Current and Future Long Baseline Neutrino Experiments

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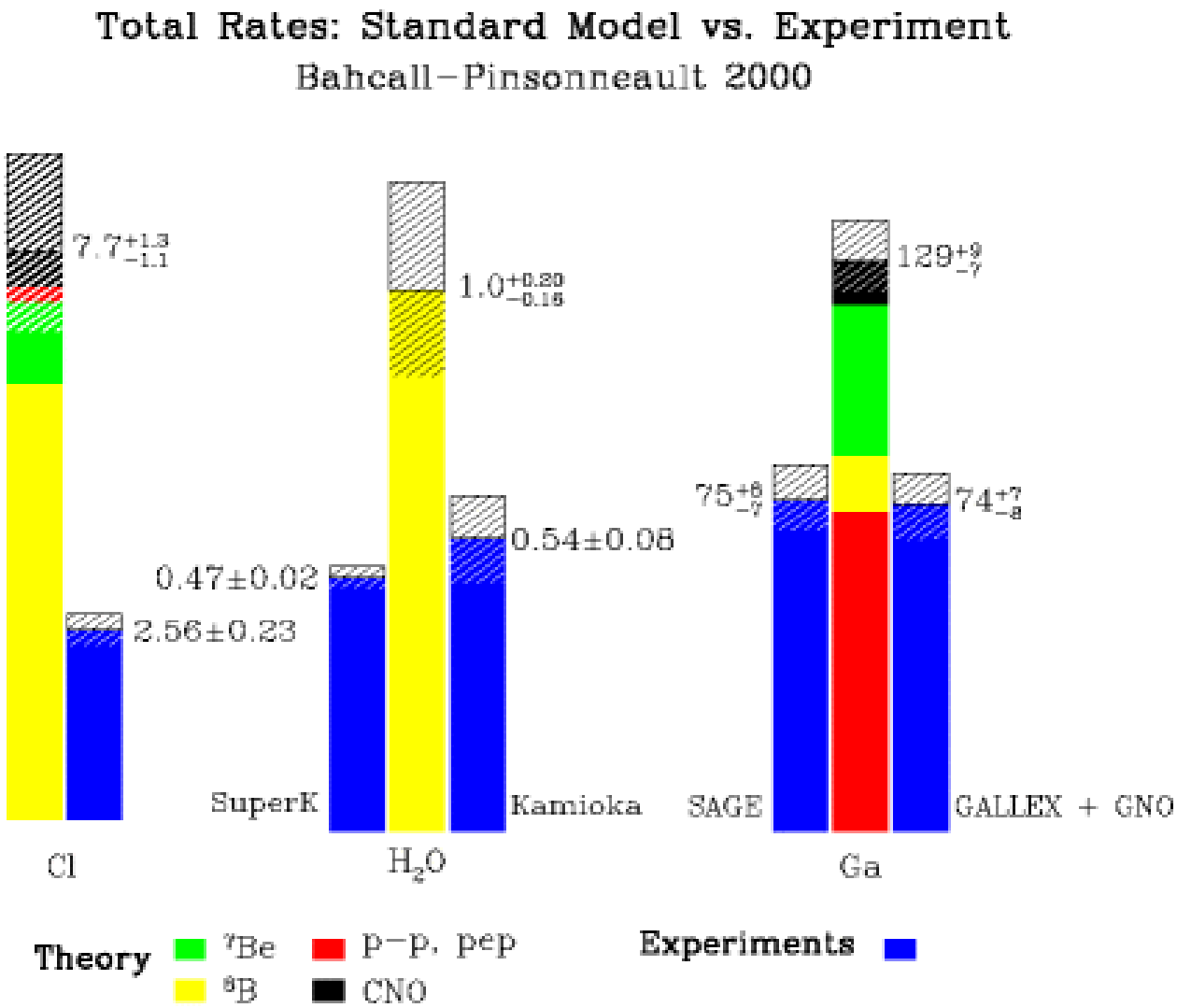
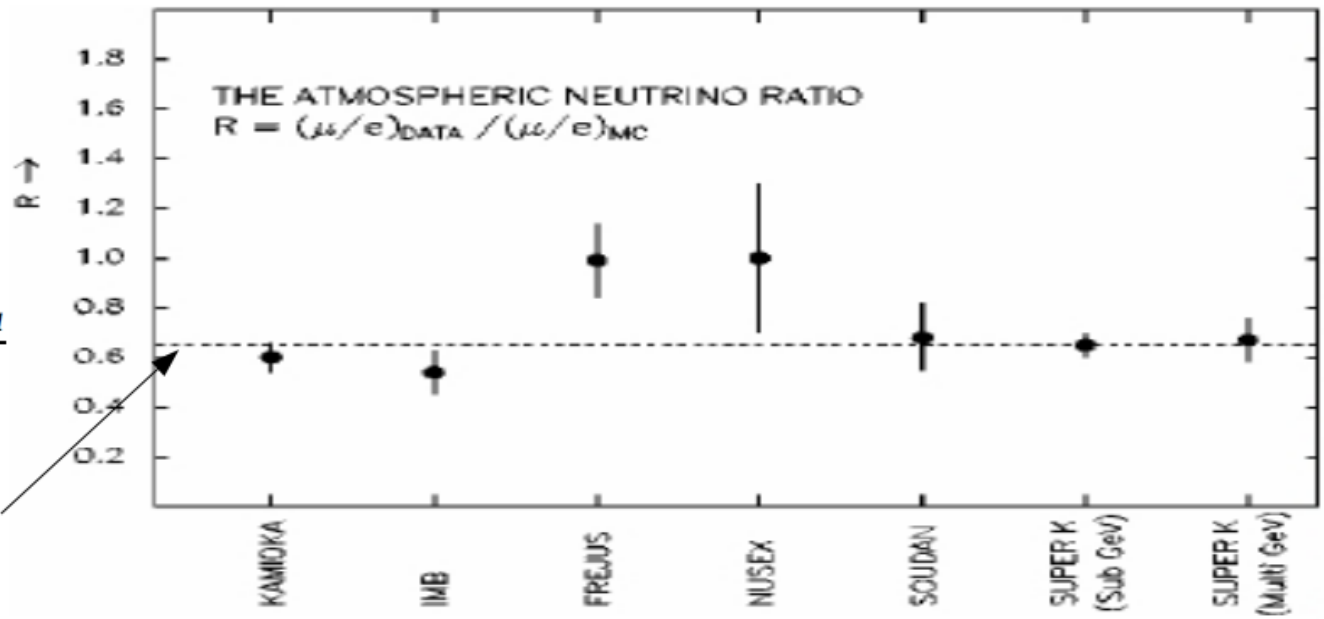
Solar neutrino deficit

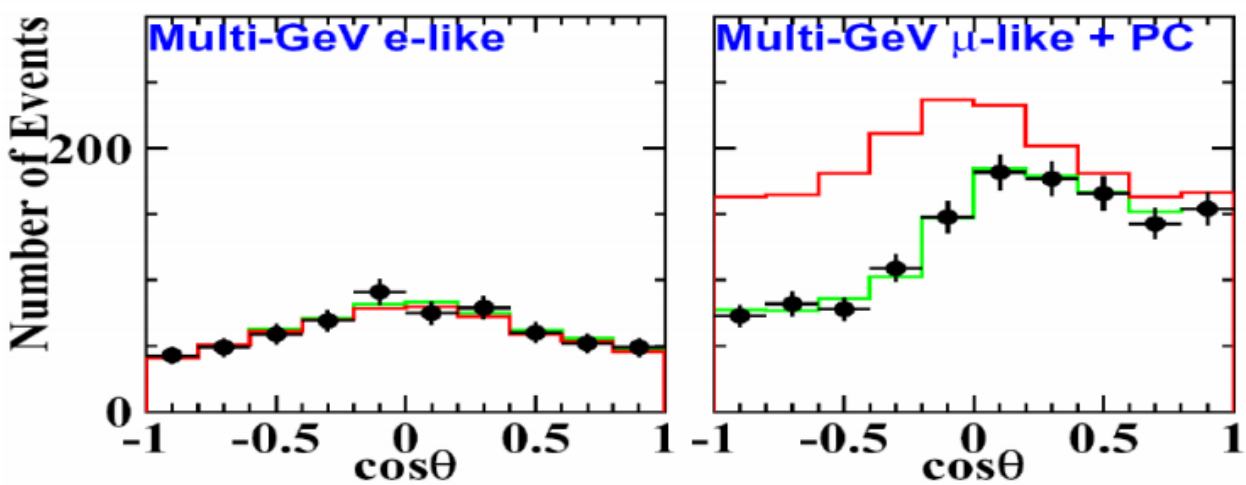


Atmospheric neutrino deficit

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

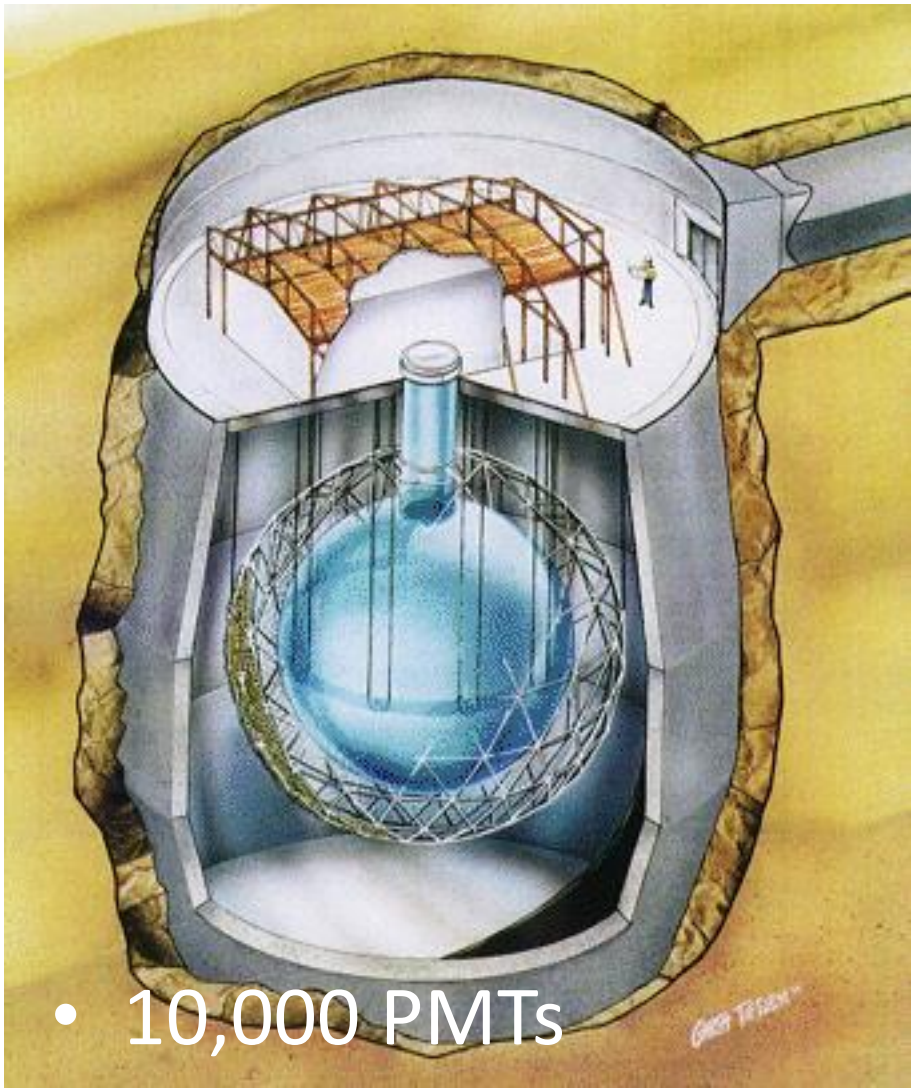
R ~ 0.6 - 0.7





The SNO experiment

- 1000 tons of D_20
- 6500 tons of H_20



- 10,000 PMTs
- 2km underground

The SNO experiment

CC $\nu_e + d \rightarrow p + p + e^-$

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 $\nu_x + d \rightarrow p + n + \nu_x$

n captures on deuteron
$^2H(n, \gamma)^3H$
Observe 6.25 MeV γ

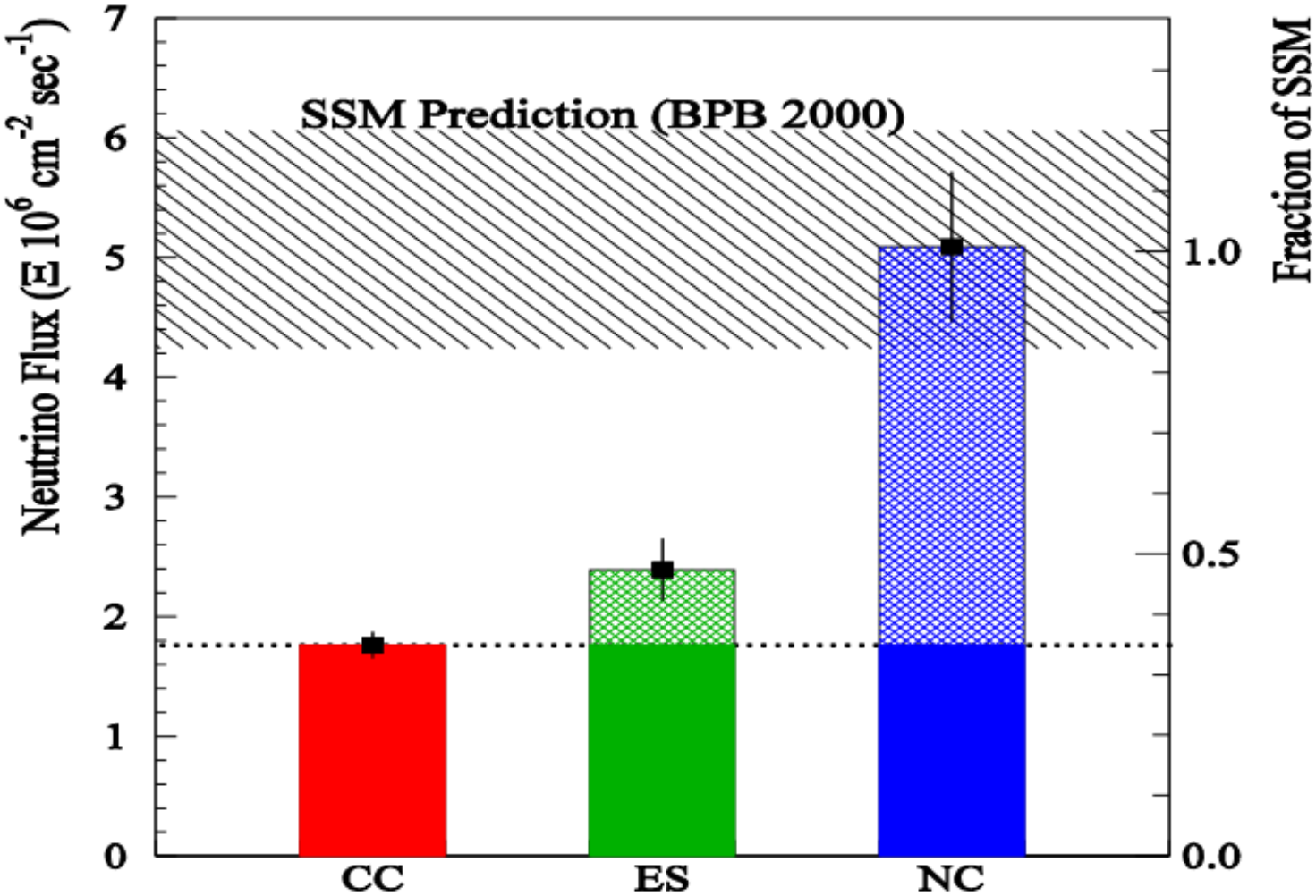
- Q = 2.22 MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

Produces Cherenkov Light Cone in D_2O

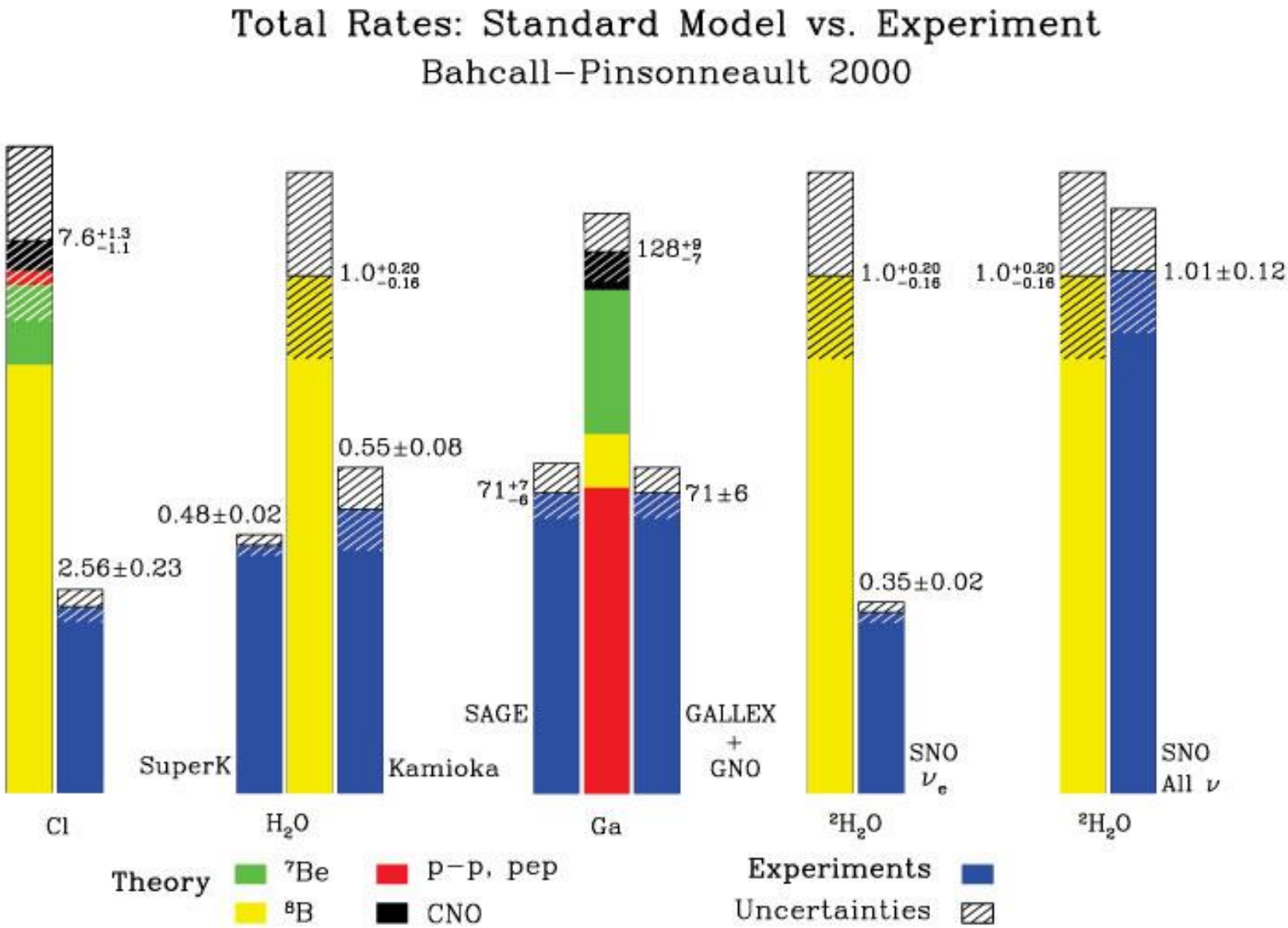
- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

SNO results



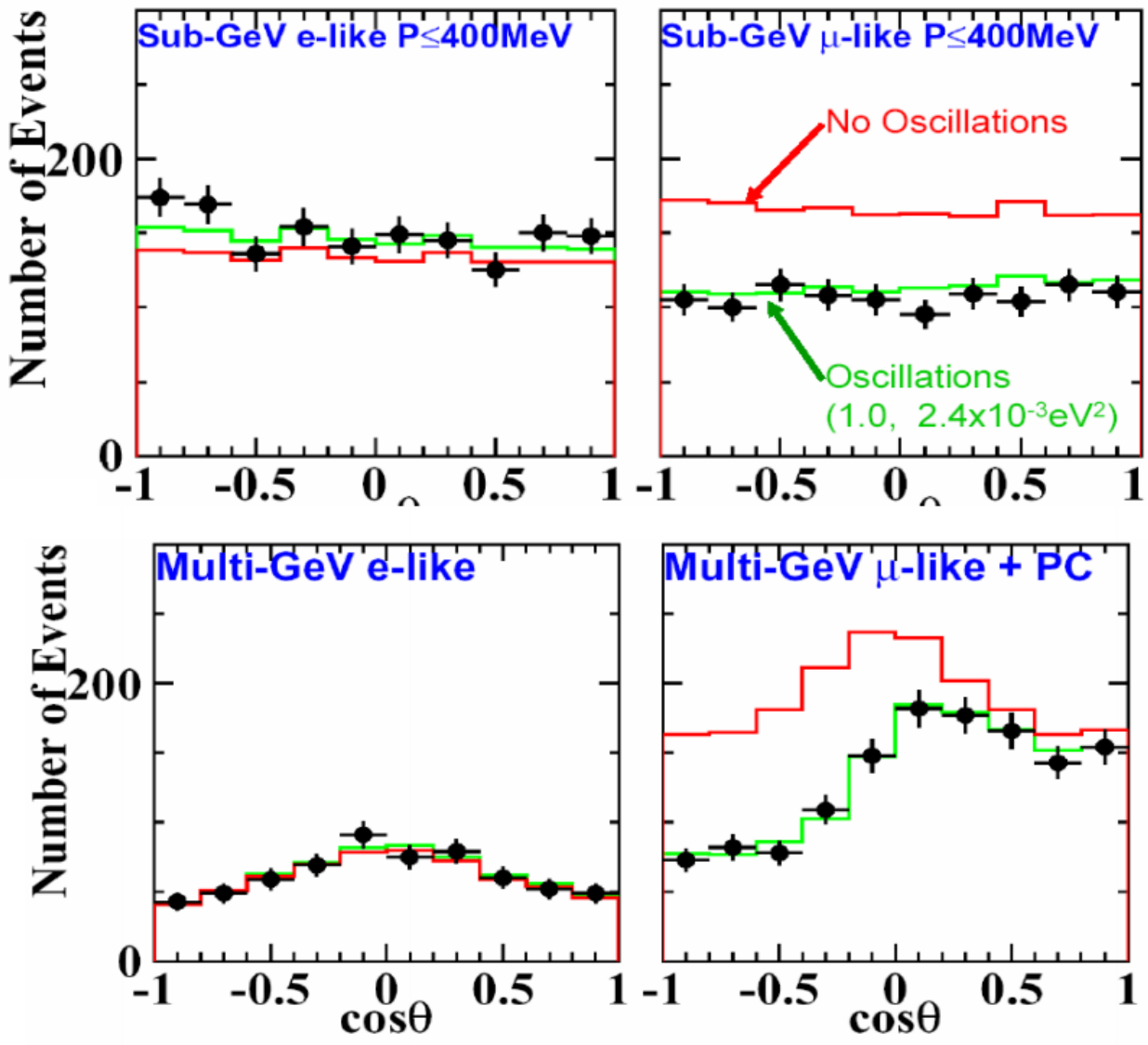
- ν_e to $\nu_{\mu\tau}$ oscillations confirmed!

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)



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

- <u>Known knowns:</u> neutrinos have mass and oscillate between flavours; θ_{12}, θ_{23}, θ_{13}, Δm_{21}^2, $|\Delta m_{32}^2|$ all measured
- <u>Known unknowns:</u> 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:

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

$$P(\nu_\alpha \to \nu_\beta)_{(\alpha \neq \beta)} = -4 [c_{12} \sin^2(1.27 \delta m^2 L/E) + c_{13} \sin^2(1.27 \Delta m^2 L/E) + c_{23} \sin^2(1.27 \Delta m^2 L/E)]$$

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

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

Long baseline accelerator neutrino physics

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

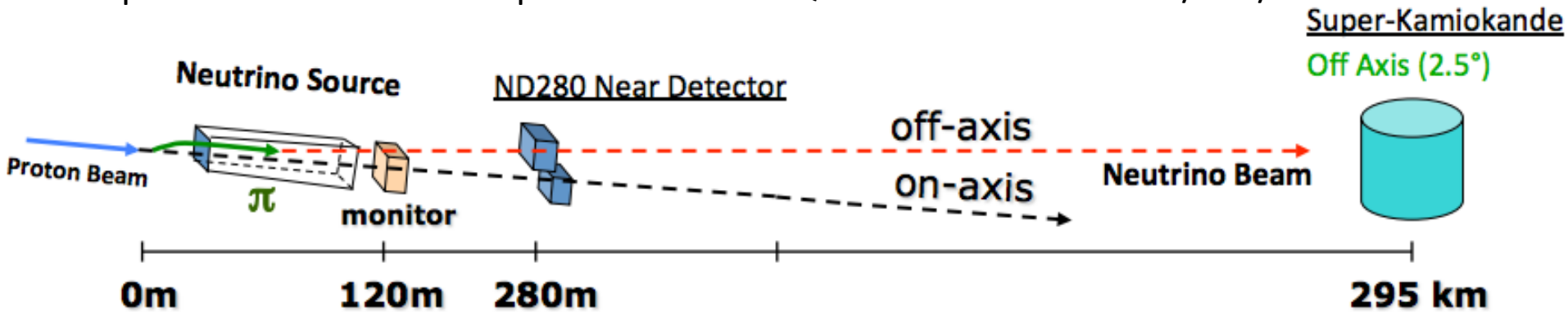
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1 - \cos^2(\theta_{13}) \times \sin^2(\theta_{23})]\sin^2(1.267\Delta m^2 L/E_\nu)$$

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

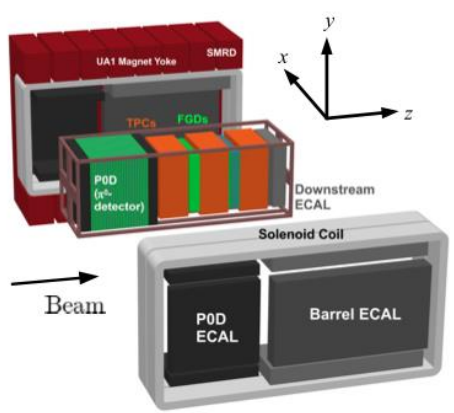
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\sin\delta_{CP}$$

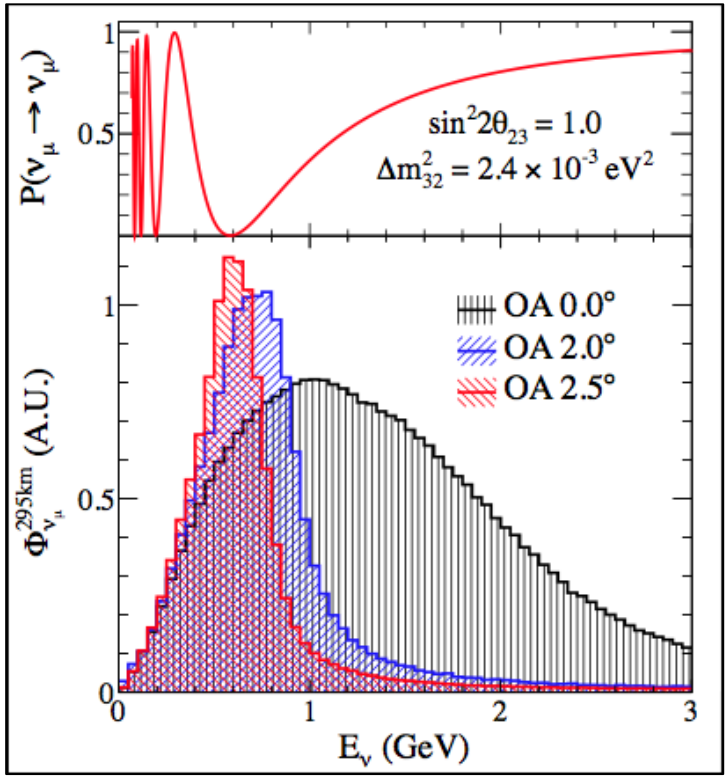
T2K (Tokai to Kamioka)

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

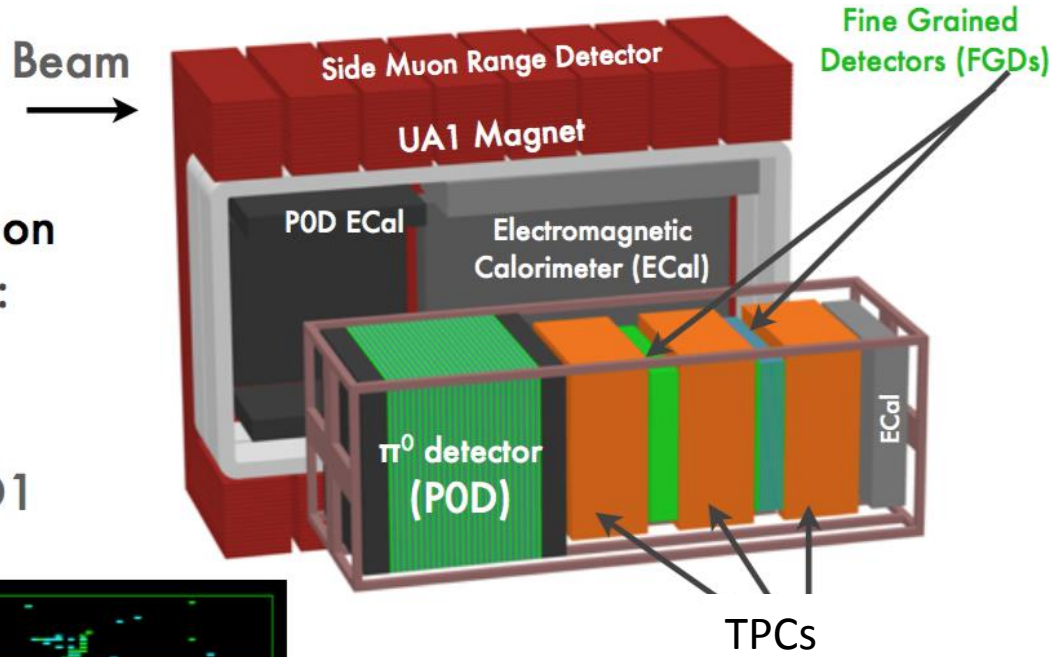


- 295km long baseline experiment
- Uses 2.5° off-axis ν_μ ($\bar{\nu}_\mu$) beam
- Data-taking started in 2009
- UK contribution to near detector (ND280) includes:
  - Electronics
  - DAQ
  - ECAL
- SK far detector

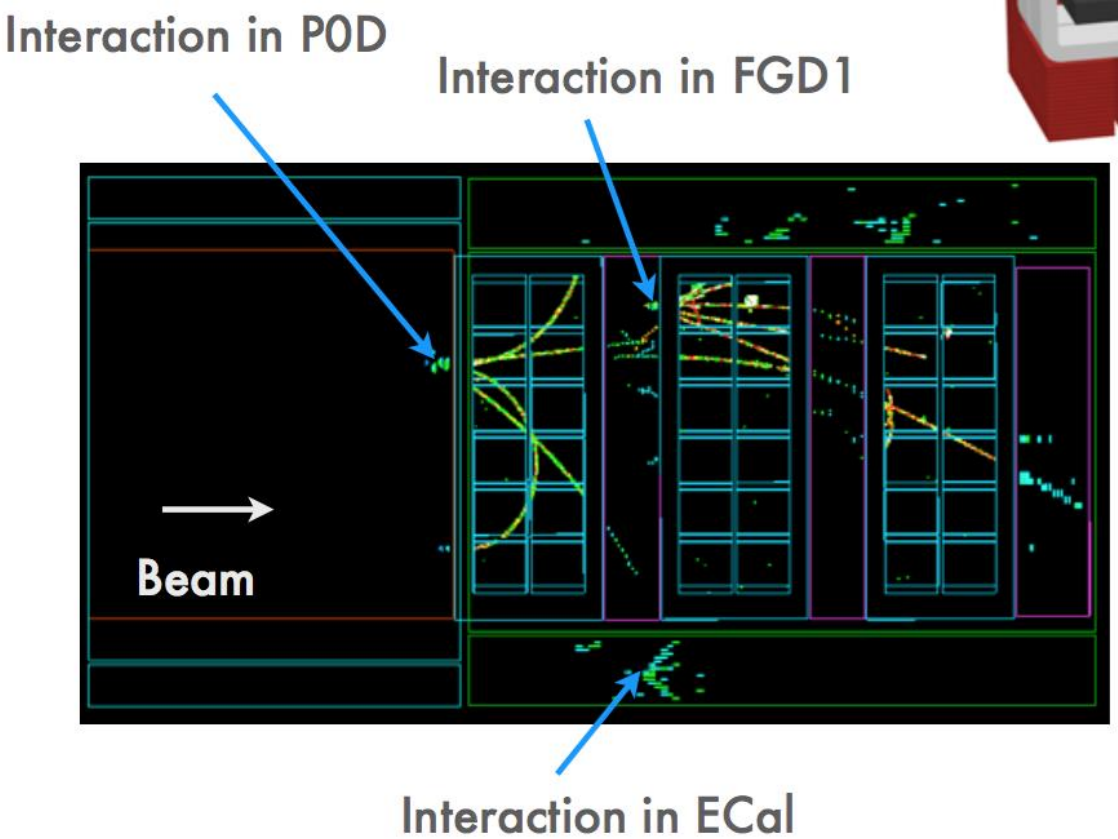




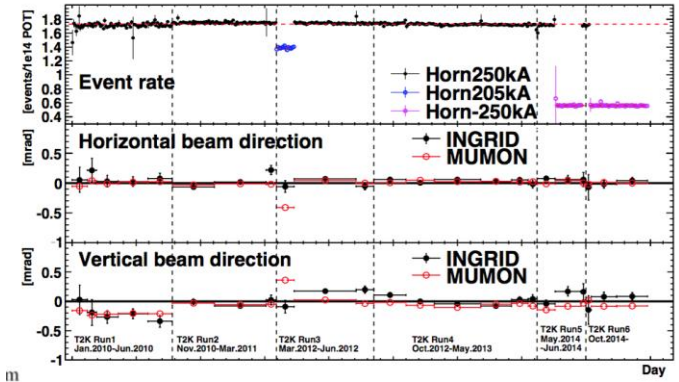
T2K off-axis near detector



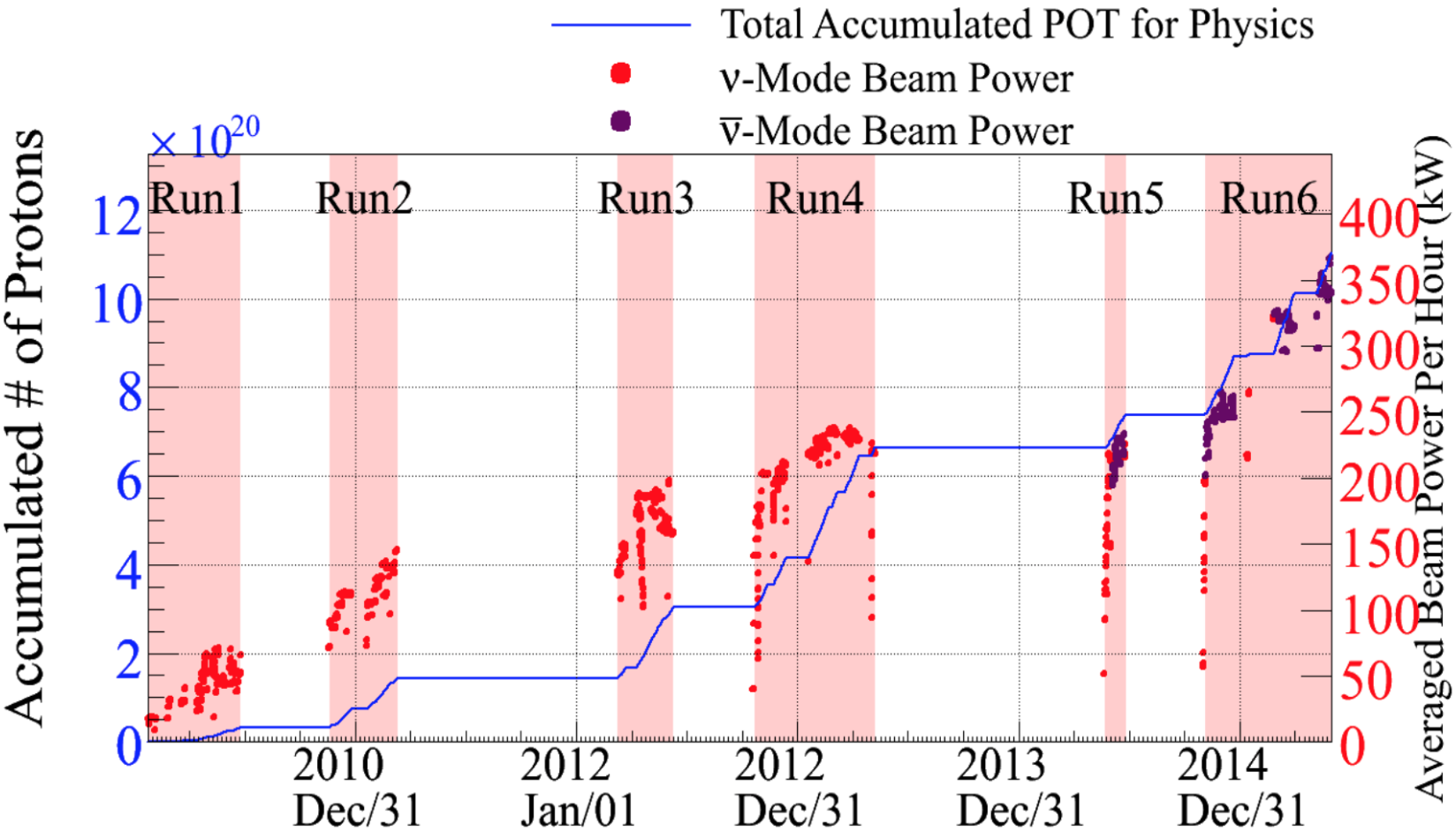
Primary Interaction Material: Carbon
Secondary Interaction Materials:
Oxygen, Lead, Brass, Argon



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



T2K beam operation and data taking

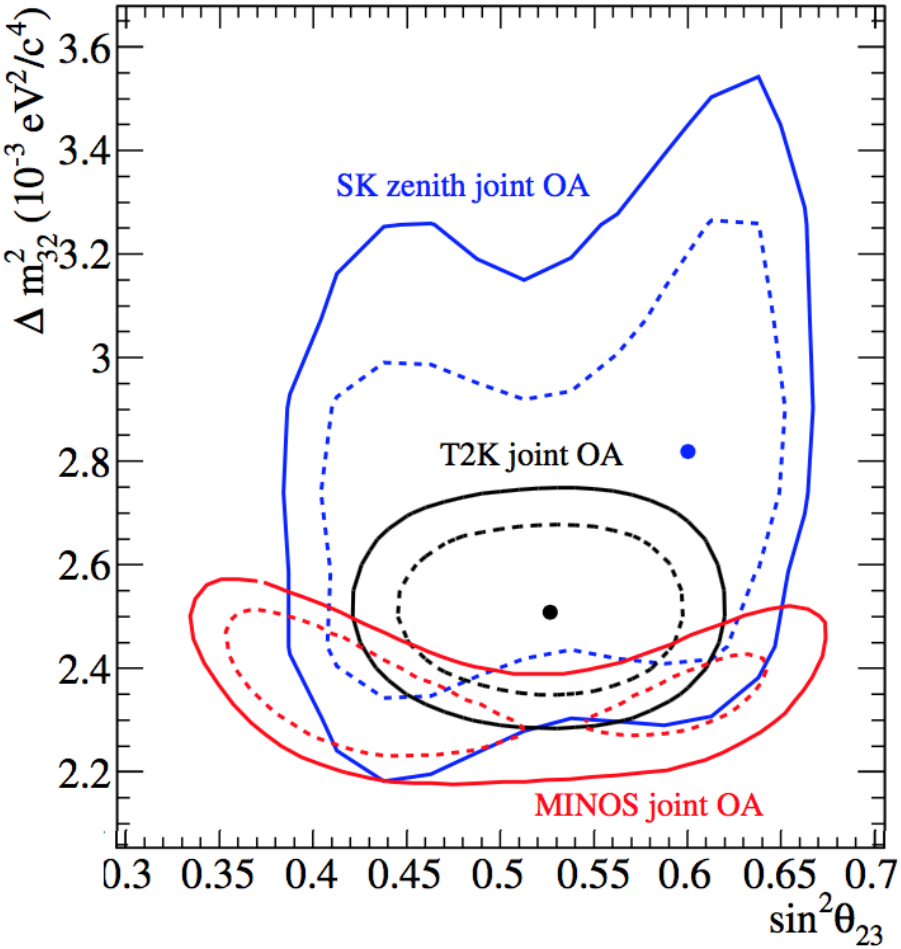


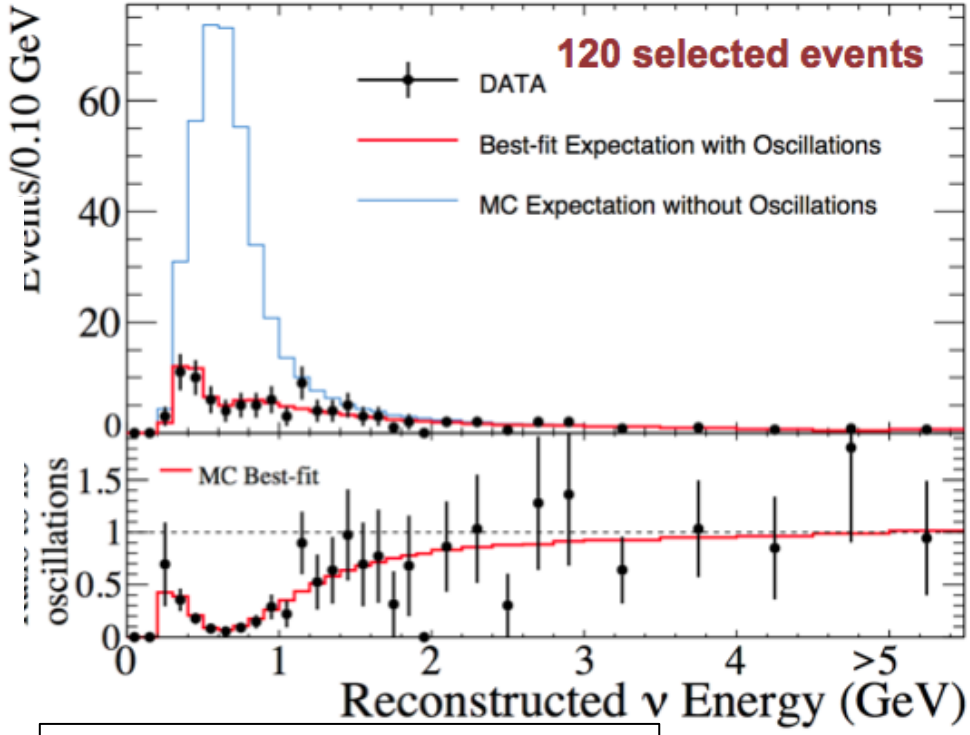
- Integrated POT:
  - Neutrino mode: 7.0×10^{20}
  - Anti-neutrino mode: 4.0×10^{20}

  Total of 11×10^{20} = 13% of total expected POT

T2K ν_μ disappearance results

- Observation of a deficit of ν_μ events in SK





Location of minimum: Δm^2_{23}
Depth of minimum: $\sin^2\theta_{23}$

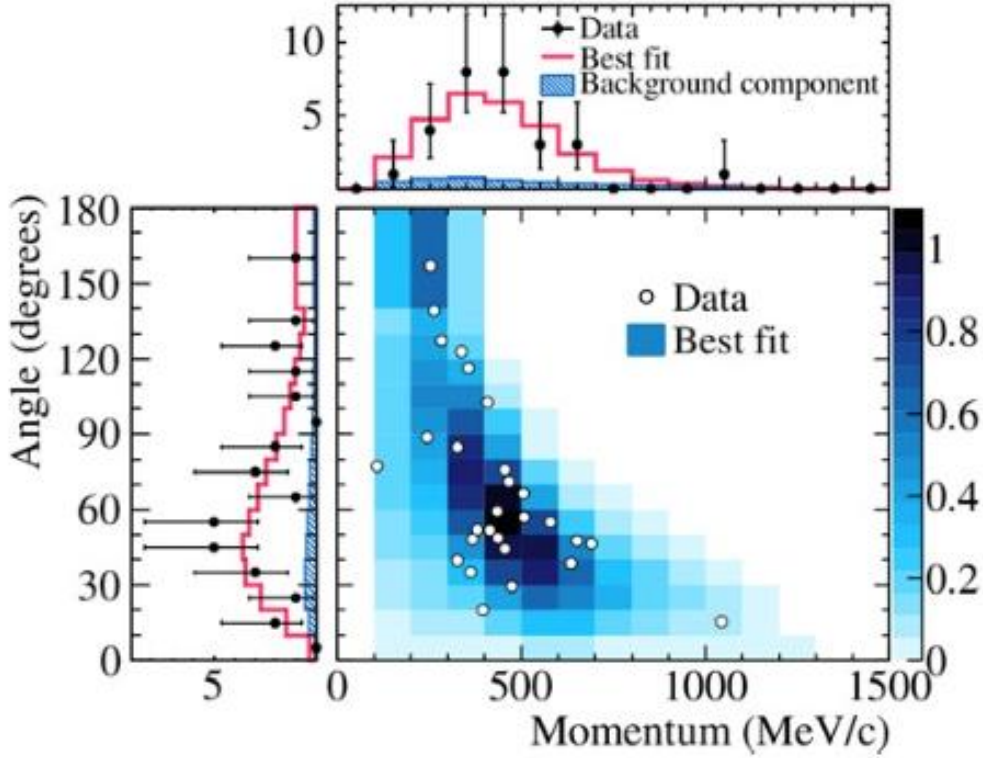
- Best fit values:

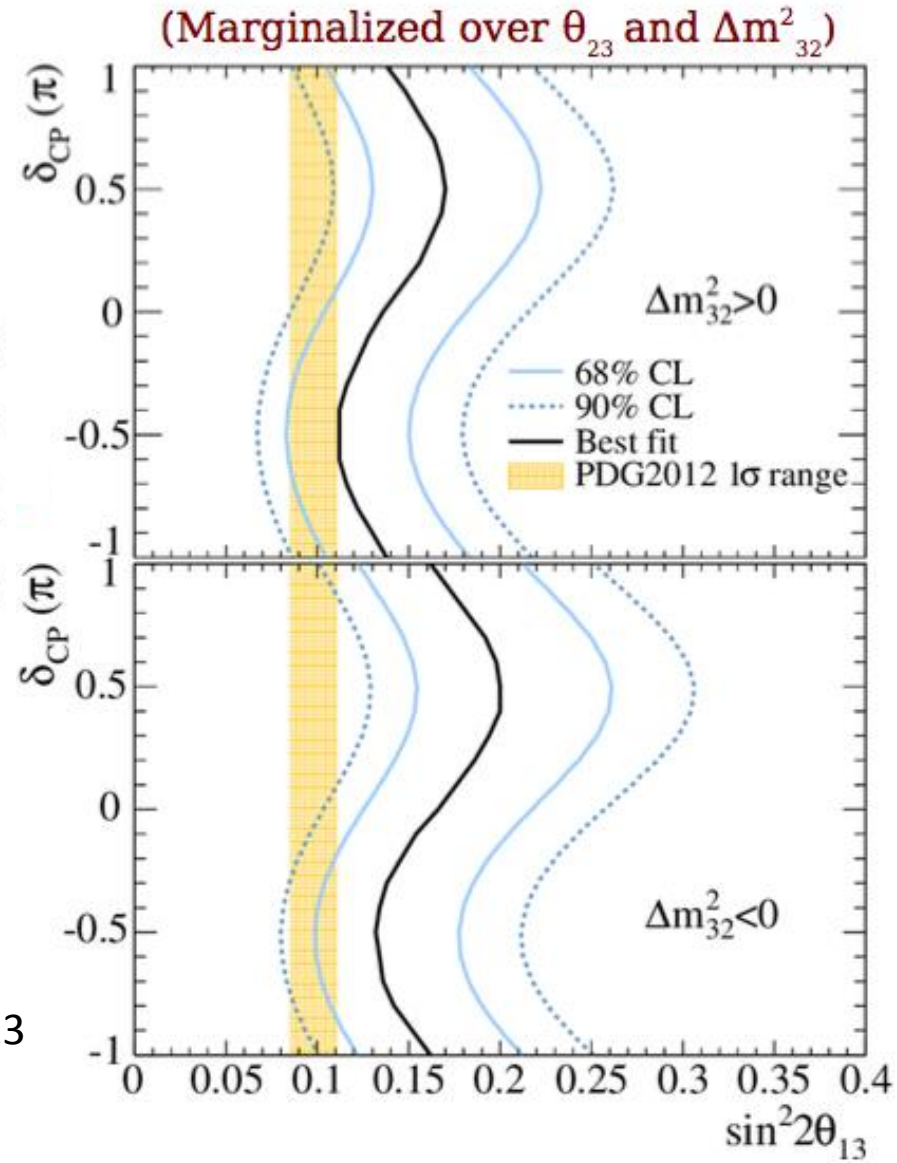
NH	$\sin^2(\theta_{23})$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32} (10^{-3} eV^2)	2.51 ± 0.10
IH	$\sin^2(\theta_{23})$	0.511 ± 0.055
	Δm^2_{13} (10^{-3} eV^2)	2.48 ± 0.10

World-leading measurement of θ_{23}

Published in Phys. Rev. Lett. 112, 181801 (2014)

T2K ν_e appearance results

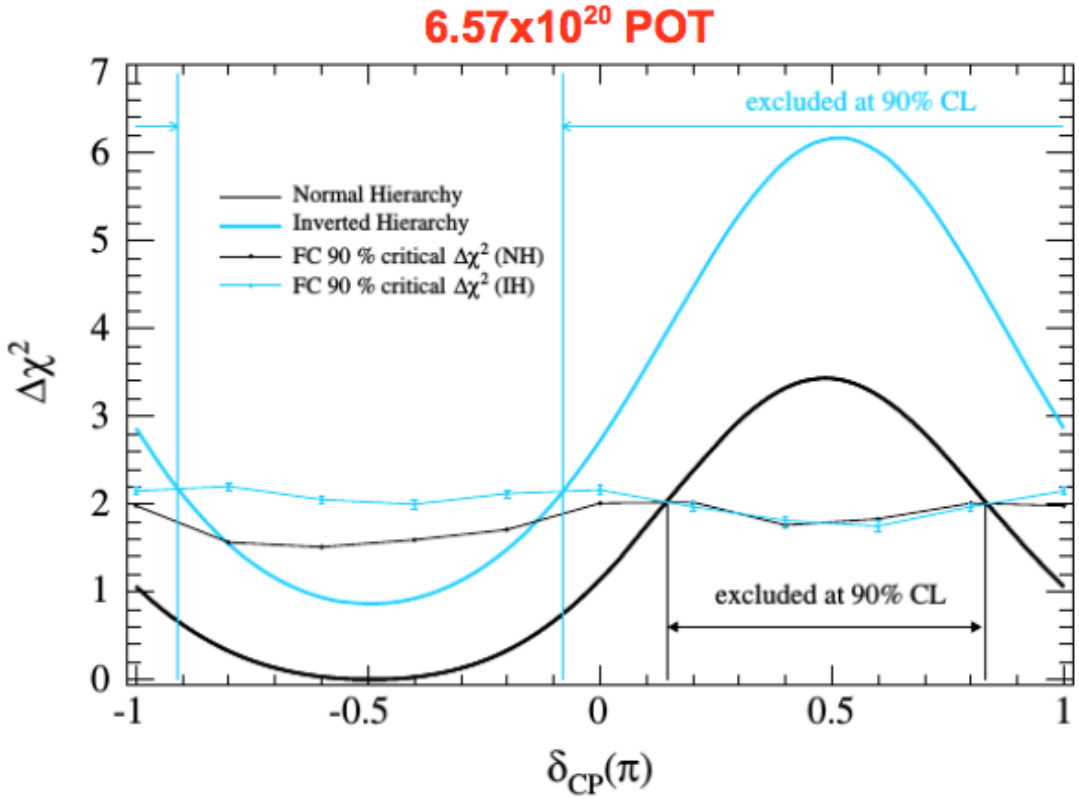




- 4.92 ± 0.55 background events expected (no oscillations)
- 28 events observed
- 7.3σ significance for non-zero θ_{13}
- First observation (> 5σ) of an appearance channel signal

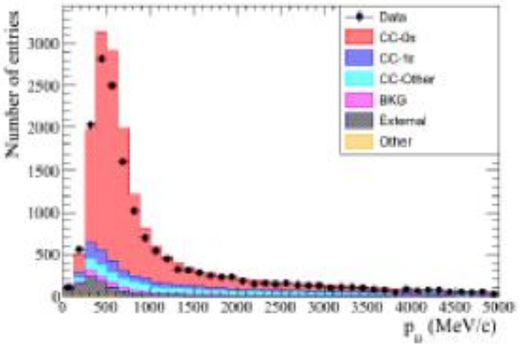
Analysis published in Phys. Rev. Lett. 112, 061802 (2014)

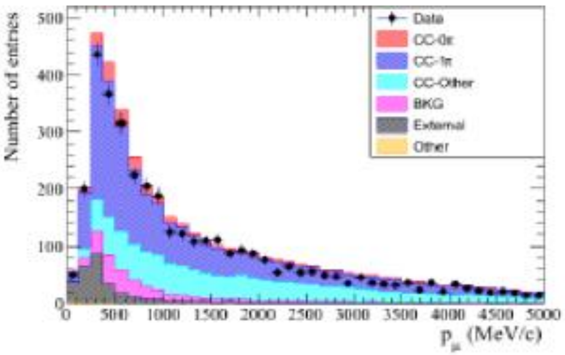
T2K joint analysis fit

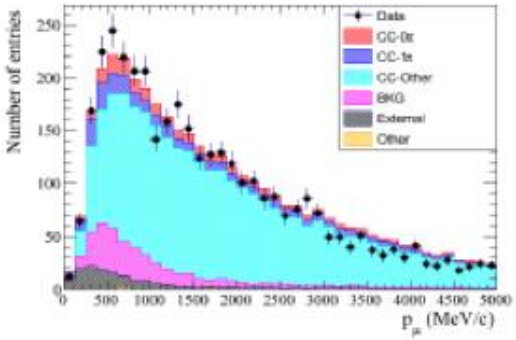


- Results from a combined likelihood ratio fit to the T2K ν_μ and ν_e CCQE samples
- Using the PDG 2013 value for θ_{13} there is a preference for $\delta_{CP} \approx -\pi/2$ and normal mass hierarchy
- Very similar results from an independent analysis based on Markov chain MC

T2K ND280 and systematic errors

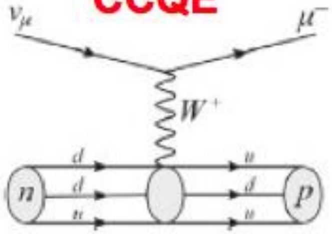




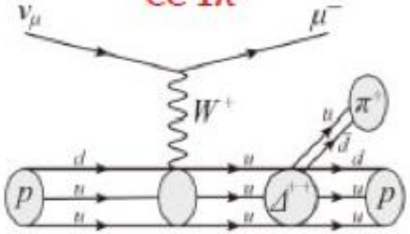


Signal channel
for oscillation
analysis

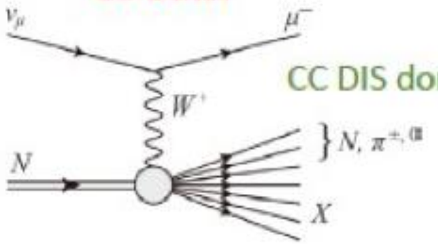
CCQE



CC 1π

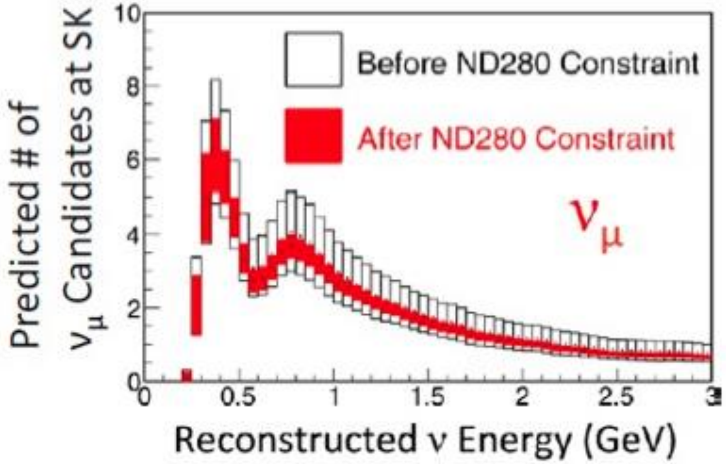


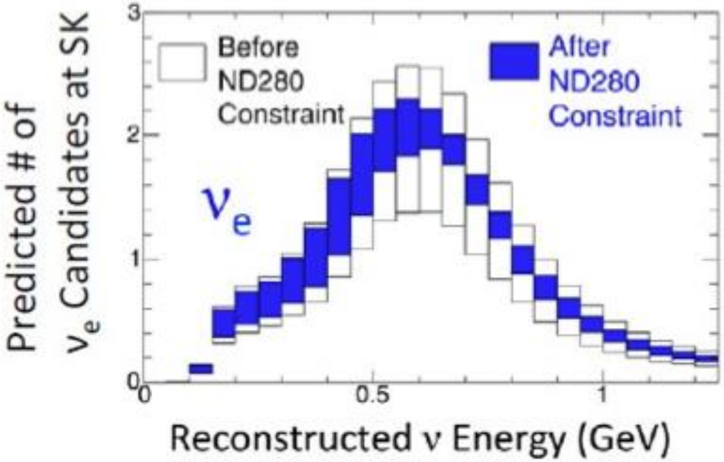
CC Other



CC DIS dominated

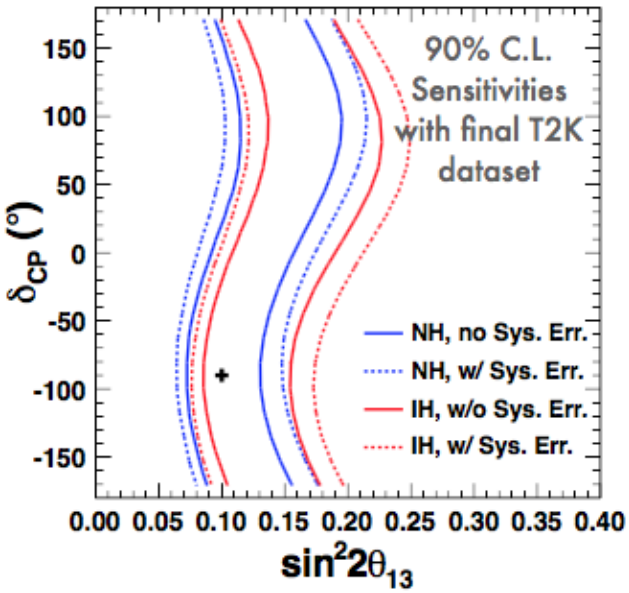
Flux and cross-section systematic uncertainty on N_{SK} significantly reduced to ~7%





T2K anti-neutrino mode running

Neutrino only



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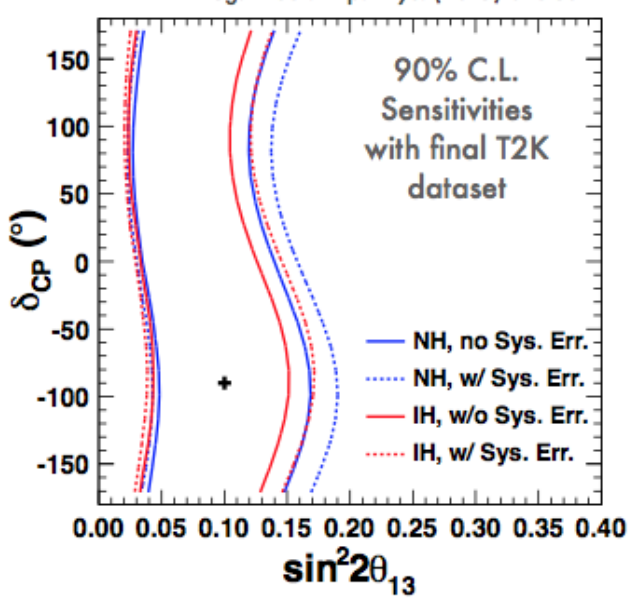
Anti-neutrino only

Prog. Theor. Exp. Phys. (2015) 043C01



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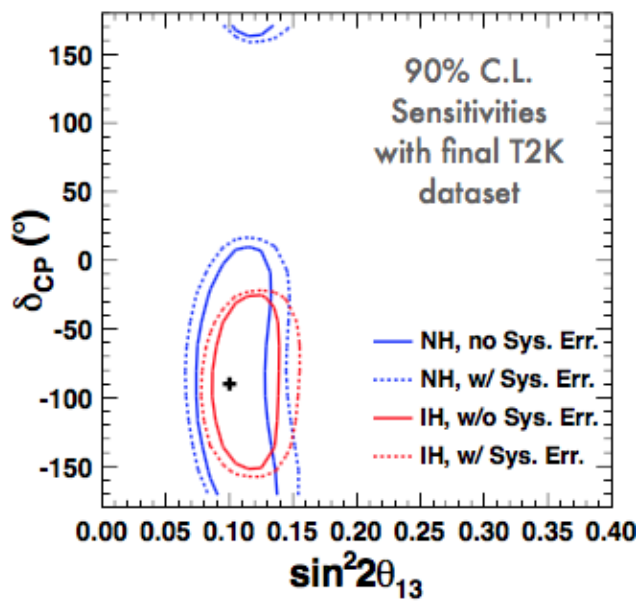
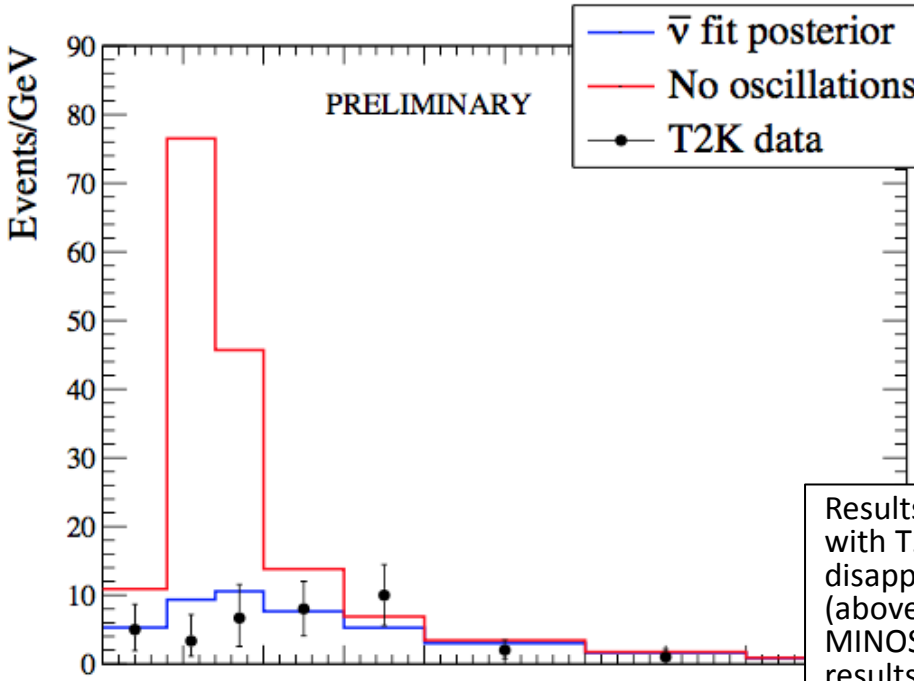
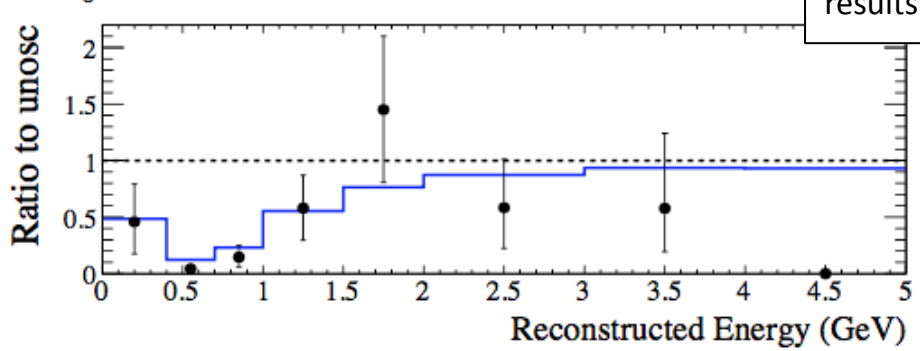
Combined data

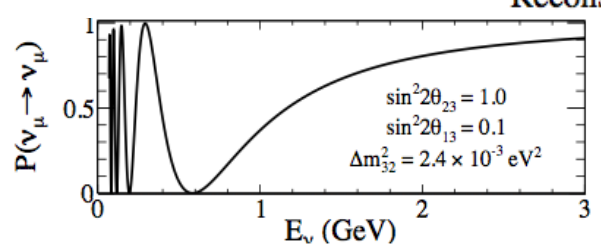


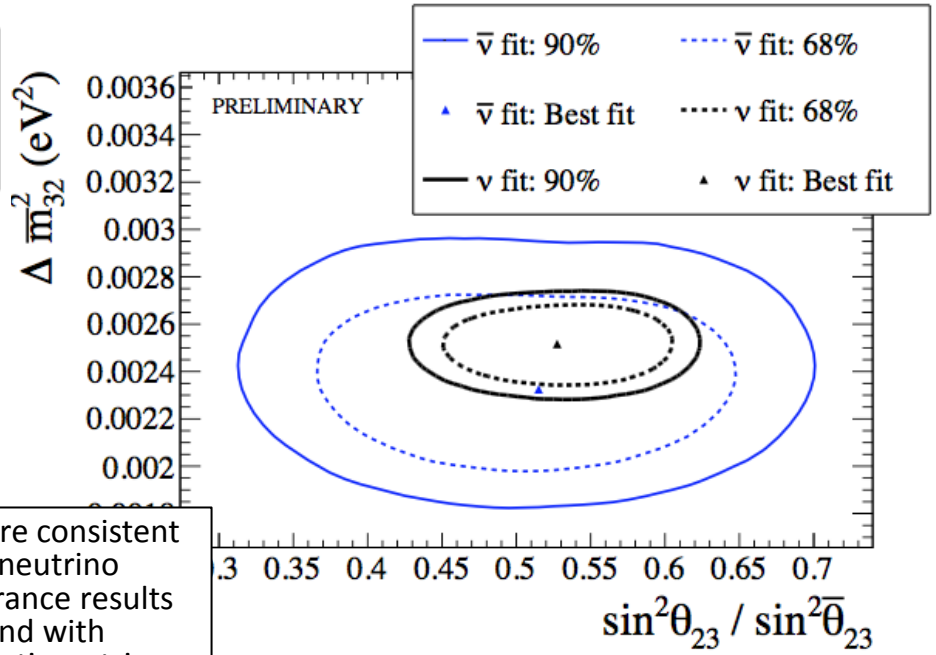
- Why run with anti-neutrinos?
  - Consistency between ν and $\bar{\nu}$ behaviour, e.g. CPT requires that the disappearance probability in both cases is the same
  - Combining data taken in both modes reduces the overall uncertainties on δ_{CP}

T2K $\bar{\nu}_\mu$ disappearance

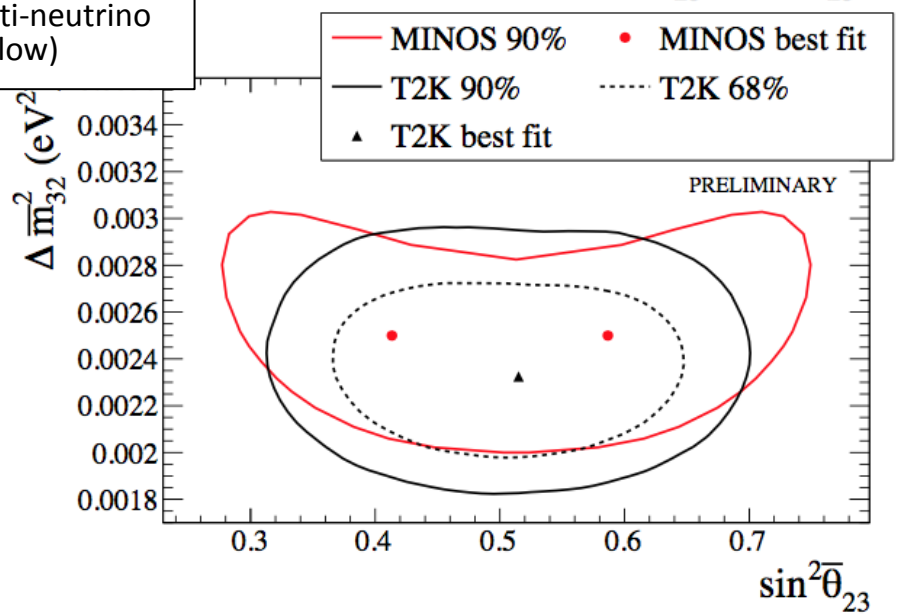






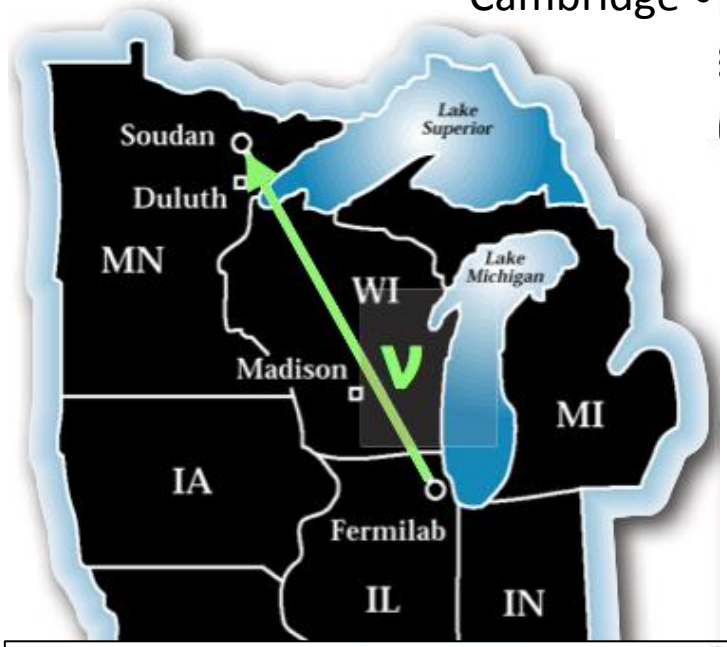


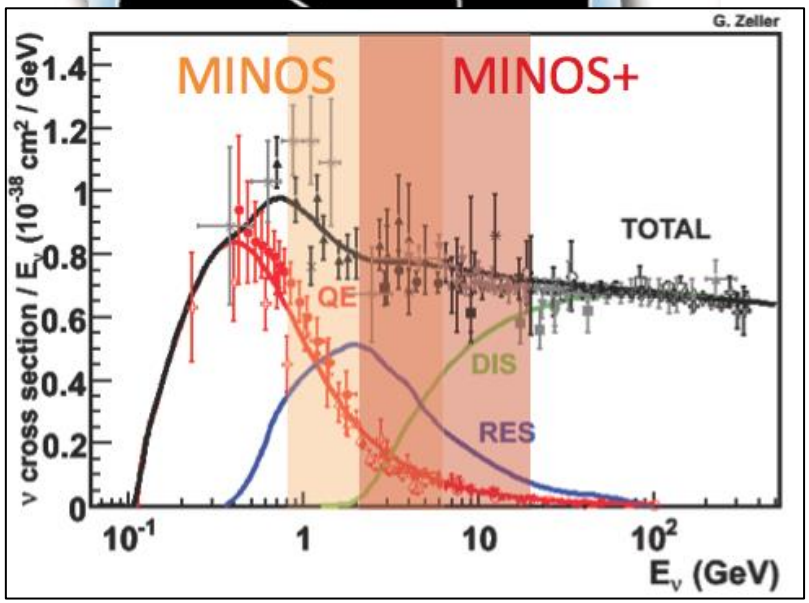
Results are consistent with T2K neutrino disappearance results (above) and with MINOS anti-neutrino results (below)



MINOS / MINOS+

Cambridge • Oxford • STFC/RAL • Sussex • UCL





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

MINOS+

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

MINOS/MINOS+ combined fit

- MINOS+ has accumulated 6.4x1020 POT from FNAL NUMI beam
- Largely focussing on exotic searches (sterile neutrinos, etc.)
- Combined MINOS/MINOS+ fit is consistent with previously reported MINOS results

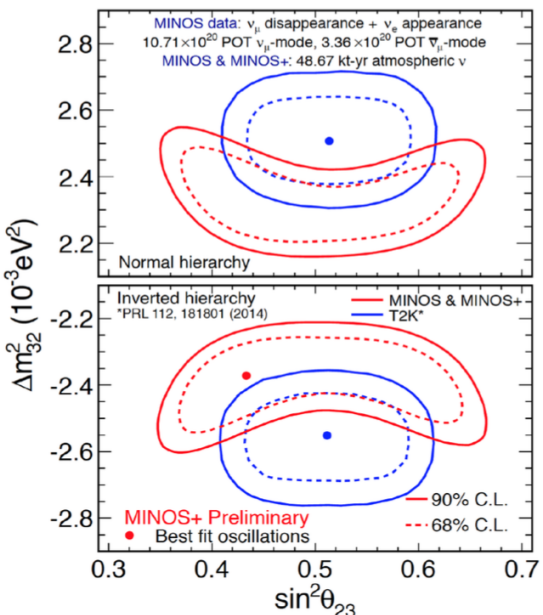
Three-Flavor Oscillations Best Fit

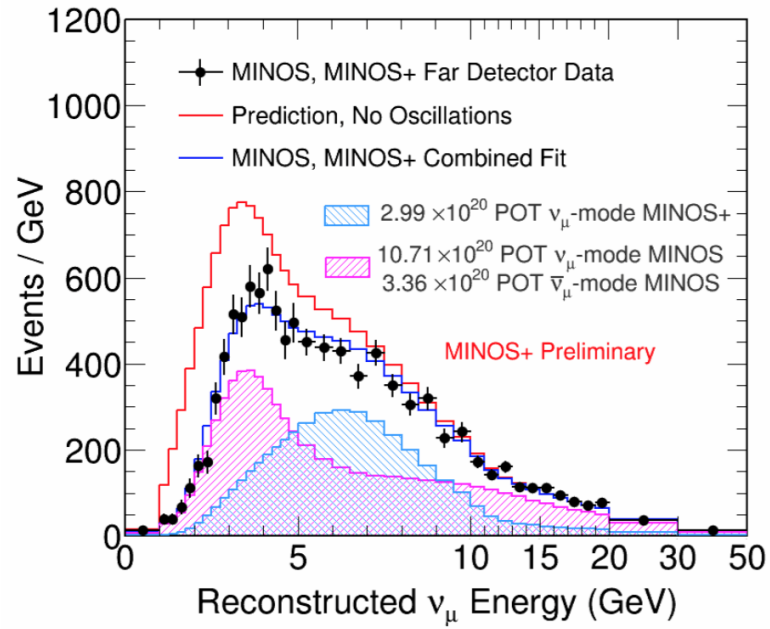
Inverted Hierarchy

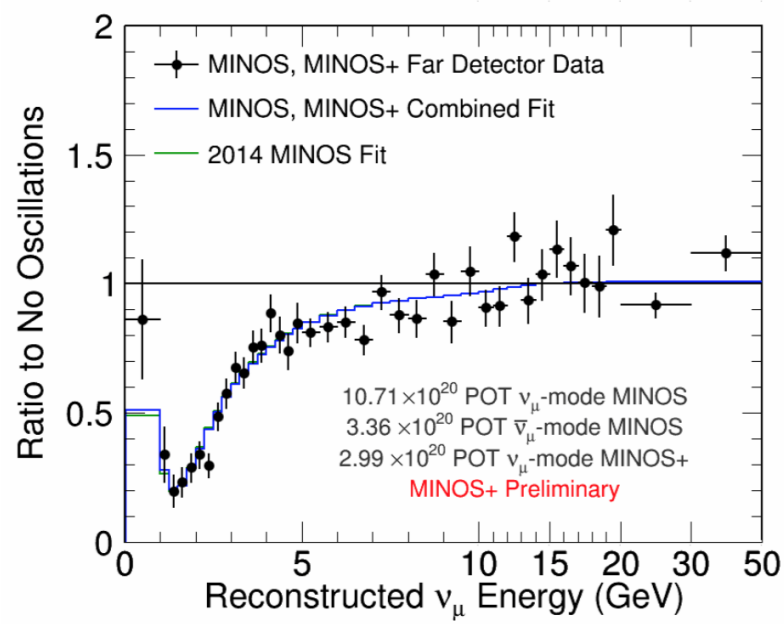
$$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3} \mathrm{eV}^2$$

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

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



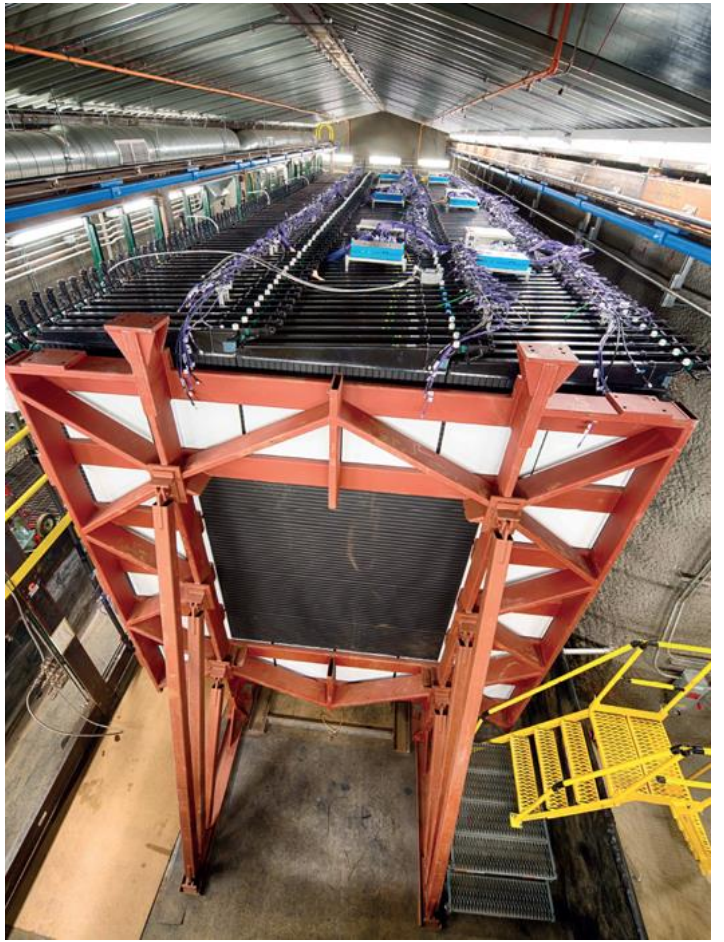




NOνA experiment and status

Sussex

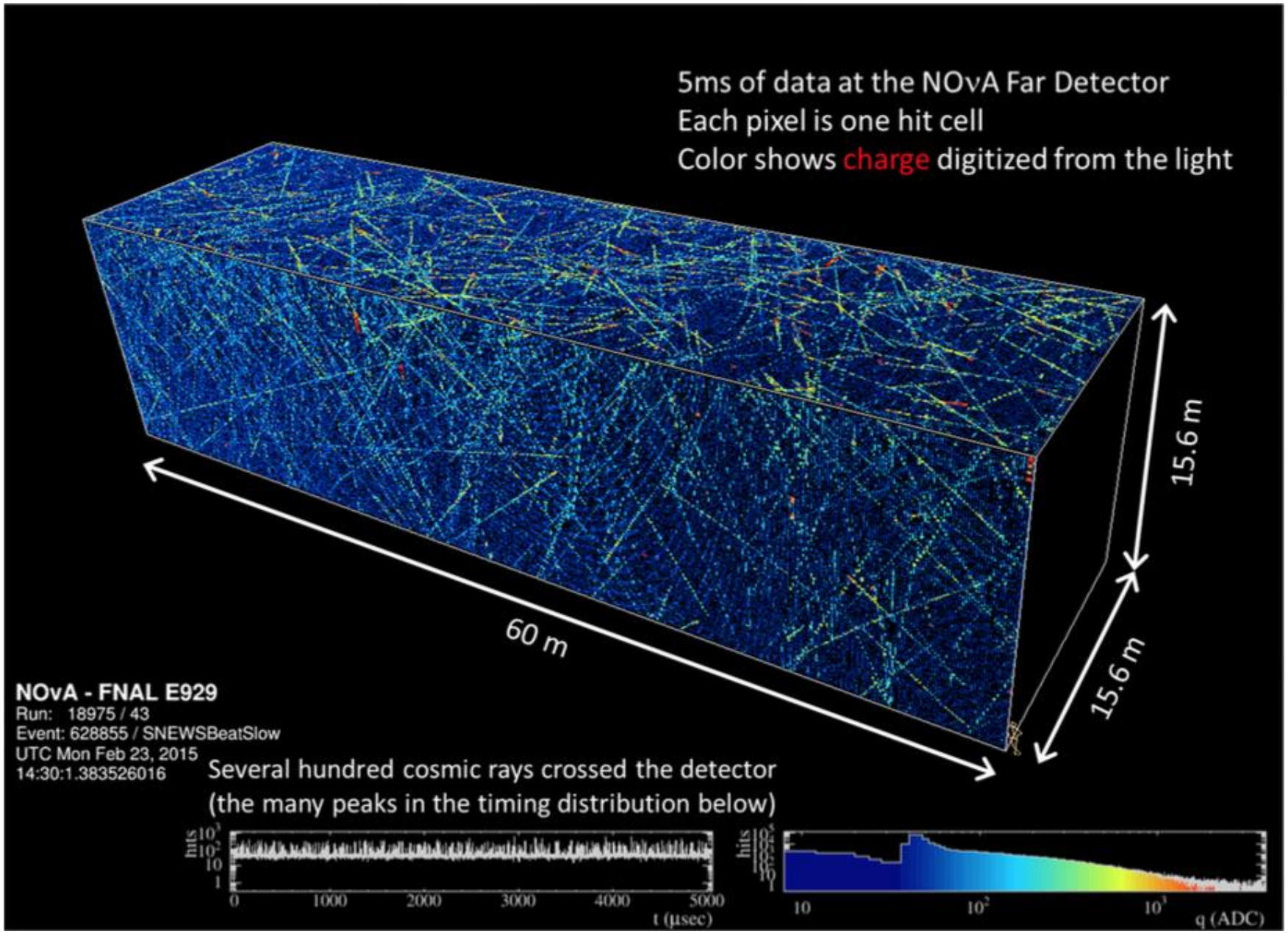
- Precision appearance/disappearance ν_μ ($\bar{\nu}_\mu$) measurements
- 810km long baseline experiment
- Off-axis narrow band FNAL NUMI neutrino beam
- 209t near detector and muon catcher
- Far detector 14kt totally active liquid scintillator



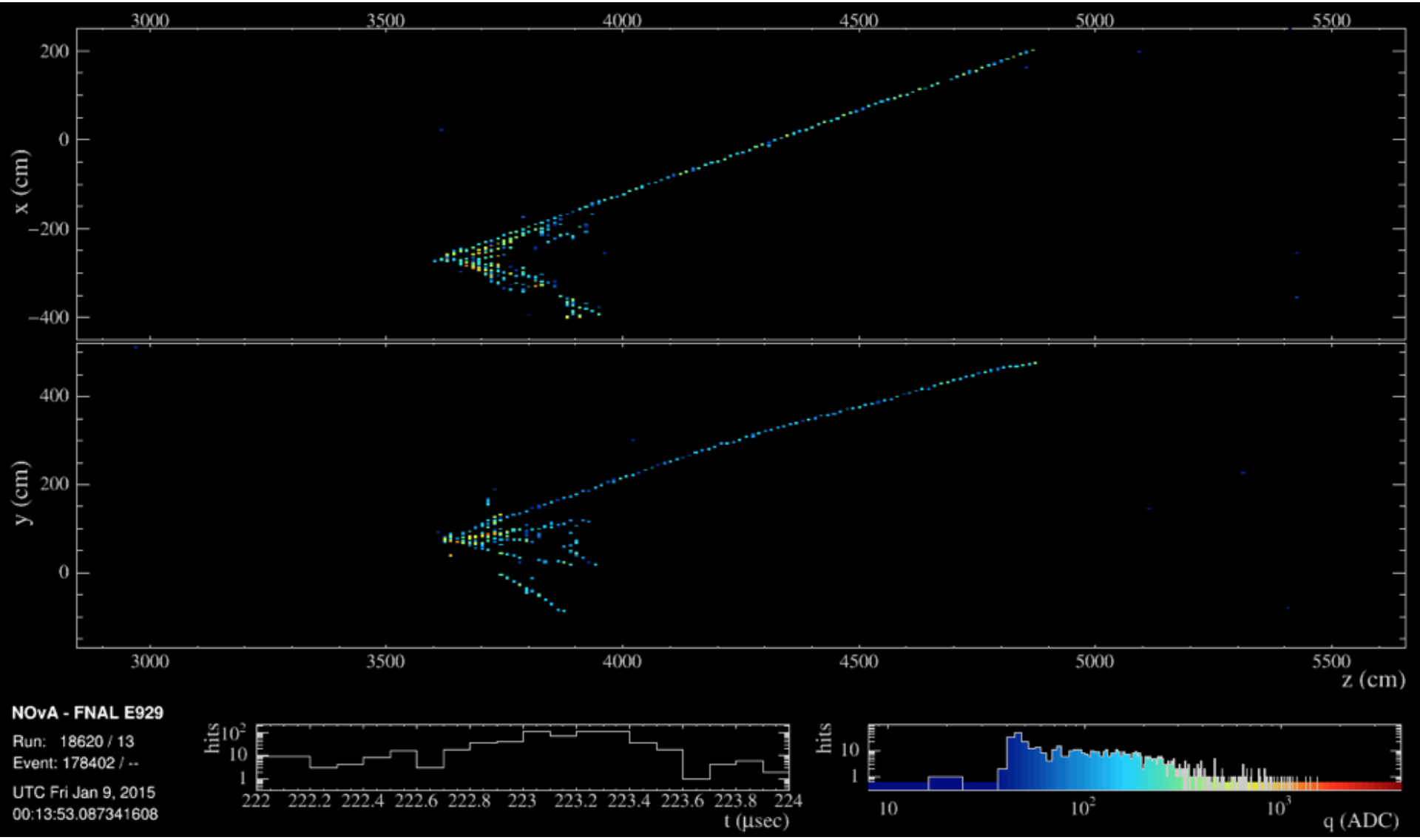
UK contribution: data driven trigger, stopping muon calibration, ν_μ analysis

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

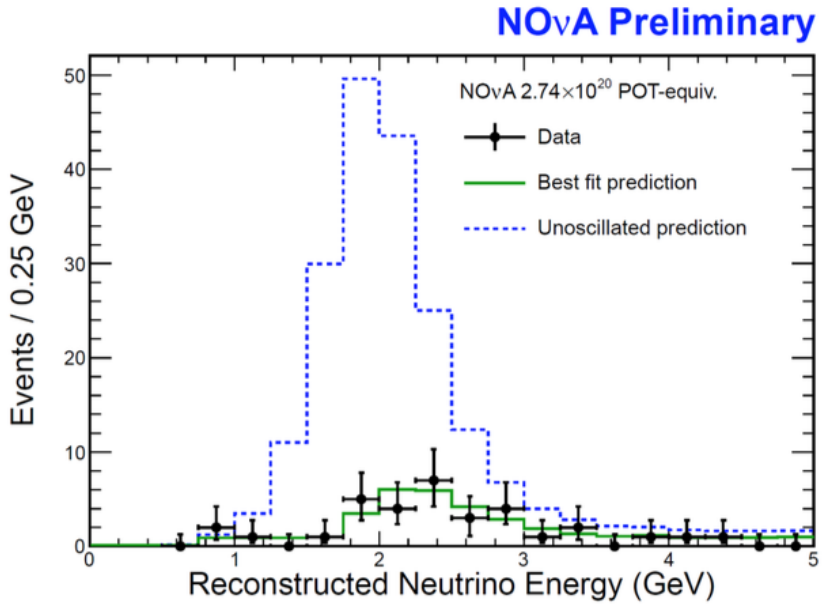
NOνA far detector data

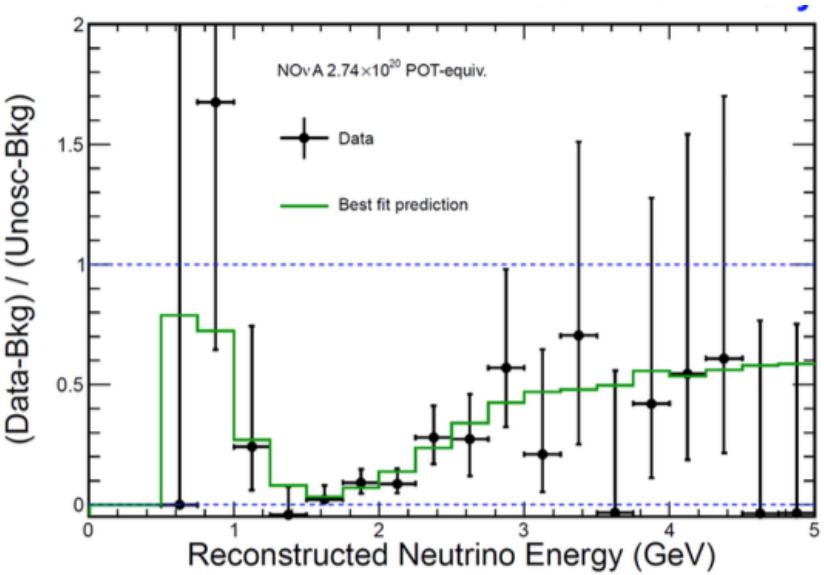


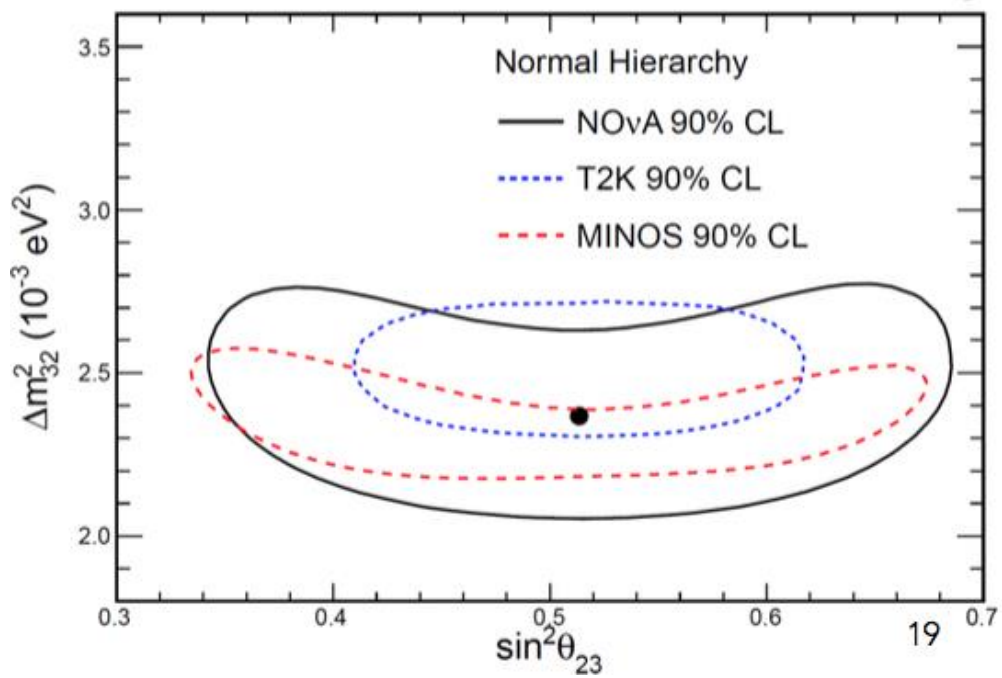
NOνA candidate ν_μ event



NOνA ν_μ disappearance results







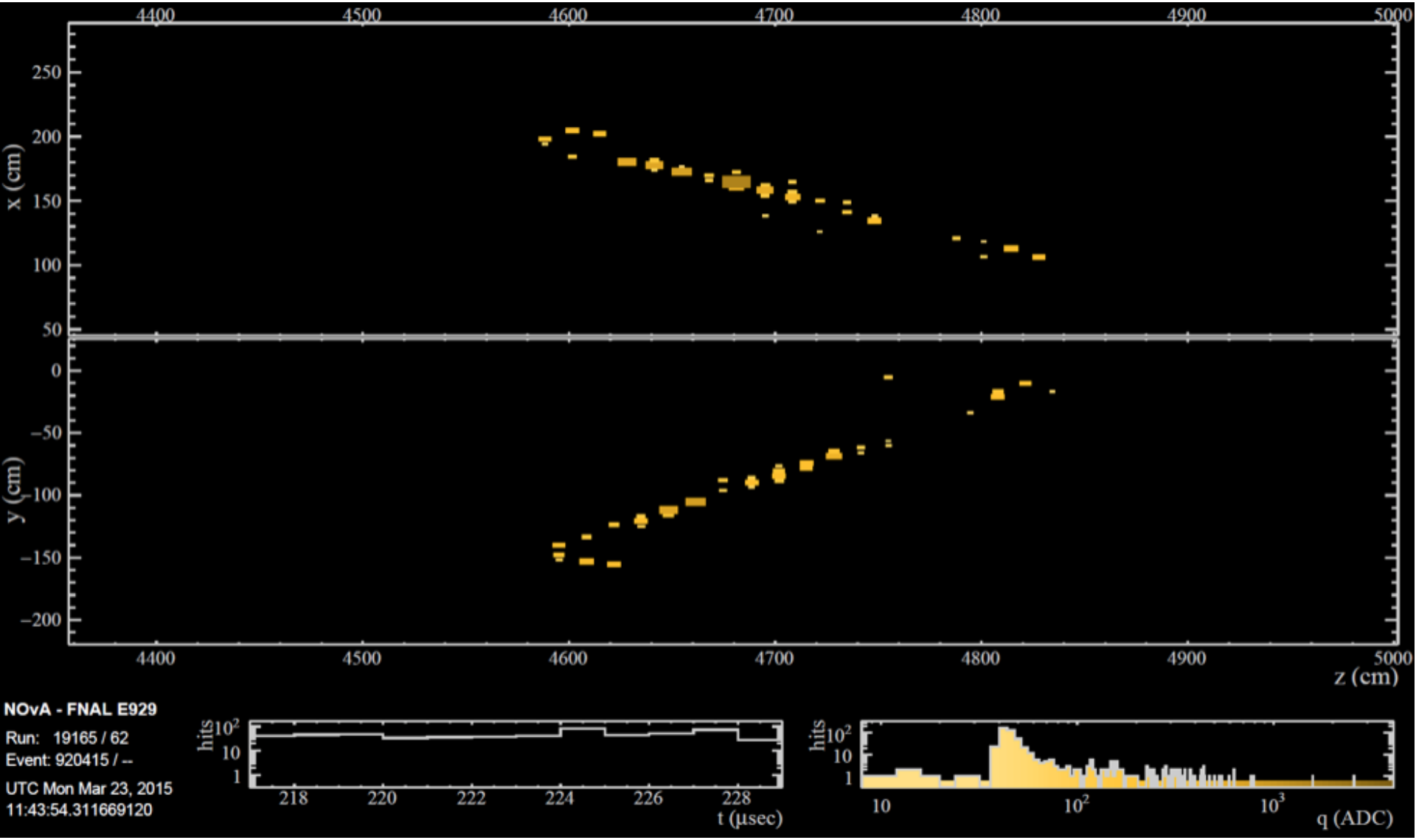
$$\Delta m^2_{32} = +2.37^{+0.16}_{-0.15} \quad \text{(normal hierarchy)}$$

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

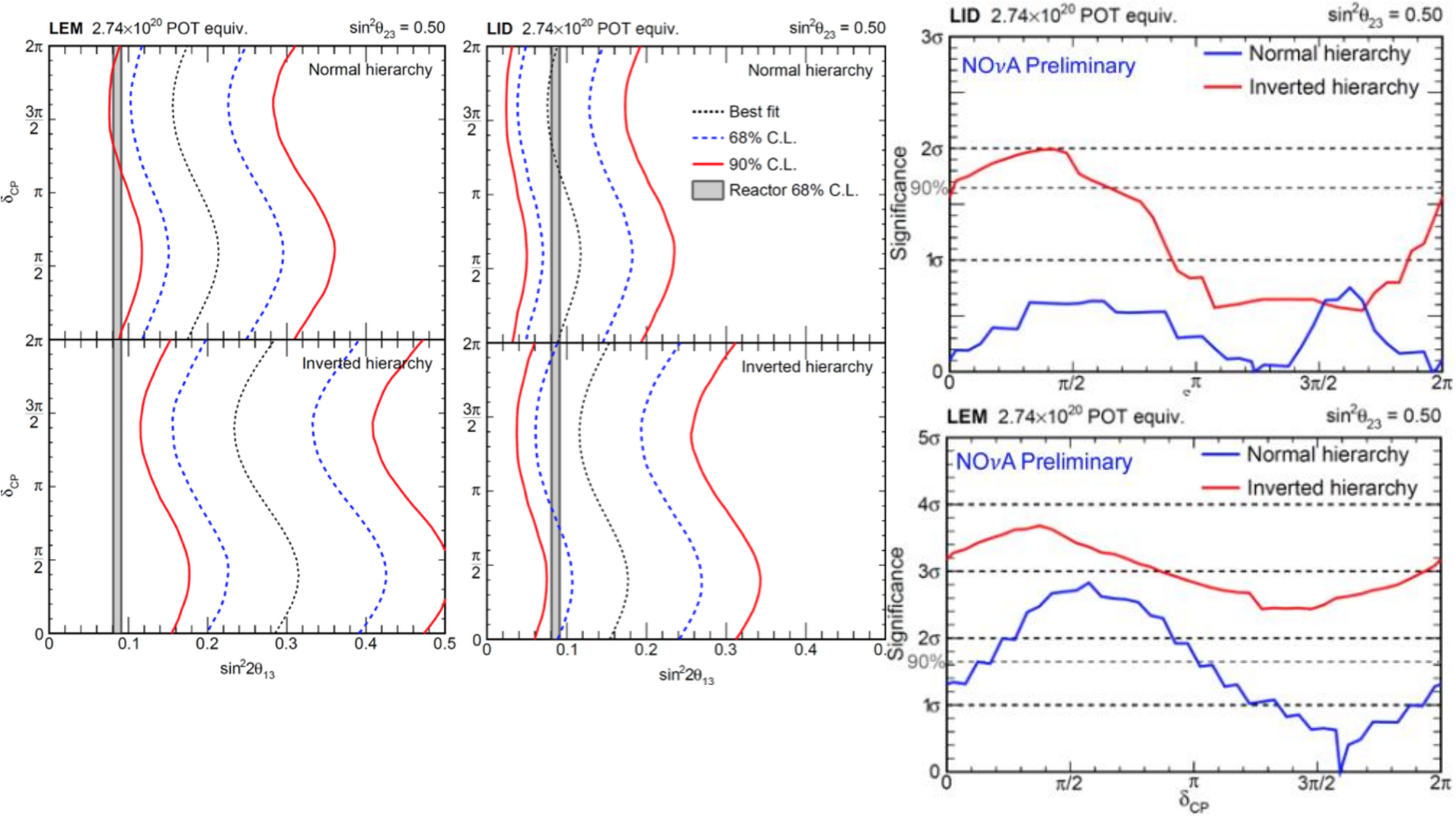
$$\sin^2\theta_{23} = 0.51 \pm 0.10$$

201 events expected, 33 observed
8% of nominal exposure

NOνA candidate ν_e event

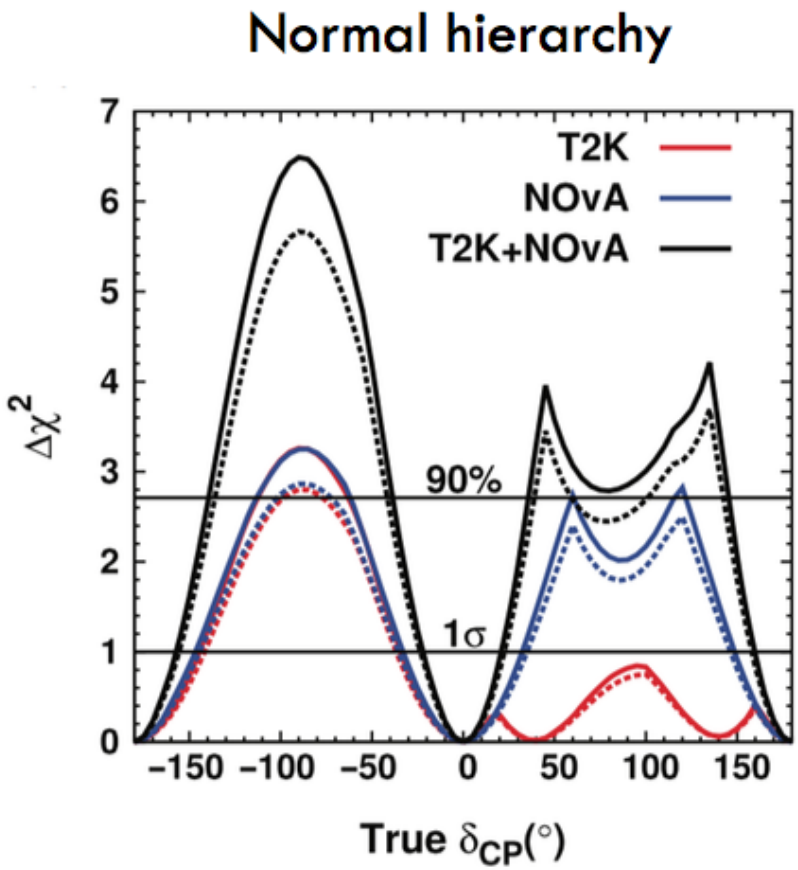


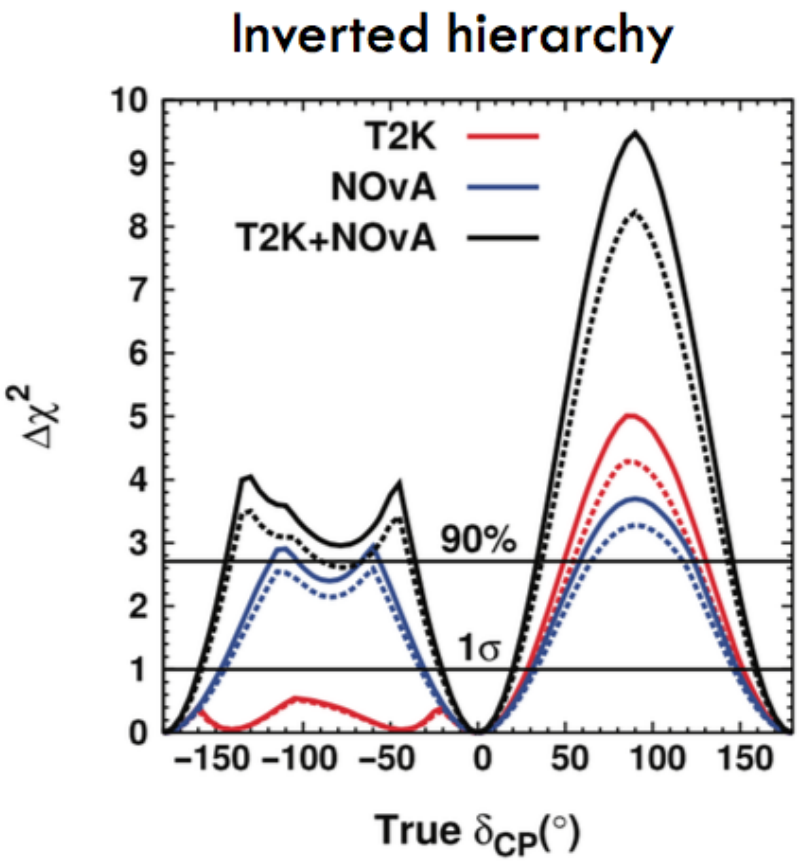
NOνA ν_e appearance results



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

NOνA and T2K complementarity

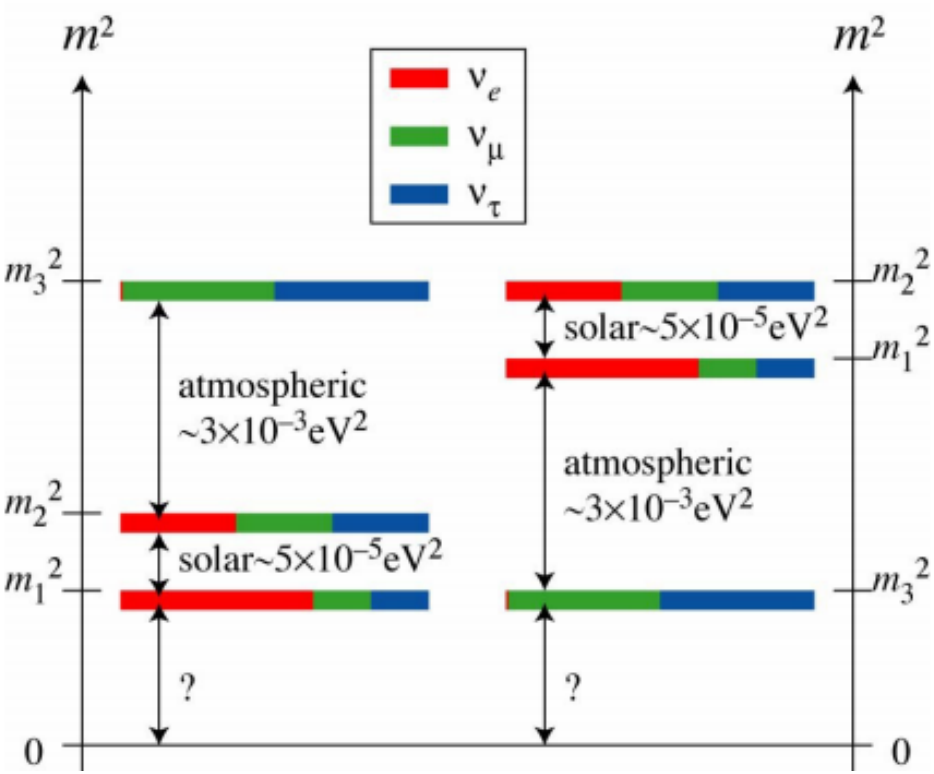




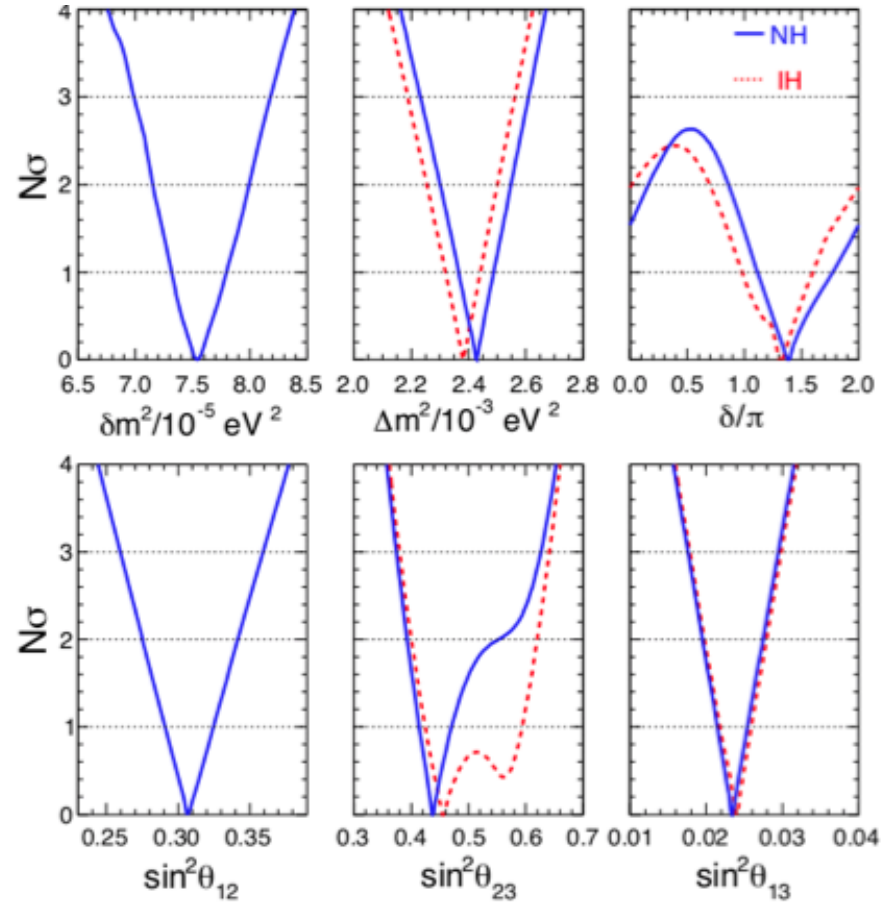
- Combining NOνA and T2K data helps break degeneracies and improves coverage in the overlap regions
- Mainly due to NOνA 's increased sensitivity to the mass hierarchy via matter effects

Current understanding

Mass hierarchy

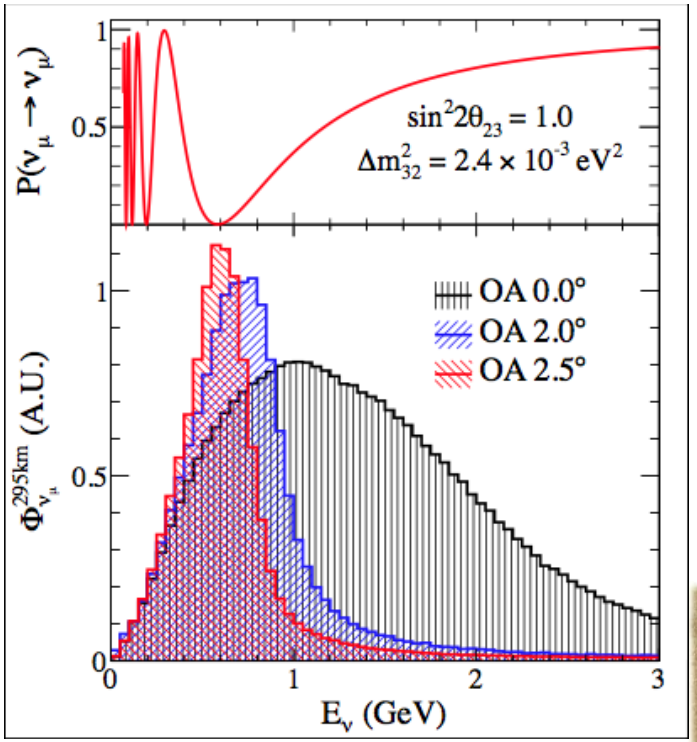


Mixing angles and mass differences



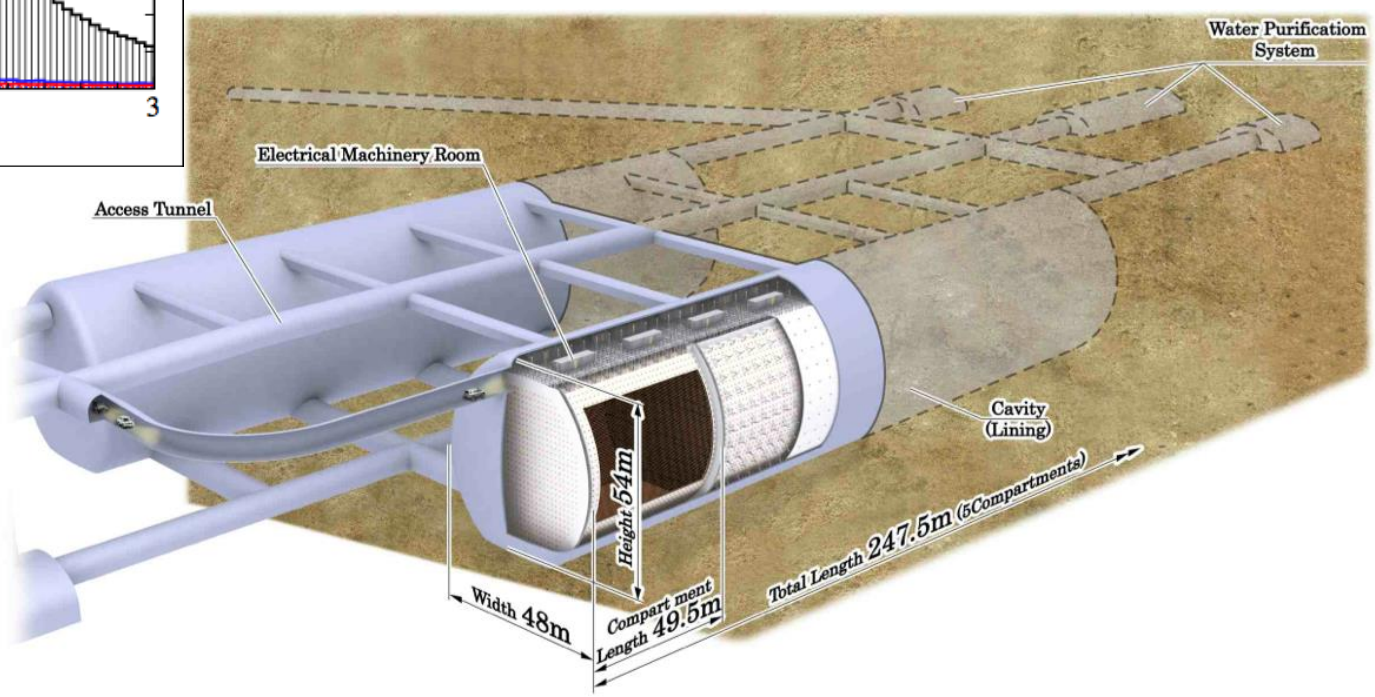
- Global fit data as of June 2014
- Uses LBL, SBL, reactor, solar, atm data
- Uses technique in Capozzi et al. PRD 89 (2014) 093018)

HyperK beam and detector



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

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



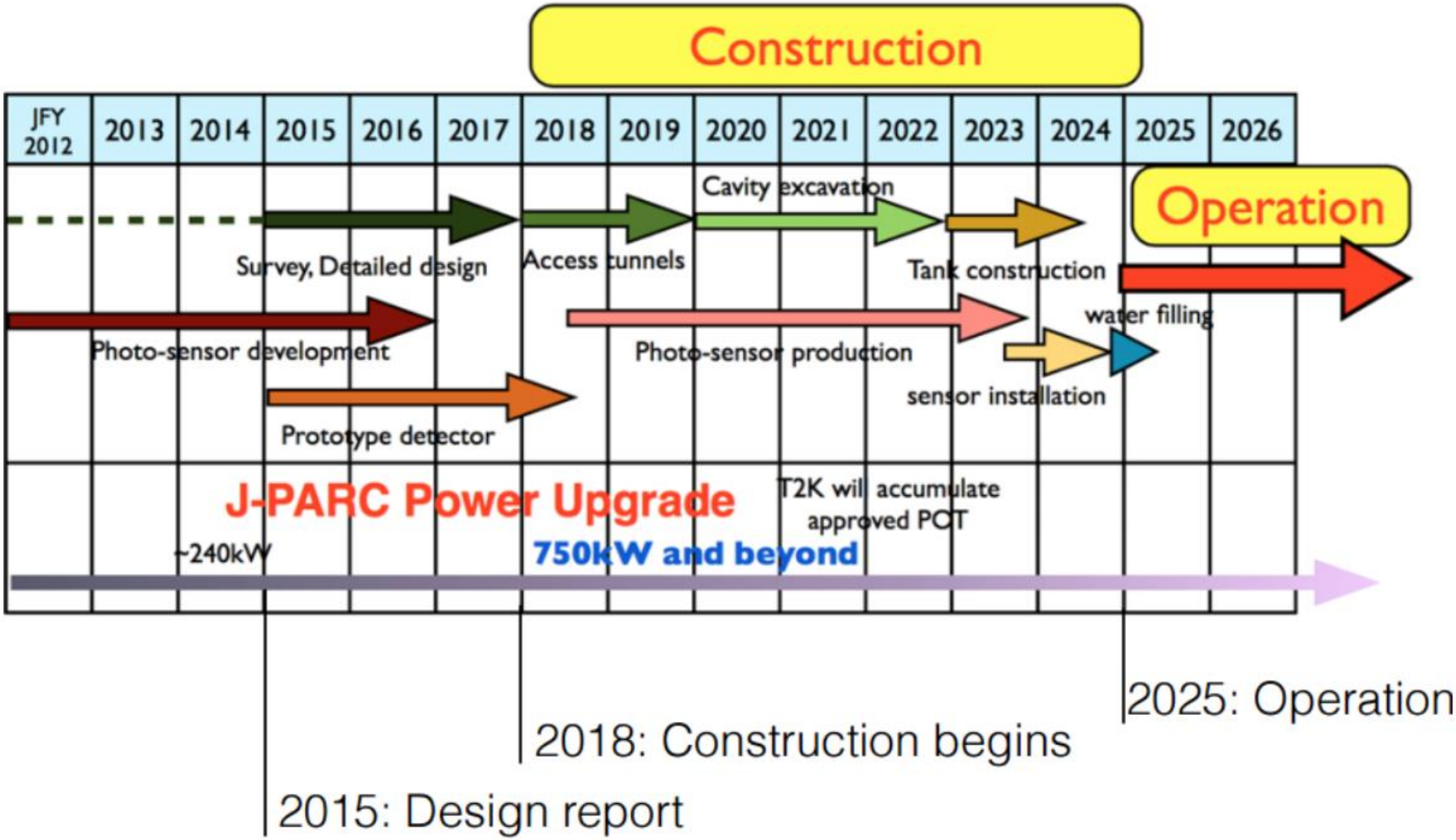
HyperK status


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

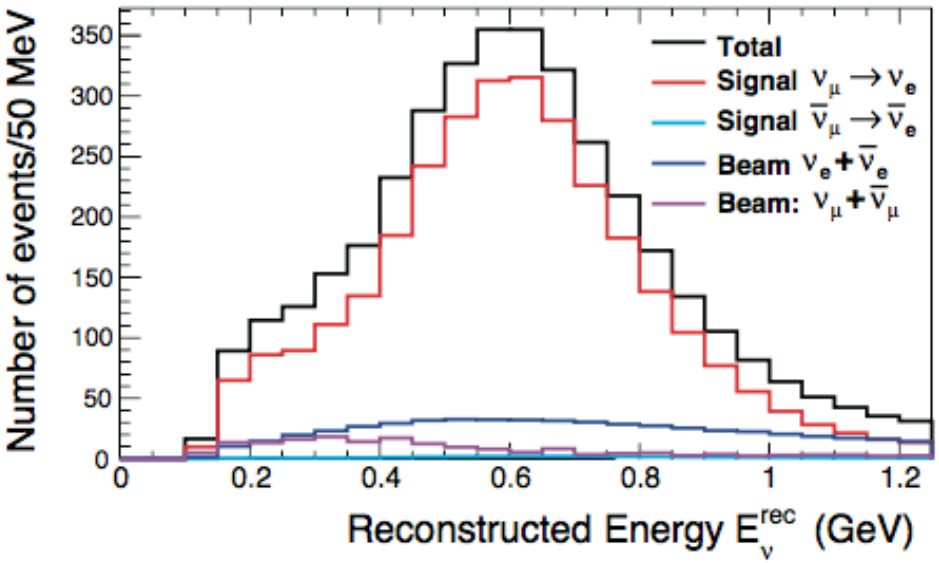
- In 2013 Japan granted a 5 year £2.3M R&D grant which includes provision for a prototype detector (+$1.2M)
- In early 2014 the Science Council of Japan selected HyperK as one of its top 27 scientific projects in its 2014 Master Plan
- Discussions with Japanese funding agency, MEXT, in progress for long-term funding
- Current Collaboration>240 people
- UK represents the second largest group of scientists after Japan

HyperK timeline

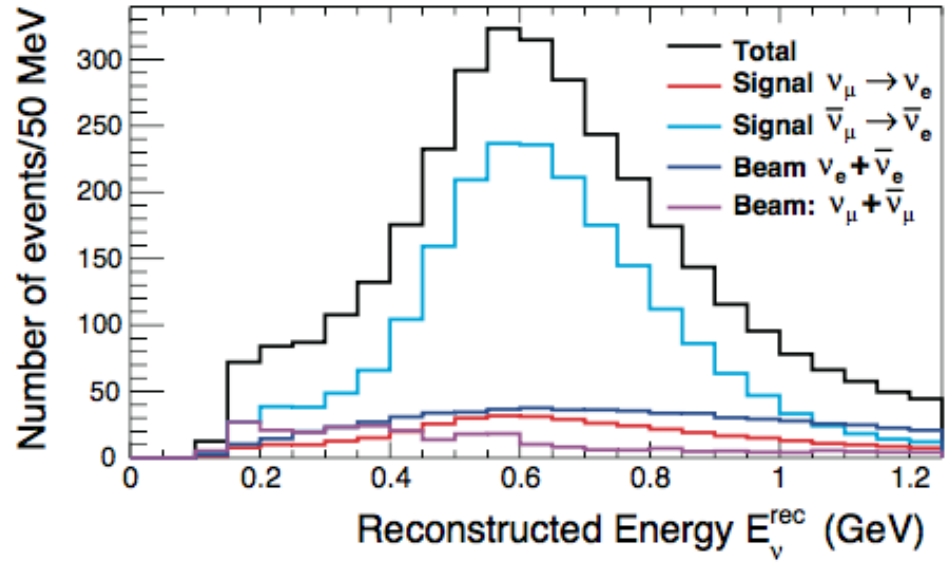


HyperK $\nu_e(\bar{\nu}_e)$ appearance events

Appearance ν_e events



Appearance $\bar{\nu}_e$ events



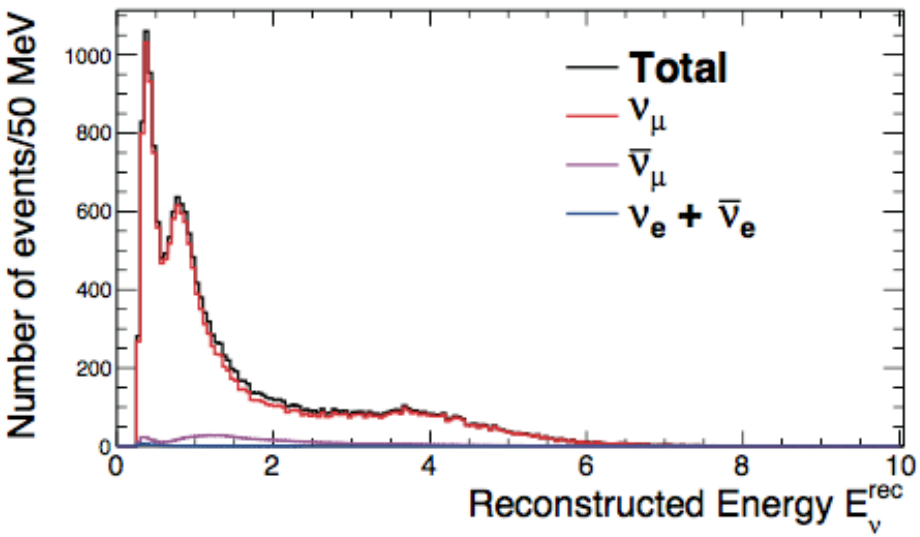
	signal		BG					Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	
ν mode	**3016**	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	**2110**	4	5	222	396	265	3397

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

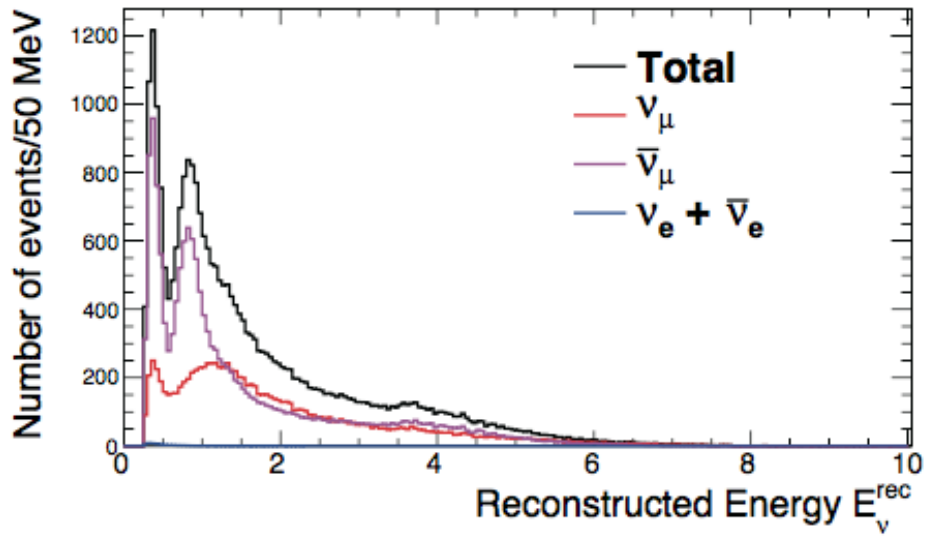
7.5×10^7 MW sec, $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP}=0$, normal MH, $\nu:\bar{\nu} = 1:3$

HyperK $\nu_\mu(\bar{\nu}_\mu)$ disappearance events

Disappearance ν_μ events



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

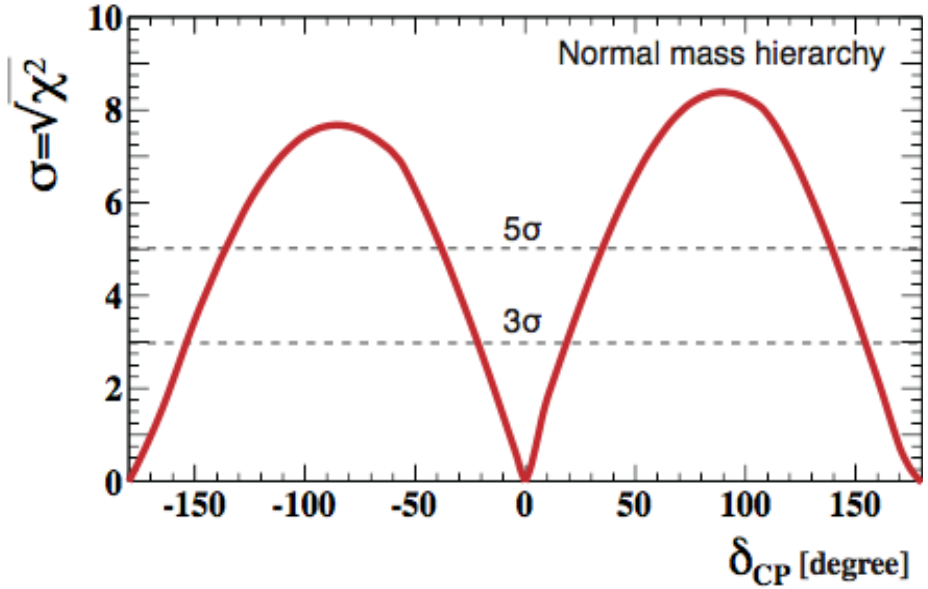


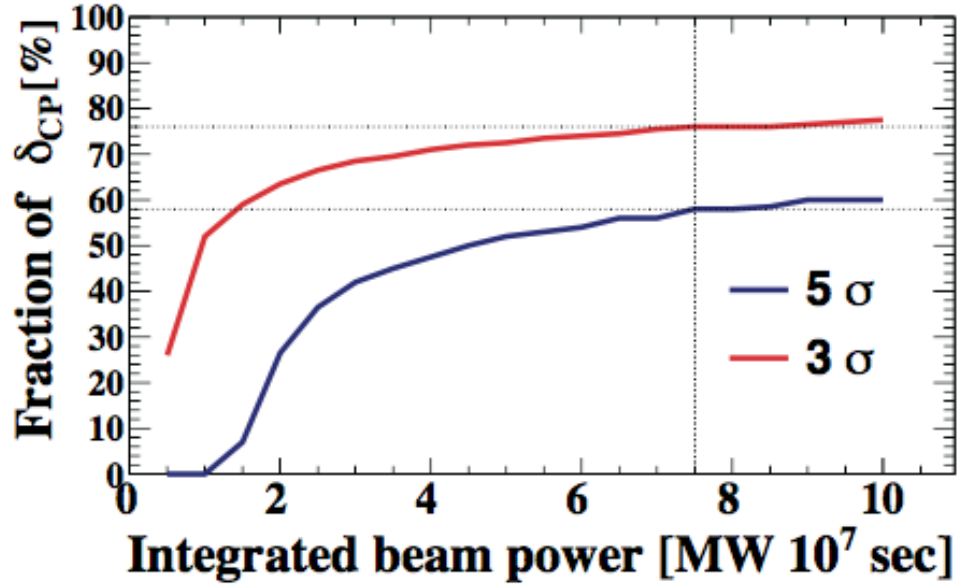
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	$\nu_\mu \to \nu_e$	Total
ν mode	**17225**	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	**15597**	7	7	1281	6	26964

- Anti-neutrino mode: significant wrong-sign ν_μ contribution

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

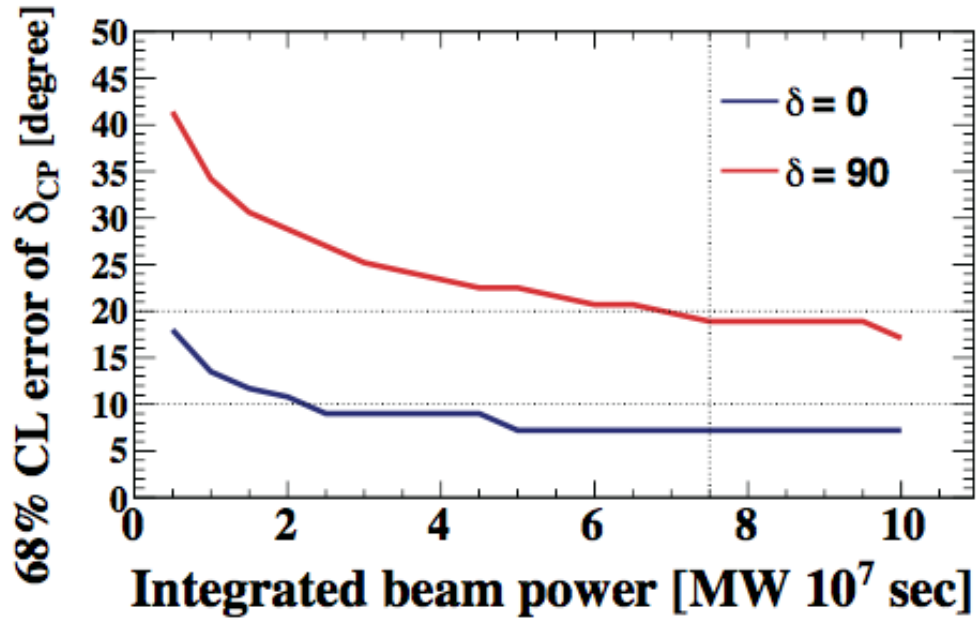
HyperK sensitivity to CP





Assuming 7.5×10^7 MW sec:

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



HyperK broad scientific programme

	Physics target	Sensitivity	Conditions
Neutrino Oscillation Physics	Neutrino study w/ J-PARC ν		7.5 MW $\times$ 10^7 s
	– CP phase precision	$<19^\circ$	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
	– CPV discovery coverage	76% (3σ), 58% (5σ)	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
	– $\sin^2\theta_{23}$	± 0.015	1σ @ $\sin^2\theta_{23} = 0.5$
Atmospheric Neutrino Physics	Atmospheric neutrino study		10 yr observation
	– MH determination	$>3\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
	– θ_{23} octant determination	$>3\sigma$ CL	@ $\sin^2\theta_{23} < 0.46$ or $\sin^2\theta_{23} > 0.56$
Proton Decay	Nucleon decay searches		10 yr data
	– $p \to e^+ + \pi^0$	1.3×10^{35} yr (90% CL UL)	
		5.7×10^{34} yr (3σ discovery)	
	– $p \to \bar{\nu} + K^+$	3.2×10^{34} yr (90% CL UL)	
		1.2×10^{34} yr (3σ discovery)	
Astroparticle Physics	Astrophysical neutrino sources		
	– ^{8}B ν from Sun	200 ν/day	7.0 MeV threshold (total energy) w/ osc.
	– Supernova burst ν	170 000–260 000 ν	@ Galactic center (10 kpc)
		30–50 ν	@ M31 (Andromeda galaxy)
	– Supernova relic ν	830 ν/10 yr	
	– WIMP annihilation at Sun (σ_{SD}: WIMP–proton spin-dependent cross section)		5 yr observation
		$\sigma_{SD} = 10^{-39}$ cm^2	@ $M_{\mathrm{WIMP}} = 10$ GeV, $\chi\chi \to b\bar{b}$ dominant
		$\sigma_{SD} = 10^{-40}$ cm^2	@ $M_{\mathrm{WIMP}} = 100$ GeV, $\chi\chi \to W^+W^-$ dominant

...

HyperK UK involvement

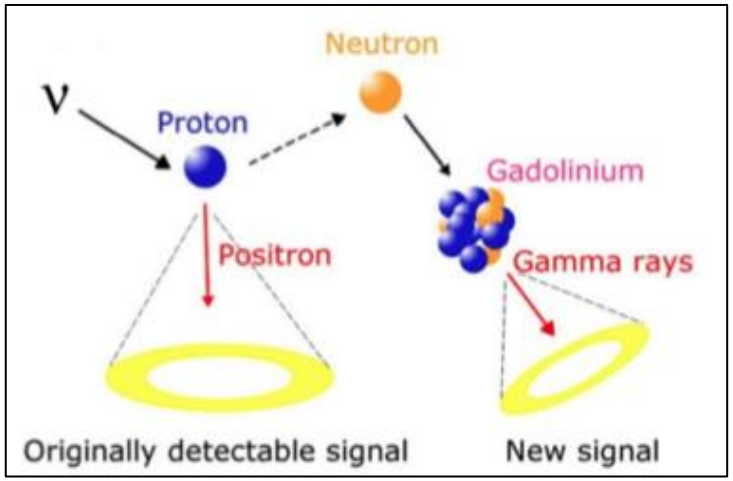
Edinburgh • Imperial • Lancaster • Liverpool • Oxford

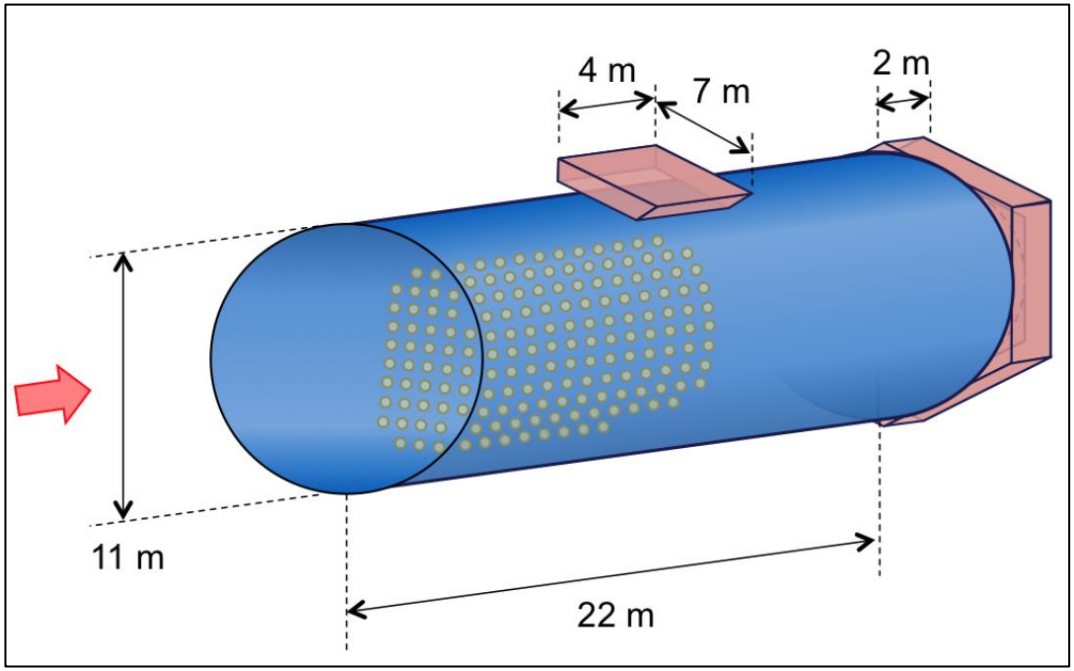
QMUL • RHUL • Sheffield • STFC/RAL • Warwick

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

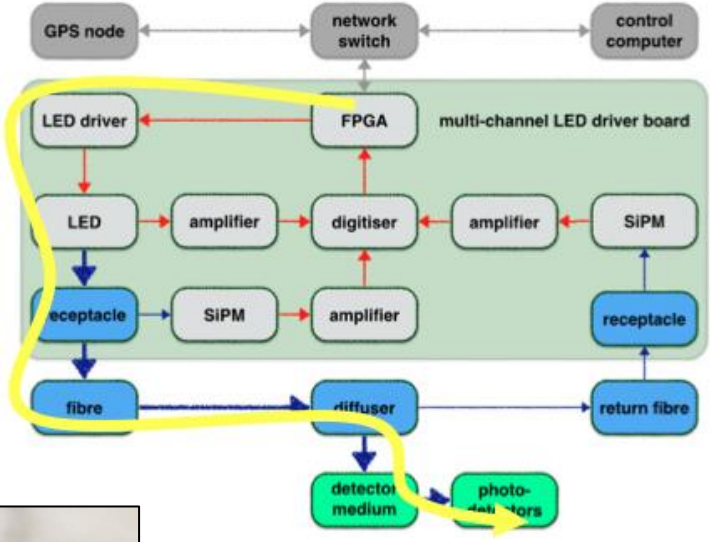
HyperK UK WP2 Detector R&D

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

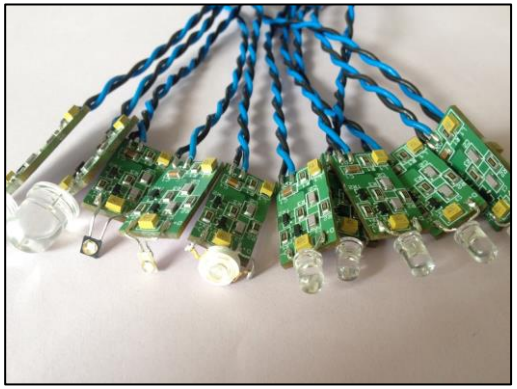




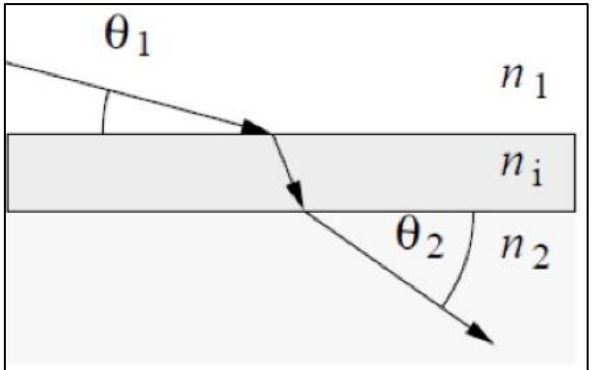
HyperK UK WP4 Calibration



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



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



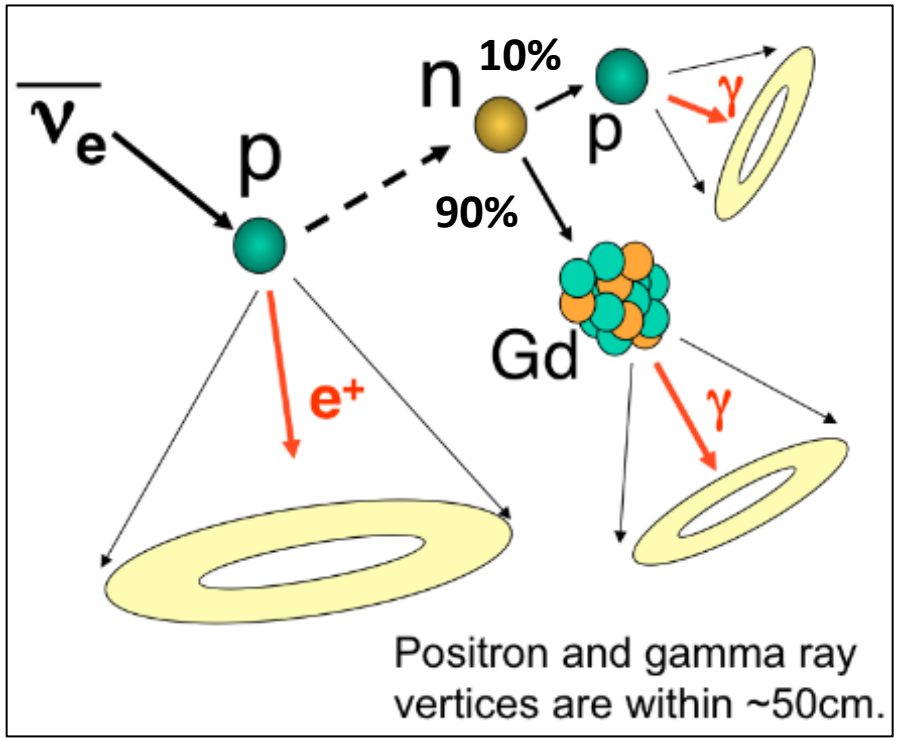
$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$
independent of n_i

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^+

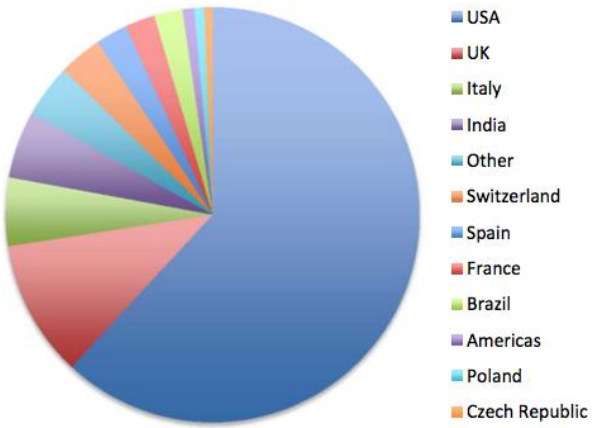


- The problem is that you need to completely remove the Gadolinium Sulphate when necessary → need a selective GD filtration system
- New system based on nano-filtration. Molecular band-pass filter analogous to electrical equivalent
- EGADS: 200ton Gd demonstrator close to Super-K
- Initial results show 66% Č light left at 20m with Gd c.f. 71% to 79% without
- Recent decision to run SK with Gd

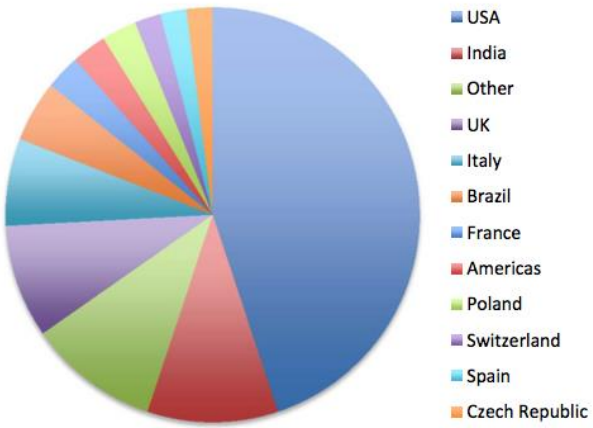
Mark Thomson seminar next week

DUNE status

776 Collaborators

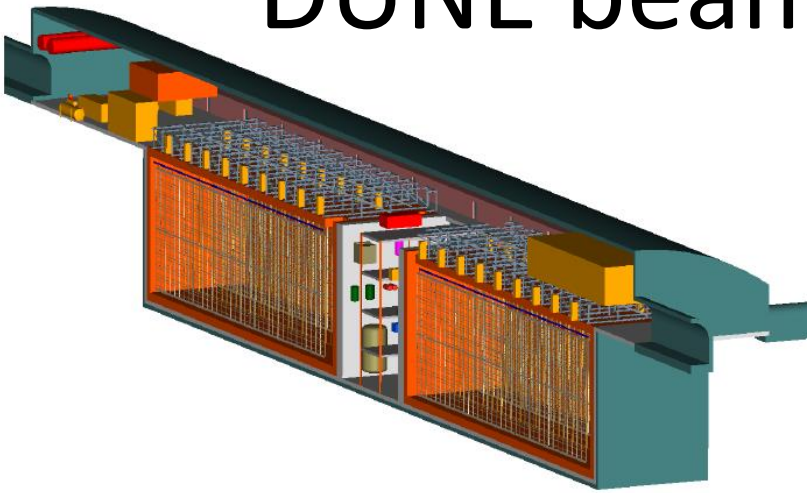


144 Institutes

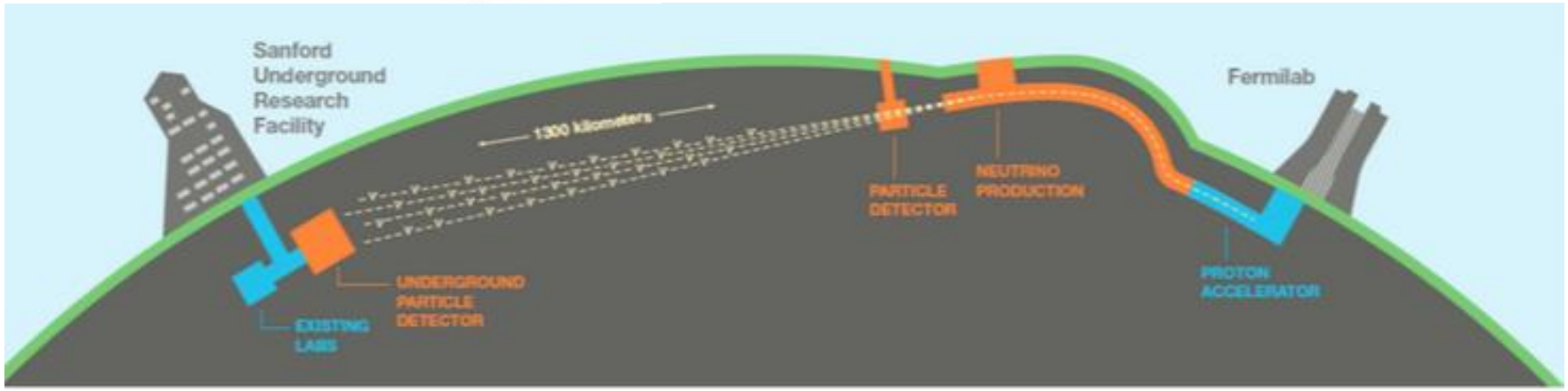


- DOE CD-1 preliminary baseline approval in December 2012
  - DOE commitment of $867M to LBNE
  - Plus PIP-II for 1.2MW beam – total of $1.5B
- Funding bids in process/successful in UK, India, Brazil, Italy,…
- UK is largest non-US group represented ~10% of collaboration

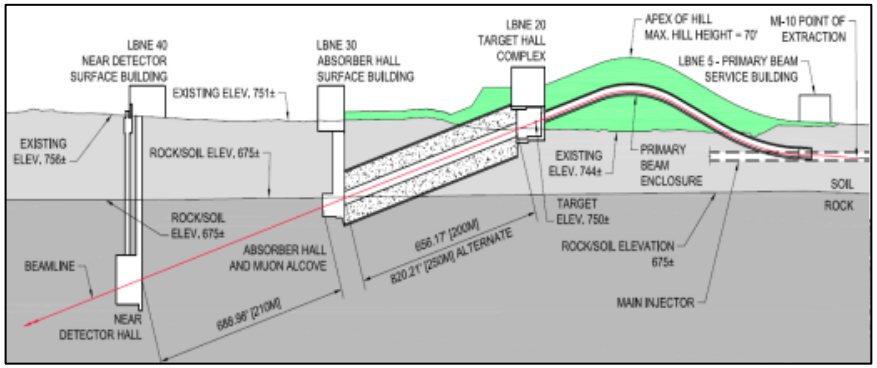
DUNE beam and far detector



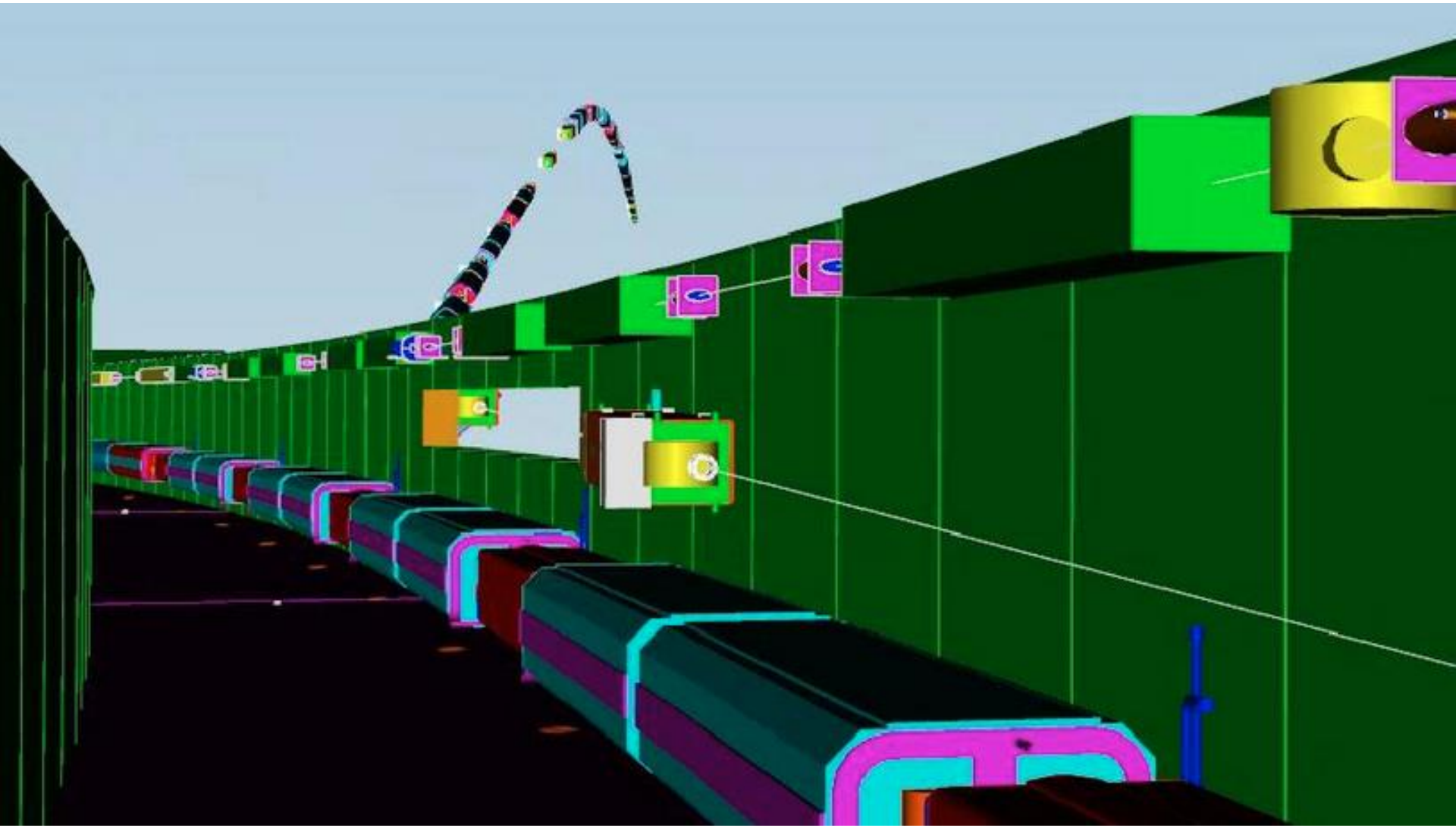
- Wide band FNAL neutrino beam
- 1.2MW upgradeable to 2.3MW
- 0.5 – 5.0 GeV sign-selected ν
- Near detector design in progress



- Far detector
  - Up to 40kt fiducial volume
  - Staged approach 4 x 10kt in separate caverns
  - Allows different designs to be considered (single vs double phase)

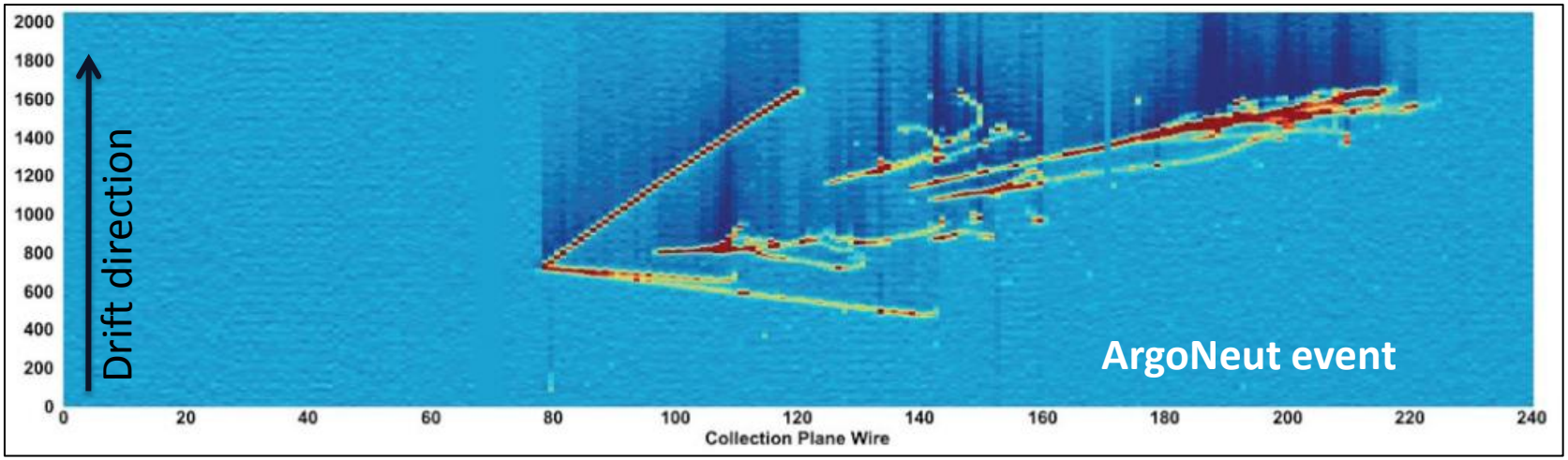


Beamline visualisation



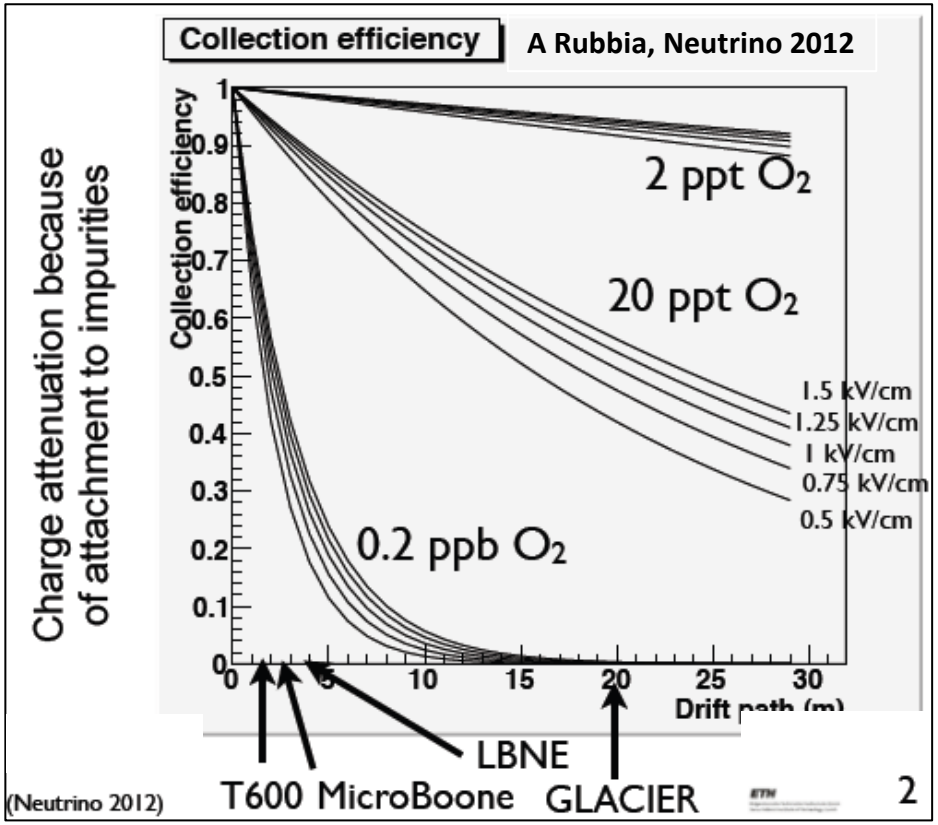
Liquid Argon TPCs

- Why Liquid Argon?
  - High density, cheap
  - Dense → good target
  - Excellent dielectric properties support large voltages
  - Free electrons from ionizing track can be drifted in long distances 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

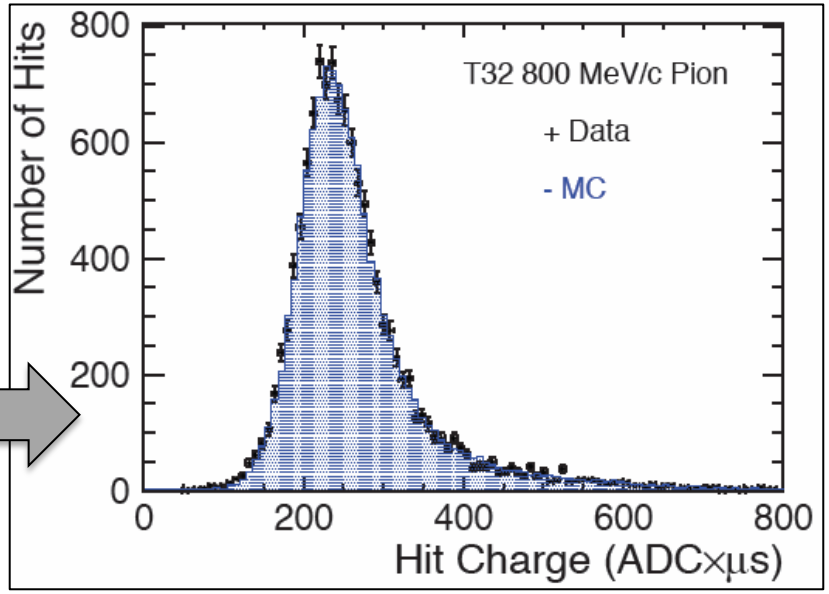
- Technical challenges:
  - to achieve long drift distances ultra-high purities (better than 100 ppt O_2 equivalent) are required
  - Drift field requires HV on the cathode
  - Operation of large wire chambers at cryogenic temps
  - No charge amplification in liquid → fC charges requiring sensitive preamps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

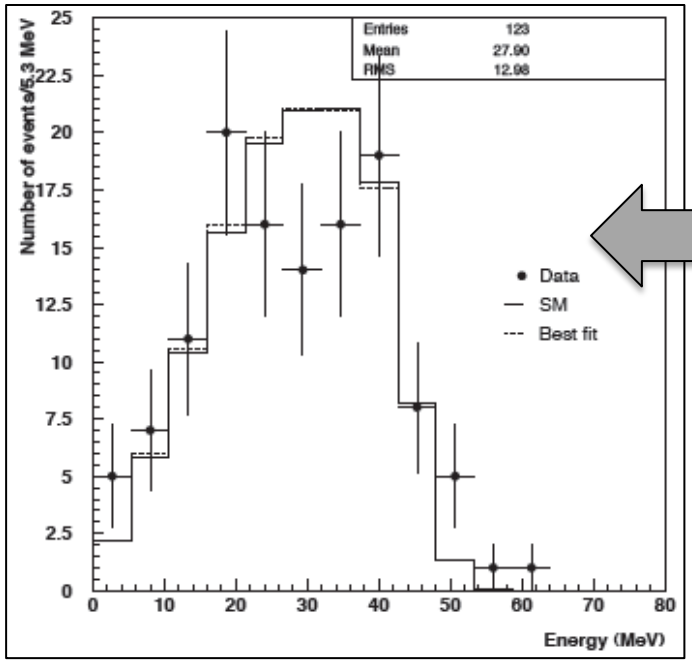


Liquid Argon TPCs: performance

- 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

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





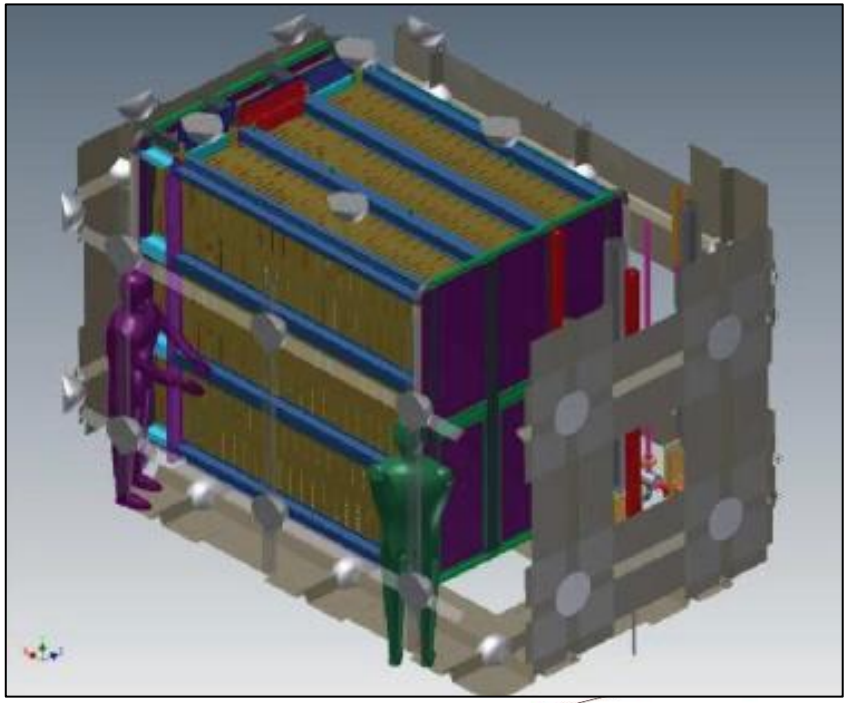
- Calorimetric Performance:
  - ICARUS data (2004) with Michel electrons from stopping muon decay

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

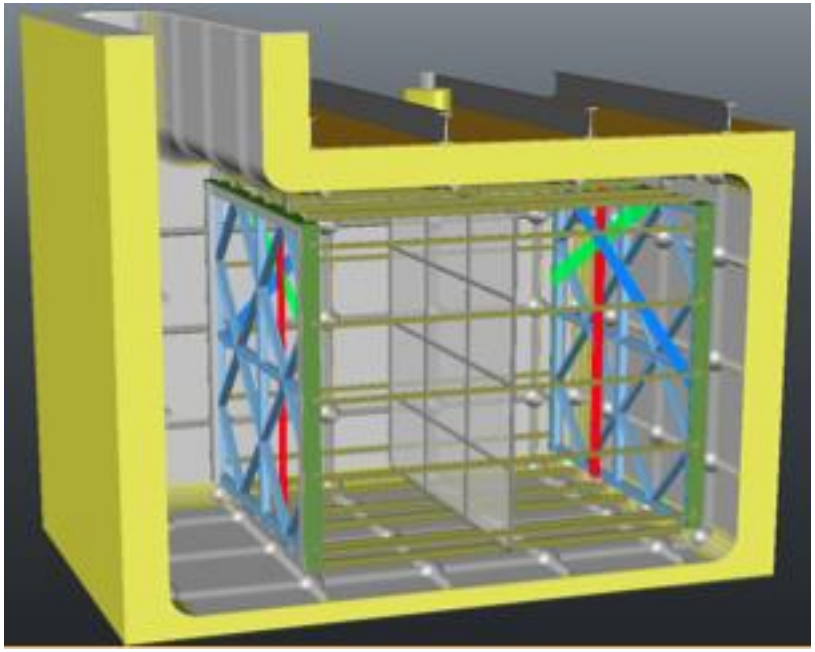
  - MC expectations (higher E):

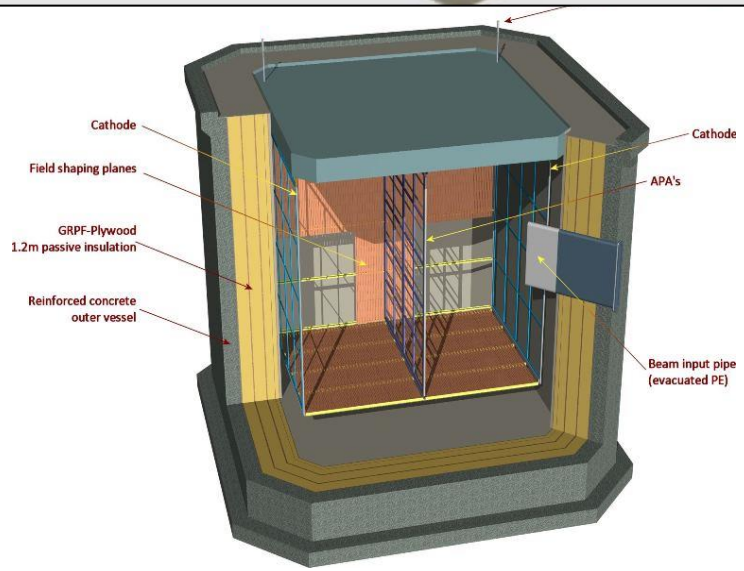
$$\frac{\sigma_{EM}^{MC}}{E} \approx \frac{3\%}{\sqrt{E}} \oplus 1\% \qquad \frac{\sigma_{HAD}^{MC}}{E} \approx \frac{15\%}{\sqrt{E}} \oplus 10\%$$

LAr prototyping activities



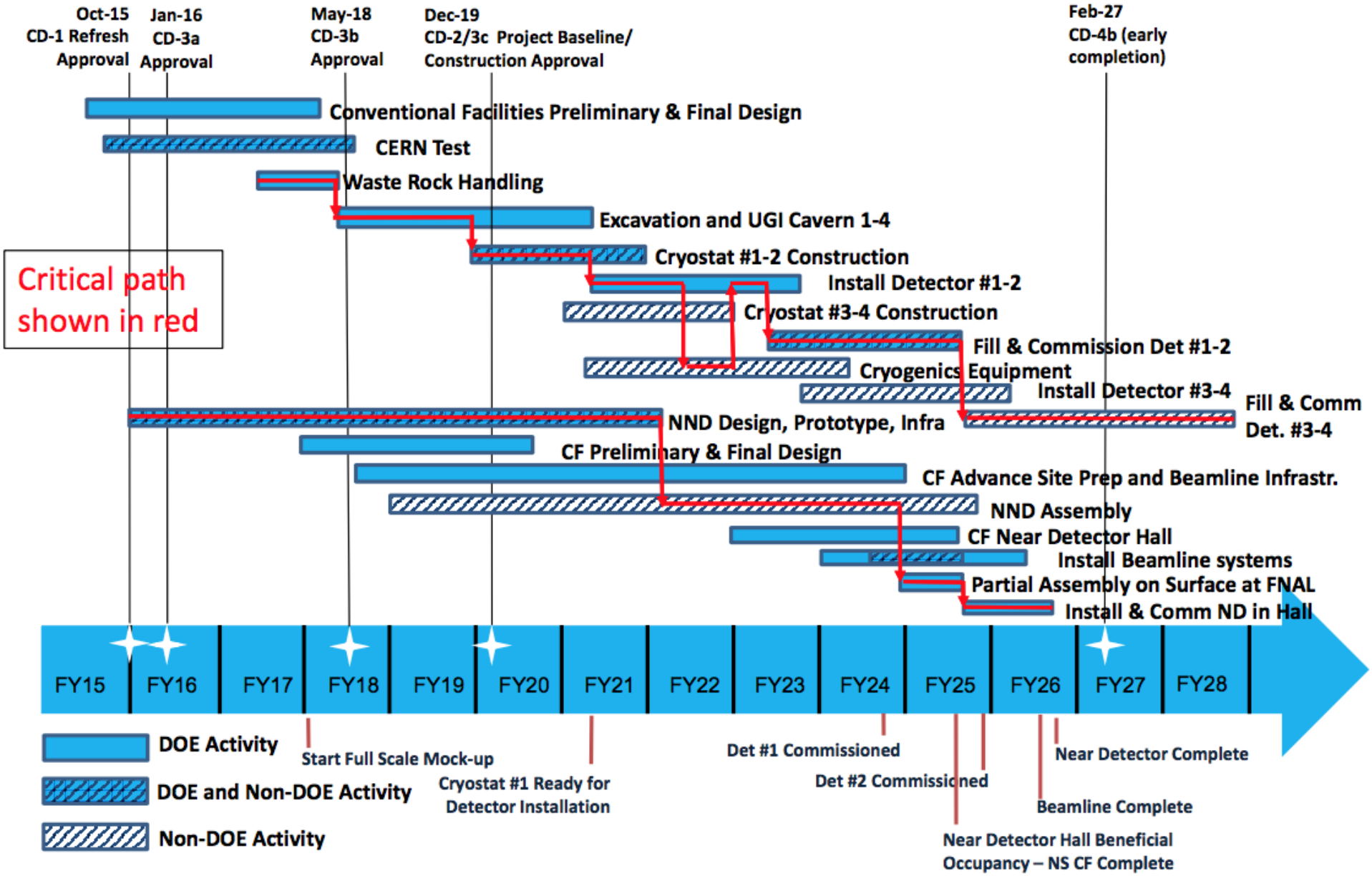
- DUNE 35 ton prototype due to take data at FNAL in late 2015
- LAr1-ND, 82t TPC for MicroBoone (2017)
- Other activities ArgoNeut, LARIAT etc.



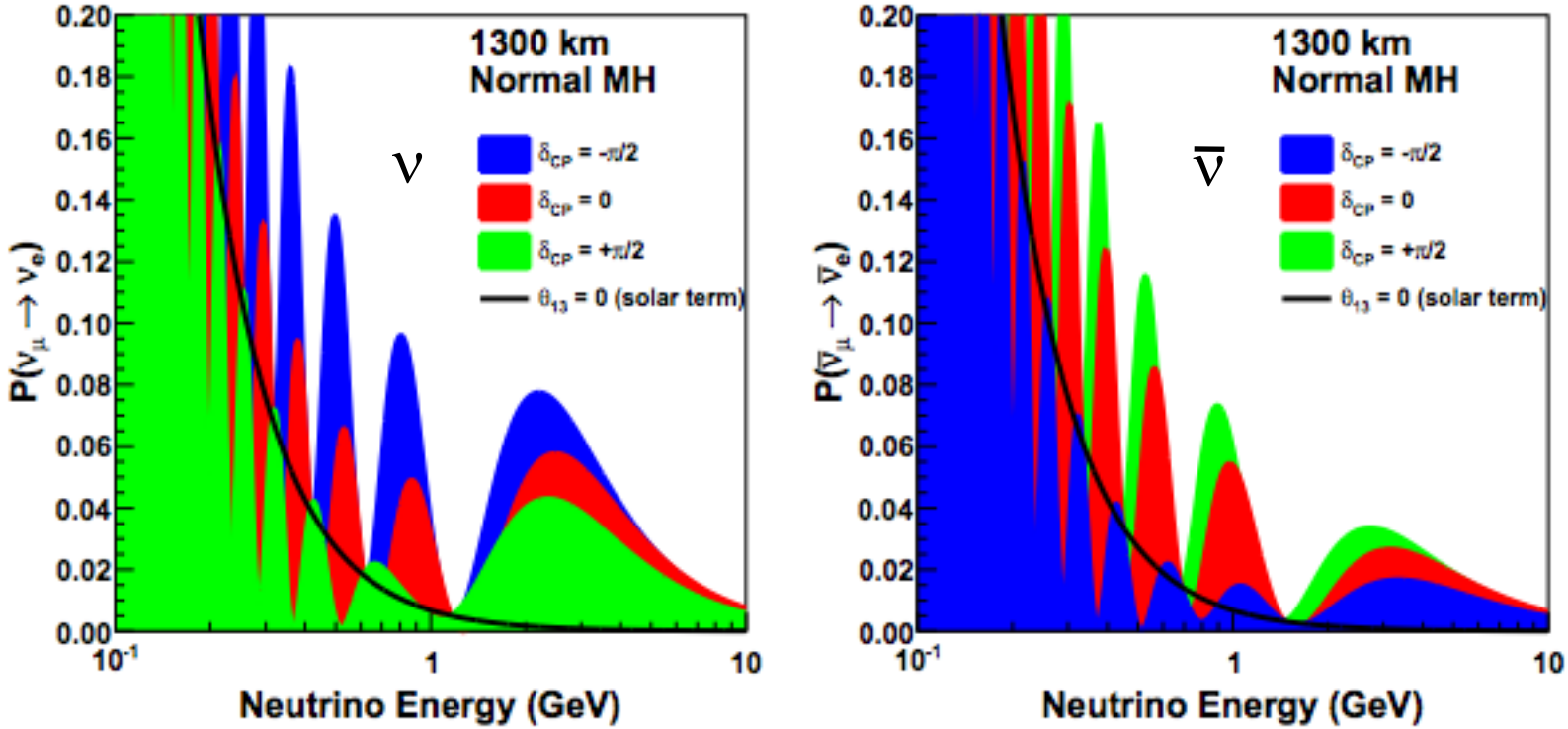


- Plans to test full scale LBNE drift cells in 8m x 8m x 8m cryostat at CERN (WA105)
- Programmes provide short term physics and analysis opportunities

DUNE Timeline



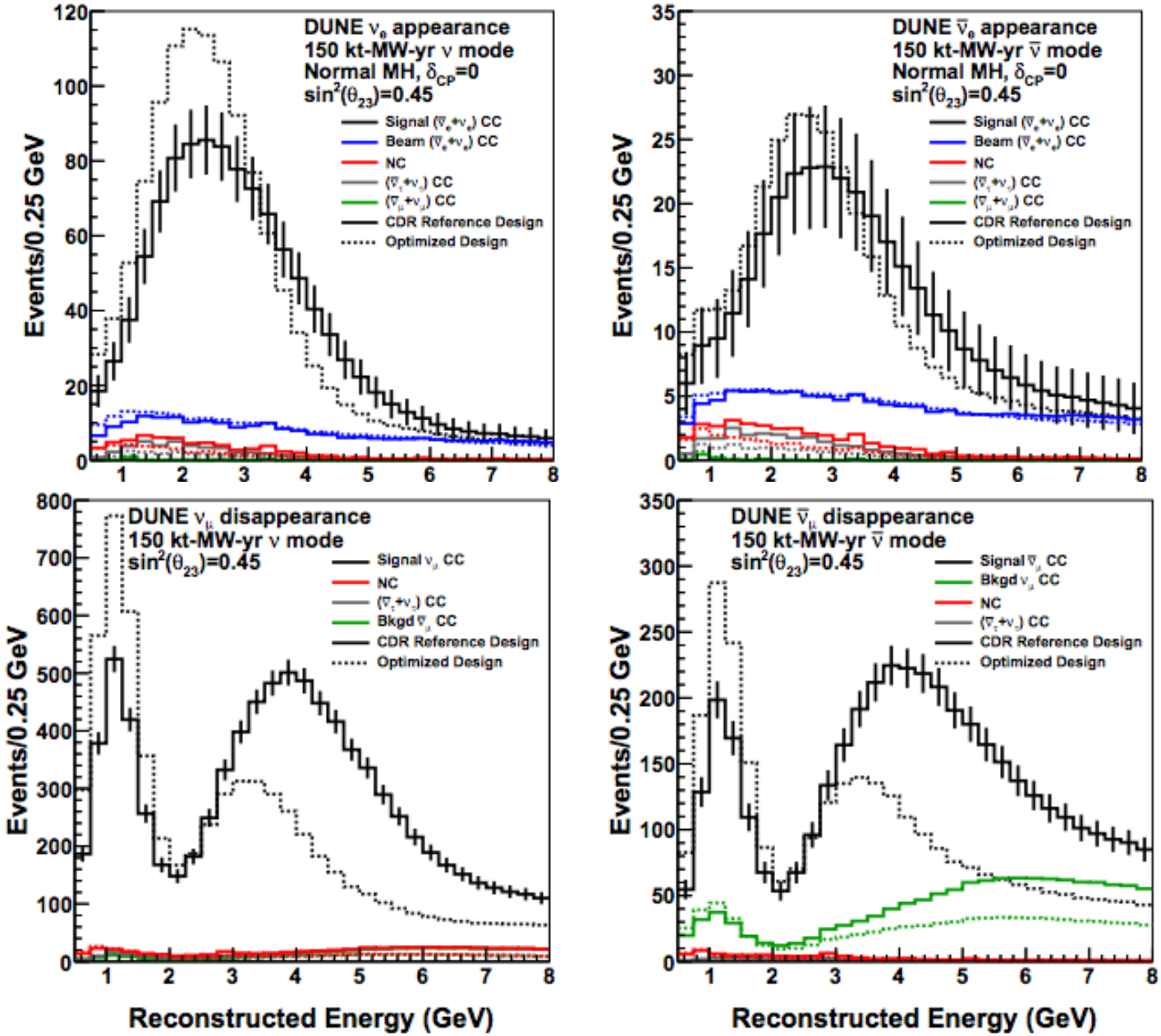
Far detector appearance probabilities



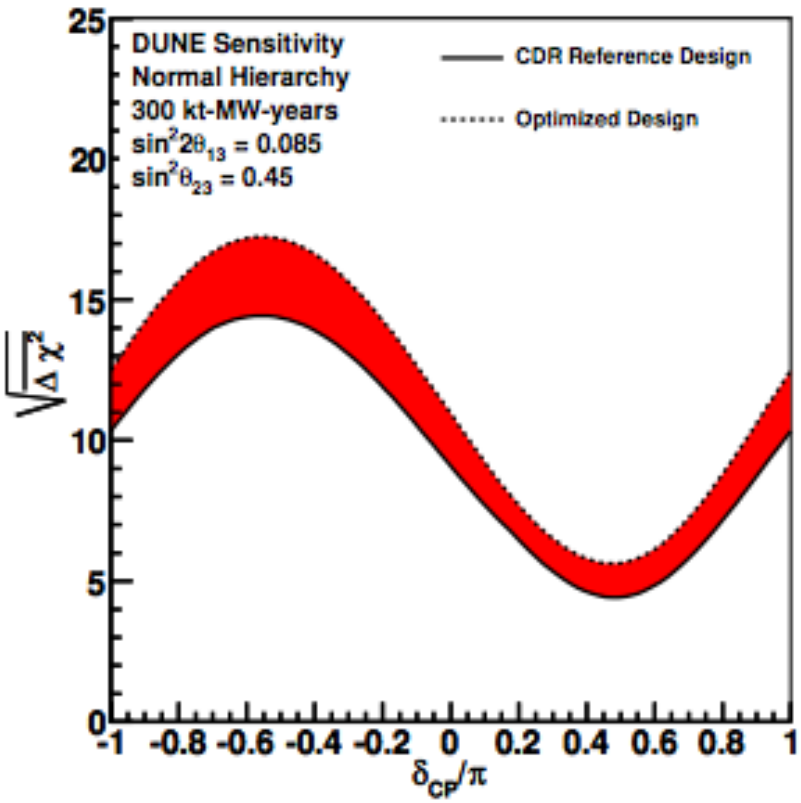
NH

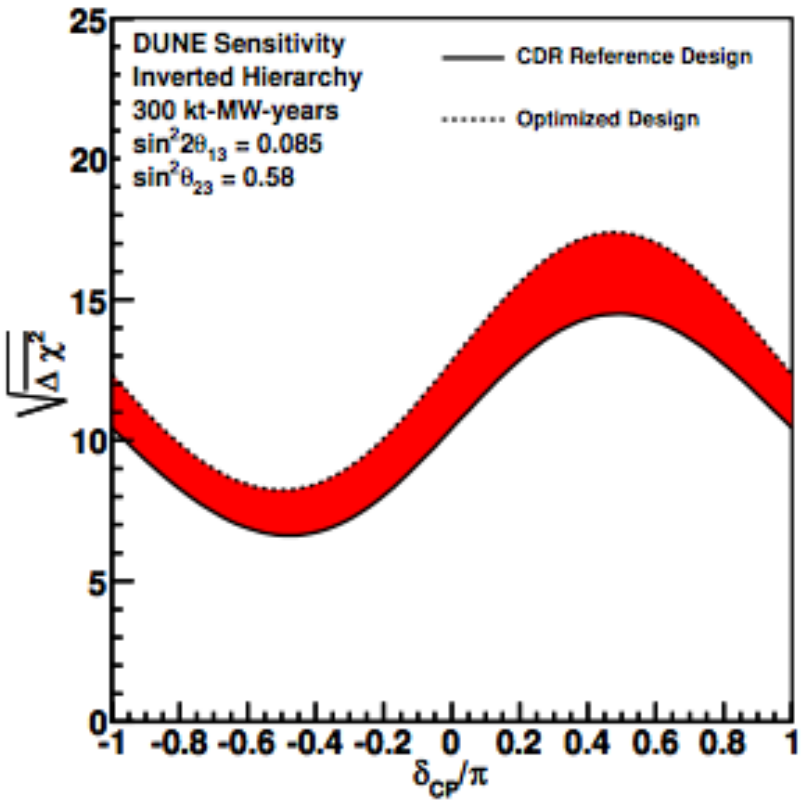
- Appearance probabilities at 1300km as a function of neutrino energy and δ_{CP} value
- Value of δ_{CP} affects both frequency and amplitude of oscillation
- Black line: probability if θ_{13}=0

DUNE far detector event rates



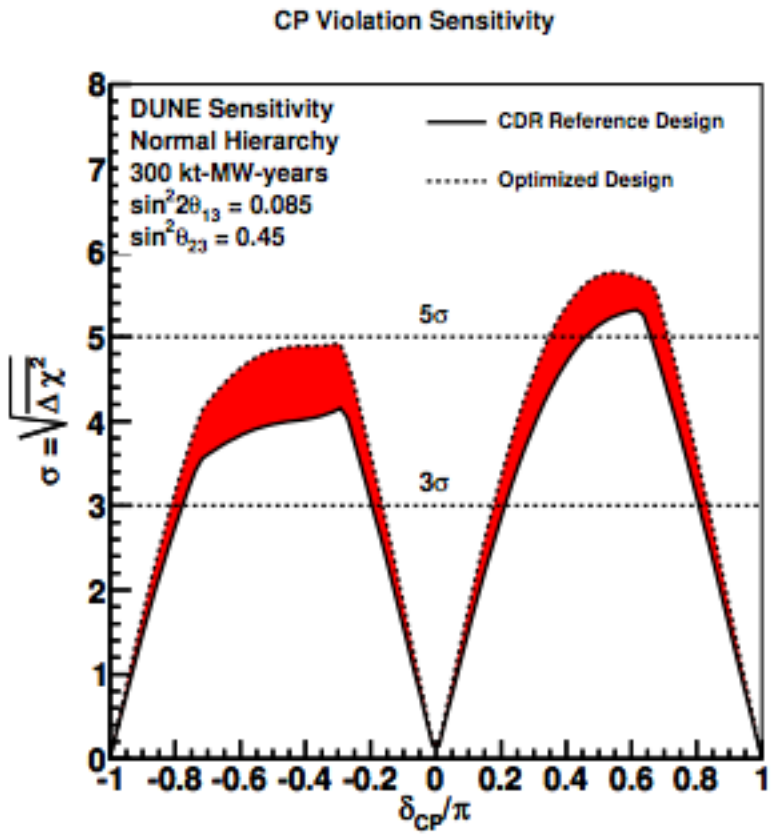
DUNE MH sensitivity

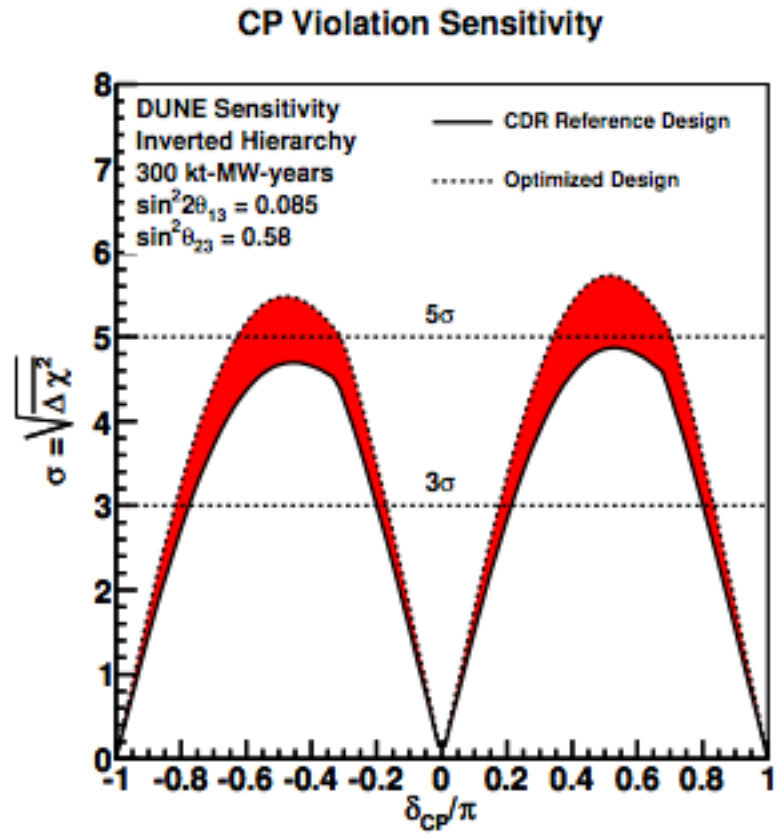




- Significance for mass hierarchy determination as a function of δ_{CP} value for 300 kt.MW.years (approx 7 years of running)
- Mass hierarchy determined with a significance of 5 or higher for 100% of δ_{CP} values (optimised beam design)

DUNE δ_{CP} sensitivity





Significance	CDR Reference Design	Optimized Design
3σ for 75% of δ_{CP} values	1320 kt · MW · year	850 kt · MW · year
5σ for 50% of δ_{CP} values	810 kt · MW · year	550 kt · MW · year

- Significance for CP violation determination as a function of δ_{CP} value for 300 kt.MW.years (approx 7 years of running)

DUNE UK involvement

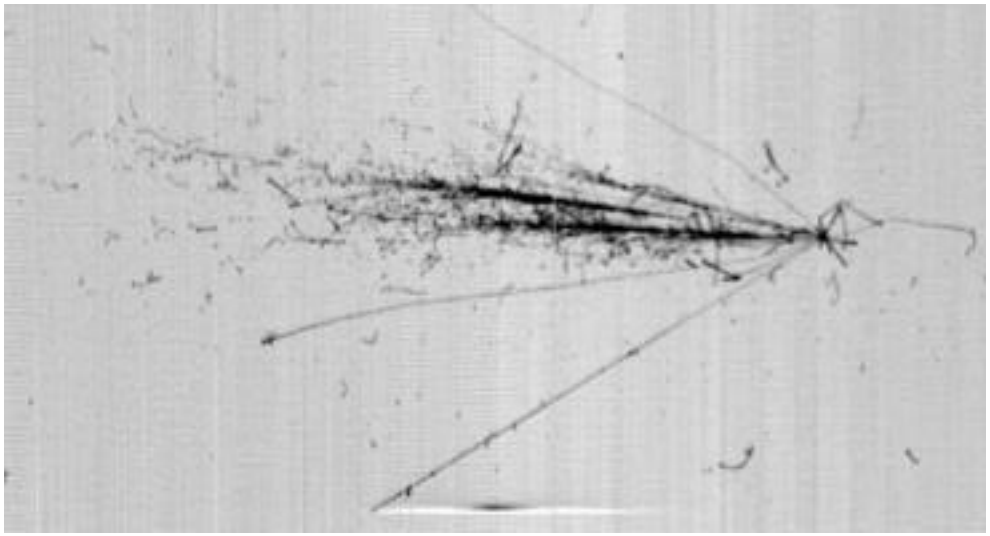
Cambridge • Lancaster • Liverpool • Manchester • Oxford

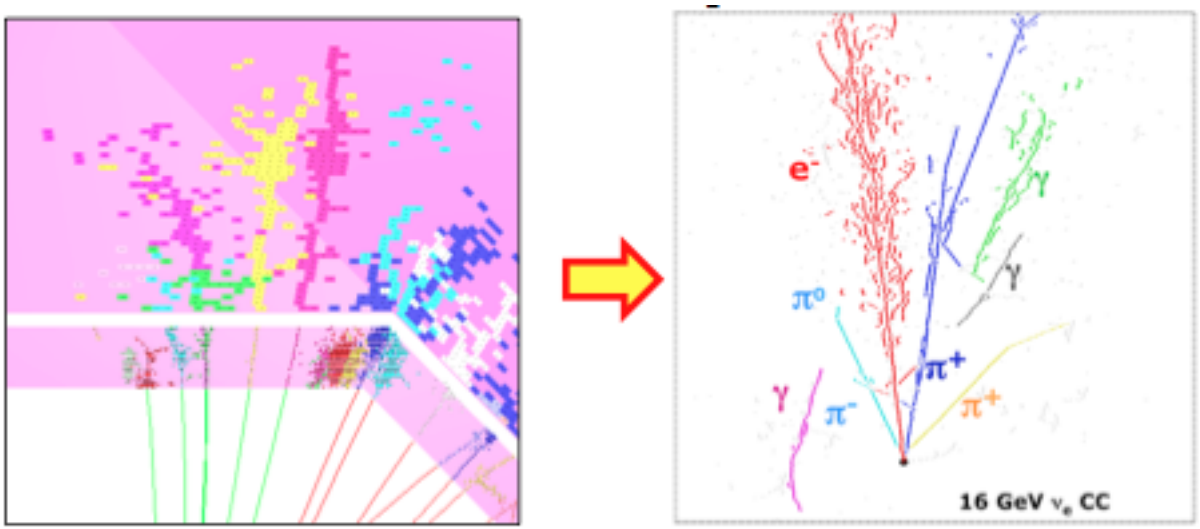
Sheffield • STFC/RAL • Sussex • UCL • Warwick

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.

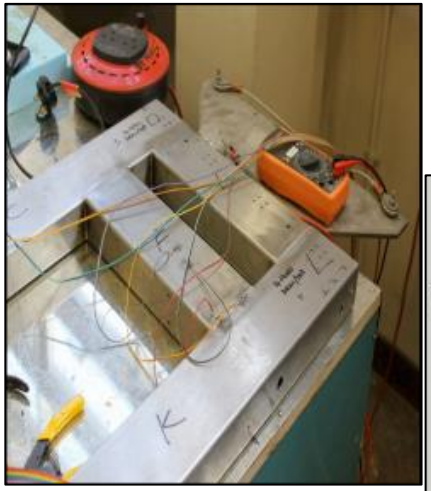
DUNE UK WP2 Event Reconstruction

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

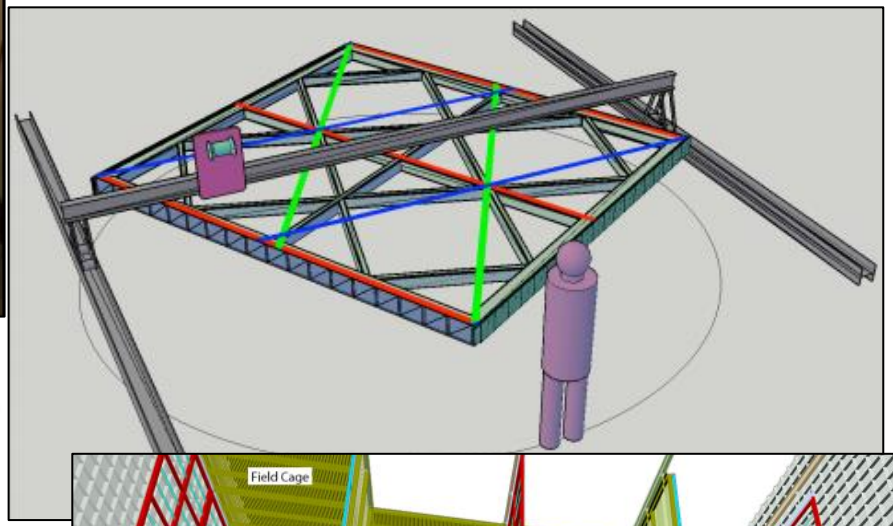




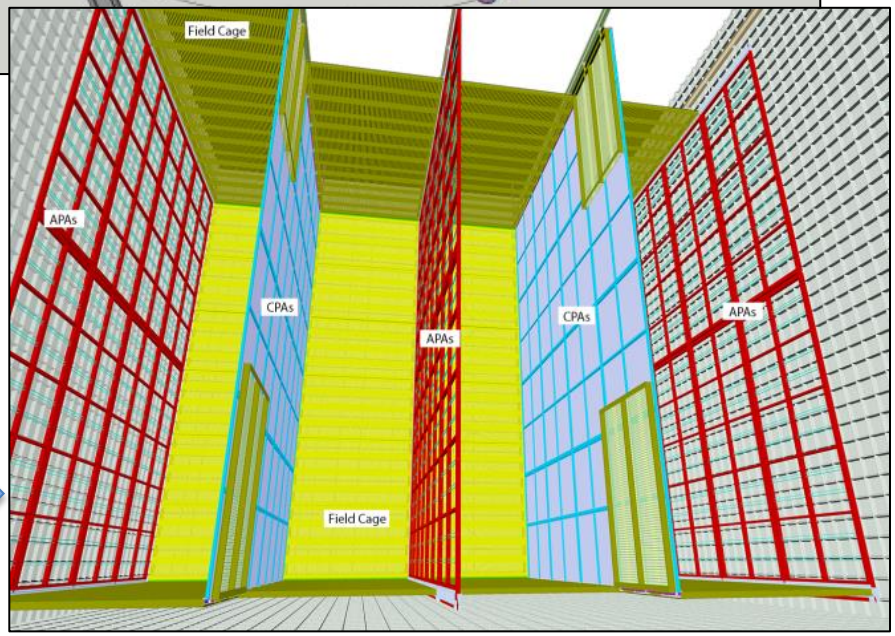
DUNE UK WP5 APA design



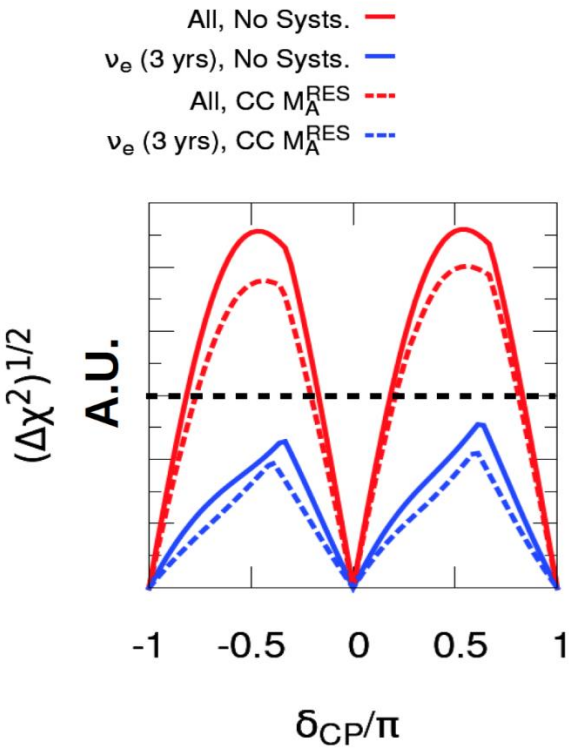
- UK-built 35t APA undergoing LN_2 cool down tests

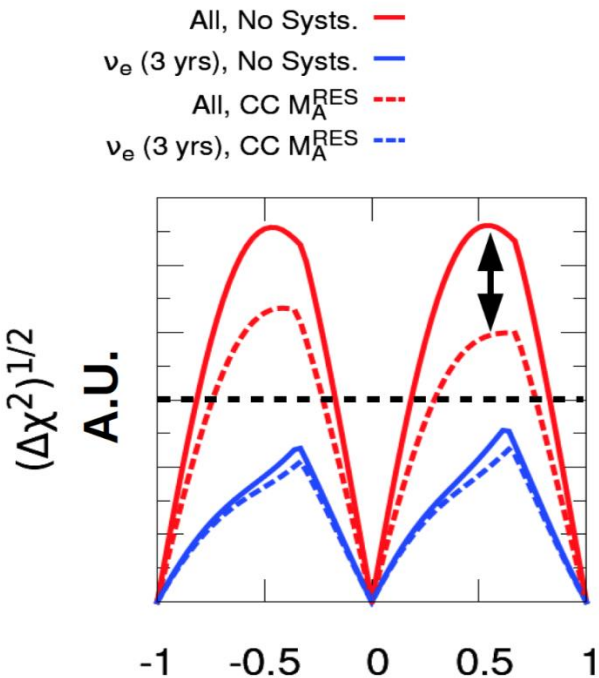


- APA wiring frame concept design
- LAr1-ND: UK proposes to build
  - One of the two APAs
  - The CPA and HV feedthrough



Systematics

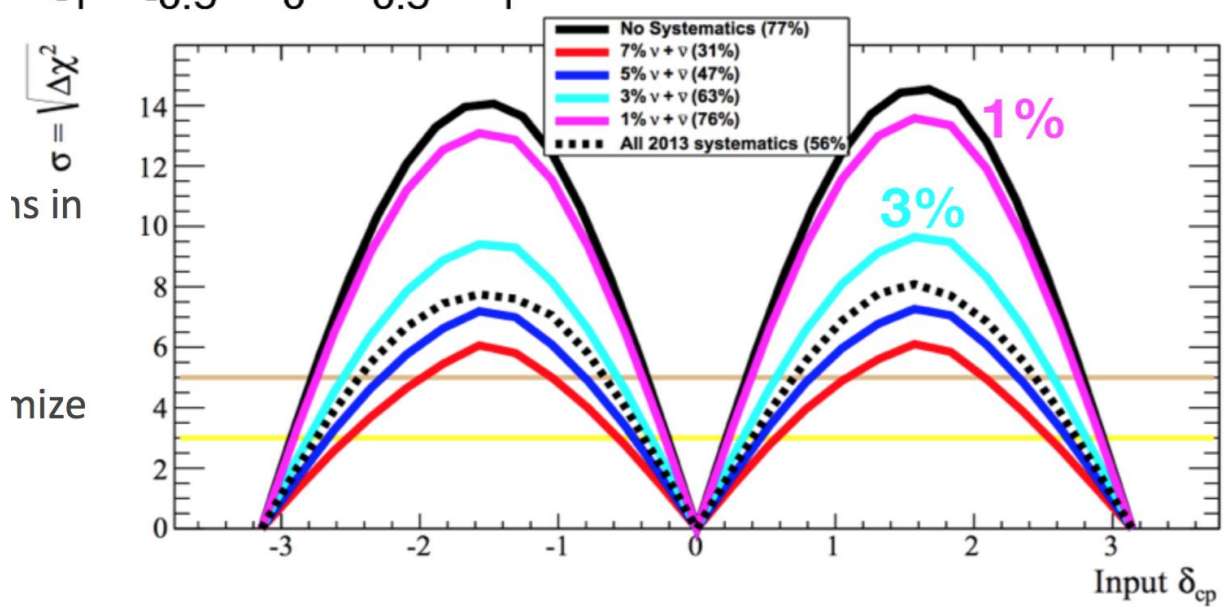




- With the promise of high statistics in the next generation long baseline experiments systematics will play a major role

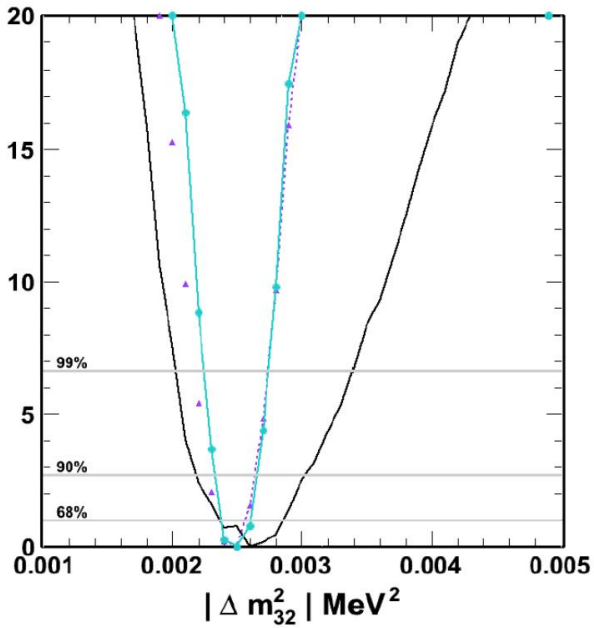
E.g. consideration of

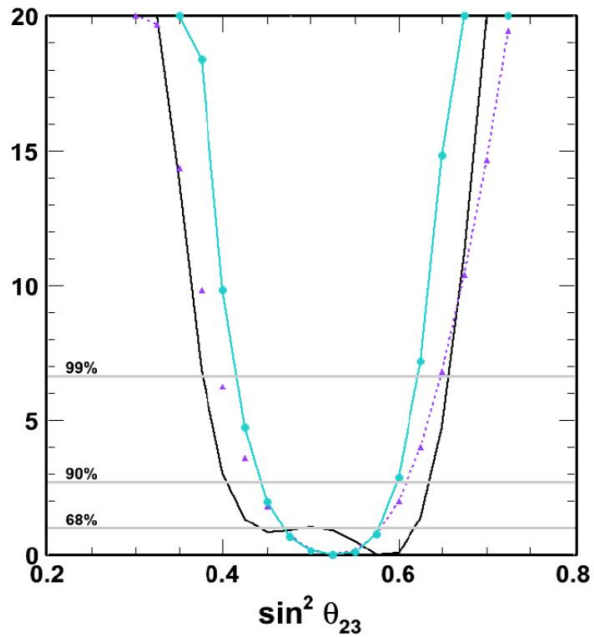
- Neutrino cross-sections
- Beam flux uncertainties

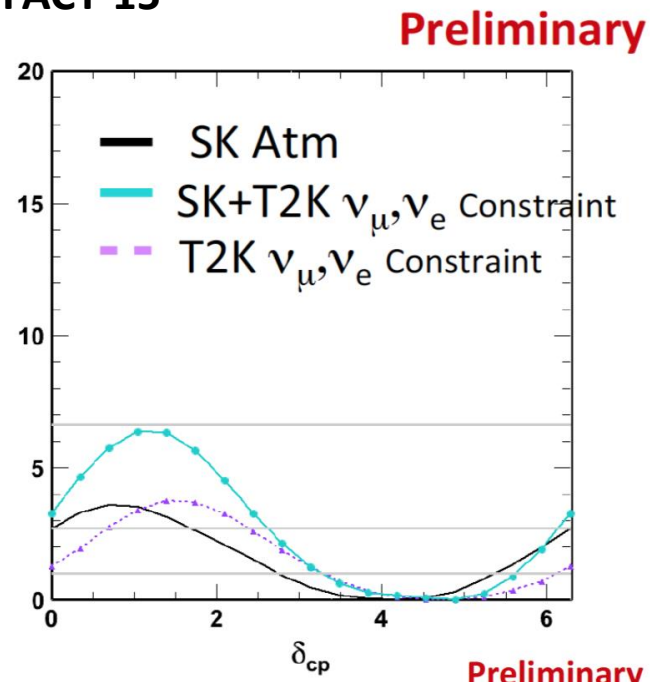


Non-accelerator based oscillations - SK

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





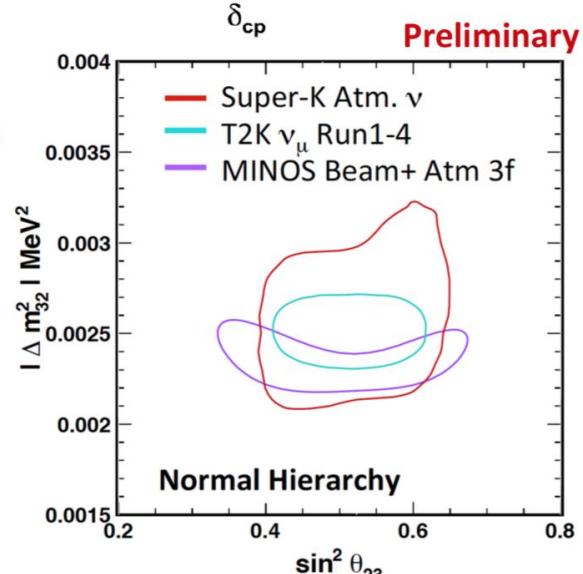


- **Normal** hierarchy favored at: $\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (-3.0 SK only)
- CP Conservation ($\sin\delta_{cp} = 0$) allowed at (at least) 90% C.L. for both hierarchies

new result with 4972 days SK data

SK-I (1996-2001) SK-II (2003-2005)

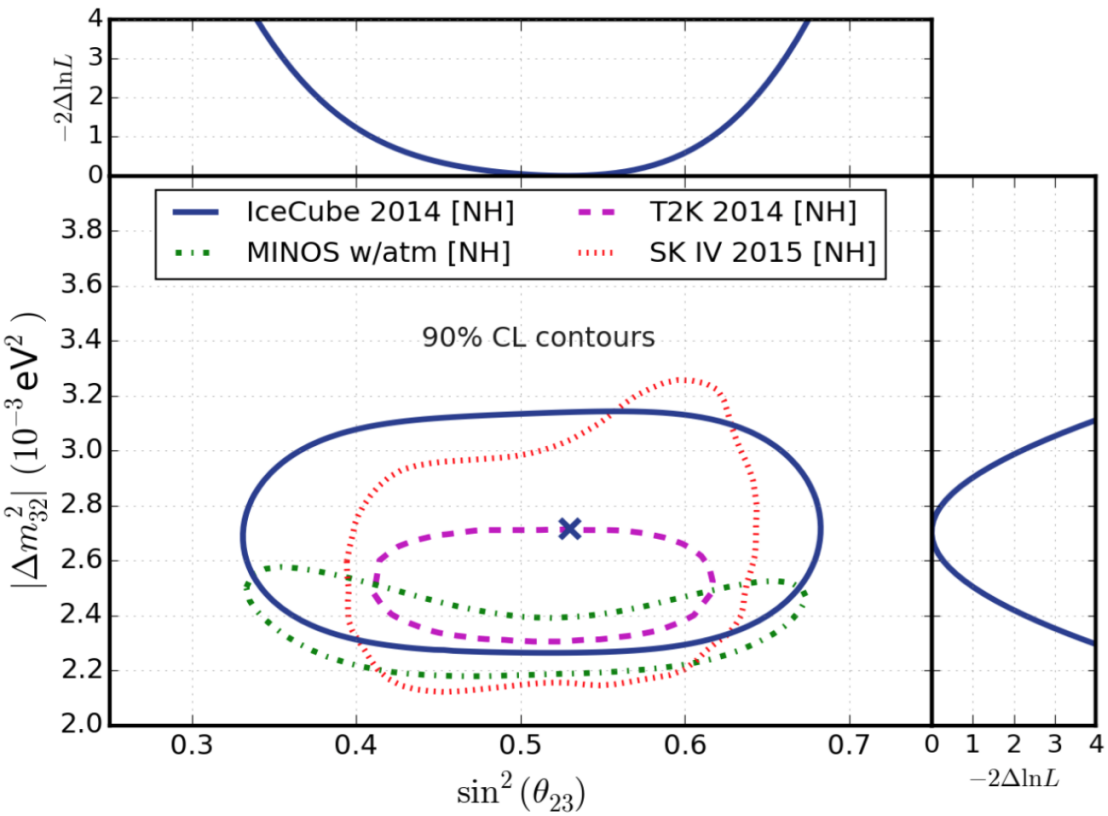
SK-III(2005-2008) SK-IV(2008-Present) → total 4972days

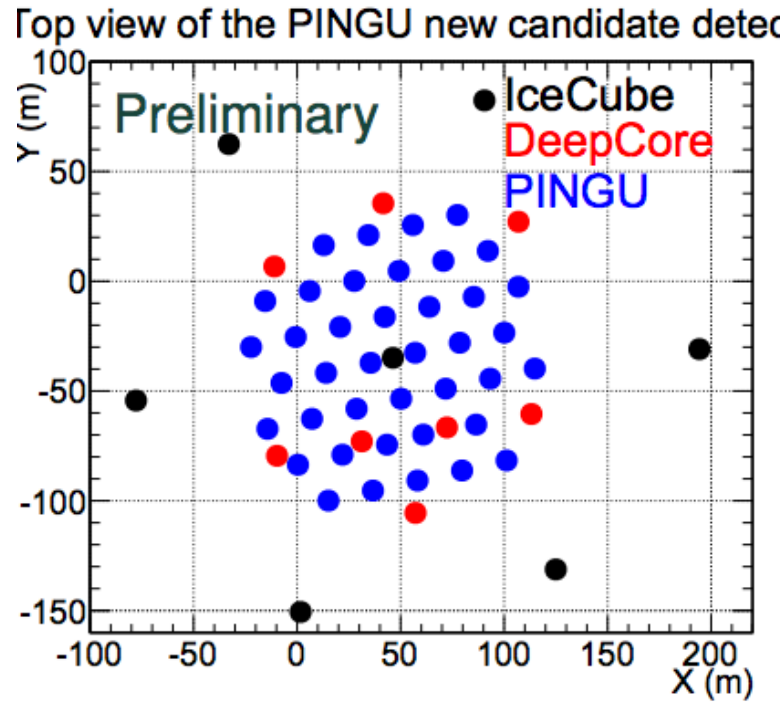


- Super-K-Gd Project approved!
  - High efficiency neutron tagging by adding 0.2% $Gd_2(SO_4)_3$
  - Allows neutrino/antineutrino discrimination

Non-accelerator – IceCube + DeepCore

PRD 91, 072004 (2015) with SK result updated





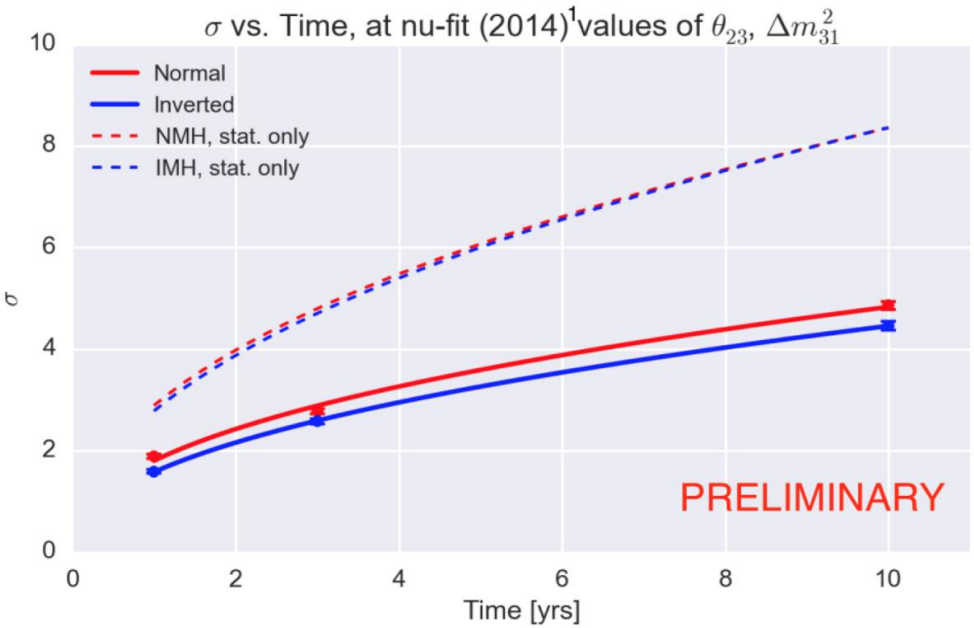
$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20}\,10^{-3}\,\mathrm{eV}^2$$

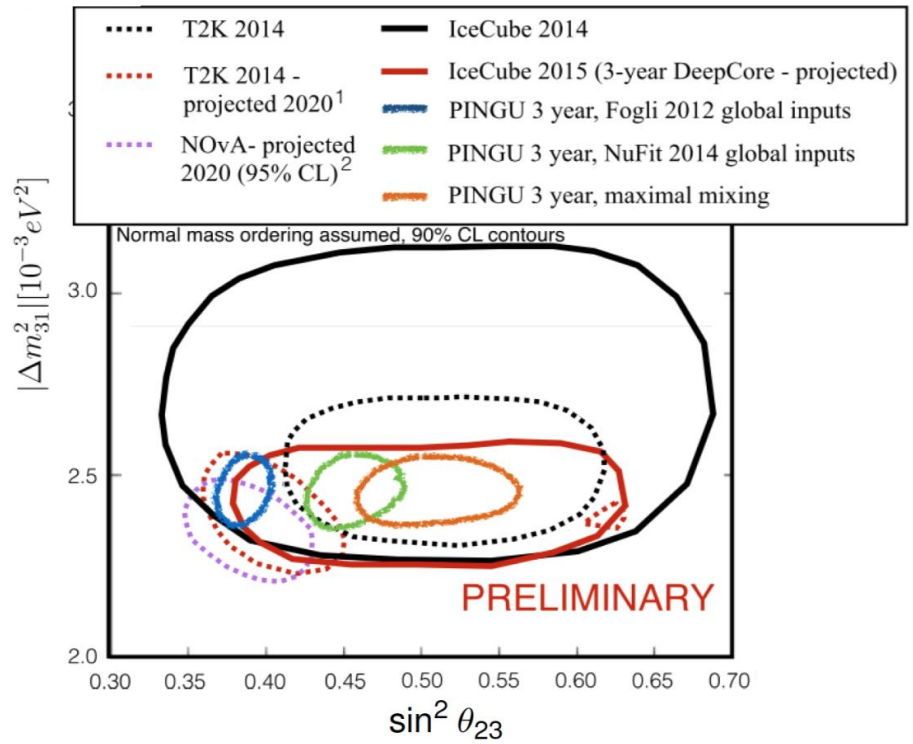
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

This measurement is still statistics limited.

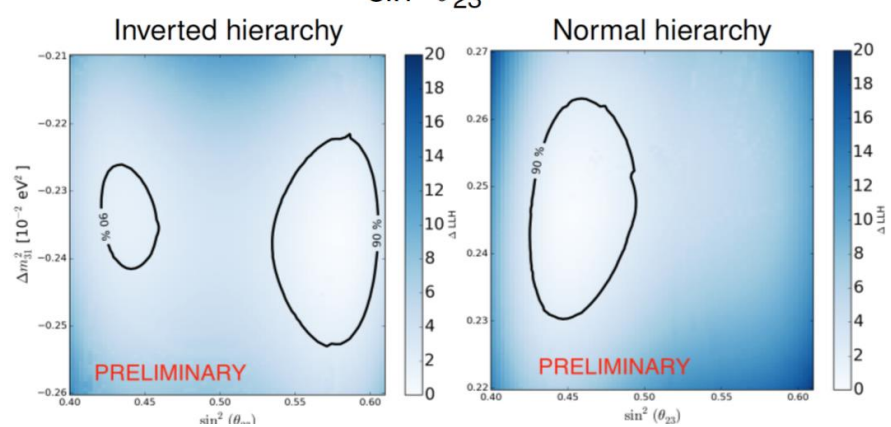
- Still working on strategy ❷: relax "golden event" requirements ⇒ expected increase by an order of magnitude of number ν in sample

Non-accelerator future – PINGU/ORCA





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



Conclusions

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

T2K $\bar{\nu}_e$ appearance

Expected # of events with our data stat.

Normal Hierarchy with actual POT (0.4×10^{21})

Expected events (NH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288
Background $\nu_\mu \to \nu_e$	0.592	0.505	0.389
Background NC	0.349	0.349	0.349
Background other	0.826	0.826	0.826
Total	3.73	4.32	4.85

Inverted Hierarchy with actual POT (0.4×10^{21})

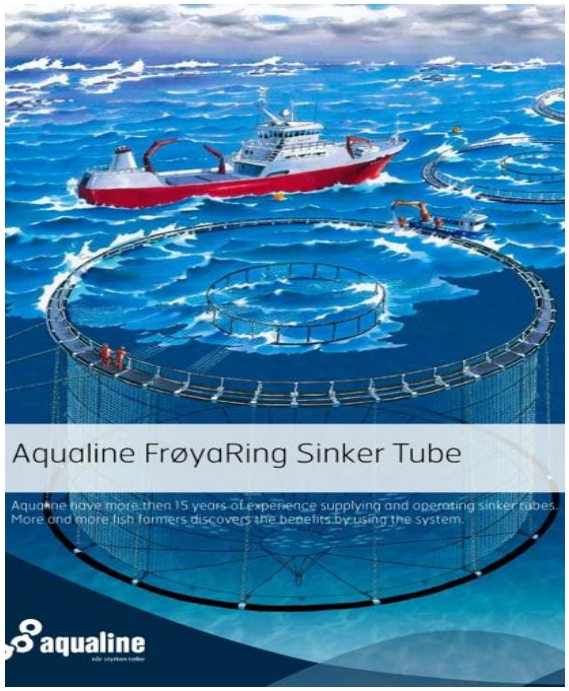
Expected events (IH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	2.481	3.254	3.939
Background $\nu_\mu \to \nu_e$	0.531	0.423	0.341
Background NC	0.349	0.349	0.349
Background other	0.821	0.821	0.821
Total	4.18	4.85	5.45

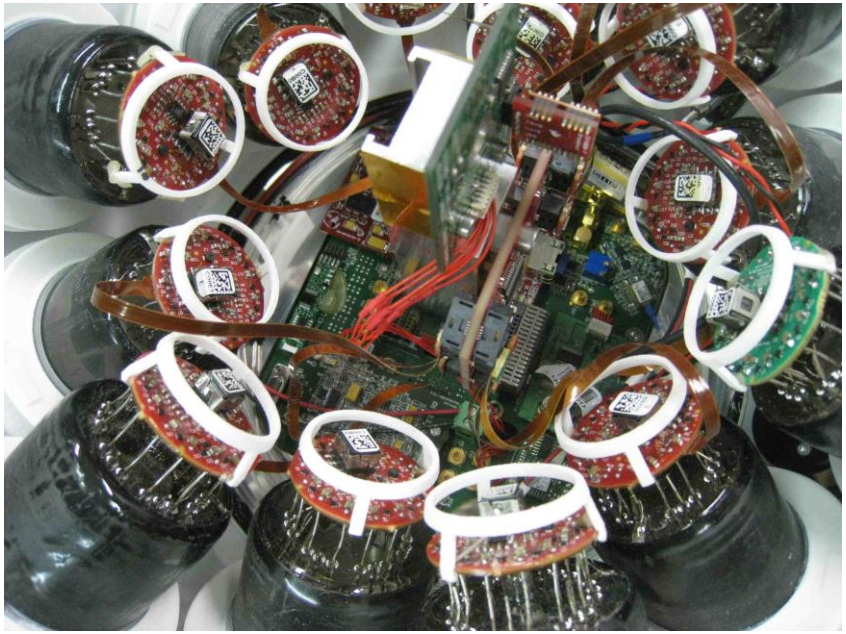
Total number of events so far: 3 !

CHIPS concept

Manchester • UCL

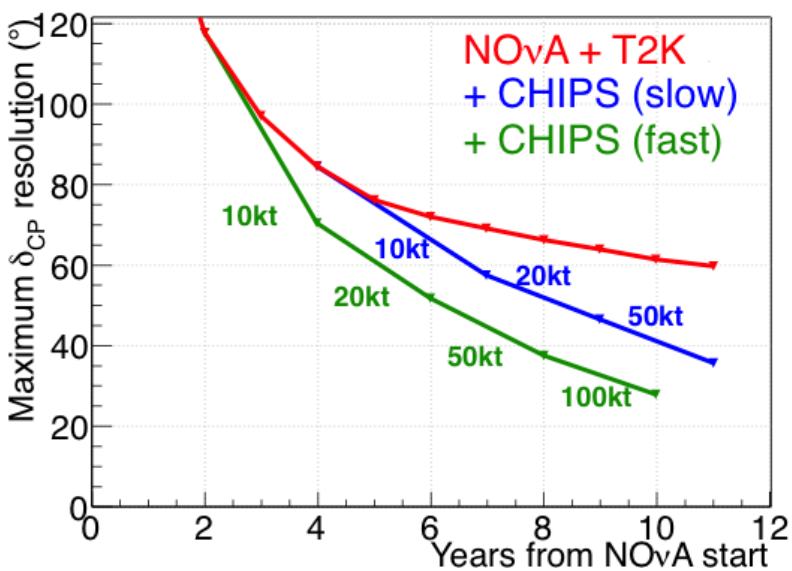
- CHIPS is a water Cherenkov detector which will be sunk in a flooded mine pit in the path of the NuMI beam
- Water will provide mechanical support
- Its main development goal is to chart a new path towards cost effective Megaton neutrino detectors, hoping to get to $200k/kt (presently $1M/kt)
- Complements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





CHIPS Physics Goals

- Short term:
  - Contribute to the measurement of 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 LBNF beam off axis
- 2nd oscillation maximum located around 0.8 GeV
  - Large quasi-elastic x-section
  - Suitable for water Cerenkov detector
    - High efficiency for QE events