	4
Russia	7
Spain	3
Switzerland	22
UK	47

Americas	62
Brazil	2
Canada	19
USA	41

- 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

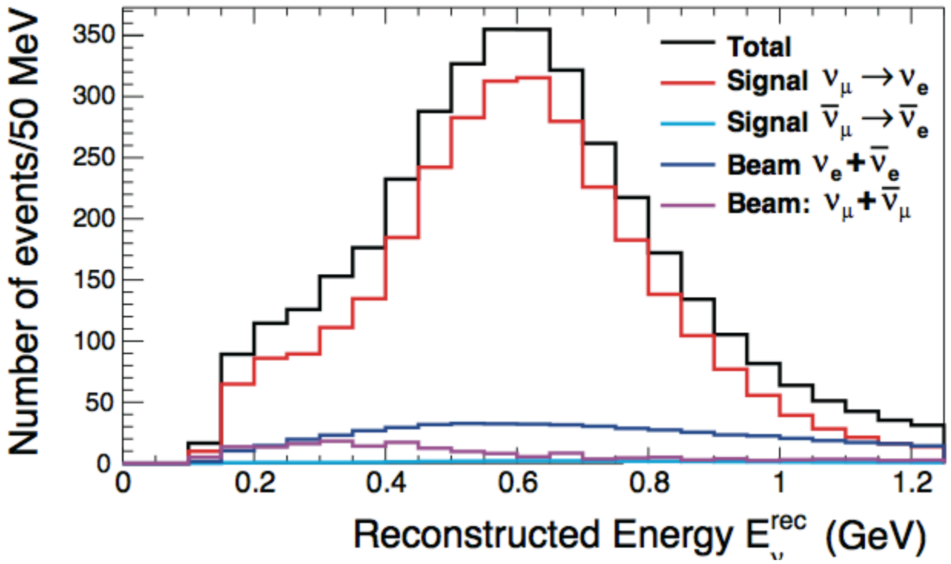
HyperK timeline



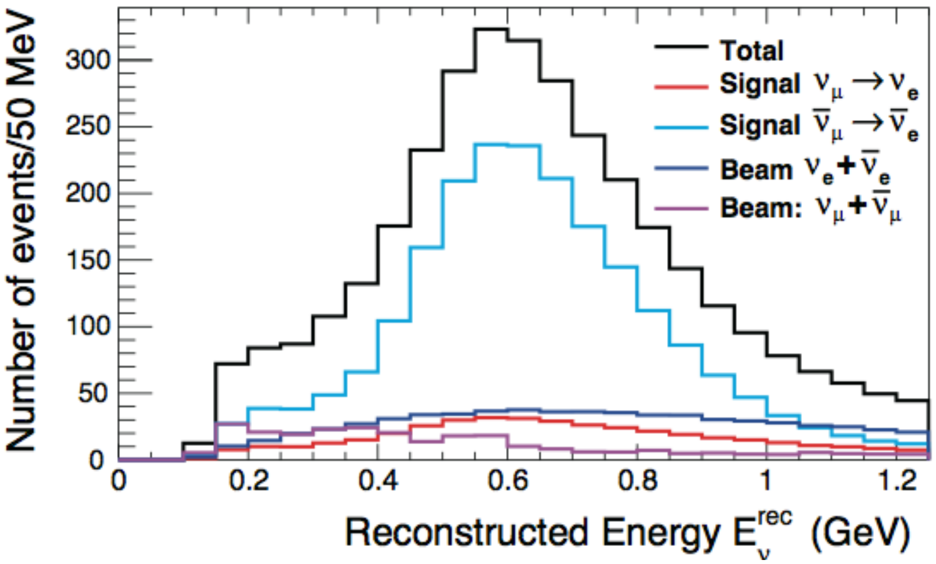
- 2015 Full survey, Detailed design (3 years)
- 2018 Excavation start (7 years)
- 2025 Start operation

HyperK appearance and disappearance events

Appearance ν_e events



Appearance $\bar{\nu}_e$ events

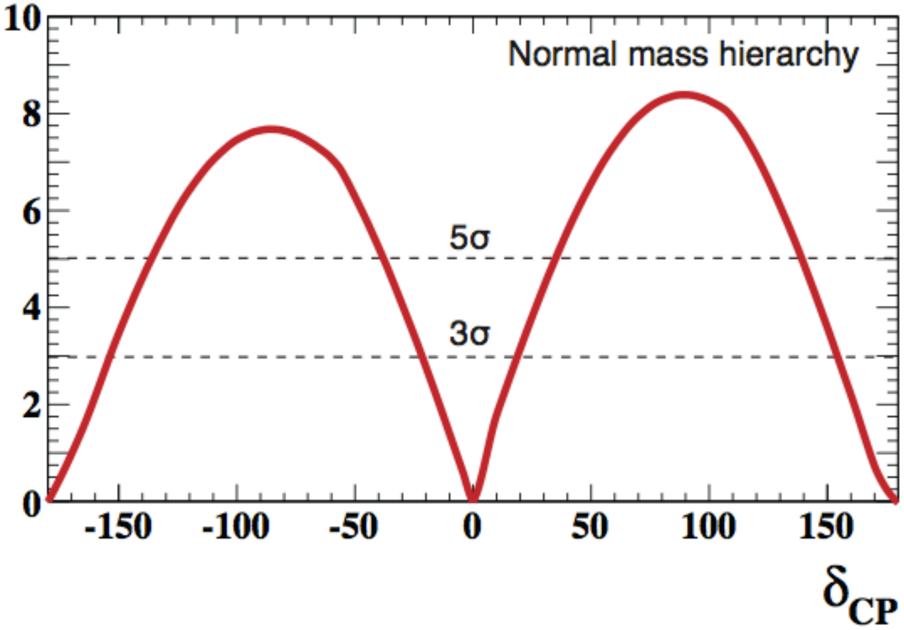


Appearance	Signal		Background				Total
	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	
ν mode	3016	28	168	9	508	21	3750
$\bar{\nu}$ mode	396	2110	86	179	226	400	3397

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

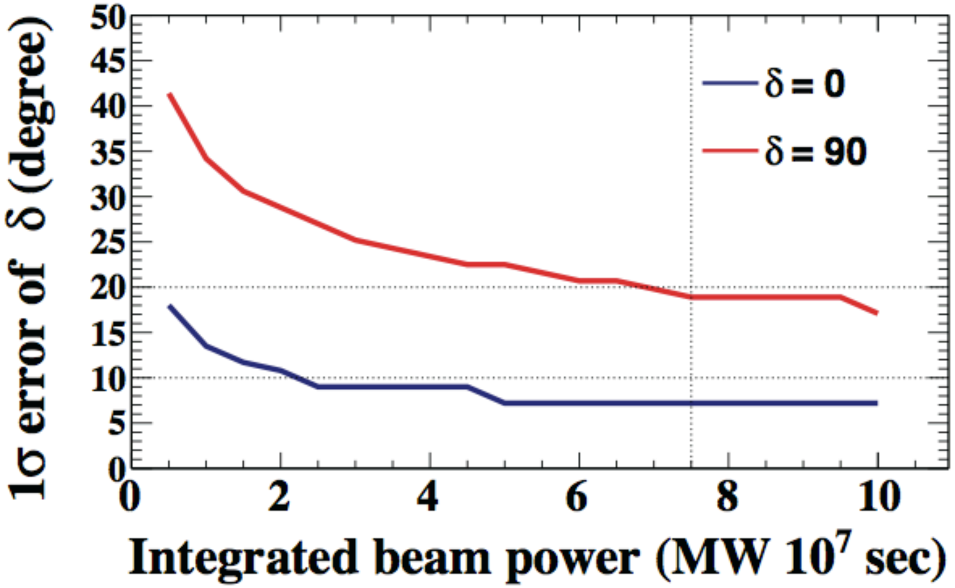
7.5 x 10^7 MW sec, $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP}=0$, normal MH, ν:ν = 1:3

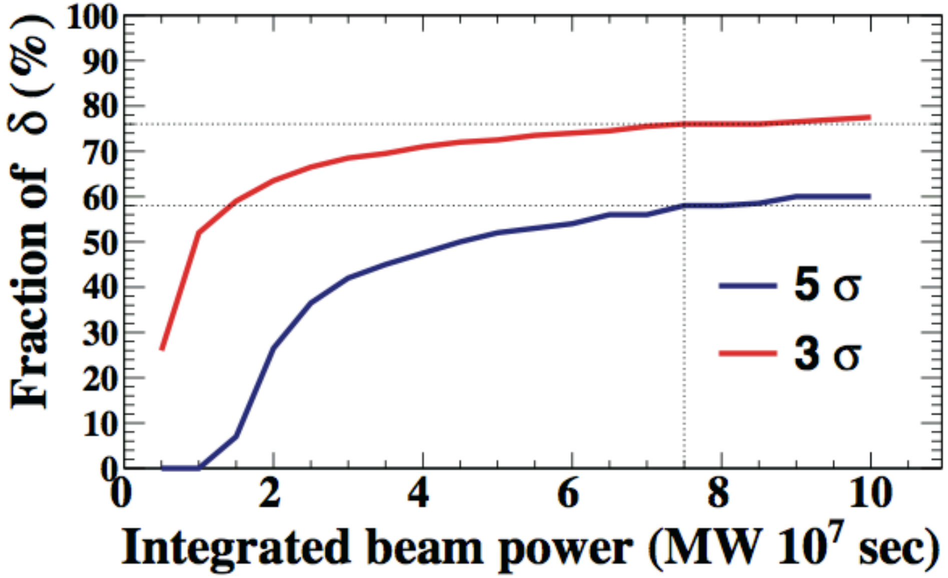
HyperK sensitivity to CP



Assuming 7.5x10^7 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

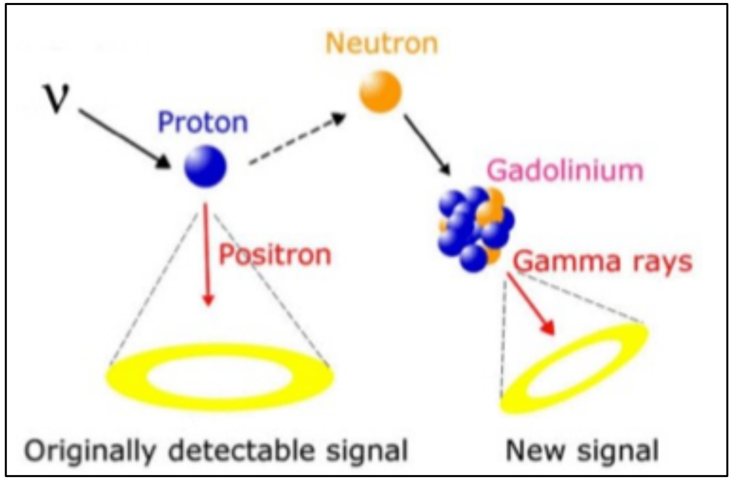
Edinburgh • Imperial • Lancaster • Liverpool • Oxford

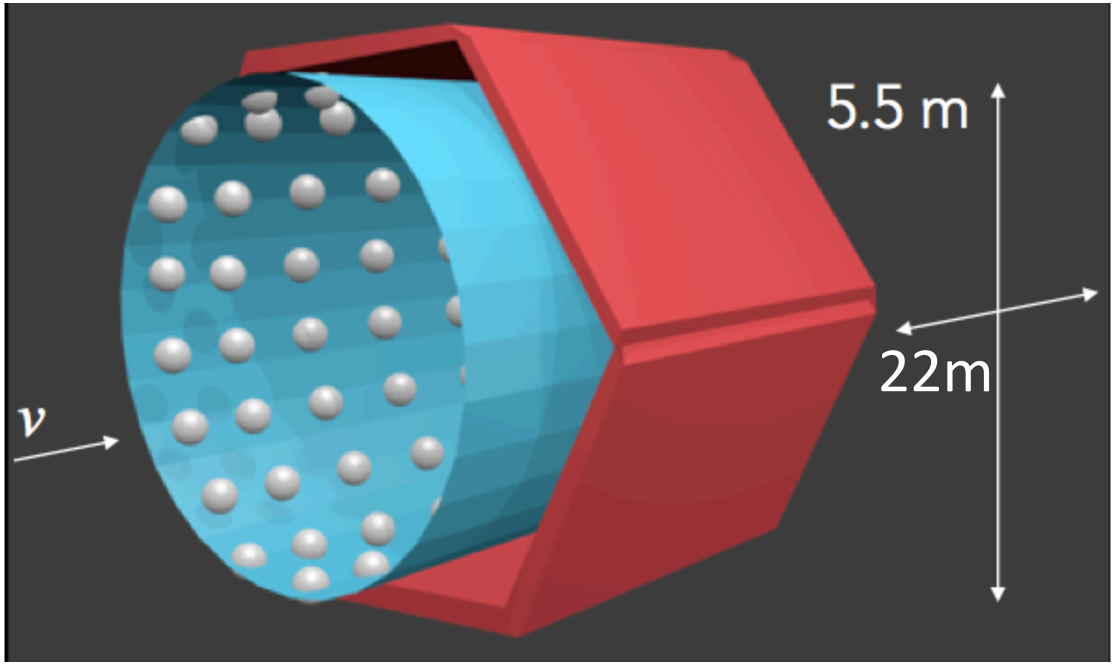
QMUL • RHUL • Sheffield • STFC/RAL • Warwick

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

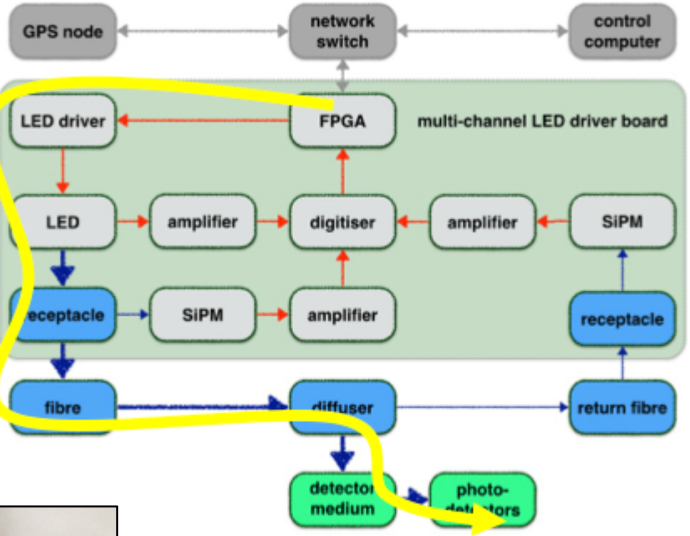
HyperK UK WP2 Detector R&D

- 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

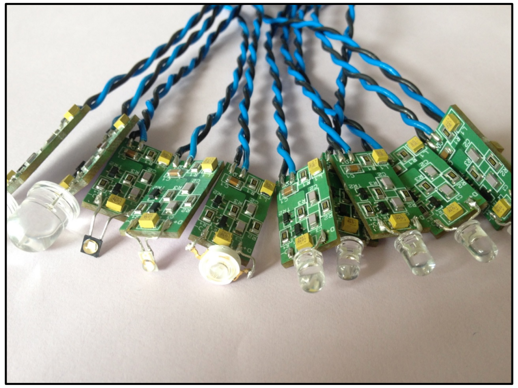




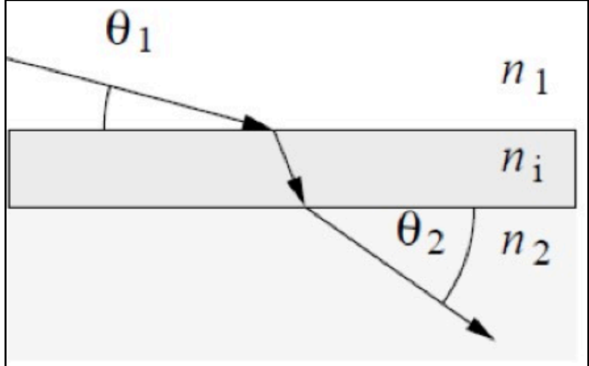
HyperK UK WP4 Calibration



- 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



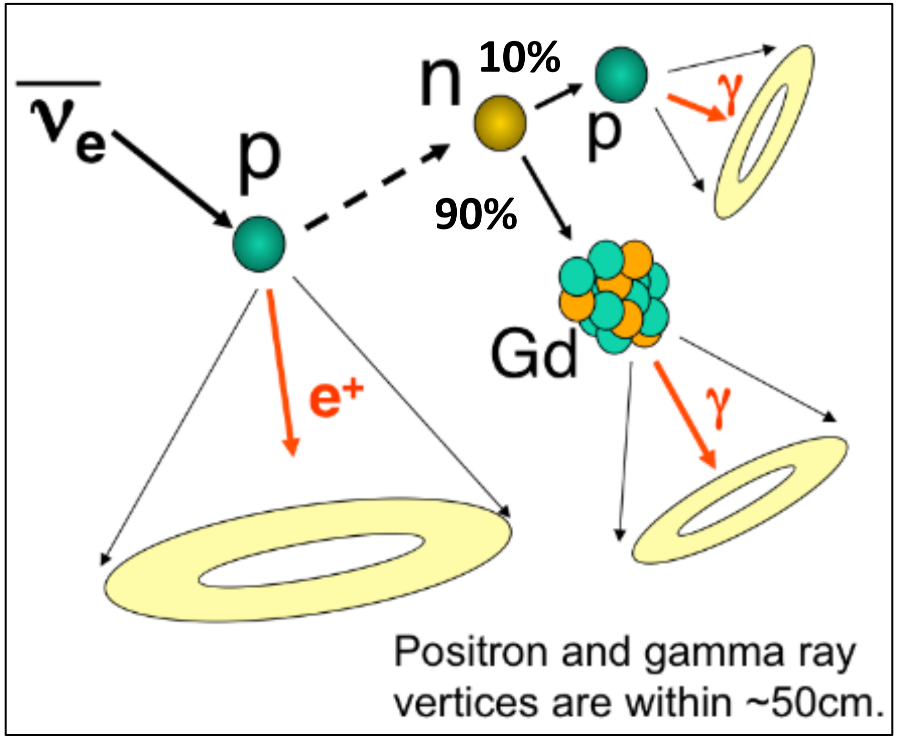
$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ independent of n_i

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

Light emitted at Cherenkov angle.

Water Č: Gd loading

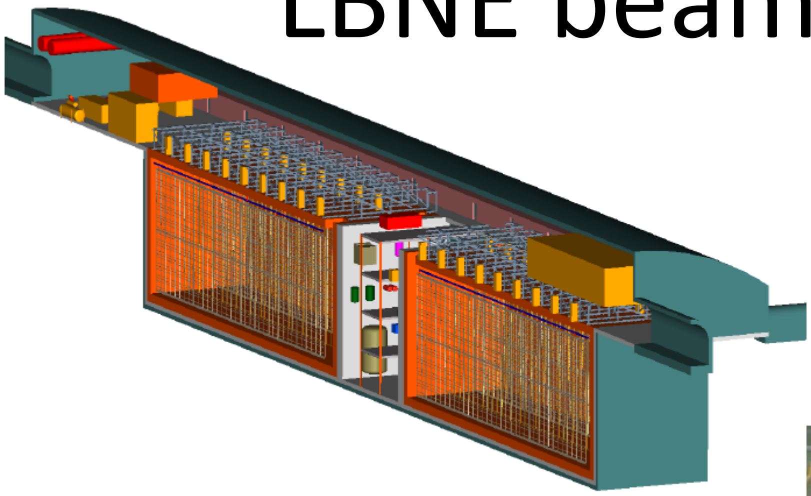
- Turn a standard Water Cherenkov detector into a anti-neutrino detector by loading with ~0.2% water soluble Gd
- Use delayed (~30μs) coincidence of γ and e^+



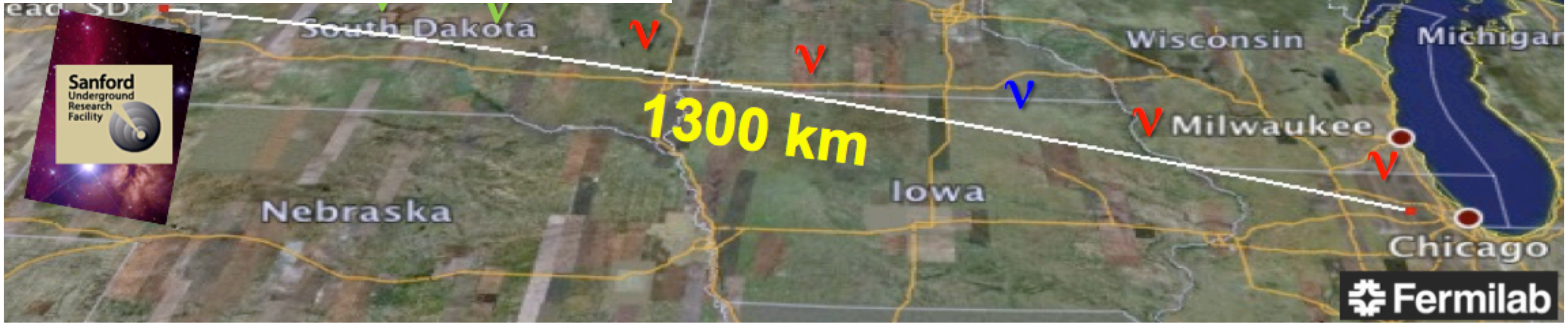
Positron and gamma ray vertices are within ~50cm.

- 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

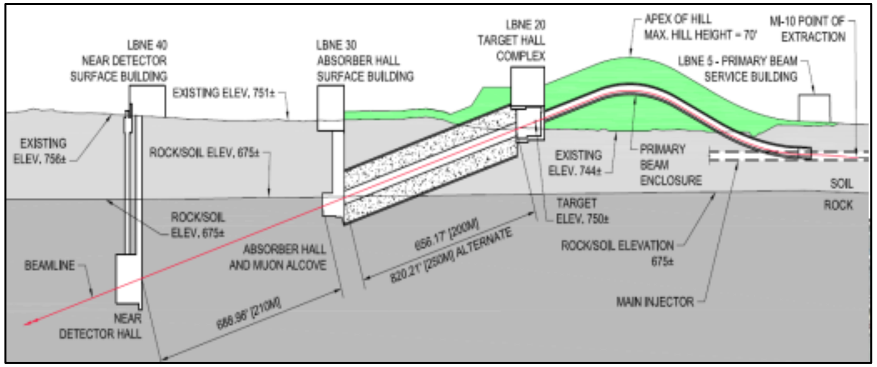
LBNE beam and far detector



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



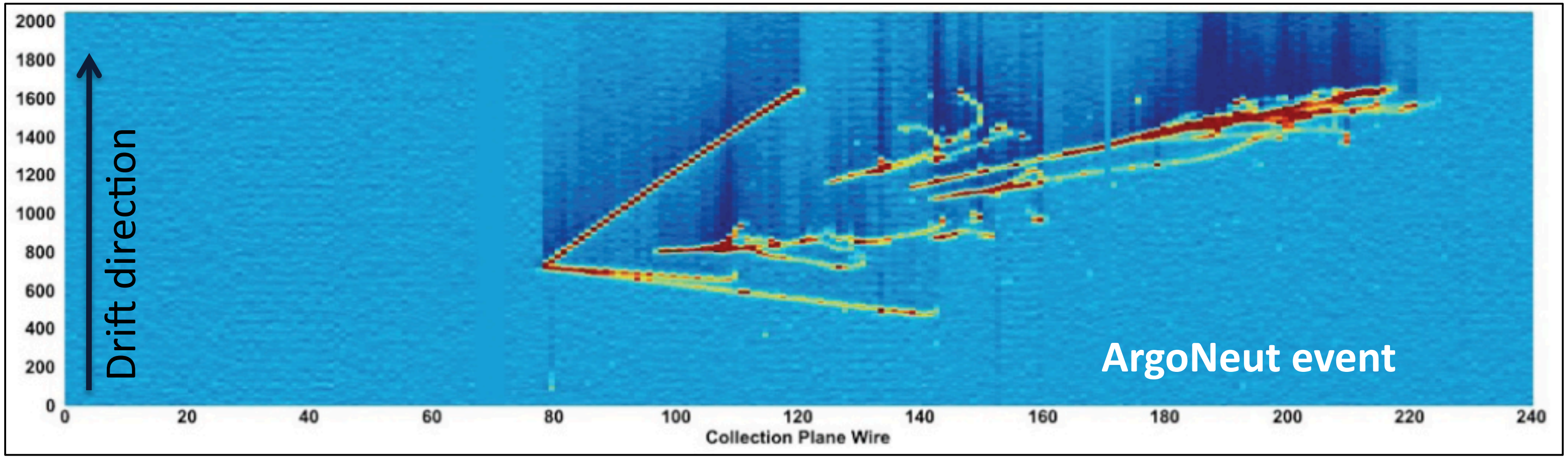
- Far detector
  - 10kt/34kt fiducial volume at 4850ft
  - 2 TPC modules each ~14m x 22m x 45m in the same cavern
  - Cosmic backgrounds ~ 0.1Hz



Liquid Argon TPCs

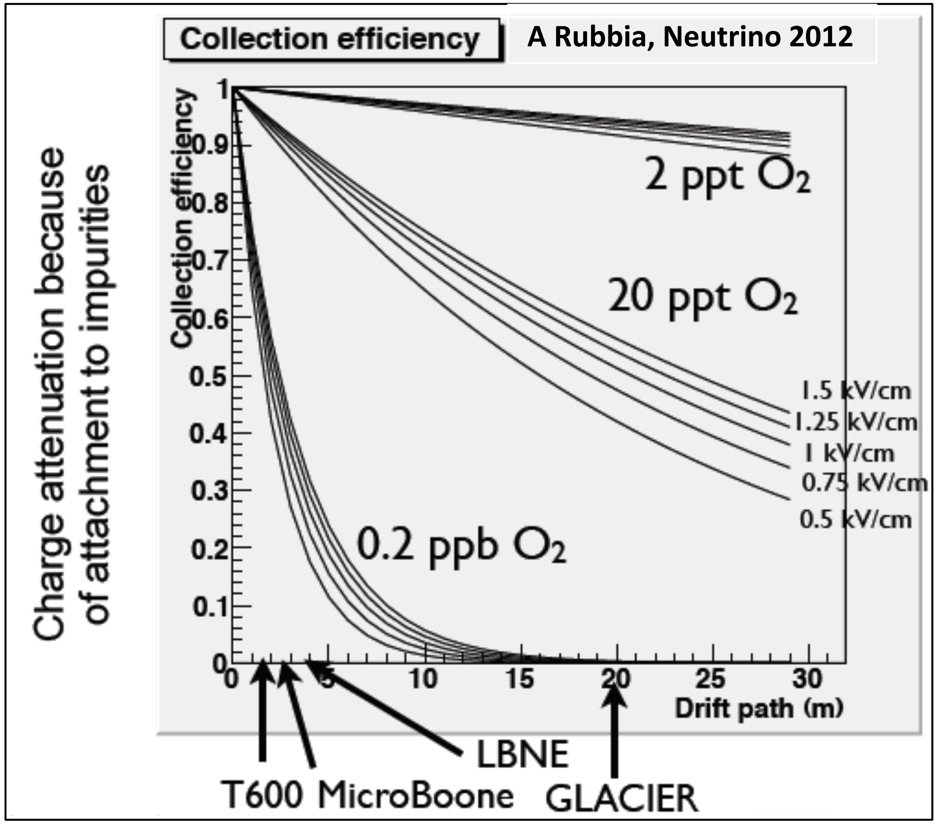
- Why Liquid Argon?
  - High density, cheap
  - Dense → good target
  - Excellent dielectric properties support large voltages
  - Free electrons from ionizing track can be drifted in long distances inLAr
  - Electron cloud diffusion is small
  - High scintillation light yield (at 128nm) can be used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

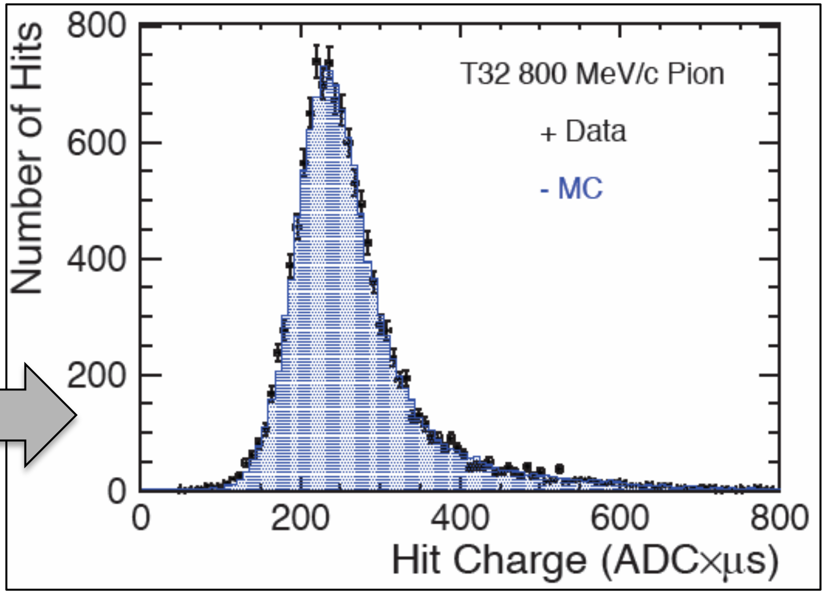
- Technical challenges:
  - to achieve long drift distances ultra-high purities (better than 100 ppt O_2 equivalent) are required
  - Drift field requires HV on the cathode
  - Operation of large wire chambers at cryogenic temps
  - No charge amplification in liquid → fC charges requiring sensitive preamps
  - Large number of R/O channels
  - Large cryogenic systems

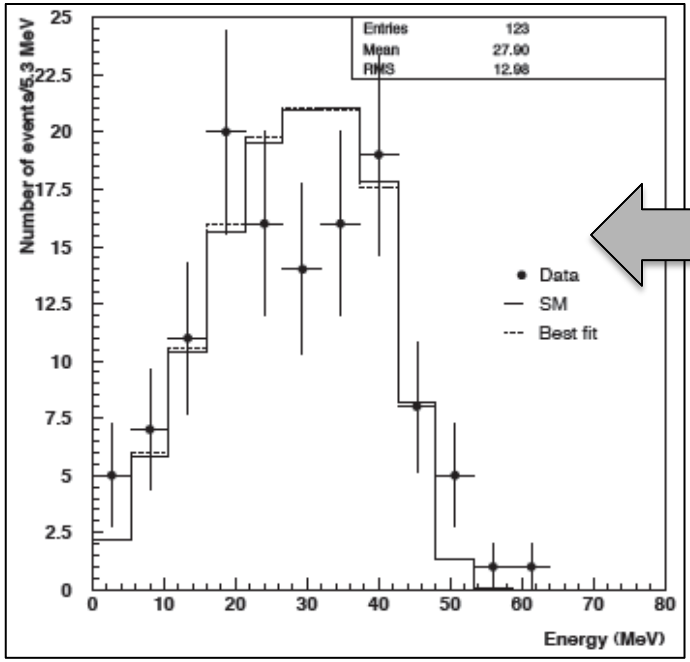


Liquid Argon TPCs: performance

- 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

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





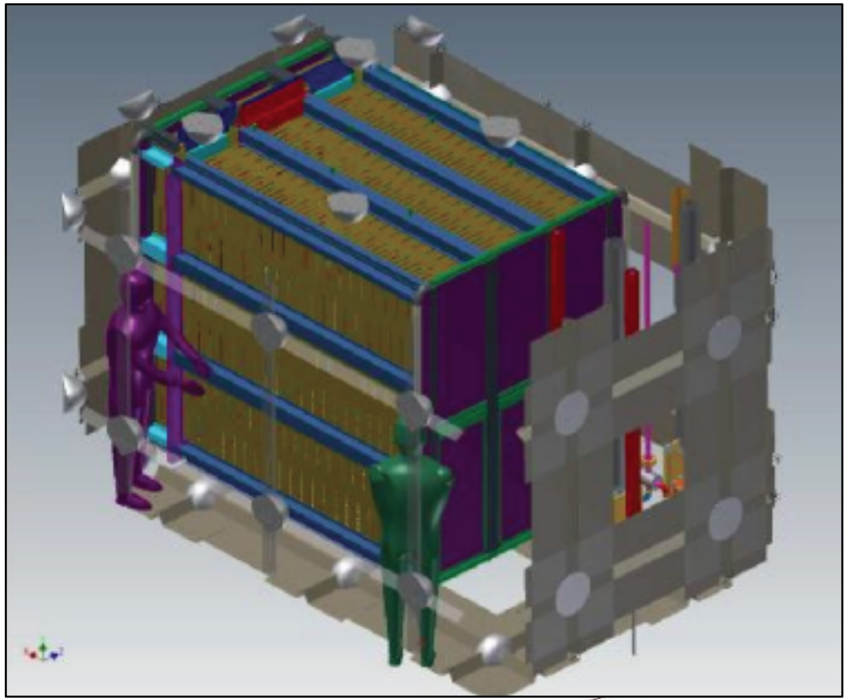
- Calorimetric Performance:
  - ICARUS data (2004) with Michel electrons from stopping muon decay

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

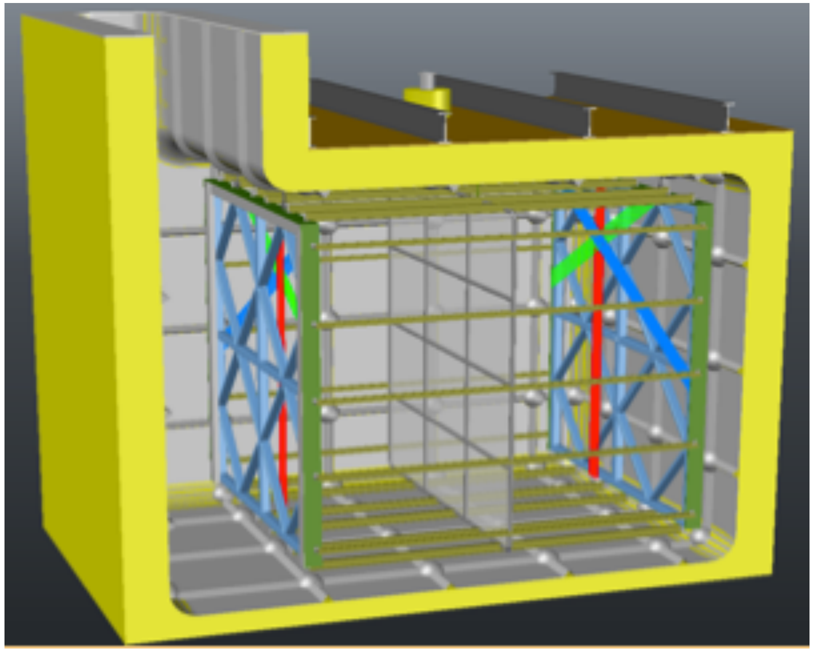
  - MC expectations (higher E):

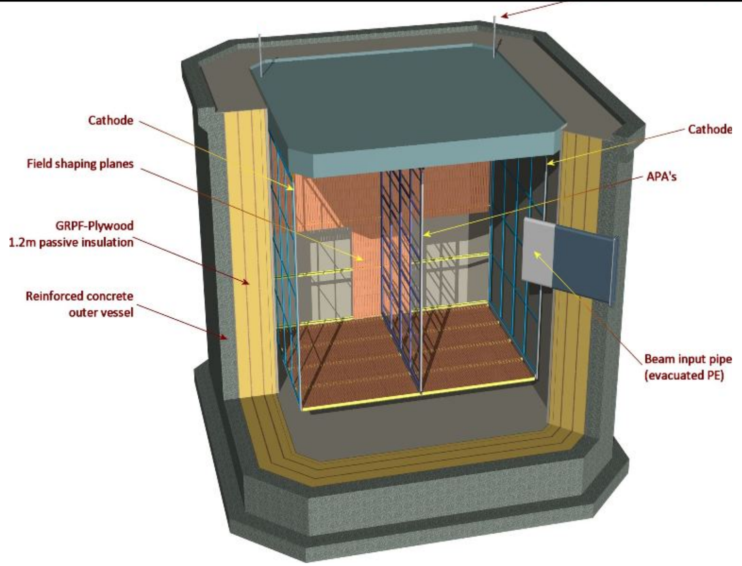
$$\frac{\sigma_{EM}^{MC}}{E} \approx \frac{3\%}{\sqrt{E}} \oplus 1\% \qquad \frac{\sigma_{HAD}^{MC}}{E} \approx \frac{15\%}{\sqrt{E}} \oplus 10\%$$

LAr prototyping activities



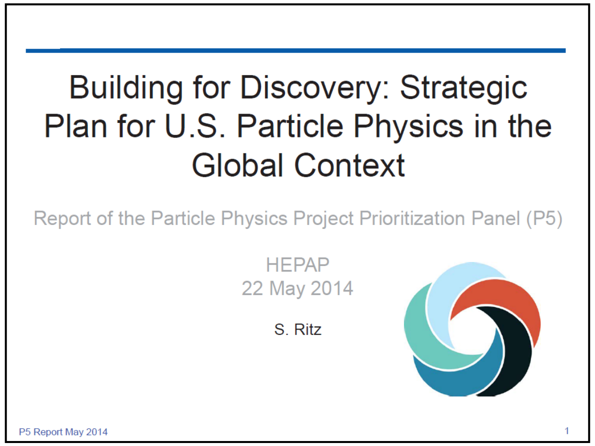
- LBNE 35 ton prototype due to take data at FNAL in early 2015
- LAr1-ND, 82t TPC for MicroBoone (2017)
- Other activities ArgoNeut, LARIAT etc.





- 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

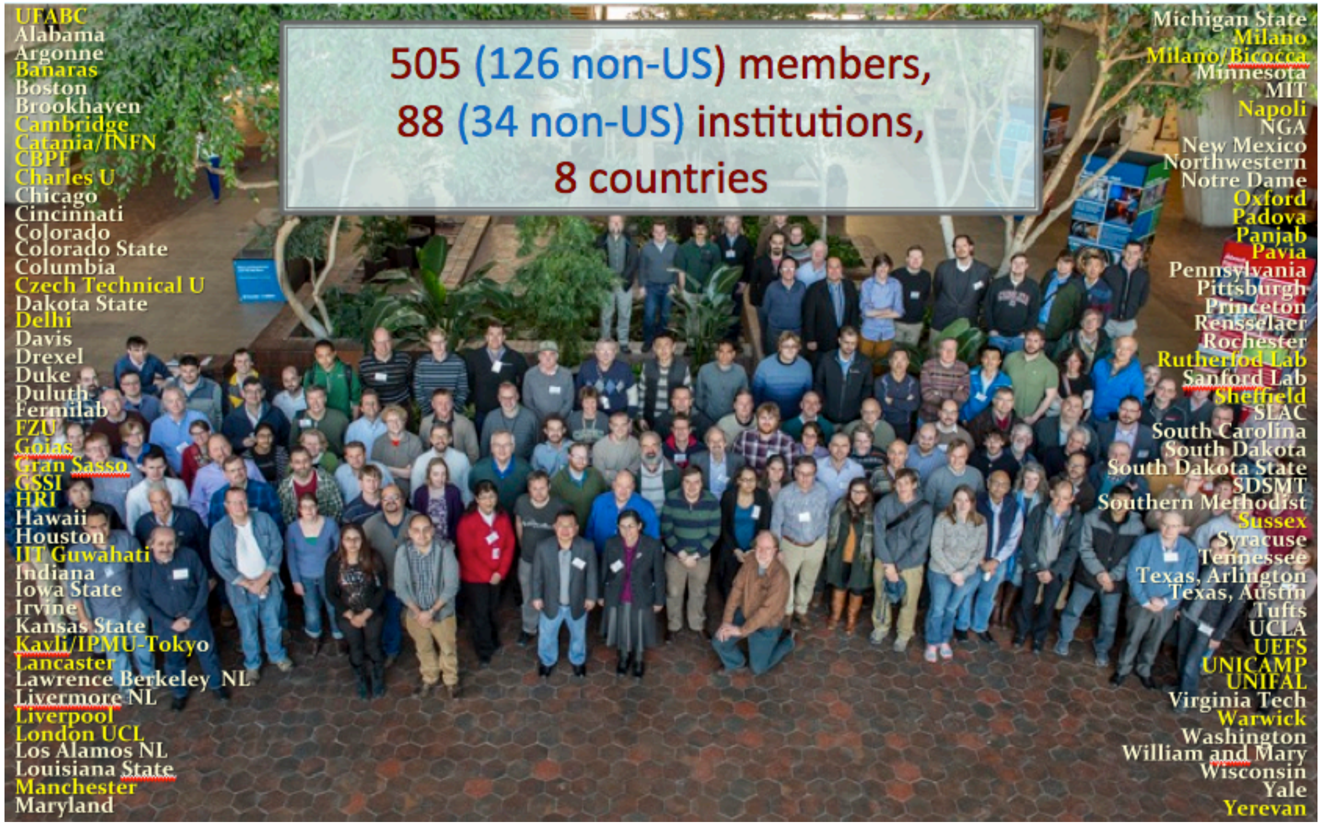
Report of the Particle Physics Project Prioritization Panel (P5)

HEPAP
22 May 2014

S. Ritz

P5 Report May 2014

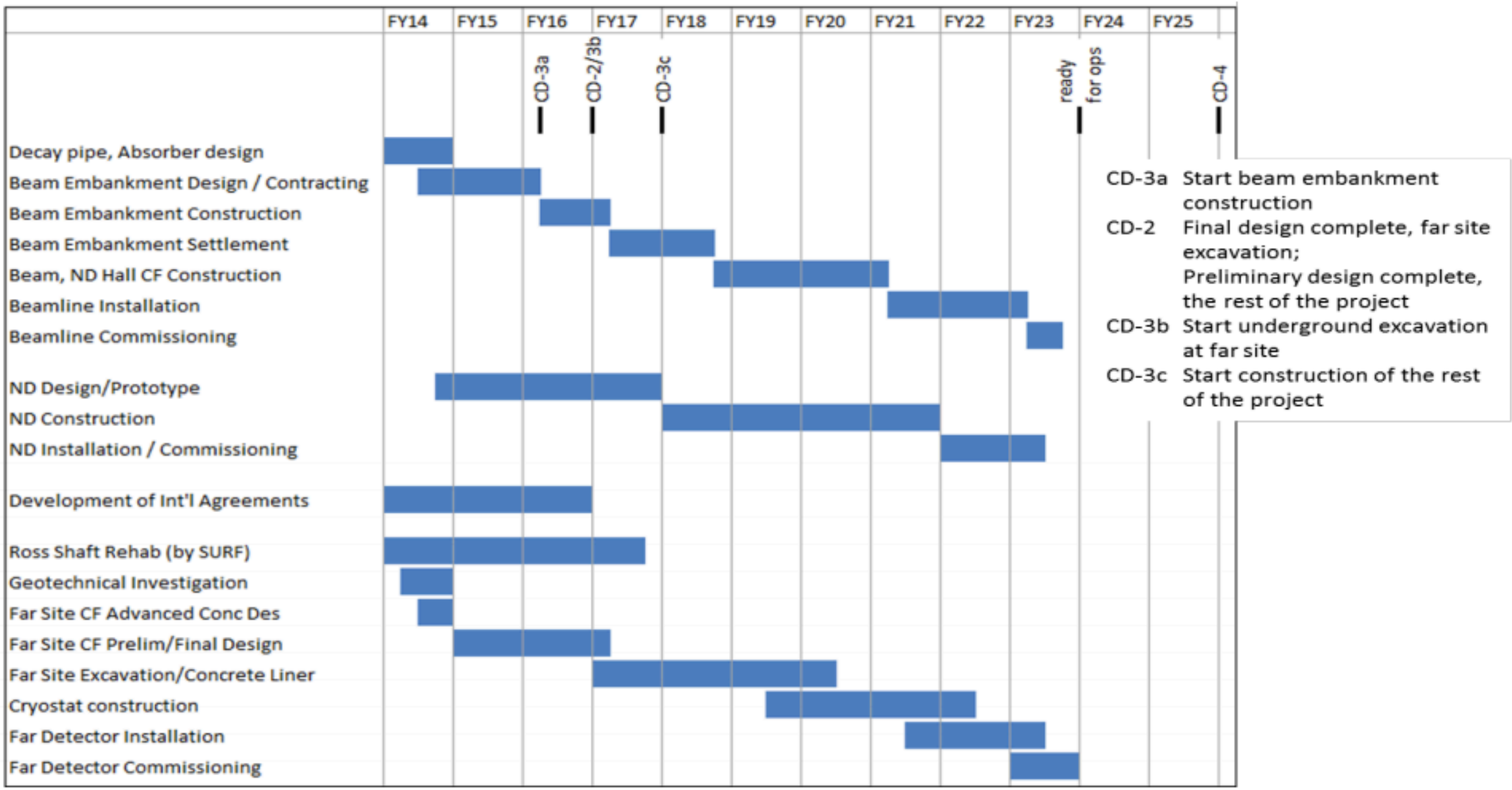
1



505 (126 non-US) members,
88 (34 non-US) institutions,
8 countries

- 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

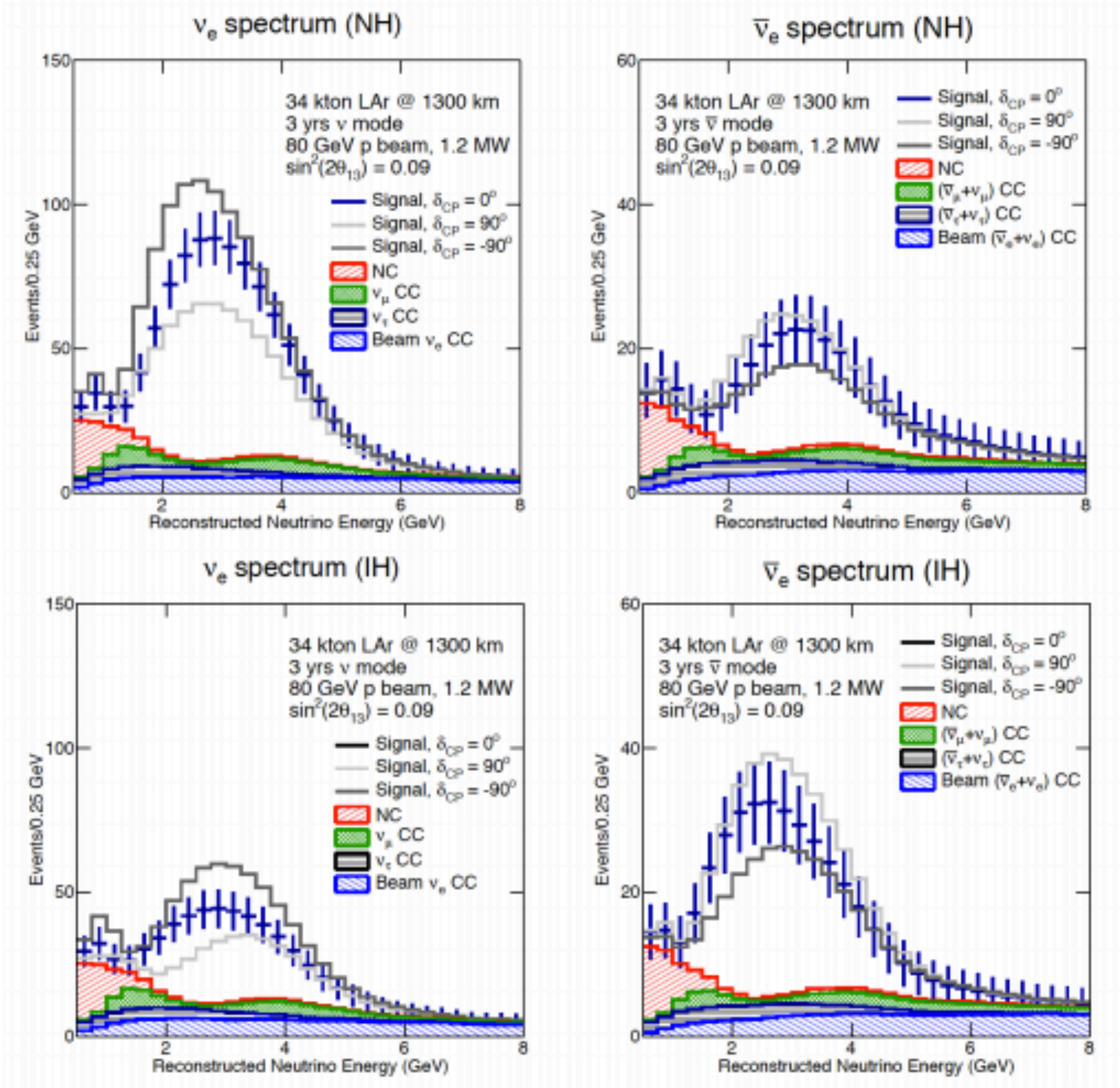
LBNE Timeline



CD-3a	Start beam embankment construction
CD-2	Final design complete, far site excavation; Preliminary design complete, the rest of the project
CD-3b	Start underground excavation at far site
CD-3c	Start construction of the rest of the project

- Schedule is strongly dependant on involvement of new international partners

LBNE far detector appearance event rates

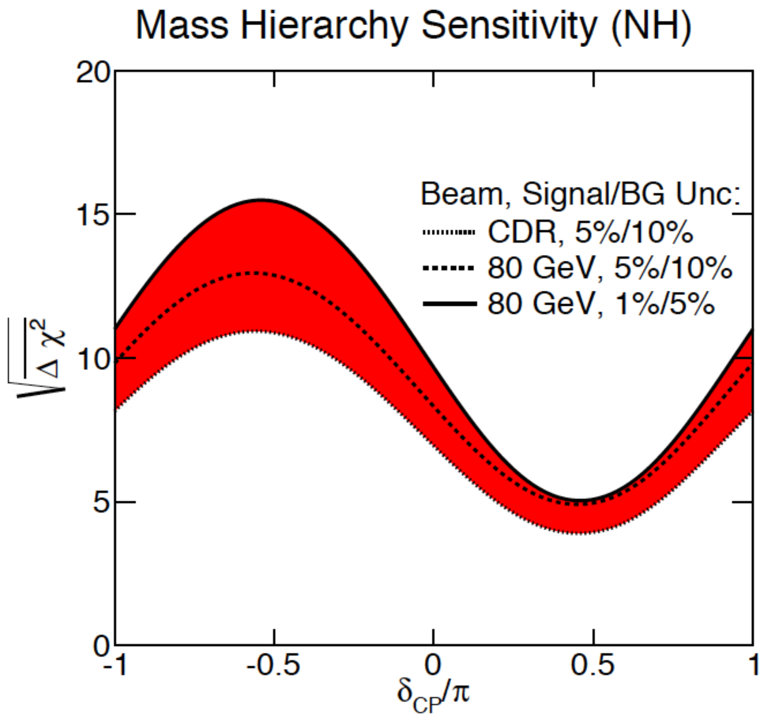


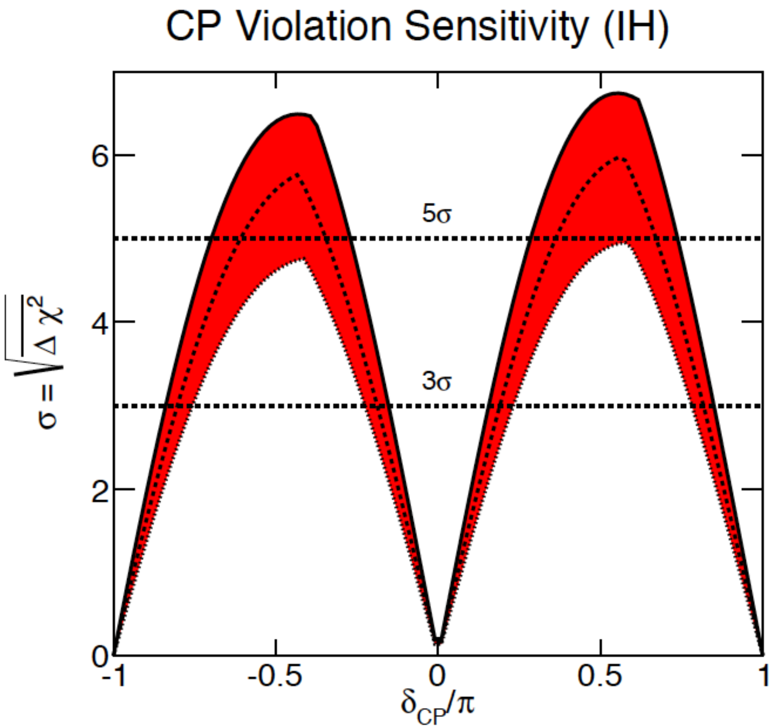
Normal hierarchy

Inverted hierarchy

- Based on 3 years ν 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 ν_e appearance channel

LBNE CP and MH sensitivity


Mass Hierarchy Sensitivity (NH)


CP Violation Sensitivity (IH)

- Mass hierarchy is well determined over most of δ_{CP} range
- CPV > 3σ over most of range and > 5σ for maximal CPV
- Atmospheric neutrinos in LBNE provide
  - an independent~$\Delta\chi^2$=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

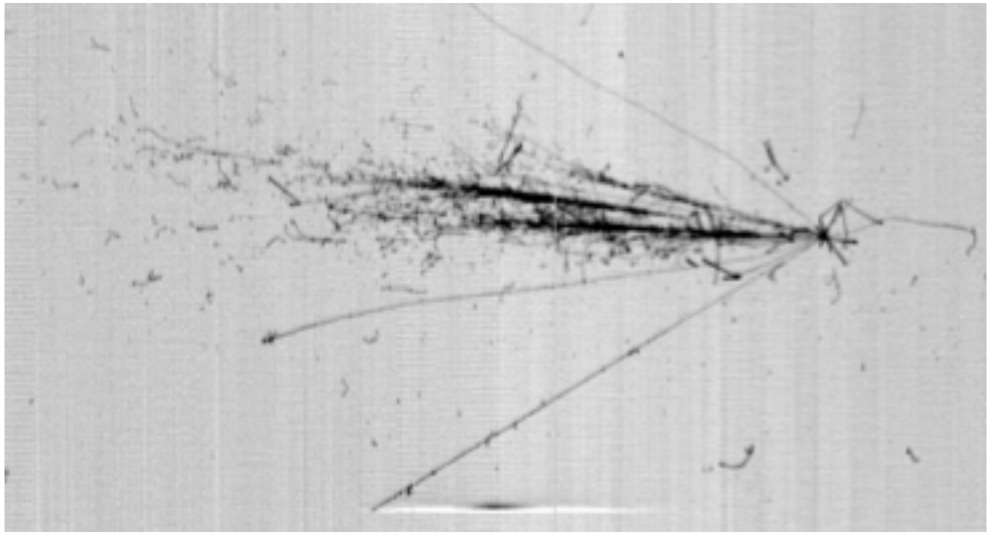
Cambridge • Lancaster • Liverpool • Manchester • Oxford

Sheffield • STFC/RAL • Sussex • UCL • Warwick

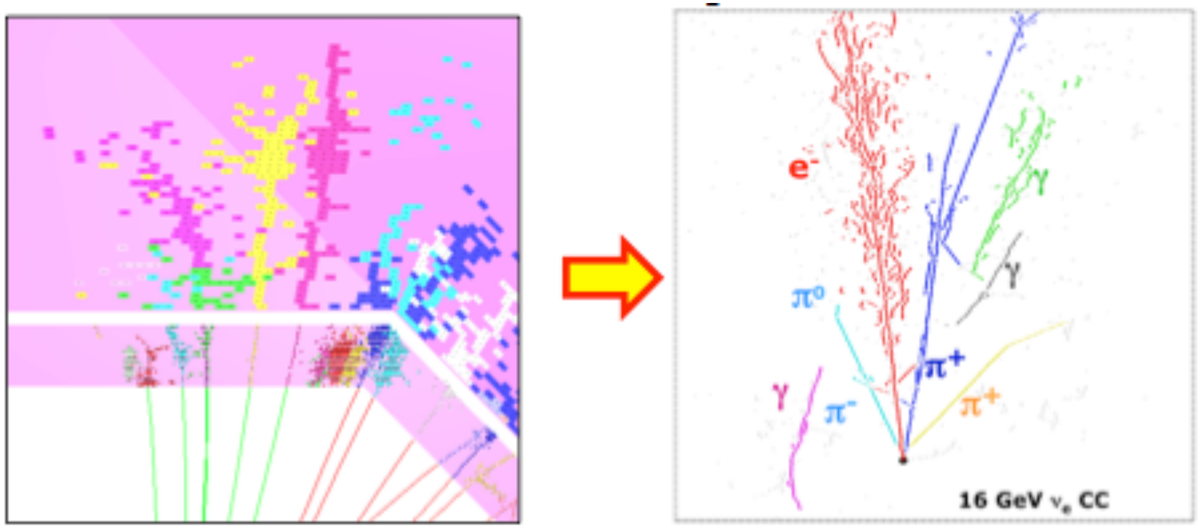
Work Package	Deliverables
WP1: Physics Simulation and Experiment Design	Oscillation physics simulation; GENIE-LArSoft interface; Near detector design studies; Target and beam design; Beam systematics study;
WP2: Neutrino Event Reconstruction	Pattern recognition software (PANDORA) and interface to LArSoft; 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

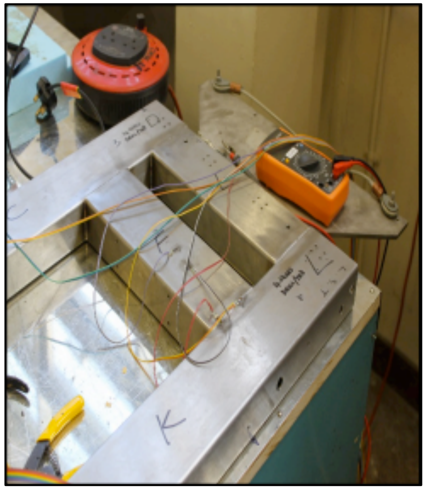
- Neutrino events in a LAr TPC give high resolution, bubble-chamber like images
- The challenge is to go from this to reconstructed physics quantities



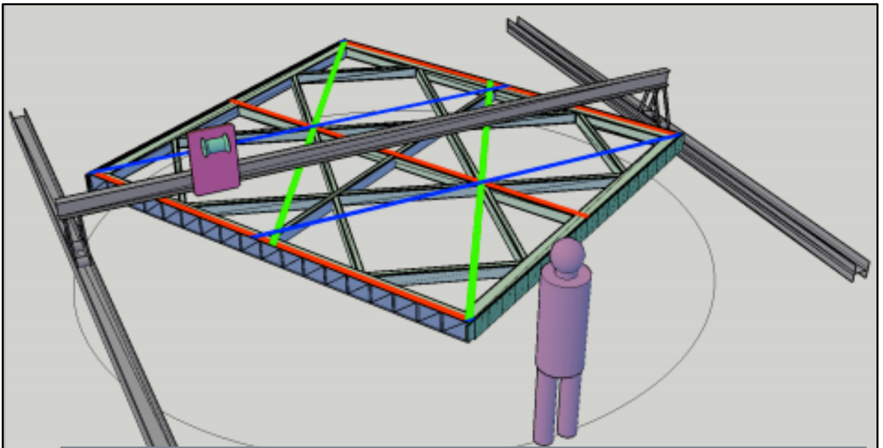
- PANDORA-based event reconstruction and LAr pattern recognition tools being developed



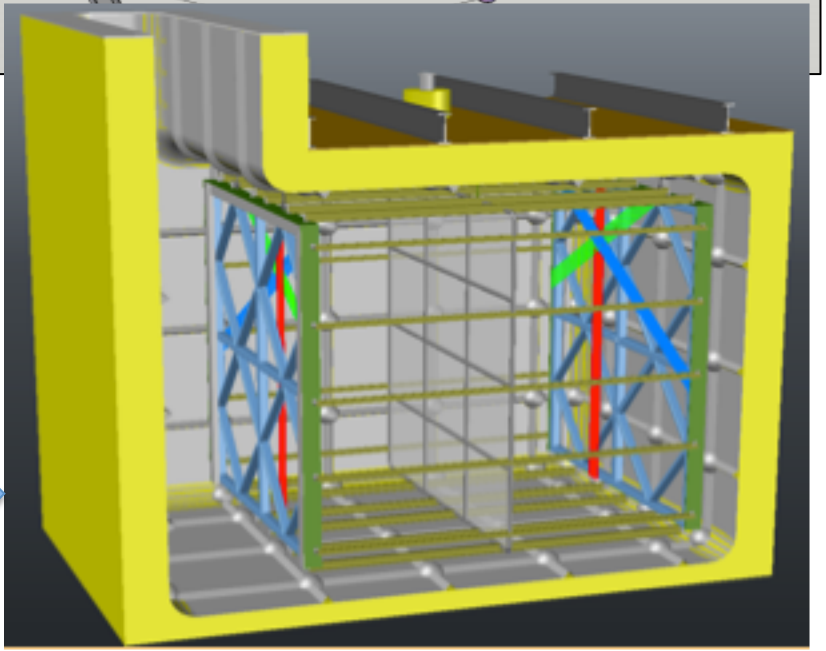
LBNE UK WP5 APA design



- 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



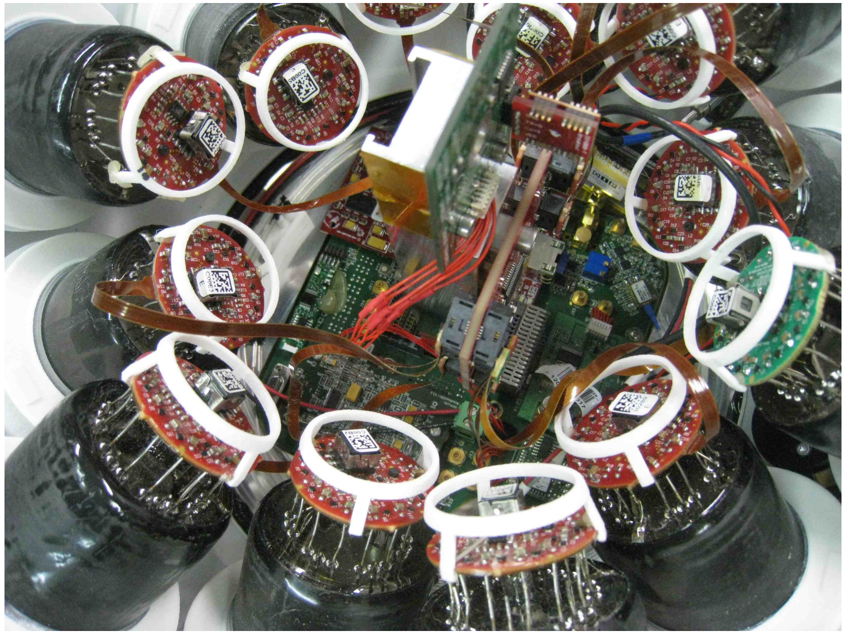
CHIPS concept

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 NOνA (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

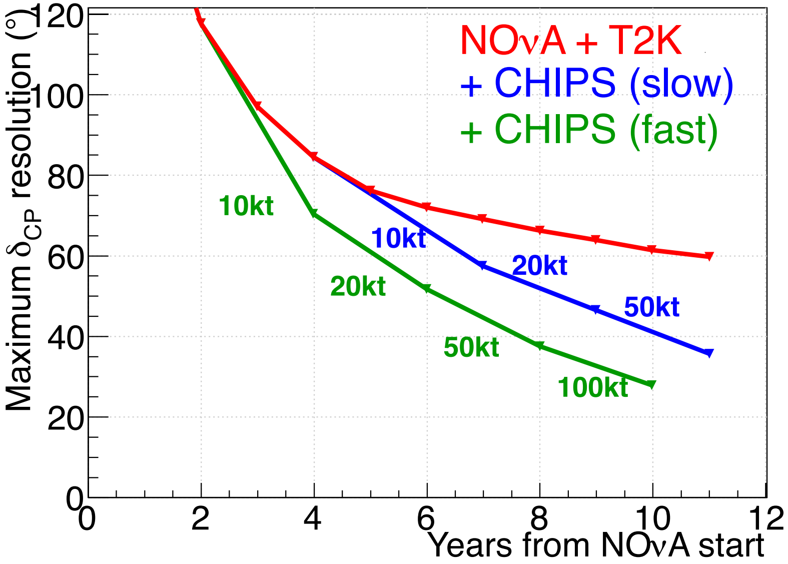

Aqualine FrøyaRing Sinker Tube

Aqualine have more then 15 years of experience supplying and operating sinker tubes. More and more fish farmers discovers the benefits by using the system.



CHIPS Physics Goals

- Short term:
  - Contribute to the measurement of δ_{CP} using neutrinos from the NuMI beam by measuring the sub-dominant ν_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

Conclusions

- Neutrino oscillations are now well-established and we are in a phase of accurately measuring the parameters of the PNMS mixing matrix
- In recent years we have definitively measured a non-zero θ_{13} mixing angle opening the door to a search for CP violation
- Current and proposed projects have excellent prospects for measuring δ_{CP} and determining the neutrino mass hierarchy
- There is a well-defined global programme of long baseline experiments reaching well into the 2020s