Neutrino Oscillations and what they have to offer in the near future

CP violation and Mass Hierarchy reach, sooner and later

Jenny Thomas, UCL, Birmingham Oct 5th.

Plan for the discovery of the mass hierarchy and CP violation in the neutrino sector

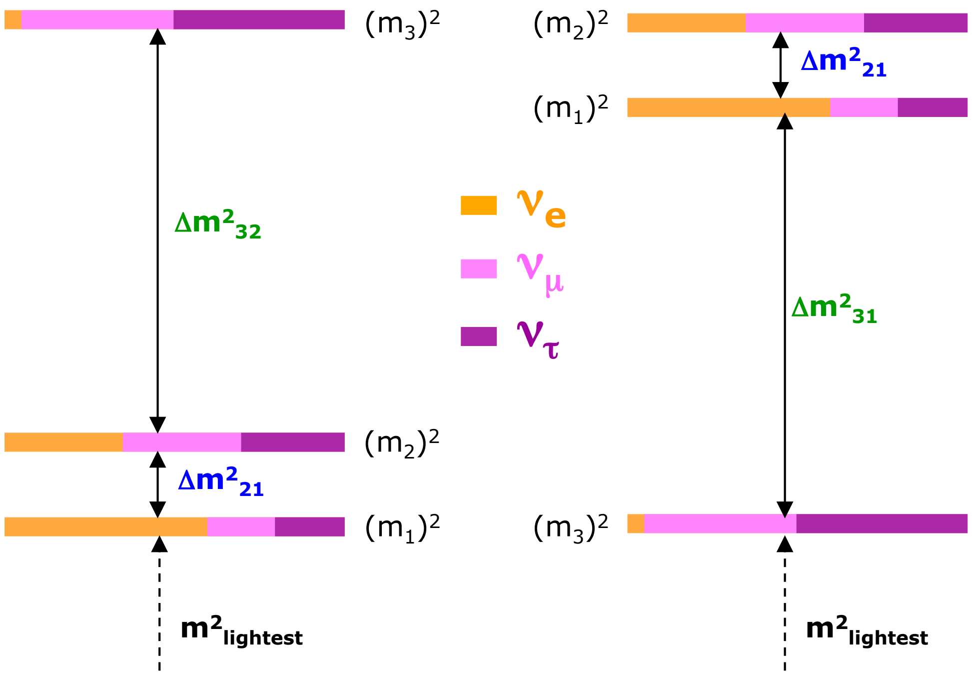
- The Present Knowledge
  - Post Neutrino 2016
- The Near Future
  - T2K, NOνA
- CHIPS : R&D for the future
- The Further Future
  - JUNO
- The Far Future
  - PINGU, DUNE

Shamelessly showing slides from neutrino 2016: P.Vahle(NOνA), A.Marrone(global fits), G.Ranucci(JUNO), J.Koskinen(PINGU) and ICHEP 2016:K.Iwamoto(T2K) also D.Cowen(PINGU), V.Paolone(DUNE), A.Cabrera (Double Chooz)

Reminder of the questions

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Normal hierarchy



- Three light neutrinos
  - Mass eigenstates mix to form weak eigenstates
- Mixing probability modified by mass squared differences
- δ_{CP} and the mass ordering are still unknown but within reach
- s_{23} now limiting next steps

Reminder of the answers so far....

Precision era in neutrino oscillation phenomenology

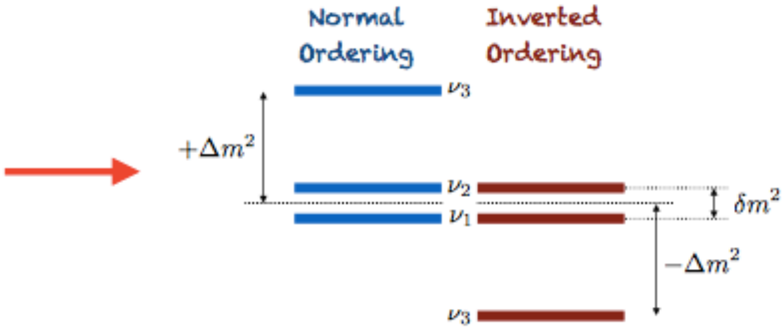
Standard 3ν mass-mixing framework parameters

Known (pre-ν2016)		Unknown
δm^2	2.4%	CP-violating phase δ
Δm^2	1.8%	Octant of θ_{23}
$\sin^2\theta_{12}$	5.8%	Mass Ordering → $\text{sign}(\Delta m^2)$
$\sin^2\theta_{13}$	4.7%	[Dirac/Majorana neutrinos, Majorana phases, absolute mass scale]
$\sin^2\theta_{23}$	$\sim 9\%$	

In this talk

$\Delta m^2 = (\Delta m^2_{13} + \Delta m^2_{23})/2$

Mass Ordering = sign of Δm^2



Reminder of the approach

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Looking at disappearance of ν_μ (or ν_e appearance)

$$1 - P(\nu_\mu \rightarrow \nu_\mu) = (C_{13}^4 \sin^2 2\theta_{23} + S_{23}^2 \sin^2 2\theta_{13}) \sin^2 \Phi_{32}$$

- First term depends on $\sin^2 2\theta_{23}$
- Second term depends on θ_{13} but also $\sin^2\theta_{23}$
- This means there is information in here about the octant of θ_{23} but its weak

Reminder of the approach

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Searching for electron neutrino **appearance** tells us about $\sin^2\theta_{13}$, mass hierarchy and δ_{CP}

$$\begin{aligned} P(\nu_\mu \to \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \\ & + 8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\ & - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta_{CP} \sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\ & + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta_{CP})\sin^2\Phi_{21} \\ & - 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2)\frac{aL}{4E_\nu}\cos\Phi_{32}\sin\Phi_{31}, \end{aligned}$$

CPV →

- Running with anti-neutrinos changes sign of CPV term

Reminder of the approach

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

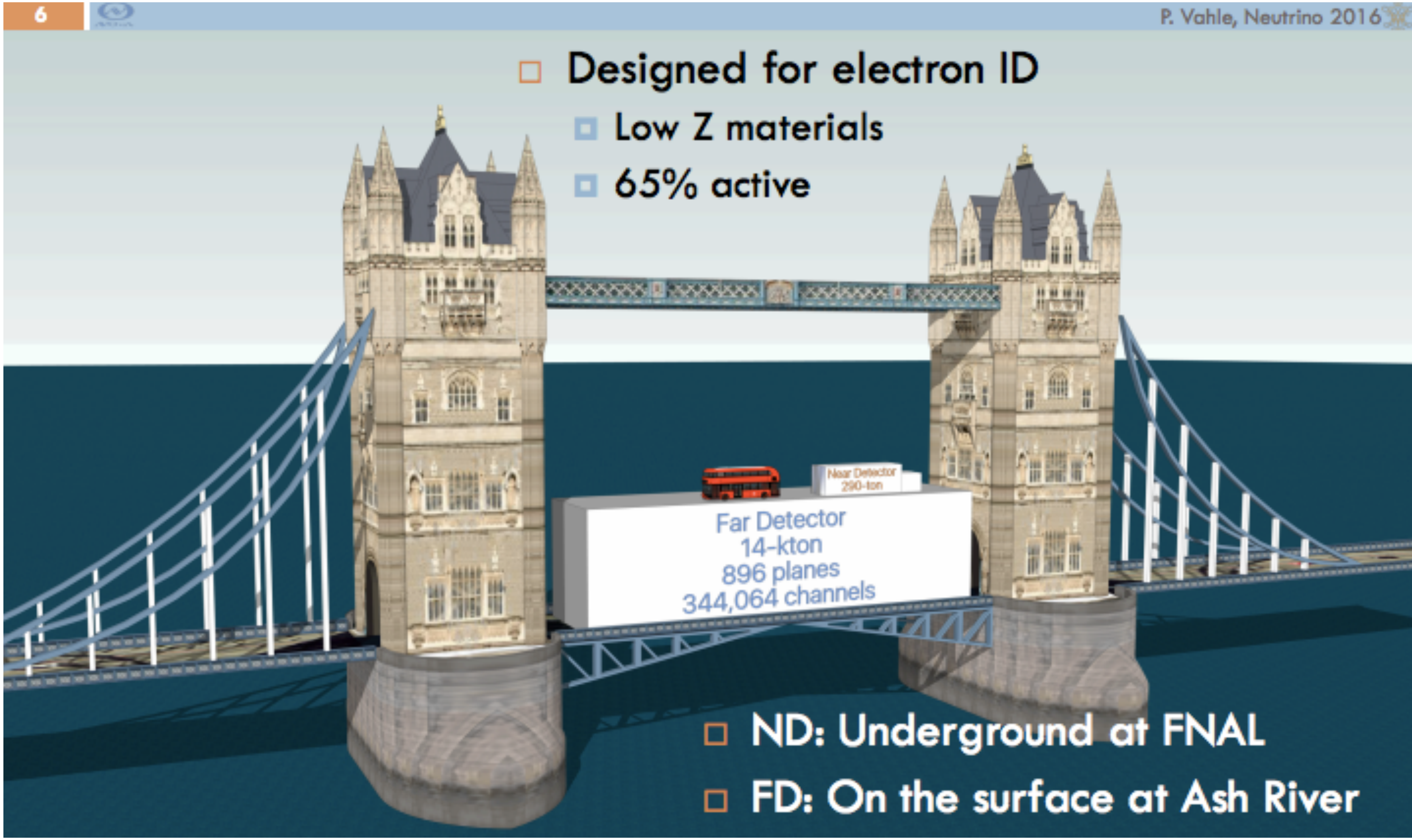
- Leading term relies also on **$\sin^2\theta_{23}$**, and **a**, related to density of electrons in the earth, leading to dependence on sign of Δm^2_{31}

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1 + \frac{2a}{\Delta m_{31}^2}(1-2S_{13}^2)\right) \\ & +8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\ & -8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta_{CP}\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\ & +4S_{12}^2 C_{13}^2(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta_{CP})\sin^2\Phi_{21} \\ & -8C_{13}^2 S_{13}^2 S_{23}^2(1-2S_{13}^2)\frac{aL}{4E_\nu}\cos\Phi_{32}\sin\Phi_{31}, \end{aligned}$$

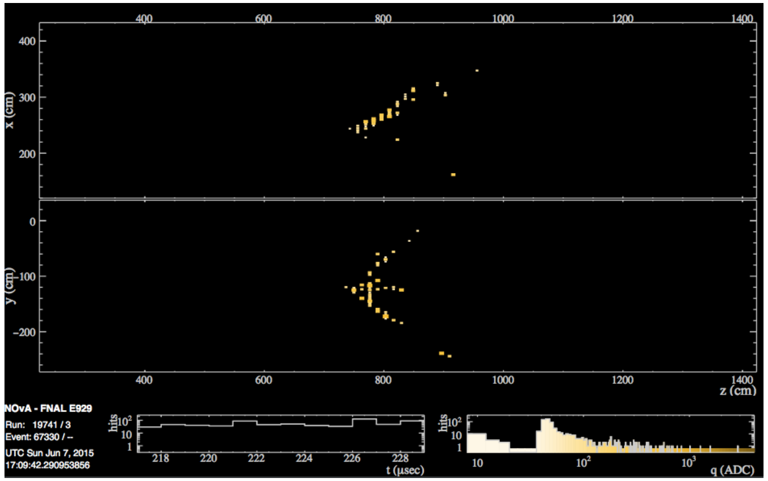
CPV →

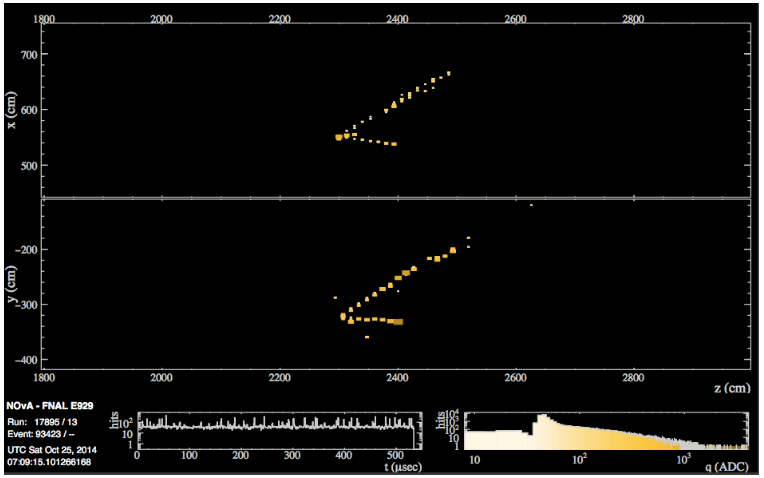
- Combining appearance and disappearance measurements tells us about the octant

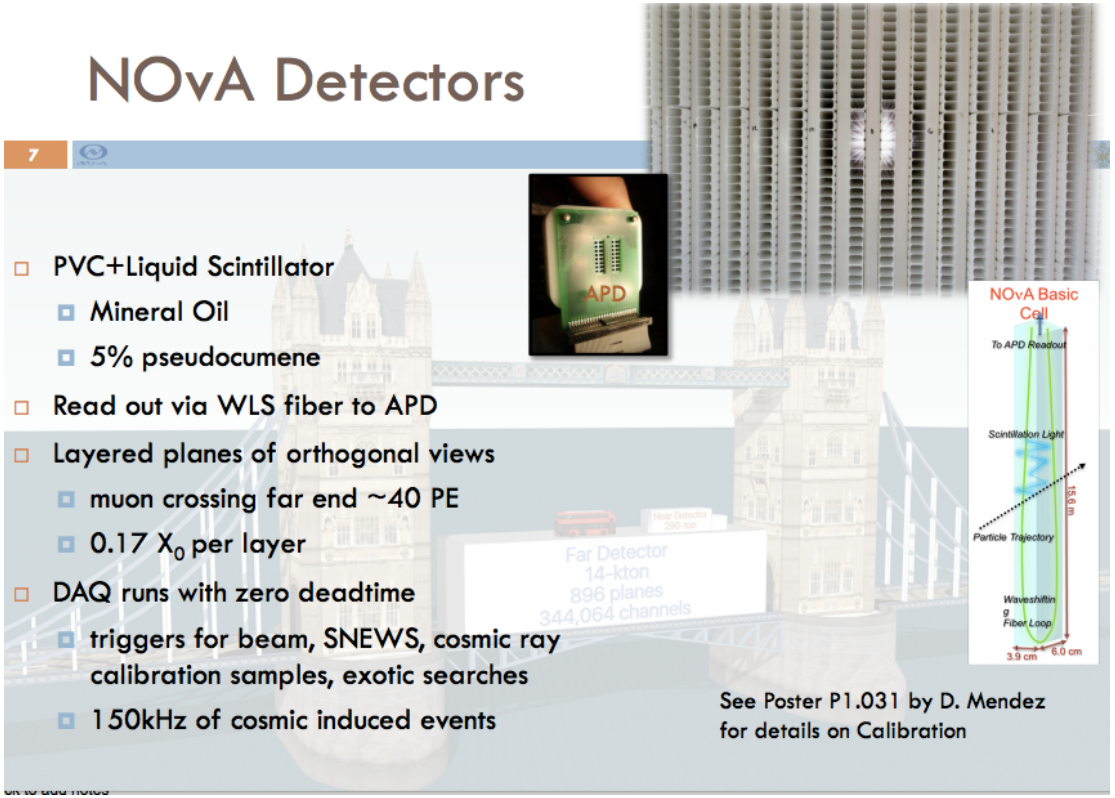
AT NEUTRINO 2016, LONDON
NOVA



New kid on the block, first appearance at a Neutrino conference with data!







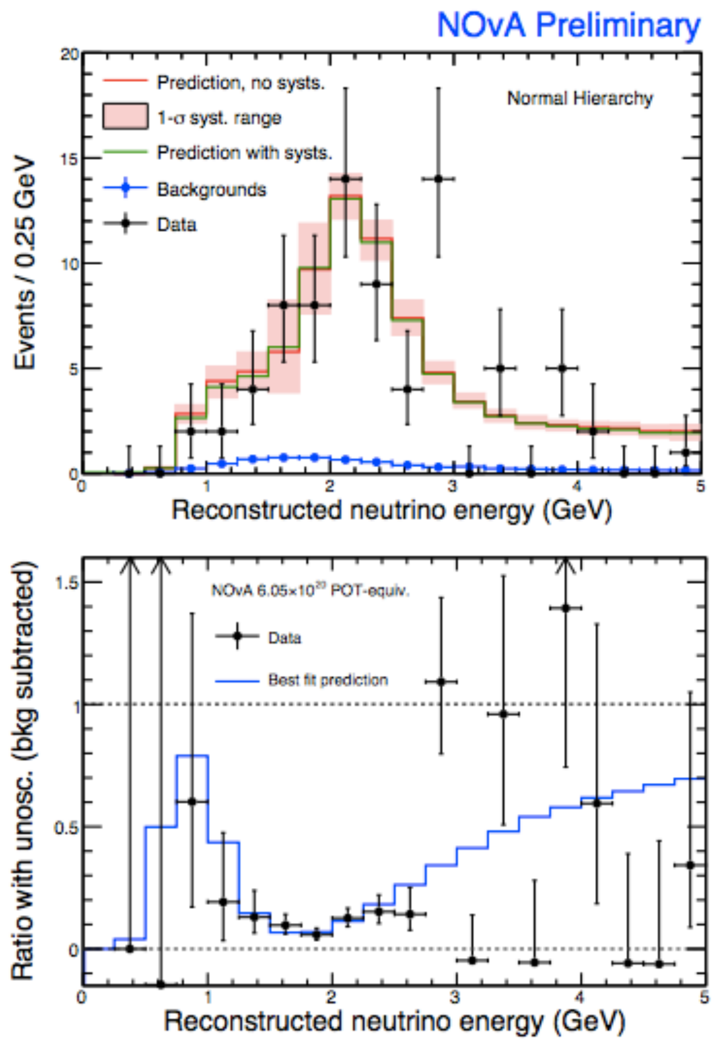
- NOνA event displays show very fine detail in this liquid scintillator detector
- Muon energy by range, EM resolution

AT NEUTRINO 2016, LONDON
NOVA

ν_μ disappearance

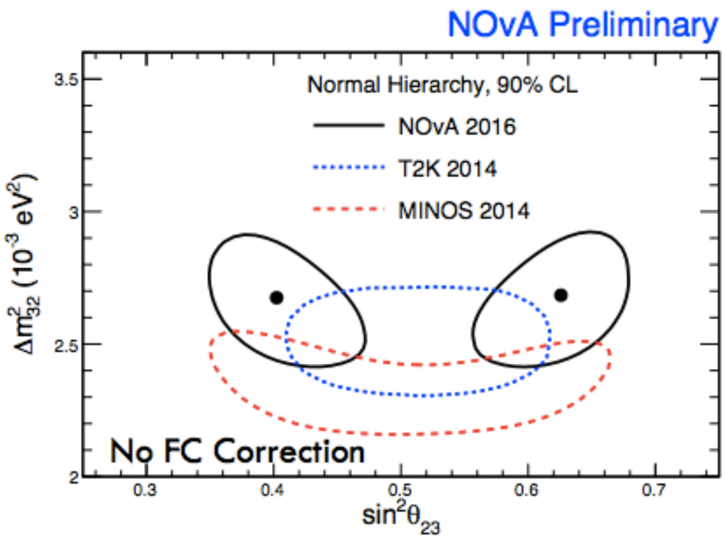
- 78 events observed in FD
  - 473±30 with no oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

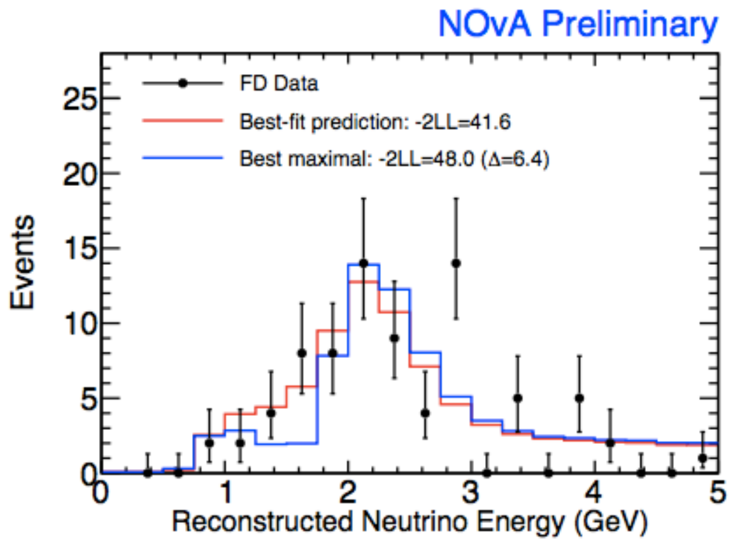
χ^2/NDF=41.6/17
Driven by fluctuations in tail,
no pull in oscillation fit



AT NEUTRINO 2016, LONDON
NOVA

- Only looking at disappearance of ν_{μ}, its not maximal at 2.5σ ! octant is degenerate…more about that later





Best Fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

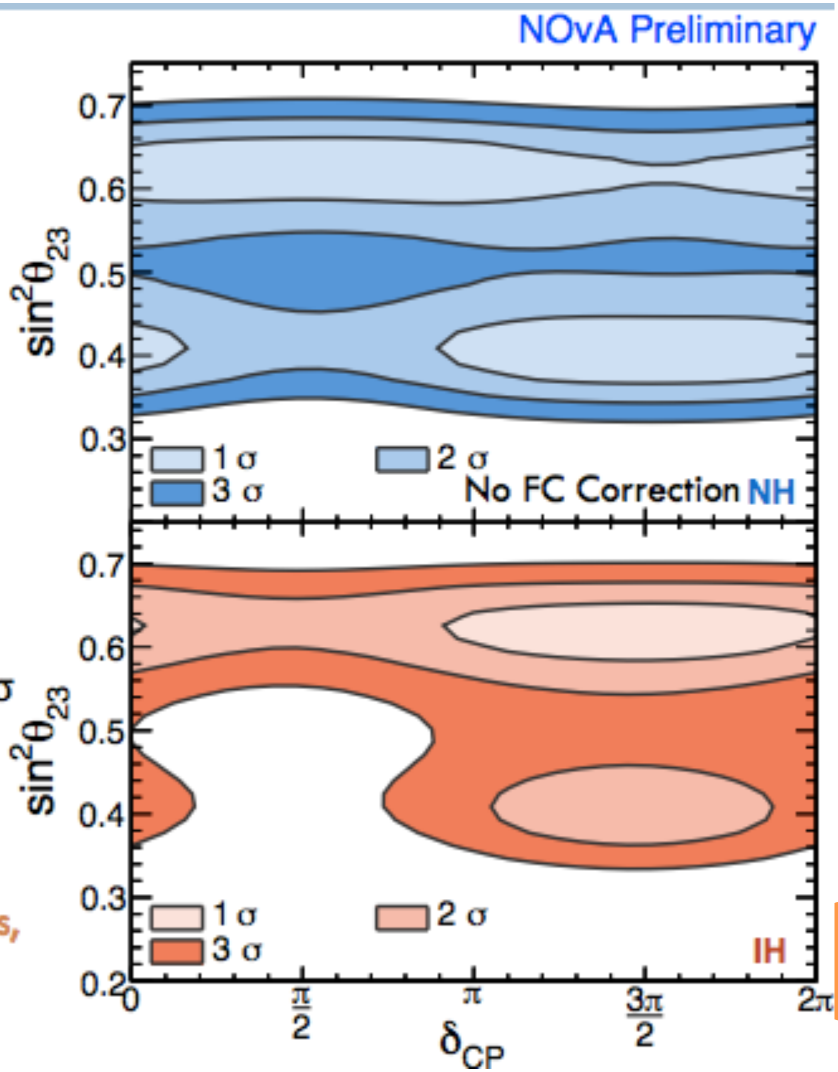
AT NEUTRINO 2016, LONDON
NOVA

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

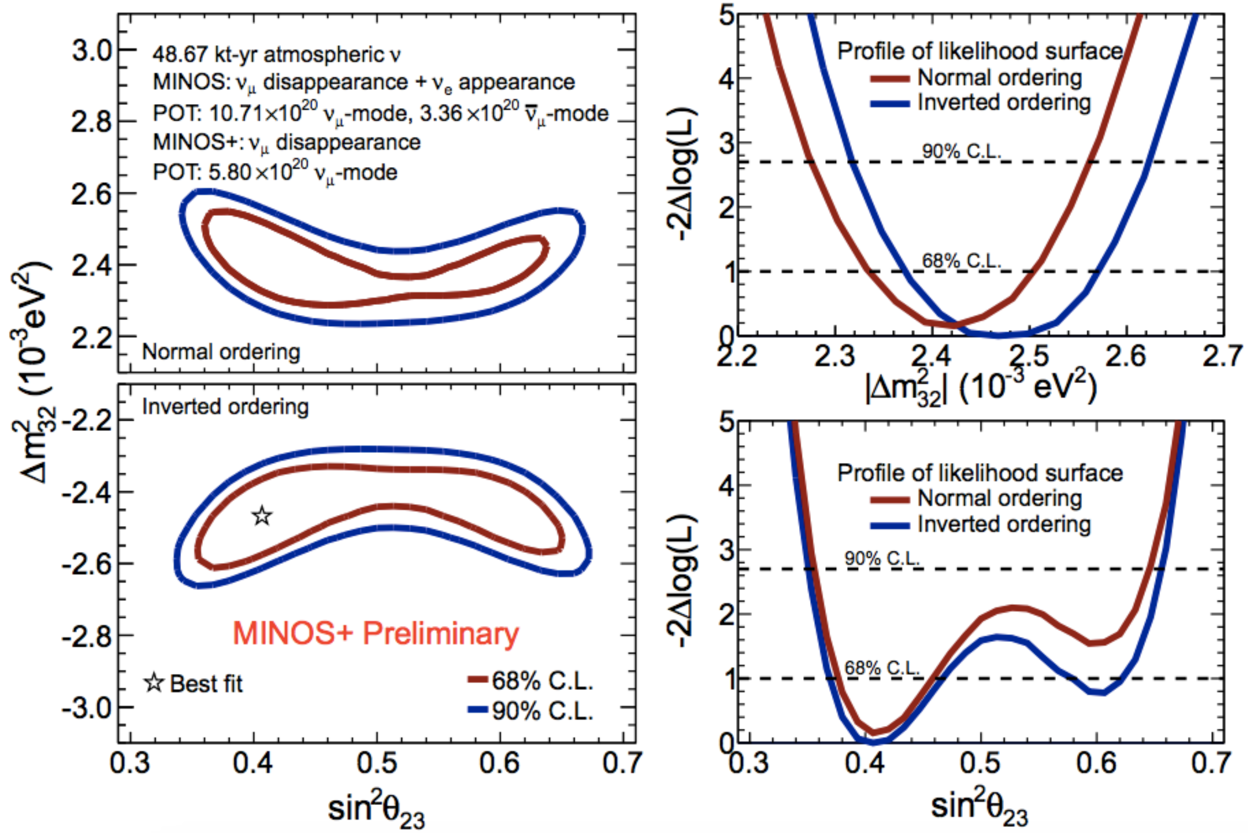
  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\delta_{CP}=\pi/2$

Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing
Planned for Spring 2017



AT NEUTRINO 2016, LONDON MINOS/MINOS+

- Combination of disappearance and appearance, slightly disfavours higher octant



$$\Delta m^2_{32} = \begin{cases} 2.42 \pm 0.09 \times 10^{-3}\,\mathrm{eV}^2 & \text{Normal} \\ -2.48^{+0.09}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2 & \text{Inverted} \end{cases}$$

$$\sin^2(\theta_{23}) = \begin{cases} 0.35\text{–}0.65\ (90\%\ \text{C.L.}) & \text{Normal} \\ 0.35\text{–}0.66\ (90\%\ \text{C.L.}) & \text{Inverted} \end{cases}$$

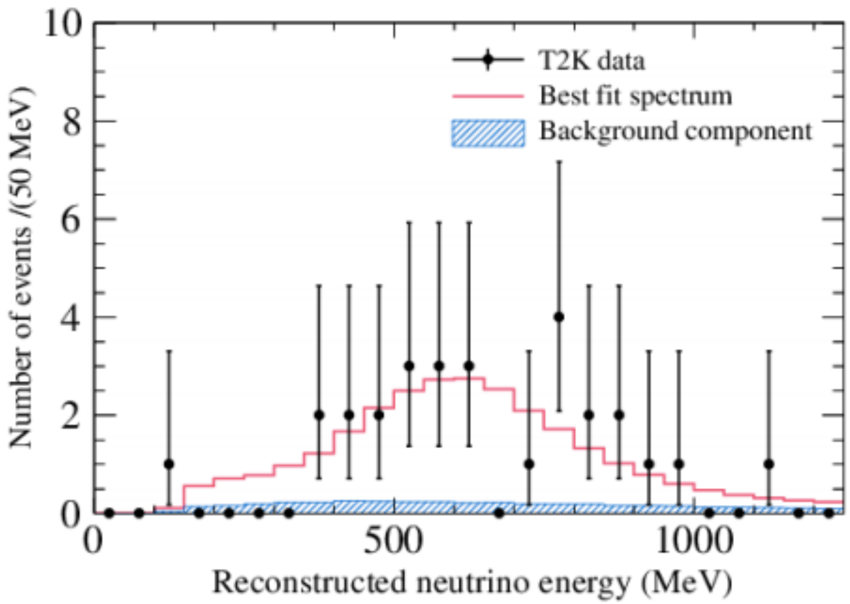
Which Octant? The new parameter of interest!

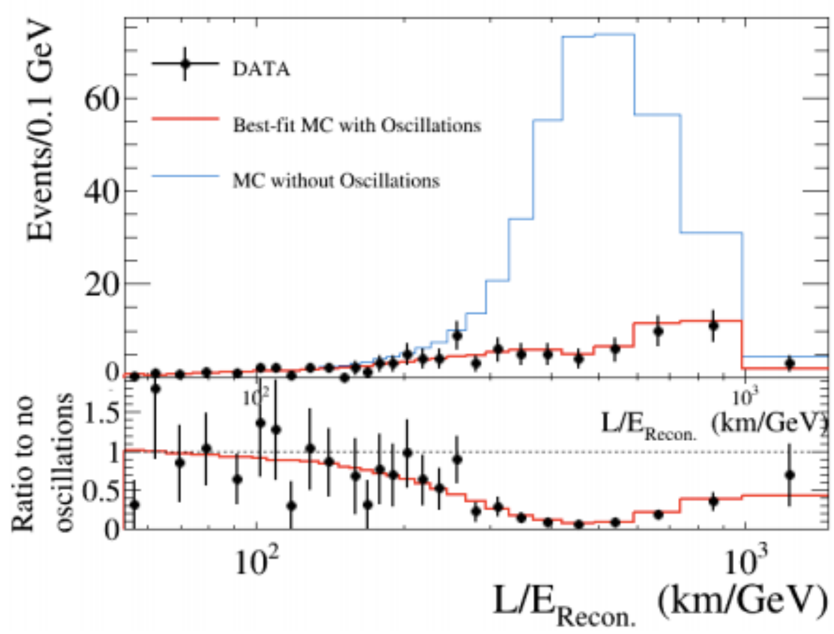
- Up until now, all data consistent with maximal mixing
  - Octant doesn't matter!
  - Remember what we measure is $\sin^2 2\theta_{23}$ to first order

- NOνA (and MINOS/MINOS+) shows non-maximal mixing evidence
- MINOS/MINOS+ has a very slight preference for lower octant
- So what does T2K say?

At NEUTRINO 2016, London
T2K

- Mixing is maximal at T2K

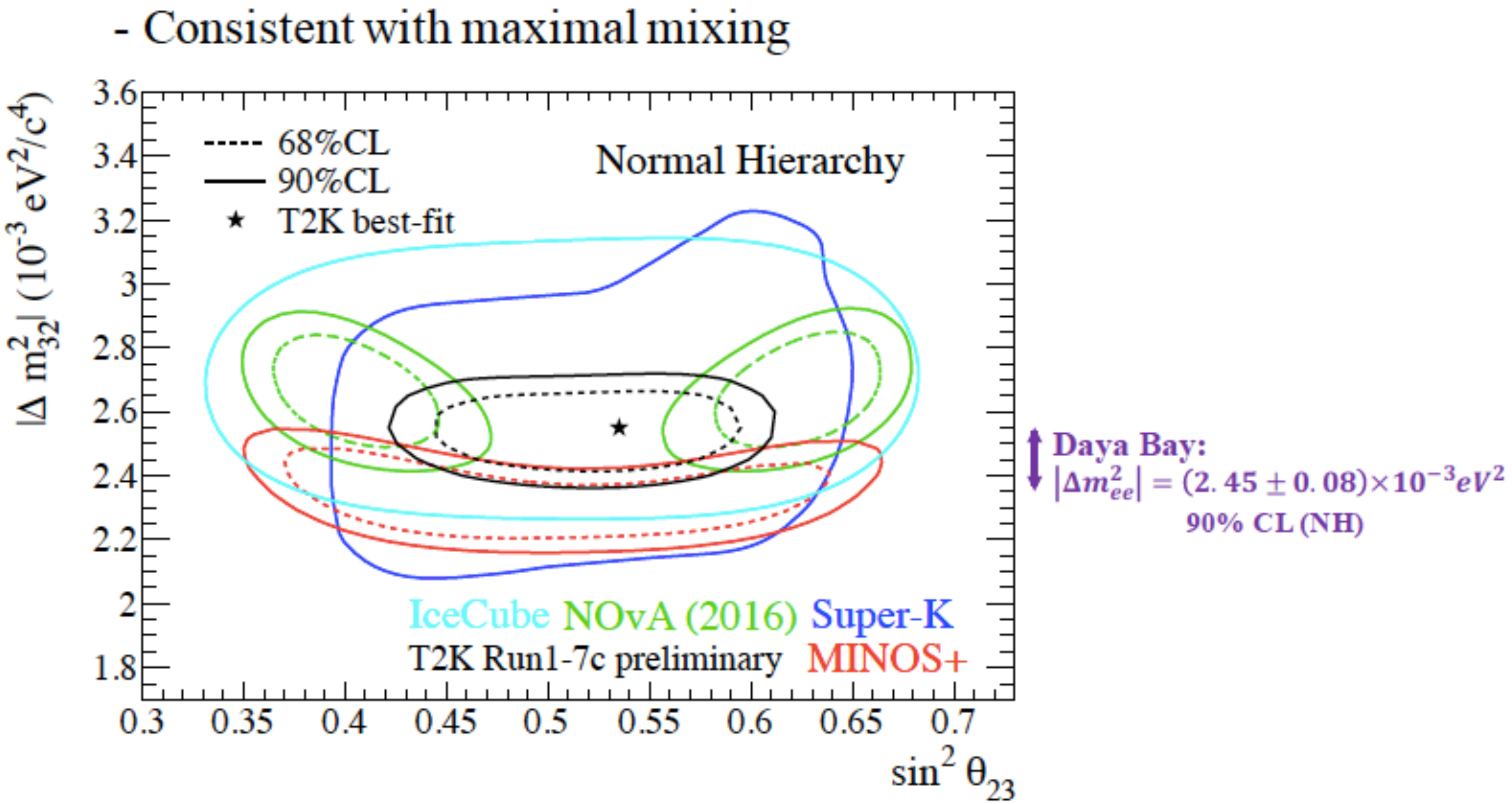




$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$
$$|\Delta m^2_{32}| = (2.51 \pm 0.11) \times 10^{-3} \mathrm{eV}^2/c^4$$

At ICHEP 2016, Chicago

- T2K combination with anti-neutrinos, the tension mounts!

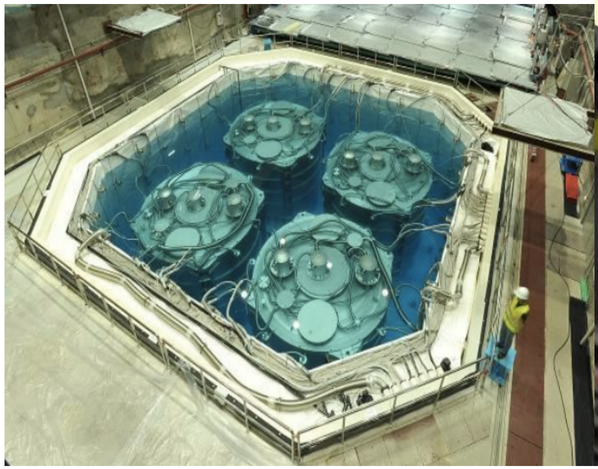


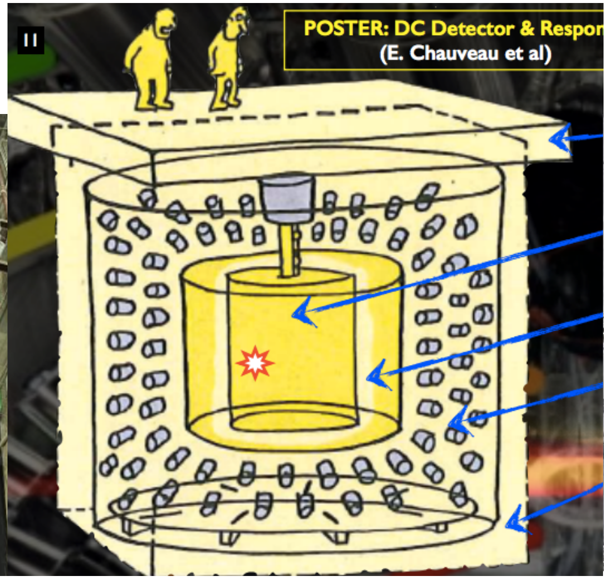
	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\|\Delta m^2_{32}\|[10^{-3}\mathrm{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

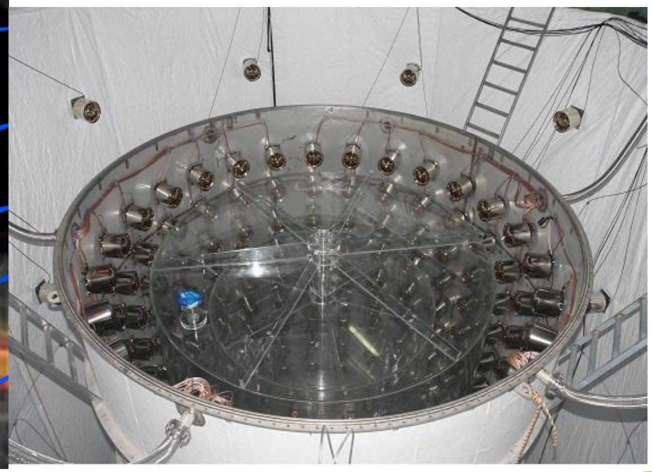
AT NEUTRINO 2016, LONDON REACTOR VALUES

- Double Chooz : $\sin^2 2\theta_{13} = 0.111 \pm 0.018$
- Daya Bay : $\sin^2 2\theta_{13} = 0.0841 \pm 0.0027 \pm 0.0019$
- Reno : $\sin^2 2\theta_{13} = 0.082 \pm 0.009 \pm 0.006$

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}$$

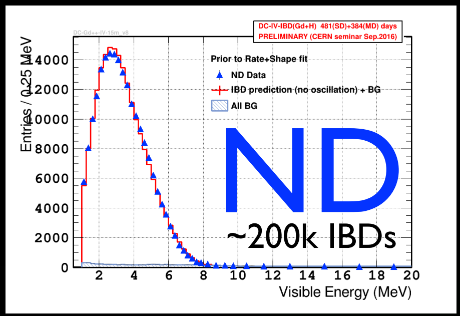


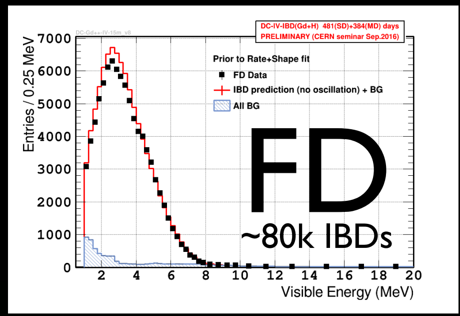


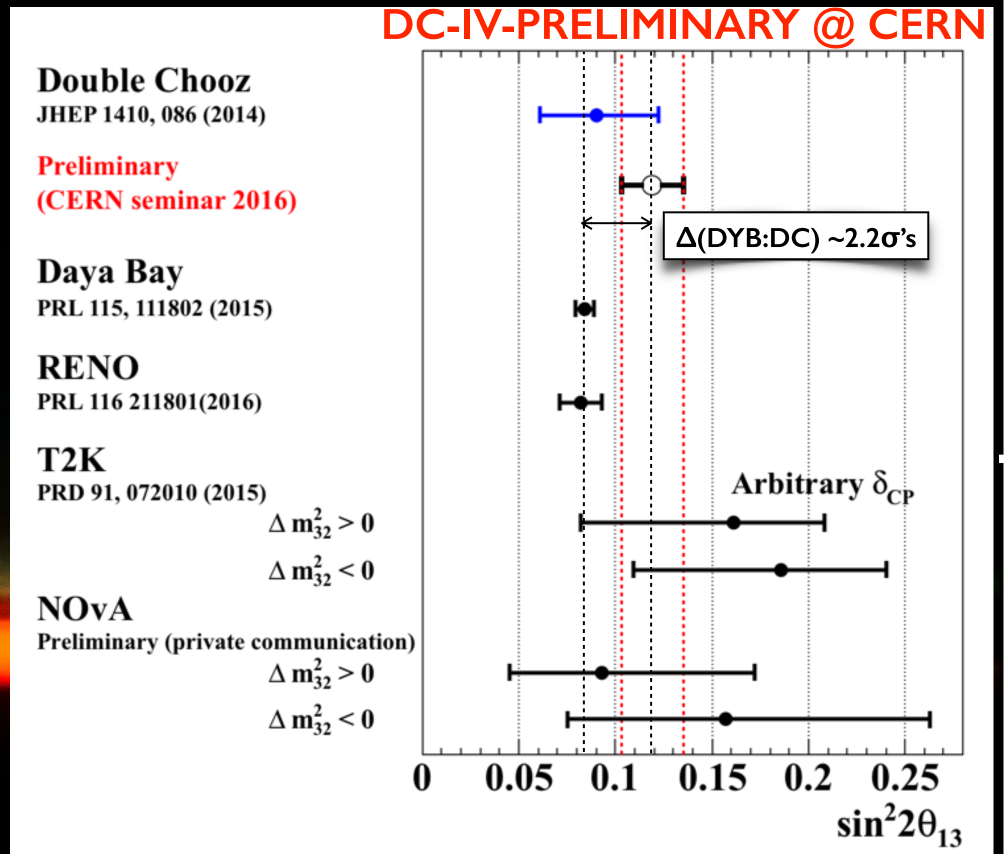


θ_{13} is the key to the Jaguar!!

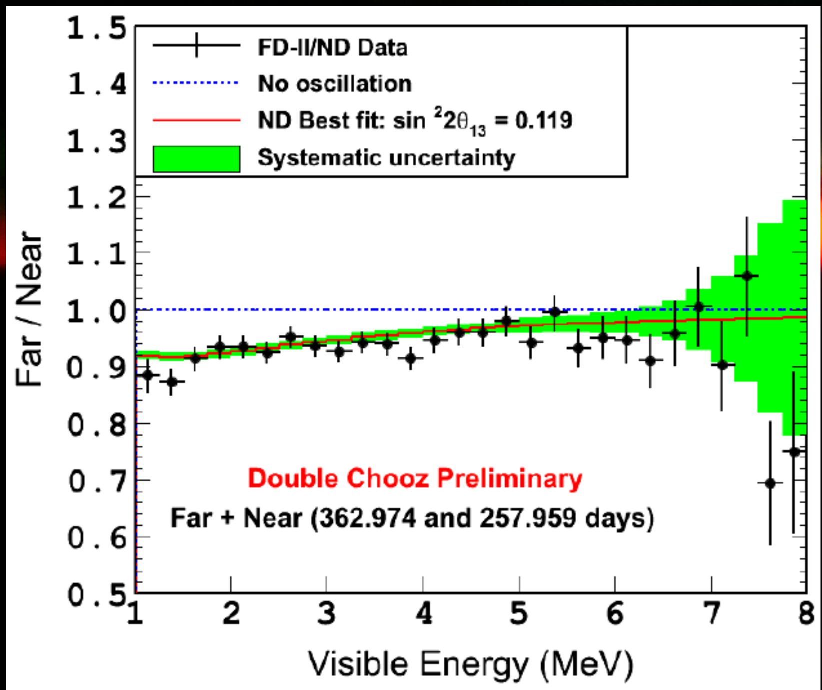
DC-IV PRELIMINARY results @CERN (Sept.2016)







3x SD-fits (MC) ⊕ MD-fit (inter-detector correlations)



$$\sin^2(2\theta_{13})^{R+S}=(0.119\pm0.016)$$

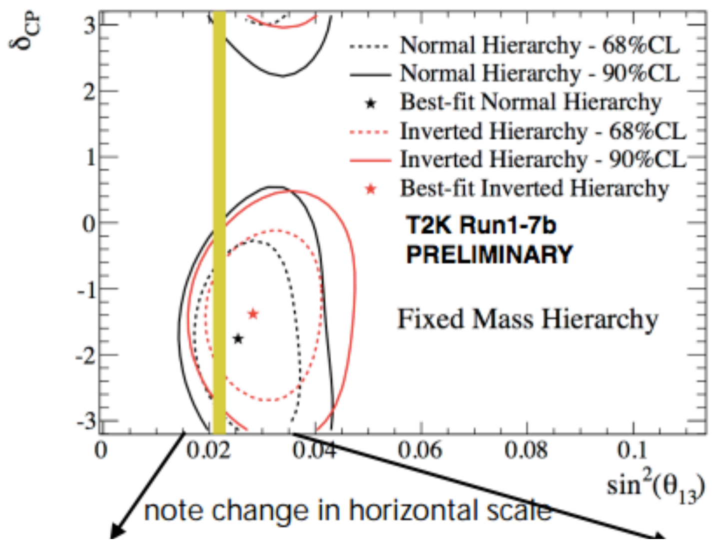
(marginalised over $\Delta m^2=(2.44\pm0.09)eV^2$)

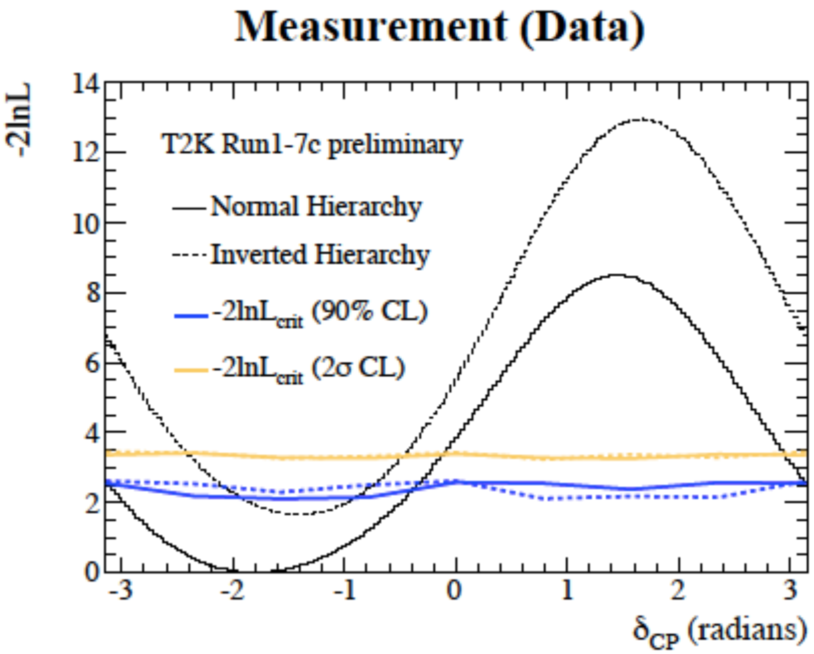
reactor-θ_{13} key for **CP-violation** & **mass hierarchy**→ **redundancy fundamental**

(DC pushing to resolve: improvements coming soon)

Anatael Cabrera (CNRS-IN2P3 & APC)

Maximal or non-maximal: a very big question : back to T2K





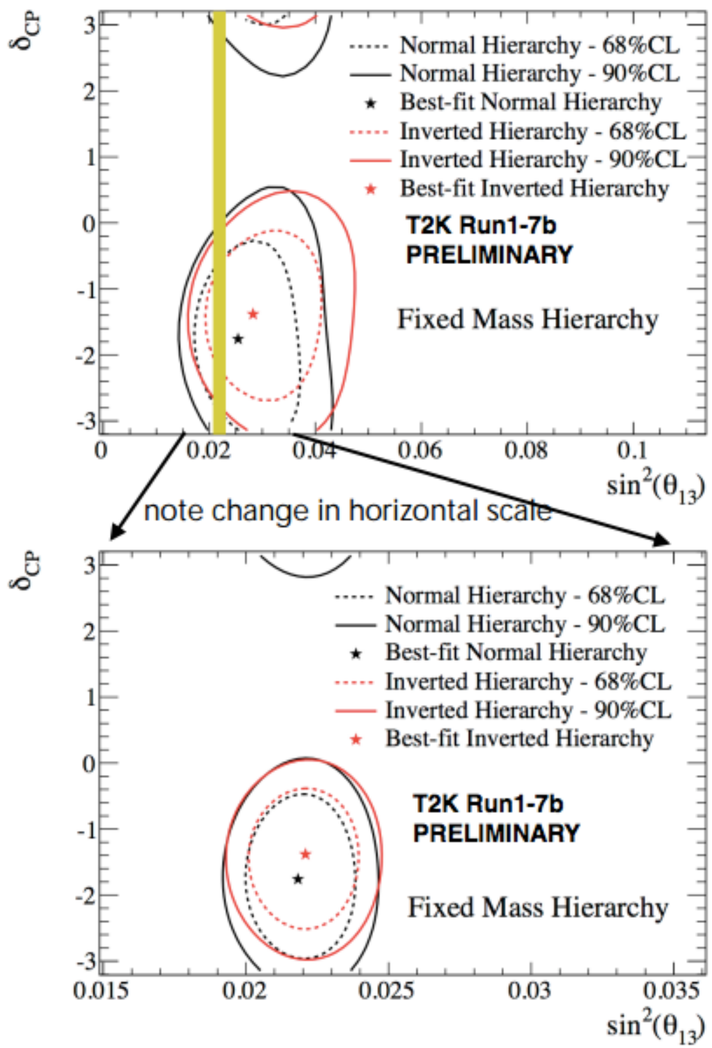
$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right)$$

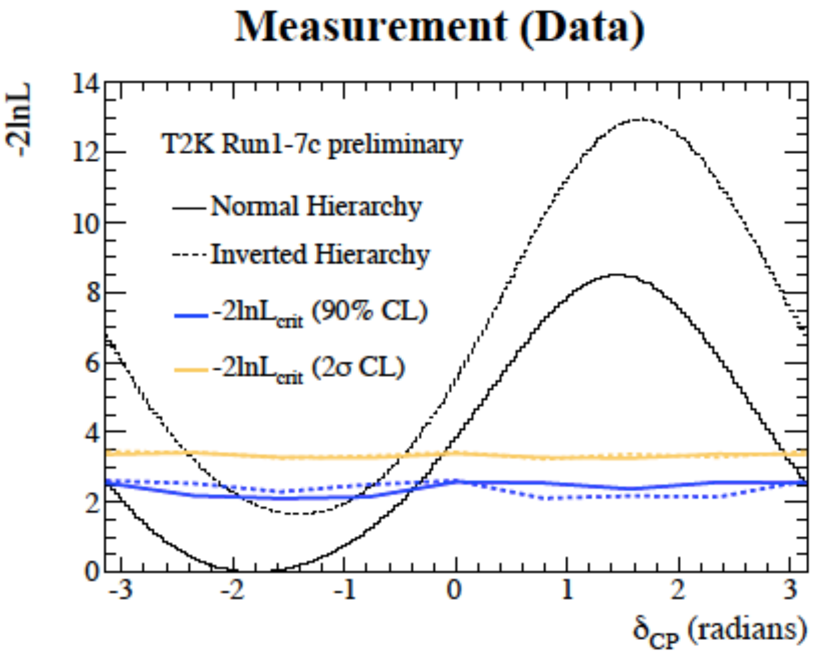
$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CPV → $$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta_{CP}\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\%\text{ CL}$$

Maximal or non-maximal: a very big question : back to T2K



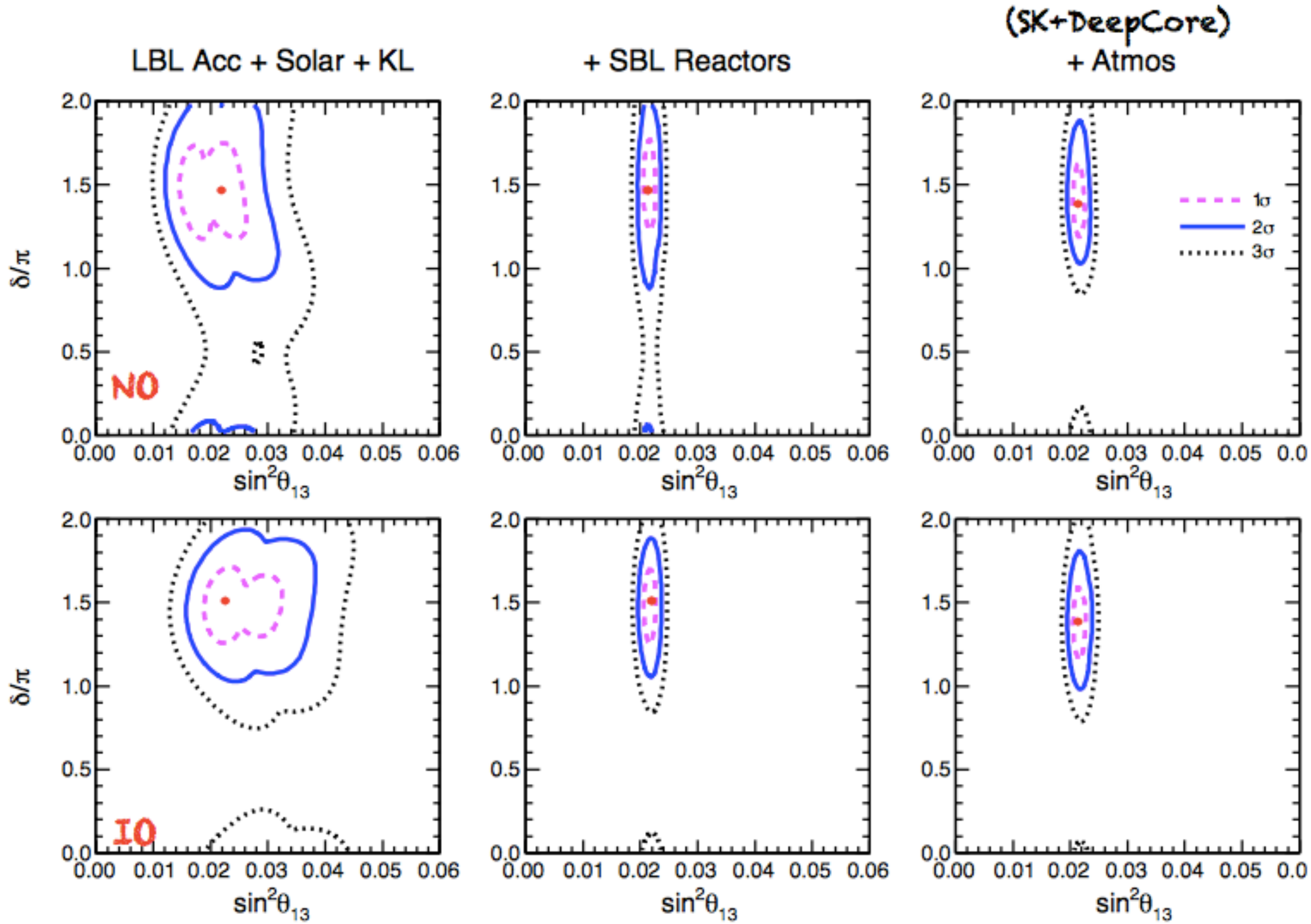


- T2K uncertainty on s^2_{23} is **very small** because its maximal
- This leads to significant reduction in δ_{cp} parameter space
- All other parameters are now marginalized over : progress

$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

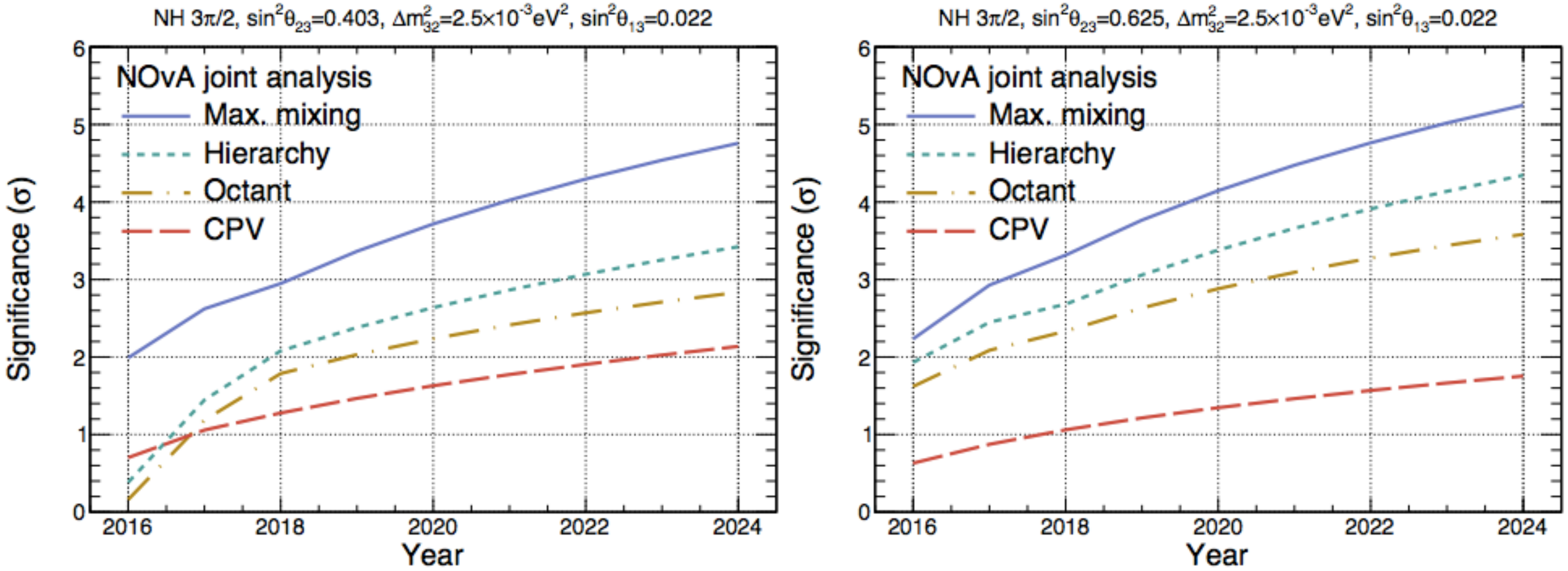
PRELIMINARY JOINT FIT IN REAL TIME! (A.MARRONNE ET AL.)

- Do we already know that δ_{cp} is not zero?



PROGNOSIS FOR MASS HIERARCHY AND CPV

- Ultimate precisions depend on run strategy
- JPARC upgrade in 2018 is significant (run until 2025)



- NH, δ_{cp}>1 is so far (slightly) preferred
- MH will likely be determined to 3σ by 2022 by NOνA even if θ_{23} not maximal
- Old sensitivities already somewhat overtaken by events

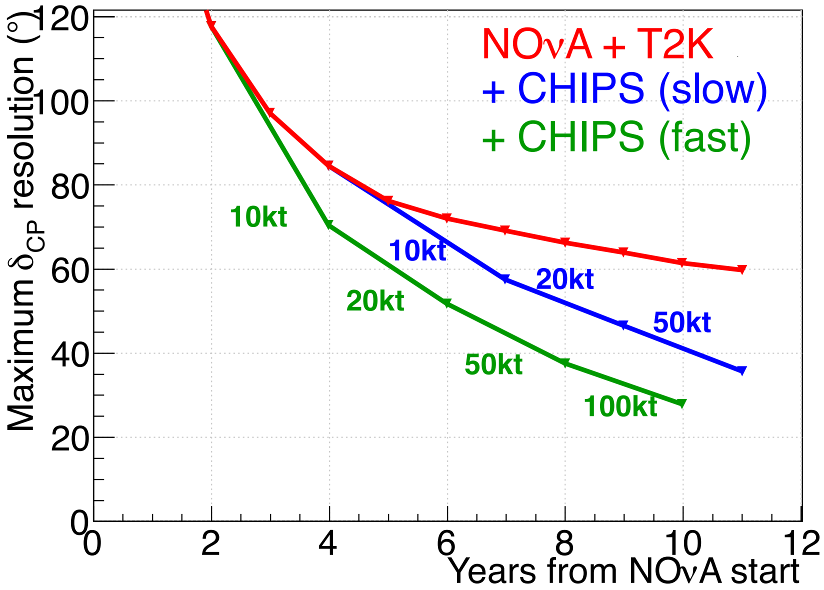
This is the fun bit, no plots, just pics!

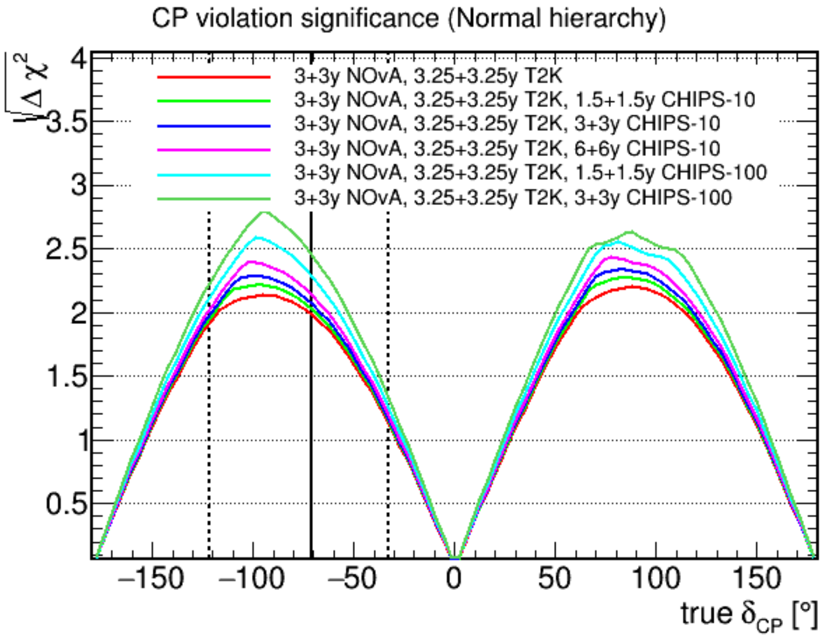
CHIPS-M

Summer 2014/2015, 50ton prototype

CHIPS

- 5-10kt WC detector will be deployed in NuMI beam (in N.Minnesota mine pit) in summer 2018
- Funded by ERC grant to UCL and Nikhef, Leverhulme grant to UCL, and large contribution from U.Wisconsin, Madison and U.Minn, French contribution of PMTs
- 7mrad off axis, will contribute to combined knowledge before 2022
- Innovative design allows detector to grow as more instrumentation becomes available
- Could point the way to affordable Mton in the future





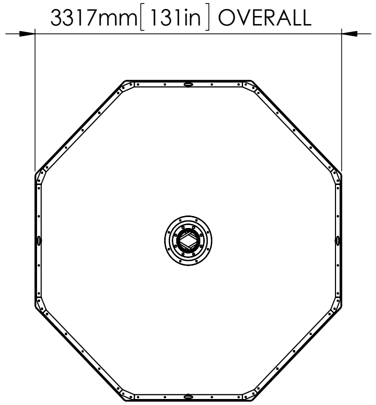
Overview

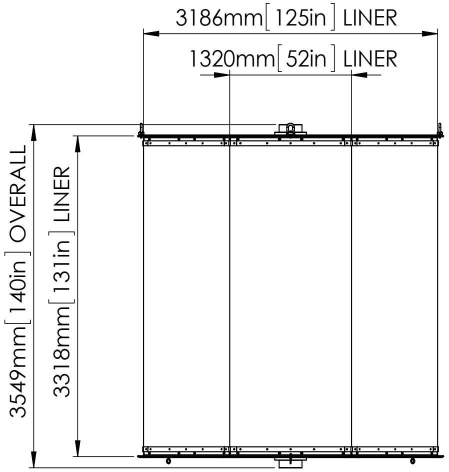
- First prototype CHIPS-M (Summer 2014, 2015)
  - Working on water 101
  - Tested liner, other materials, pump, water filtration, winter
  - Prototype PMT modules, KM3net electronics, integration of KM3net and IceCube electronics
- CHIPS-10 (Summer 2018)
  - 10kt vessel footprint
  - Instrumentation mass depends on PMT availability and $$
  - Demonstration of working detector, under water, identification of signal events and demonstration of costs
- Data taking until 2022

CHIPS-M BEING DESIGNED

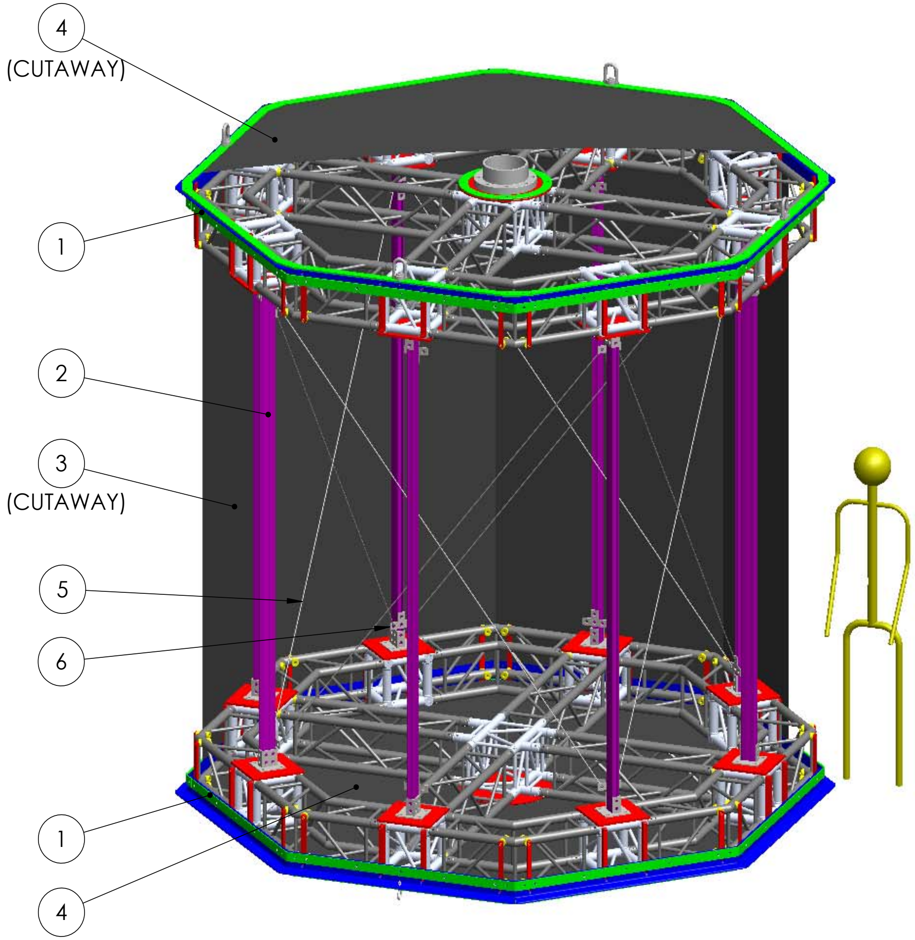
ITEM NO.	DESCRIPTION	Material	Vendor	QTY.
1	End Truss Assembly			2
2	Column	304 SS Double Strut Channel (Back-to-Back), 120in stock (cut to length)		8
3	Wall Liner	Seaman XR-5 PW		1
4	End Liner	Seaman XR-5 PW		2
5	Lateral Bracing Wire Rope Assembly	304 SS, 1x19 const, 3/16in dia, ~132in length	McMaster p/n 3461T18 plus end hardware and turnbuckles	8
6	Strut Channel T-Plate	304 SS		8

REVISIONS				
REV	BY	DESCRIPTION	DATE	APPROVED





EST. DRY WT. 1500 lb
EST. WET WT. 970 lb



MAT'L

CHIPS-M STRUCTURE 3.27.14

USED ON

ASME Y14.5M 1994 APPLIES

UNLESS NOTED 63/
UNITS: INCH
3-PLACE: +/-.005
2-PLACE: +/-.010
1-PLACE / FRAC: +/-.015
ANGULAR: +/-0.5 DEGREES

DATE 3.27.14
DRAWN TLB
CHK'D -
APPR'D -
SCALE

PHYSICAL SCIENCES LABORATORY
UNIVERSITY OF WISCONSIN
(608-877-2200)

NO REQ'D -
SHEET 1 OF 2
DWG NO
REV

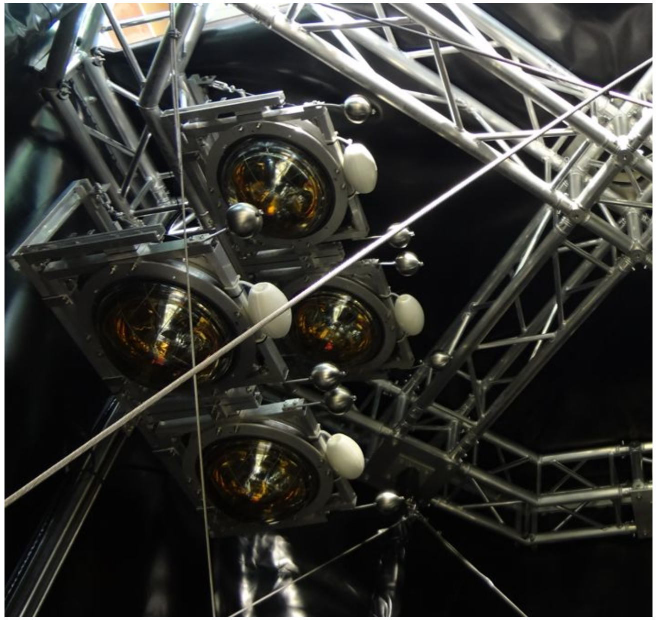
DRAWN WITH SolidWorks

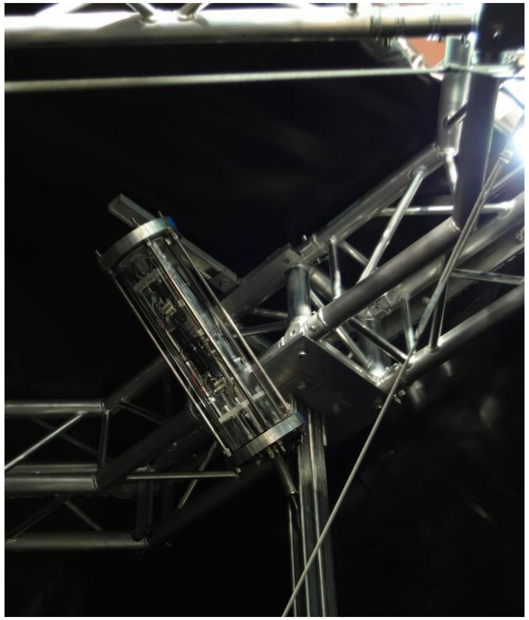
CHIPS-M BEING CONSTRUCTED

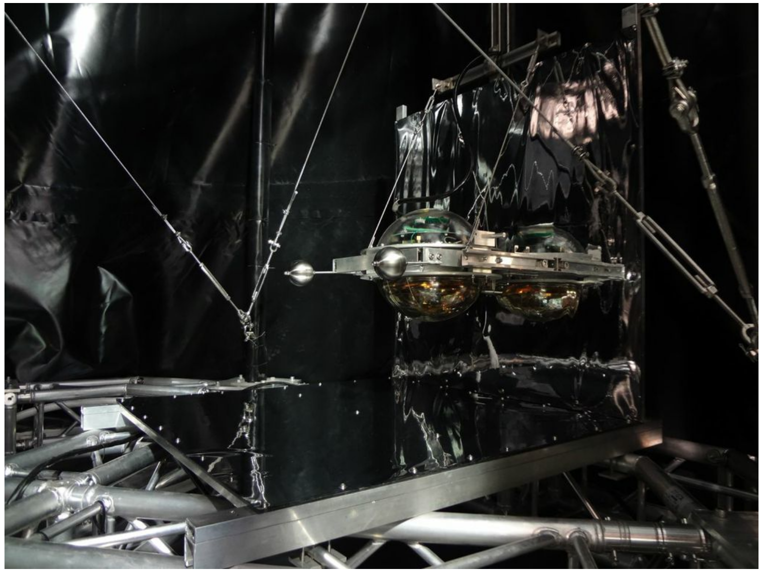
- Parts built at W&M, constructed in Soudan surface building
- Dedicated team of youngsters : 1 postdoc, 3 grad students, 5 undergrads

CHIPS-M being PVC liner: black on inside

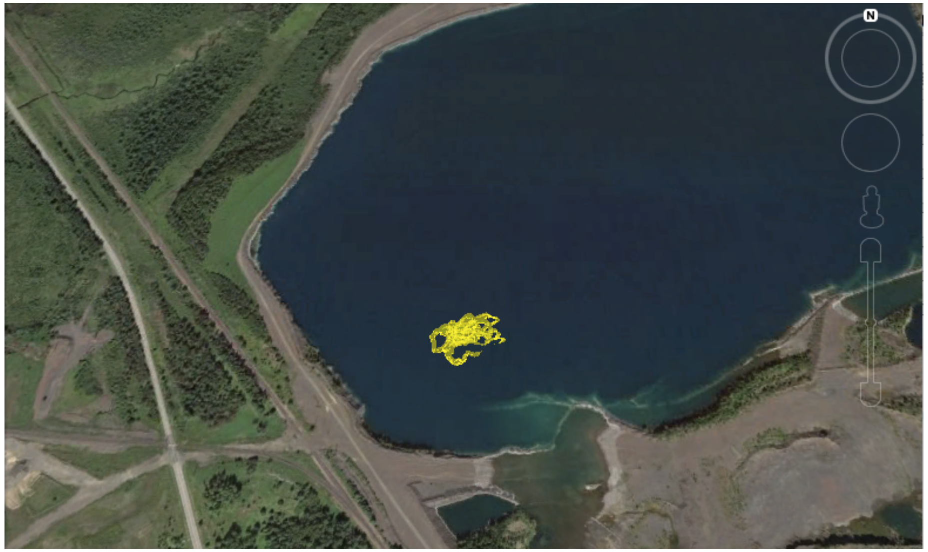
IceCUBE DOMS and camera inside

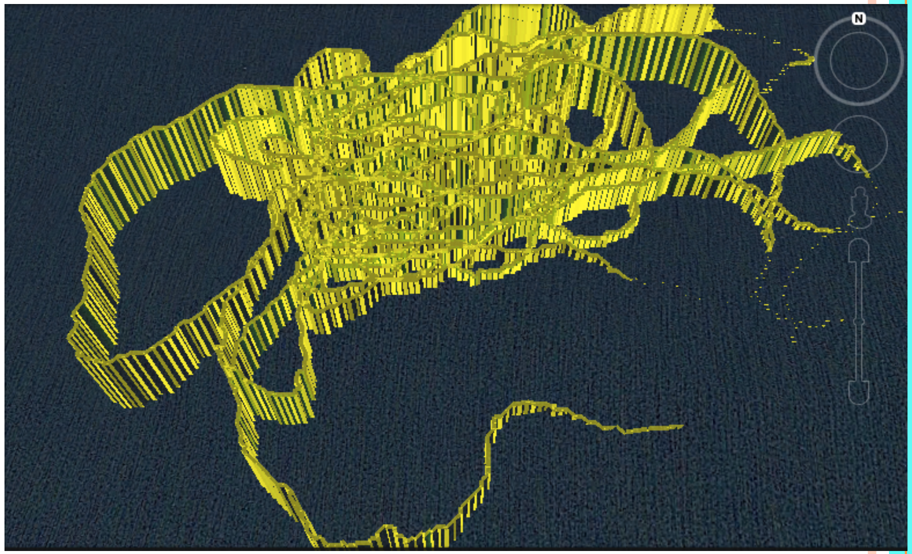






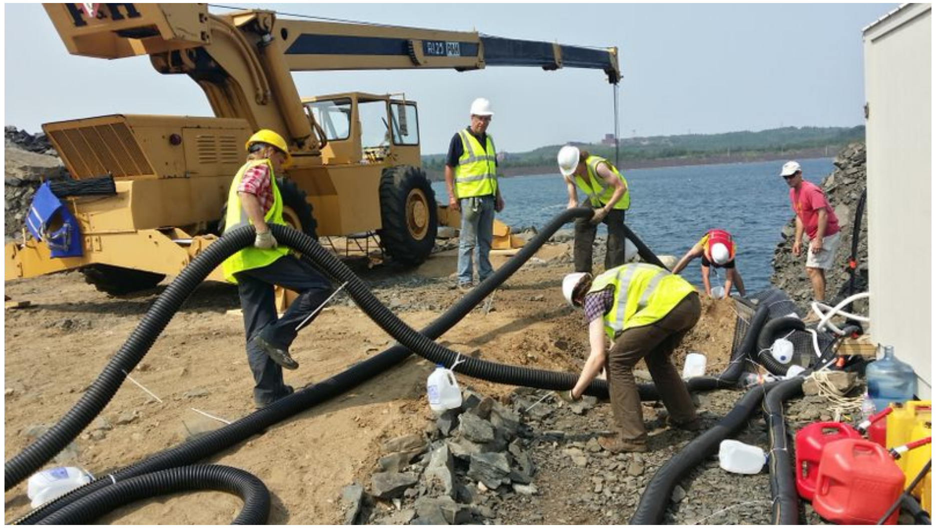
Where to put the detector?






w Sonar Chart Window Help
Bottom Depth: 175.15ft
Cursor Depth: 91.09ft
Sounding: 6110
N 47°34'35.6"
W 92°08'10.1"
1.94 mph, Track=310°
Frequency: 200kHz
itivity
ColorLine
7/11/2014

Umbilical: carried water and signals



- 200m umbilical contains 400m of water pipe, 5+3 cat5 cables for IceCube DOM readout and power, power to central power box
- Fibre deployed for read out, all buried for winter

CHIPS-M DEPLOYMENT AND RECOVERY

- Being submerged in 2014 ←←←←
- After one year under the water →→→

- Liner is robust, light-tight and mostly pristine after a year under the water
- Sealing method is robust
- Survived the winter

Water Studies

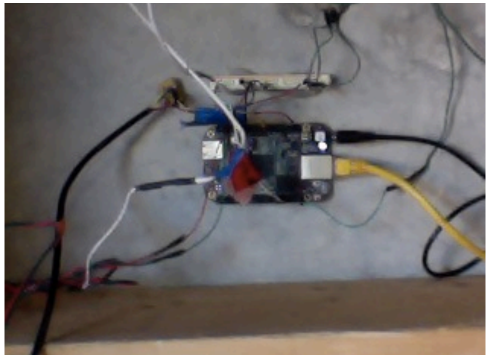
Water Clarity

- CHIPS has advantage of being under about 6 bar pressure and at 4-8^{o}C :
  - Good for crushing bubbles and bacterial blooms respectively
- Filters provide
  - a raking of the particulates in the water down to 0.2 micron
  - A UV sterilizer to eliminate life + a carbon filter to make sure
- We have small model of CHIPS-M (micro-CHIPS) on surface
  - Using 405nm laser and 3m upright column, we watched the water clarity over 6 months
  - This is likely worse than in reality because it is not pressurized or cold
- Needed to know how clear we can make the water with simple filtering, for simulation benchmarking, and for system design

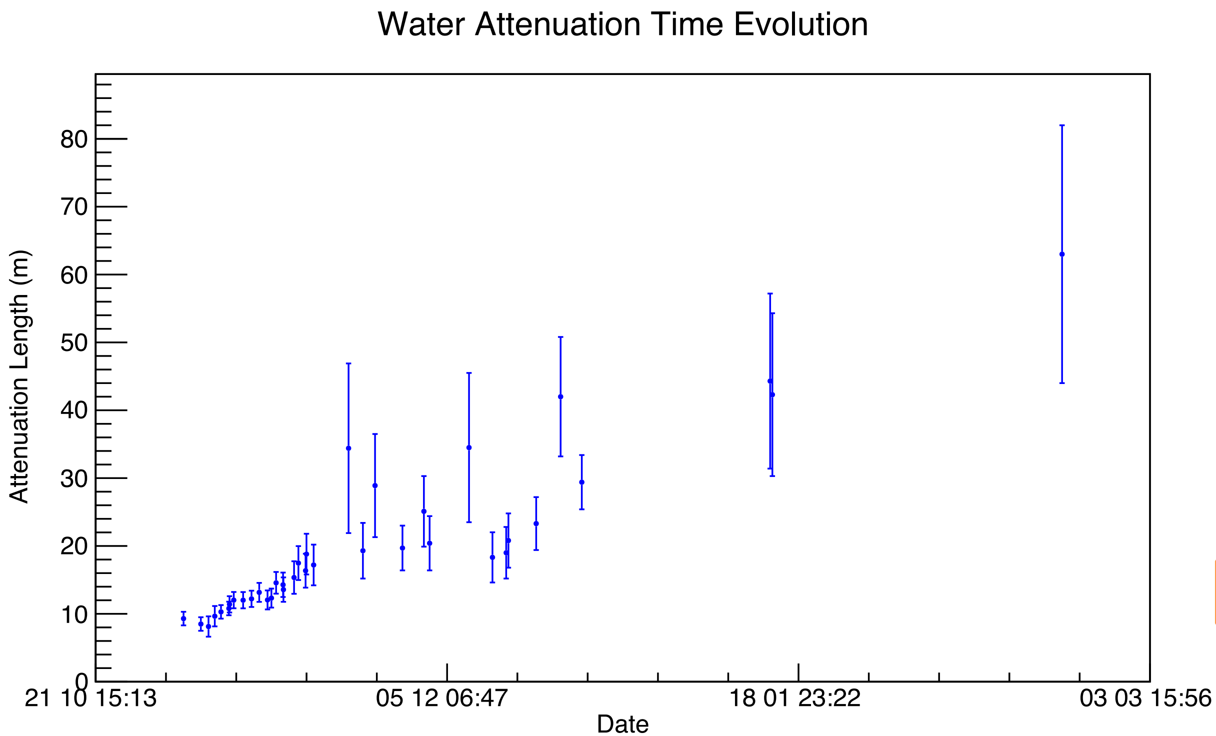
The Water System

- UV Sterilizer + series of filters down to 0.2microns
- Circulates at 3-5 gpm
- Pit was a taconite mine. Lots of red stuff in it

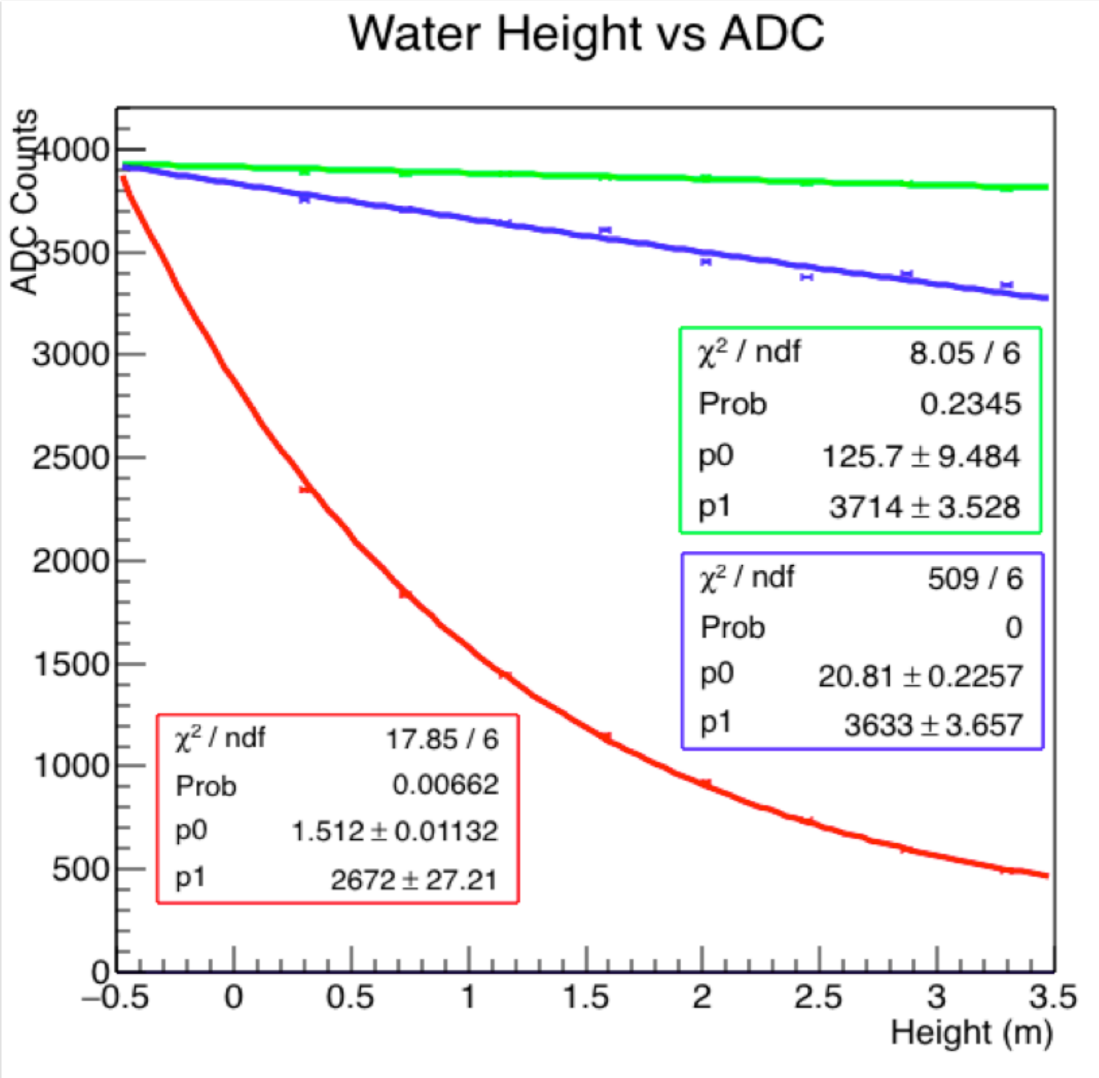
WATER STUDIES



- Automated attenuation length measurements using BeagleBoneBlack, servos, relays
- PIN diode at top and 405nm laser at base provide the baseline : simple op-amp circuit to get correct voltage for the BBB
- 50 gallons of RO'd water circulated at equivalent of 4gpm in CHIPS-M
- UV sterilizer, 0.5μm + carbon, 0.2μm filters
- Full recycle time of about 10 days
- System is the equivalent of what was in CHIPS-M : straightforward and cheap but without the low temperature which keeps bacteria better under control at the bottom of the lake and pressure which reduces bubbles



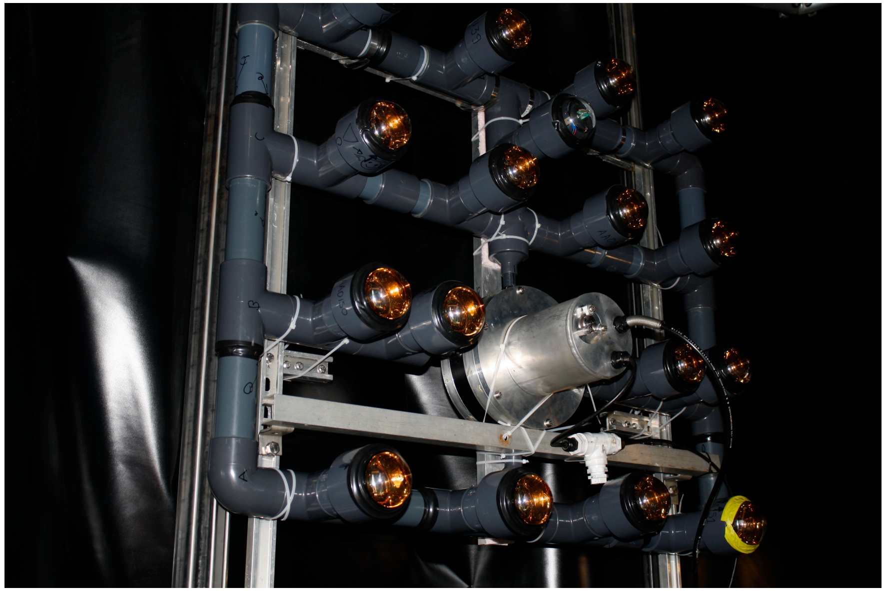
WATER : CONCLUSIONS

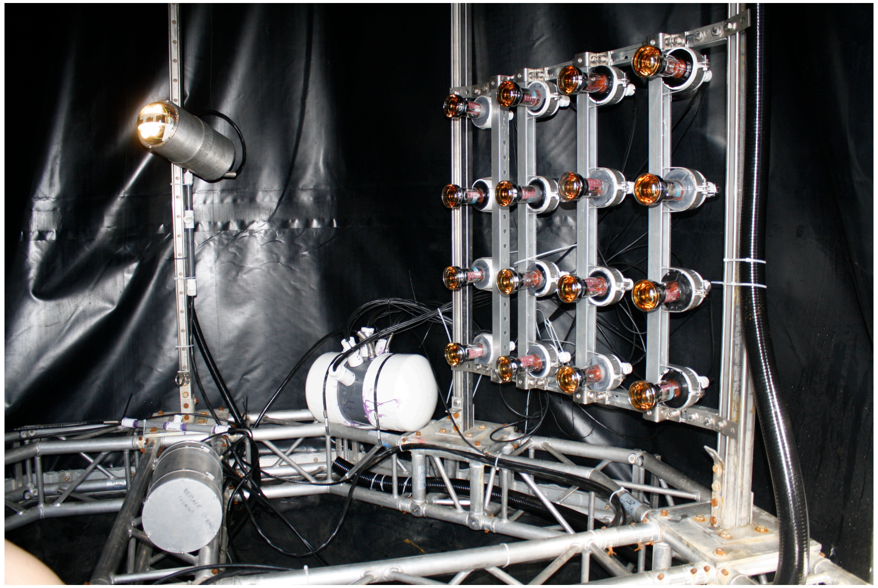


- Simple filtering can clean the water to ~100m at 405nm
- Means dissolved solids do not cause bad attenuation at this wavelength
- Check with other wavelength light
- Implication is for cost of water plant and strength of structure

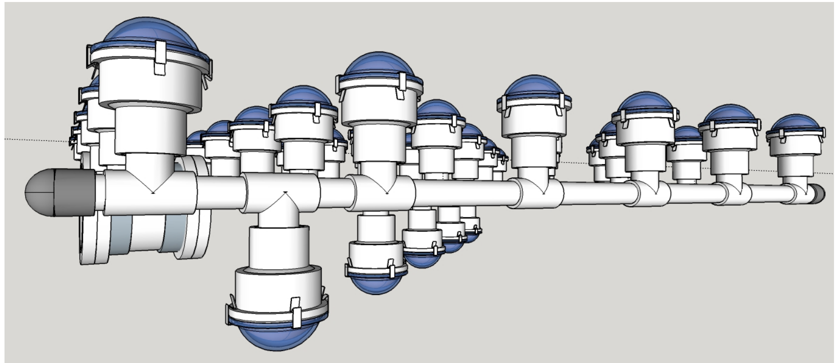
Detector Planes

Nihkef





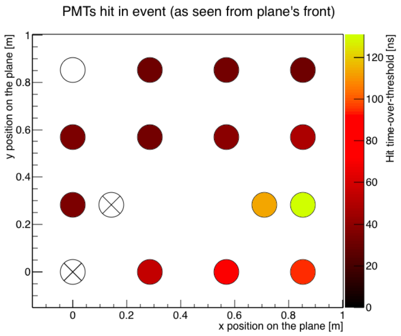
Madison

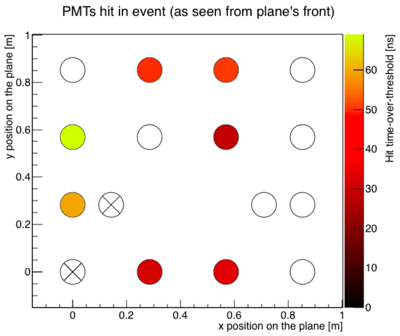


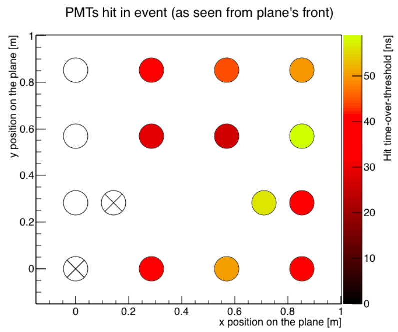
- Two prototypes were tested, one from Nikhef with KM3Net readout, one from UW Madison with ParisROC readout.

Nikhef Detector Plane Data

- Event window is 30ns with at least 5 hits
- Use events to compare with CRY simulation
- Verify cosmic rate prediction from MC at OUR 50m depth

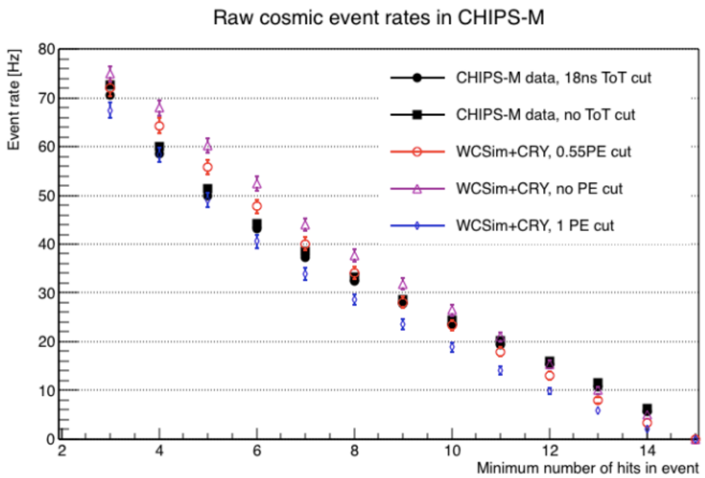




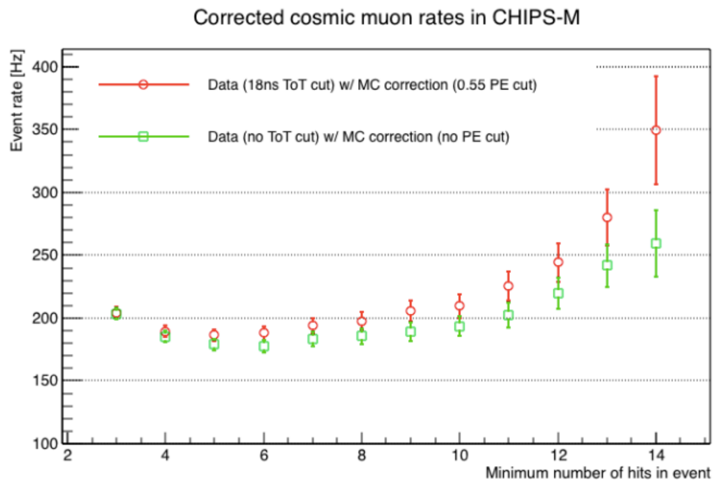


10μs NuMI spill for a 10kt CHIPS = 0.14 (14.4kHz in CHIPS-10)

Raw rates comparison



Corrected rates



Less than 1% dead-time in 10kt detector!!!

CHIPS-M : WHAT WE LEARNED

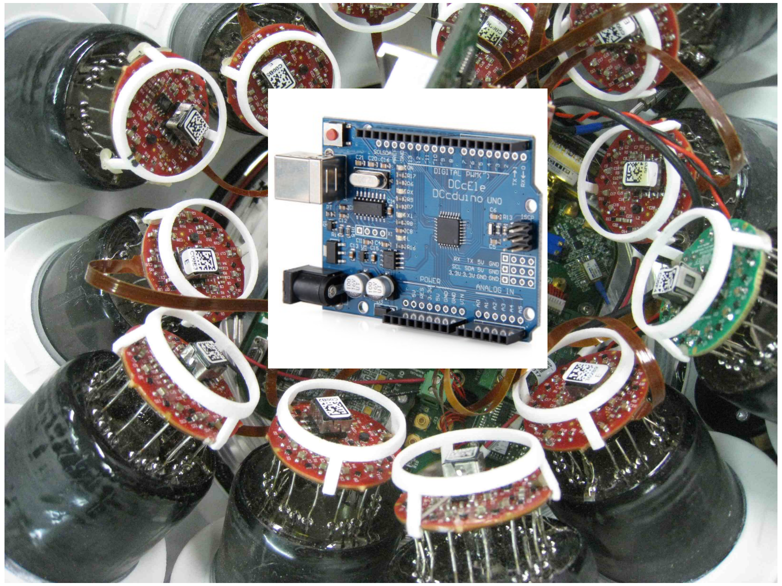
- Liner is robust and totally light tight
- Water can reach ~100m attenuation length (at 405nm) after 3 months of circulating with simple filters
- Detector planes withstand pressure
- Readout to surface achievable with fibre cable
- Water circulation carries on throughout winter with the winter defence system
- Measurement of cosmic rate shows 10kt detector possible with 14.4kHz rate and 0.14 cosmic events per spill in entire detector
- Cable grips can work, but need better quality control tool while installing
  - We used compressed air to look for leaks, but this was not sufficient
  - Maybe potting will be a better solution

CHIPS-10KT

The near future

Recent Innovation: iPHONE and ARM

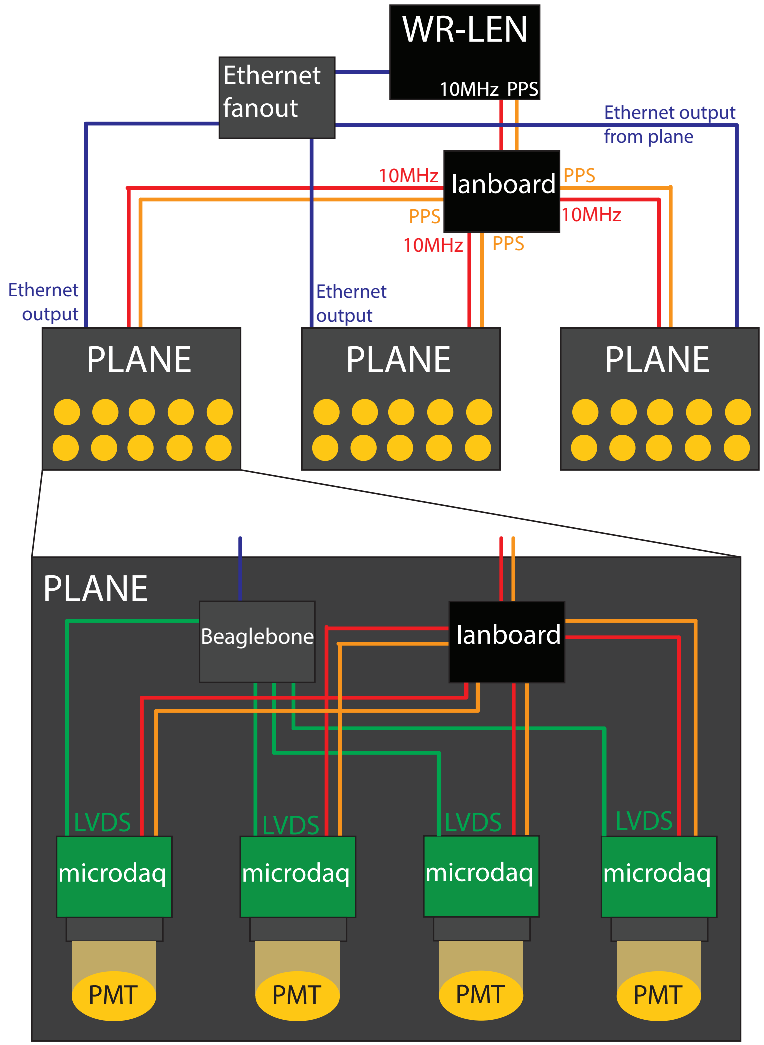
- We are riding a revolutionary wave in development
- $20 for a BBB to collect signals and transmit to Ethernet
- Reduce cost to minimum



- Side comment: Industrially available ASICs in version 100 (ish): home grown electronics is typically in version 2-5the combination of cheap processors such as Raspberry Pi, BeagleBone and Arduino combined with the WWW means progress goes incredibly fast as solutions are known instantaneously
- Developers are like the Borg: and **resistance is futile..**

DAQ Development : iPHONE and ARM Madison

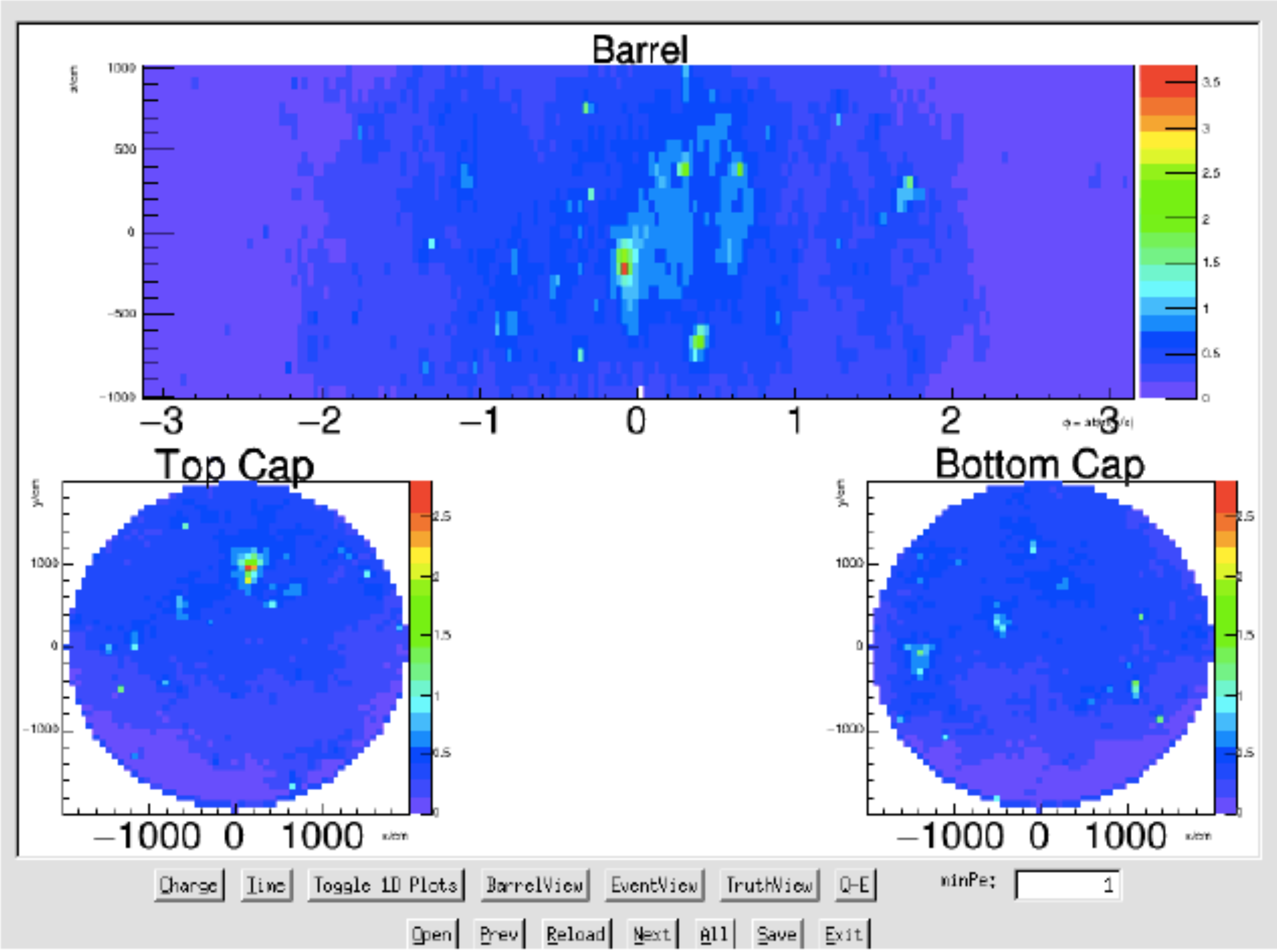
- Working in conjunction with IceCUBE IceTop and HAWC @ Madison
- Micro processor on PMT
- TOT to ~waveform from series of delays
- 1ns absolute timing
- WR provides clock
- BBB builds events
- Ethernet back to WR switch and the world
- +ve CW base being fabricated for all donated PMTs



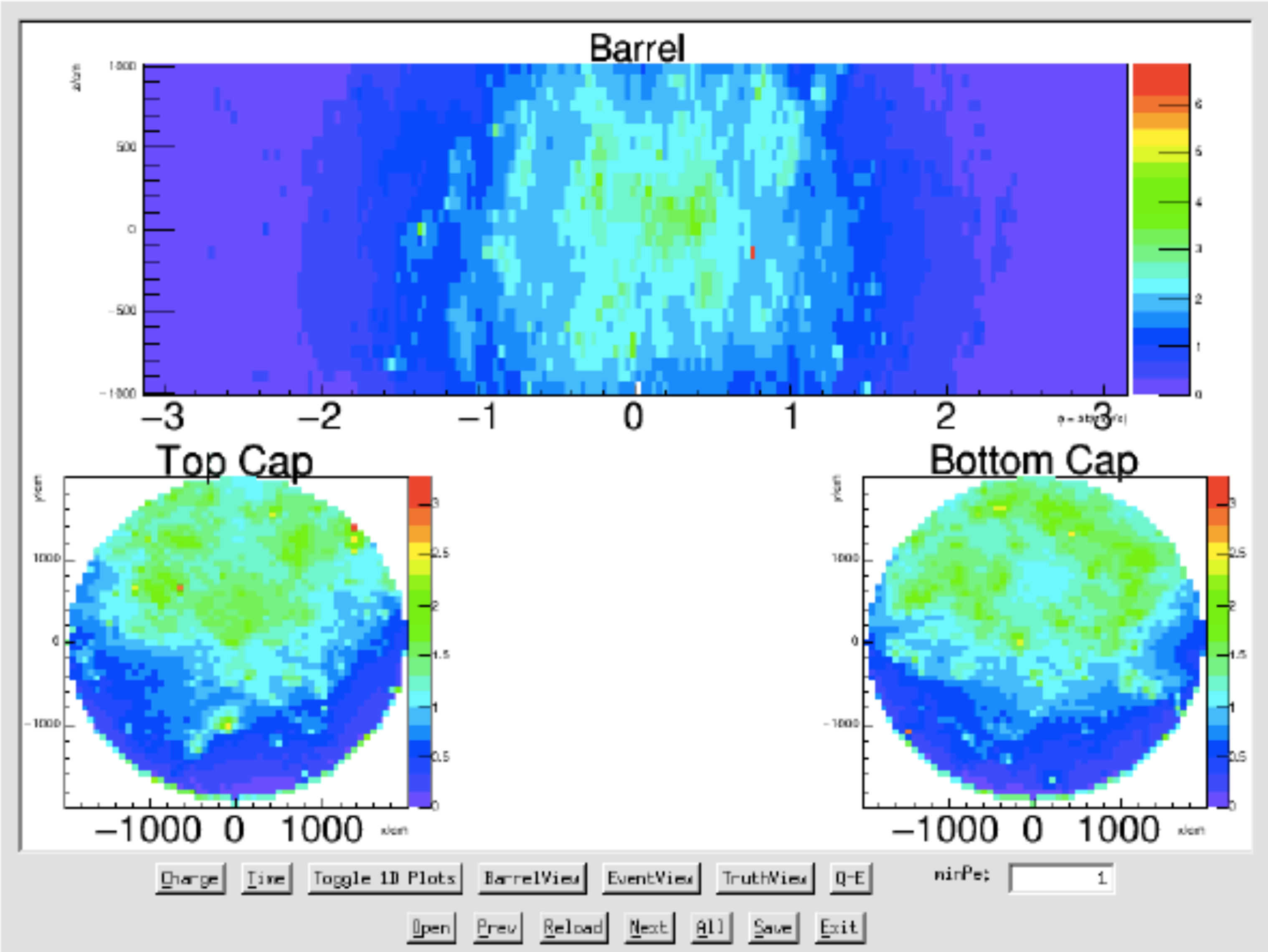
Simulation

- Based on WCSim developed for LBNE WC option
  - Run-time description of geometry and PMTs using xml files - make changes without recompiling
  - New PMT simulation with full dynode chain
- New features allow pattern of different PMTs throughout the detector
  - First time this has actually been properly simulated
  - Optimal layout of PMTs will be understood before PA modules go into production: this will be by early 2017
- Reconstruction based on MiniBOONE algorithms has been developed and is being tested
  - Includes charge and time likelihood pieces used with equal weight
  - Good time resolution and long travel distances give timing more power

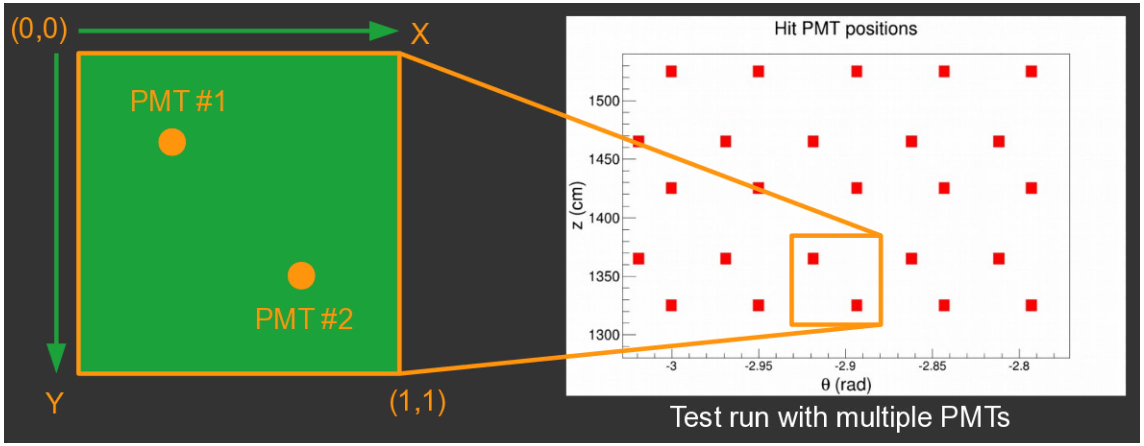
Hit Map 2000 ν_μNC Events



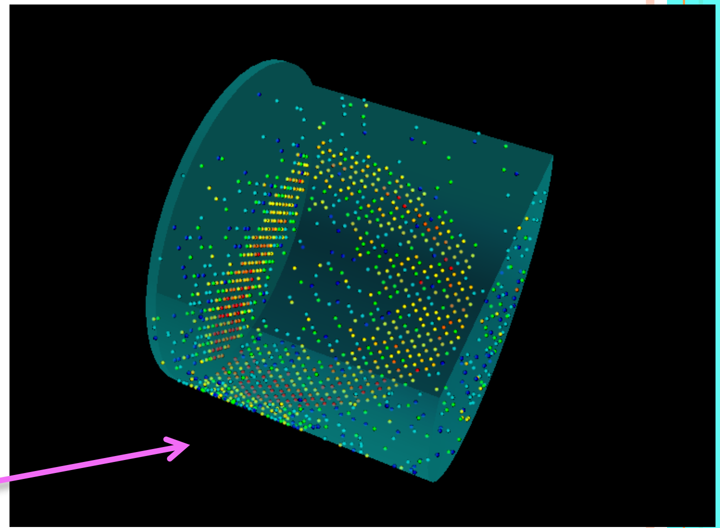
Hit Map 2000 ν_eCC Events

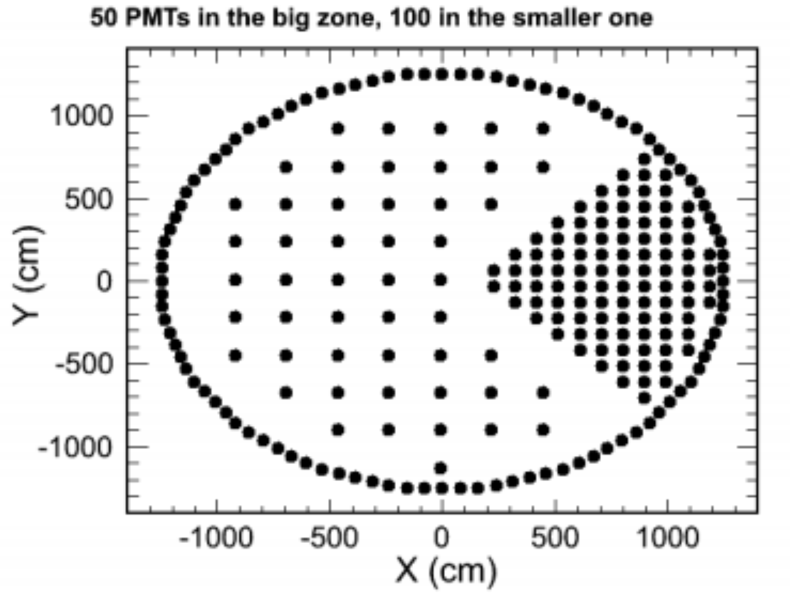


PMT LAYOUT

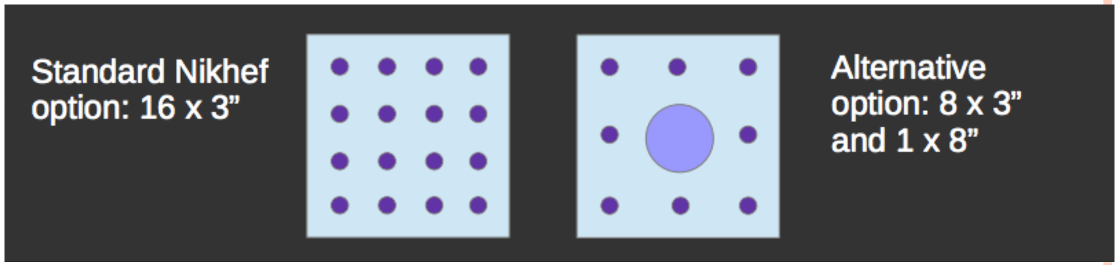


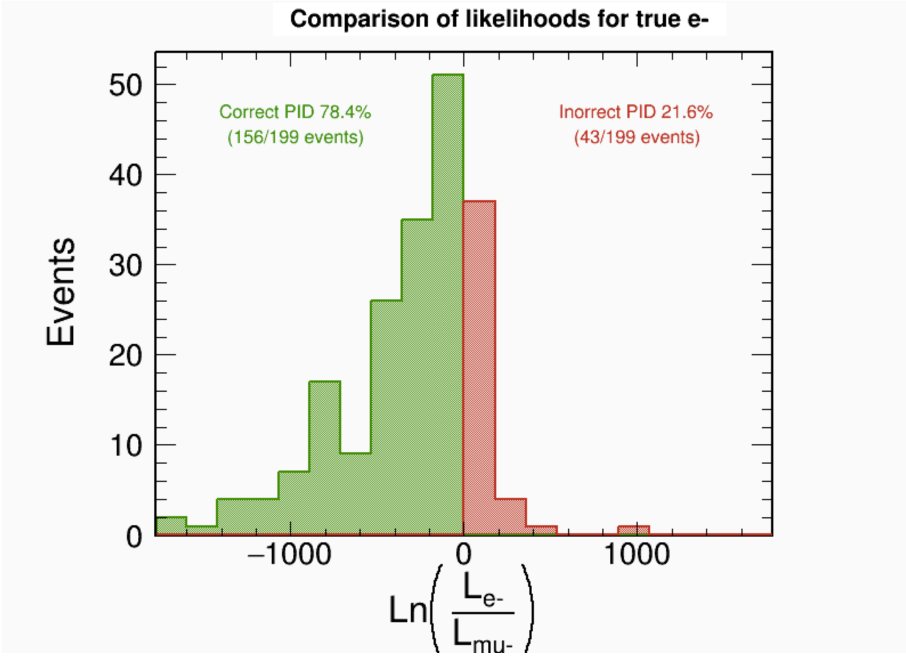
ν_μ CC event with the 2 PMT per cell layout

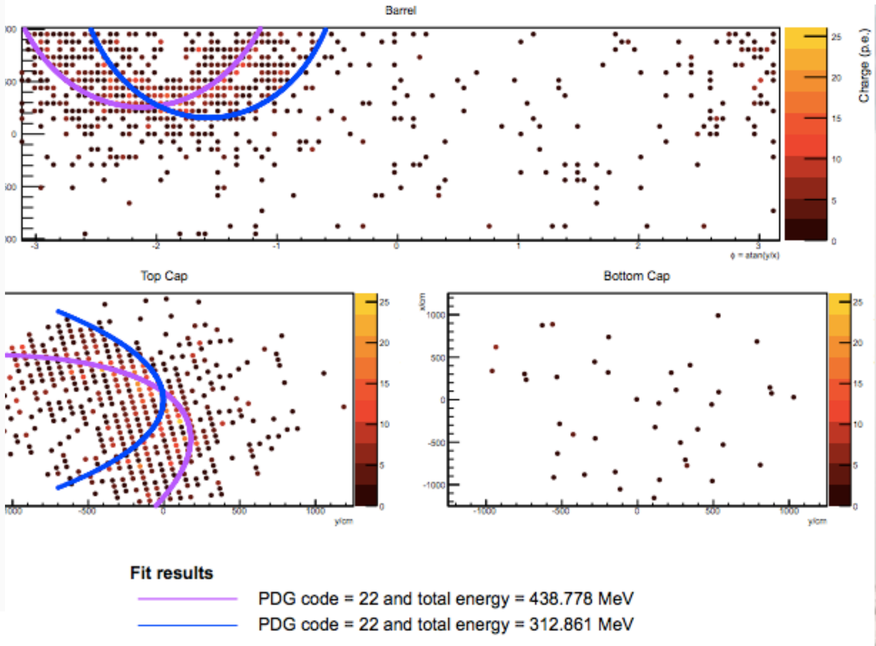


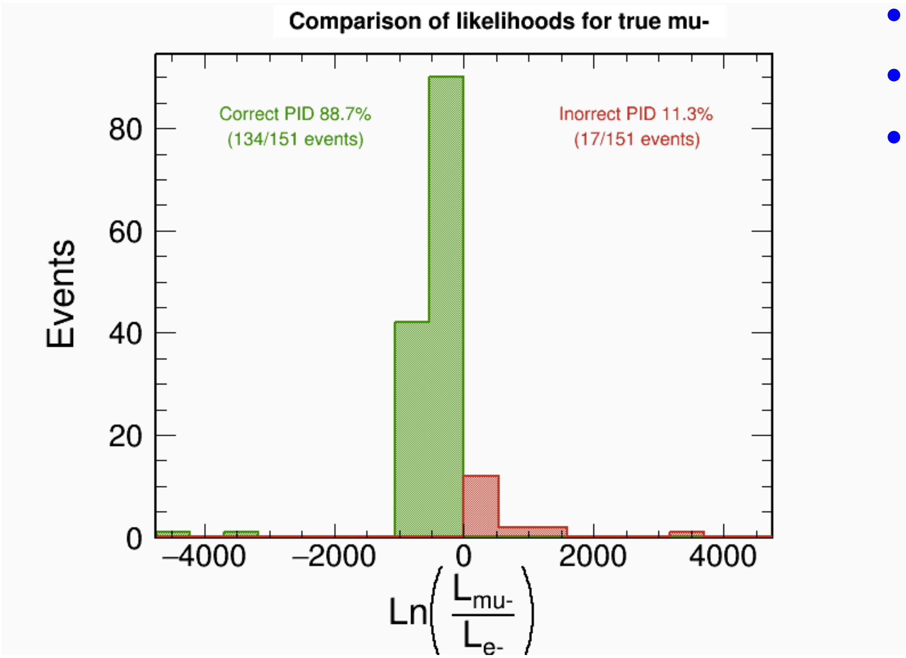


- New feature to lay out PMTs in more complex patterns
- Potential to model the effects of different-sized PMTs side-by-side
- Model the efficiency of non-uniform coverage

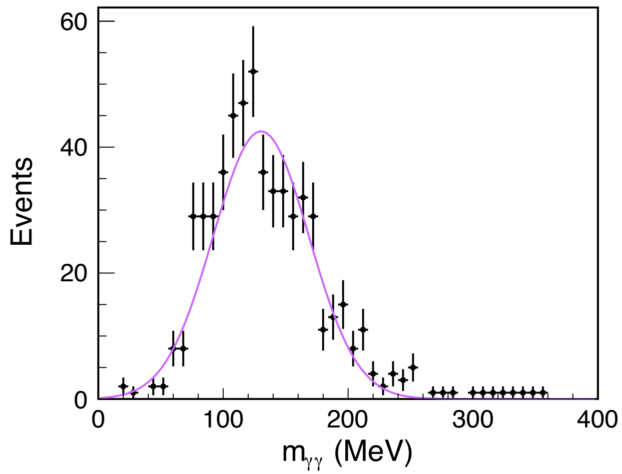








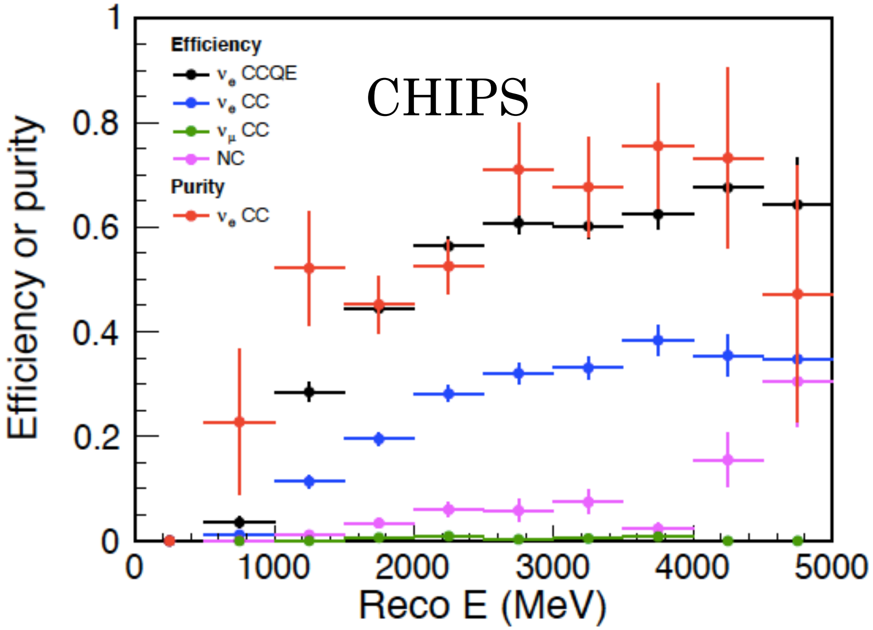
- Two track fitting is possible
- Cosmic rejection also possible
- Implications for detector depth

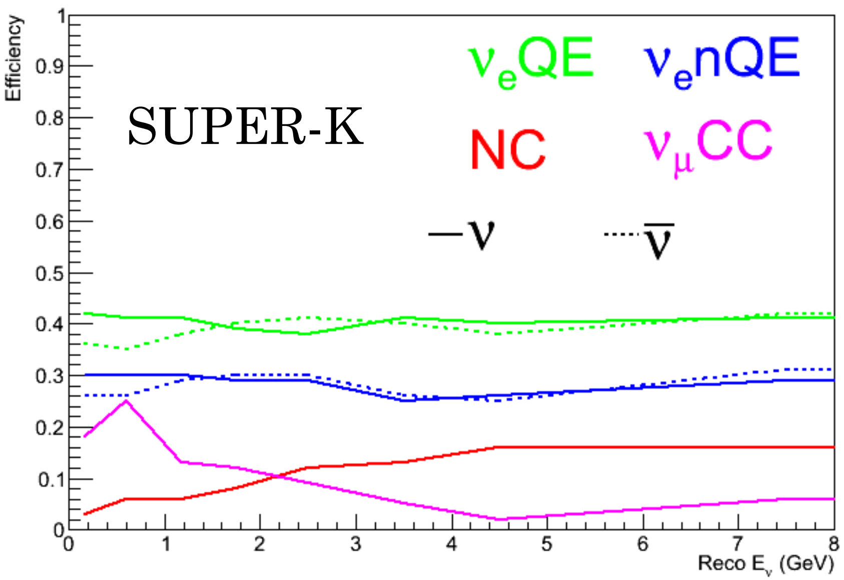


Reconstruction Bottom Line

Table 1. The resolutions of various reconstructed parameters from single ring electron (muon) track fits to a sample of CCQE ν_e (ν_μ) interactions with energies following those expected from the NuMI beam.

Sample	Geometry	Reconstruction Resolution			
		Position (cm)	Time (ns)	Direction (°)	Energy (MeV)
	10 inch, 10%	35	0.9	2.1	208
CCQE ν_e	3 inch, 10%	35	0.84	1.9	210
	3 inch, 6%	38	0.89	2.1	211
	10 inch, 10%	47	1.35	2.6	113
CCQE ν_μ	3 inch, 10%	44	1.14	2.7	110
	3 inch, 6%	51	1.28	3.0	113





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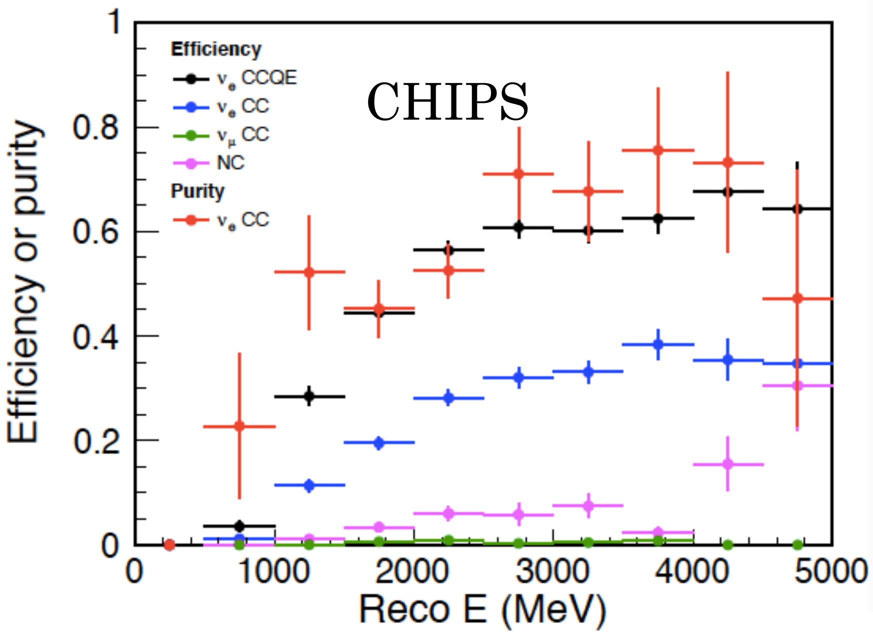
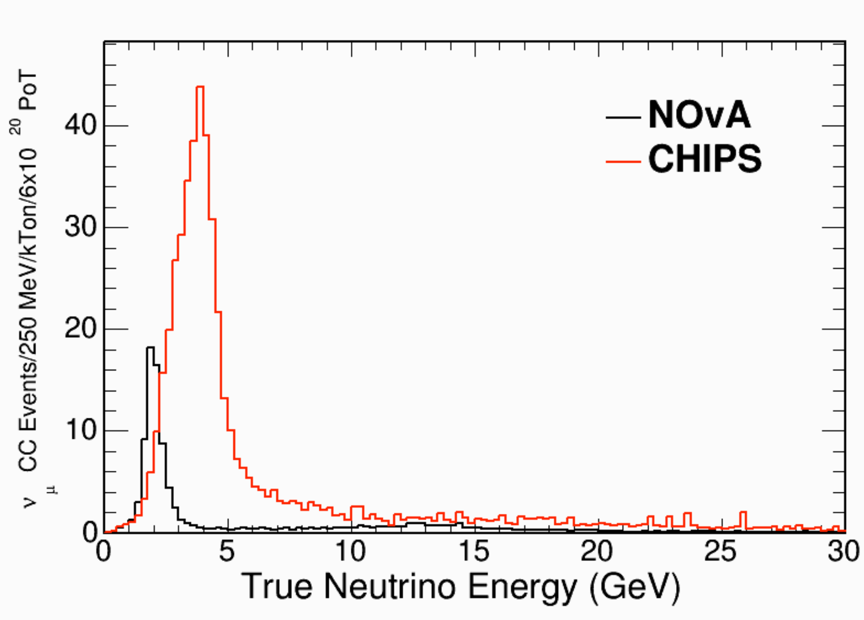
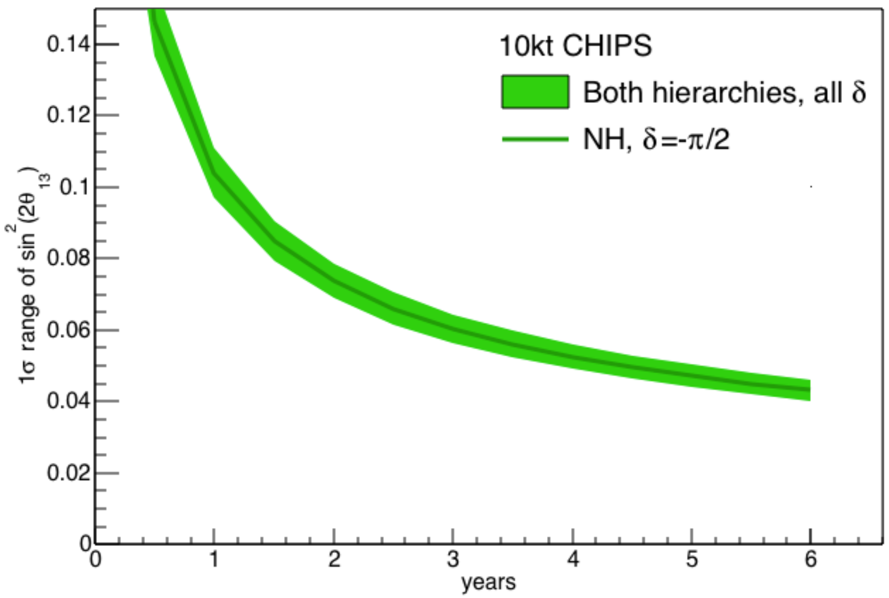




Hopes and Desires

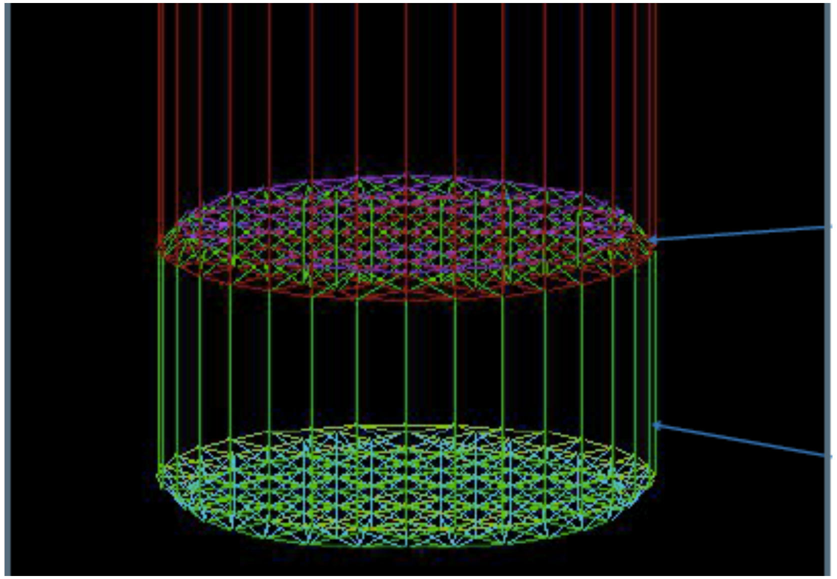
- by 2019 we could possibly have 10kt instrumented in the water
  - Depends on available cash/PMTs
- We have proved the background rejection for 6% coverage at a level of that used in original simulations (10” PMT with 10% coverage with old SuperK efficiencies)
- A lot more work can be envisaged reagarding the reconstruction algorithms
- Also, google NN has been shown to work very well at NOVA
- We should to be able to measure θ_{13} with water in NuMI

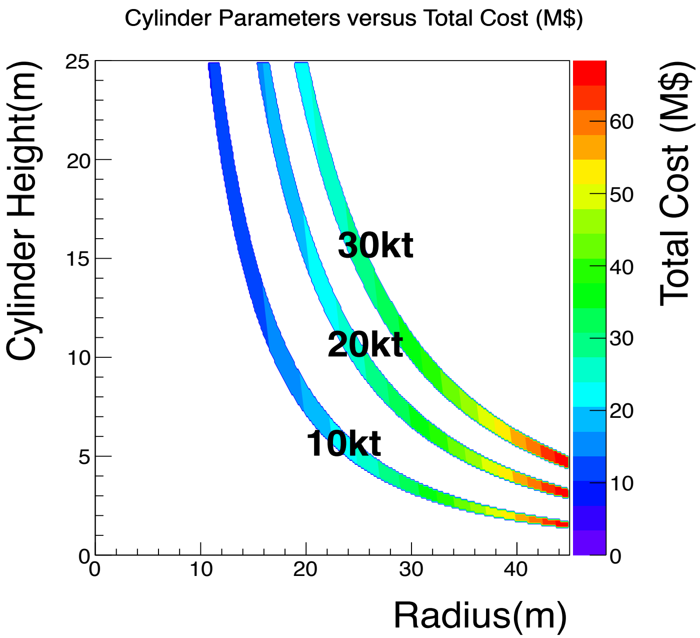


Mechanical Design

- Work on-going on the mechanical design
  - Separate planes of PMTs easily attached
- Structure will be built on and into the water
  - Model is to use undergraduate labor a la NOνA for both module construction and integration
- Neutral buoyancy will be designed in to our advantage
- Largest possible structure should be considered
  - CHIPS-10 would have a 20-30m diameter footprint depending on cost

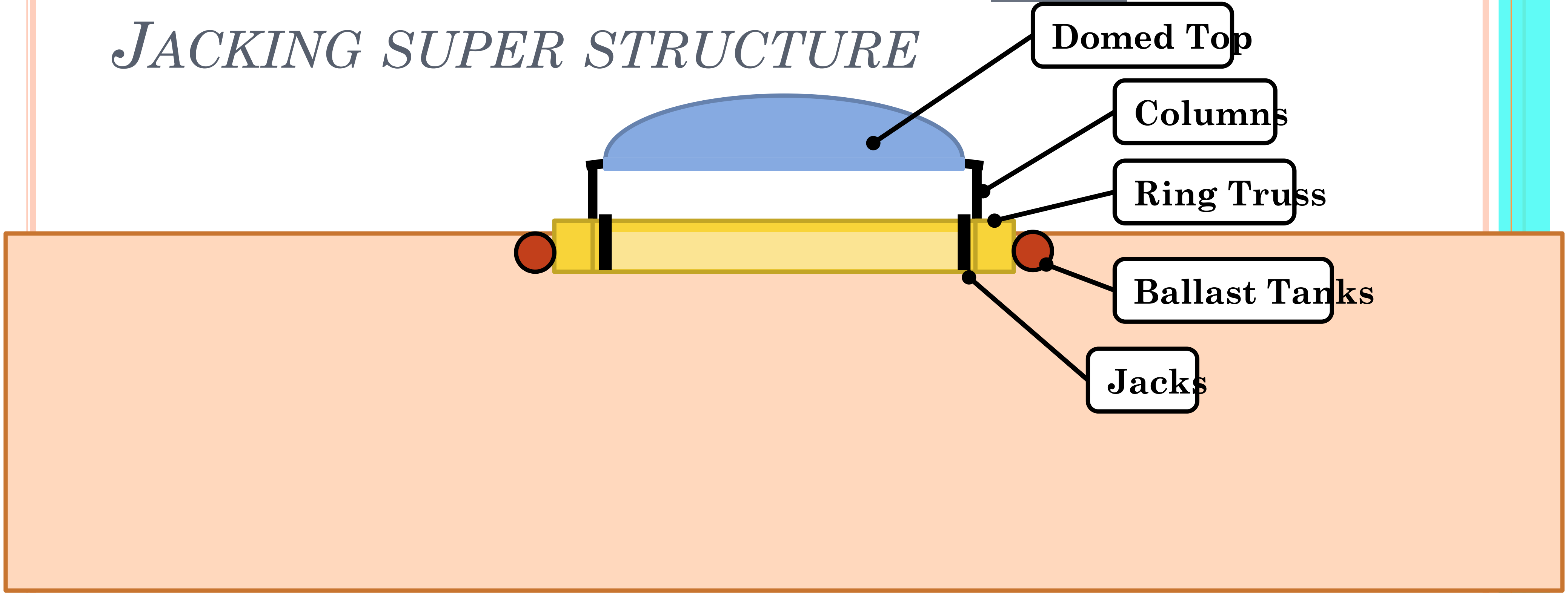
Mechanical Structure





- New idea is to hang bottom spaceframe end cap from top one with Dyneema ropes (used in Km3Net)
- Allows volume to grow if more PMTs are available
- Saves 50% cost of the spaceframe sides
- PMT planes attached to ropes
- Make footprint large enough: bang for buck is impressive for walls

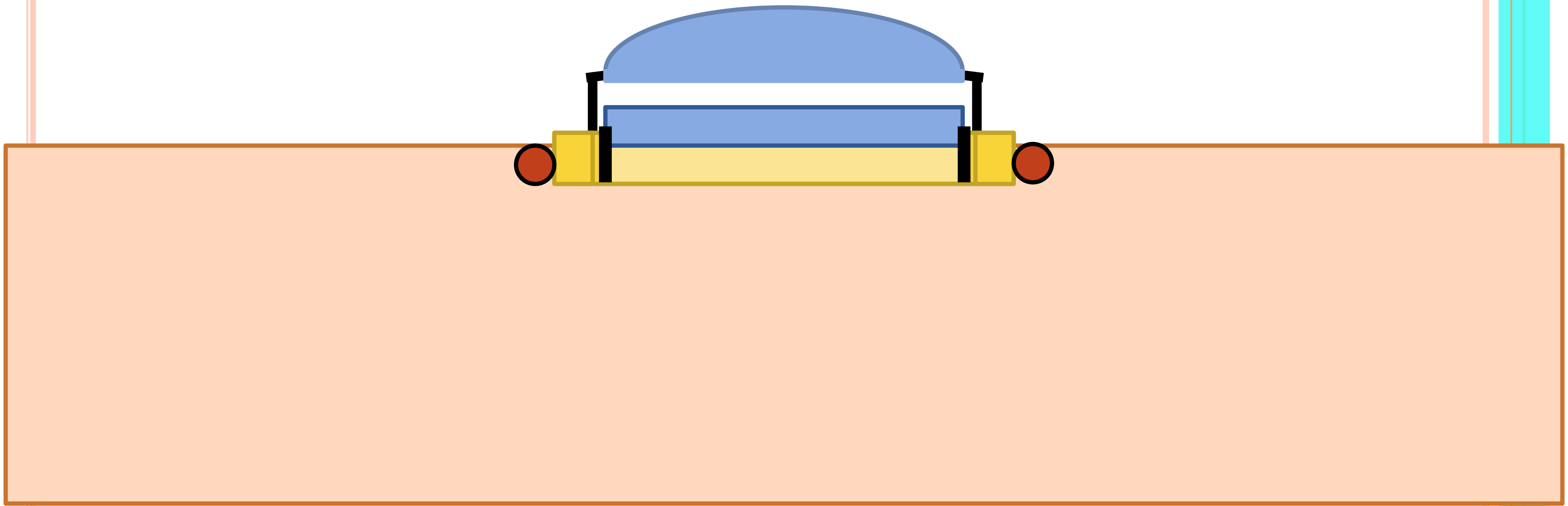
SPACEFRAME AND LINER: TOP
JACKING SUPER STRUCTURE



- Domed roof self-supporting in air
- Supported by circumferential columns
- Columns supported by floating ring truss equipped with ballast tanks
- Entire assembly built next to shore with crane support
- Floating ring truss provides work surface
- Temporary curtain around circumference to keep inside of detector clean
- Dome's roof could be equipped with a radial crane

SPACEFRAME AND LINER: TOP

JACKING SUPER STRUCTURE

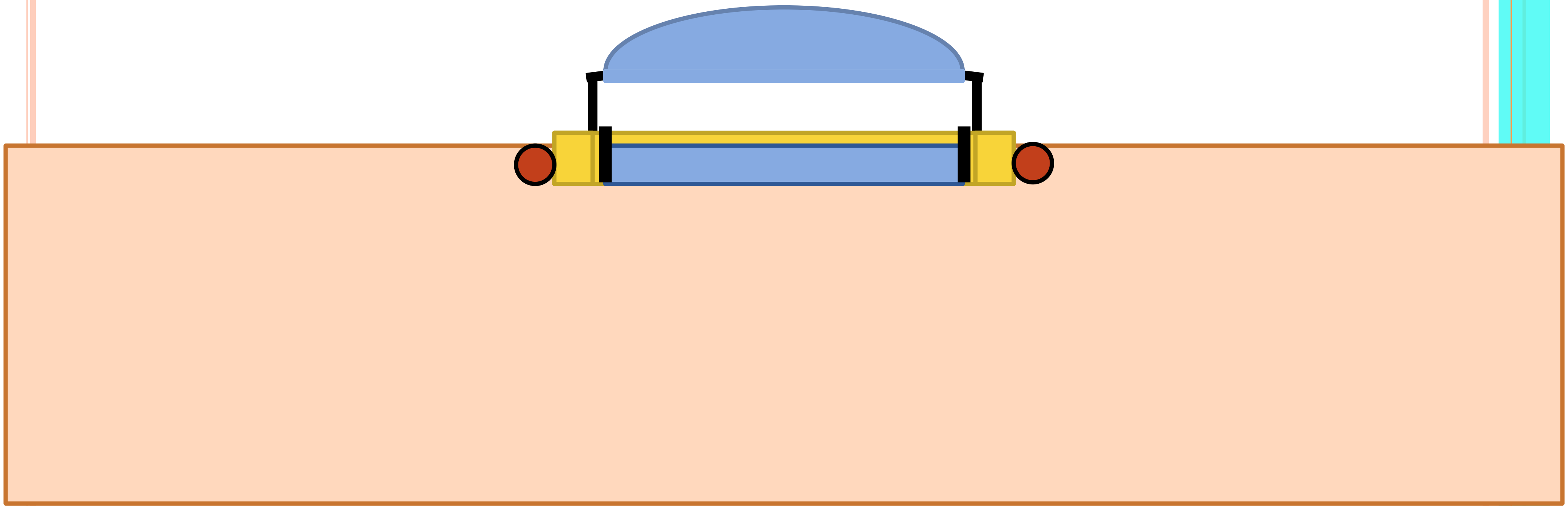


Assembly sequence on water

1. Build floor and first wall layer. The wall layer also attaches to the floating ring jacks

SPACEFRAME AND LINER: TOP

JACKING SUPER STRUCTURE

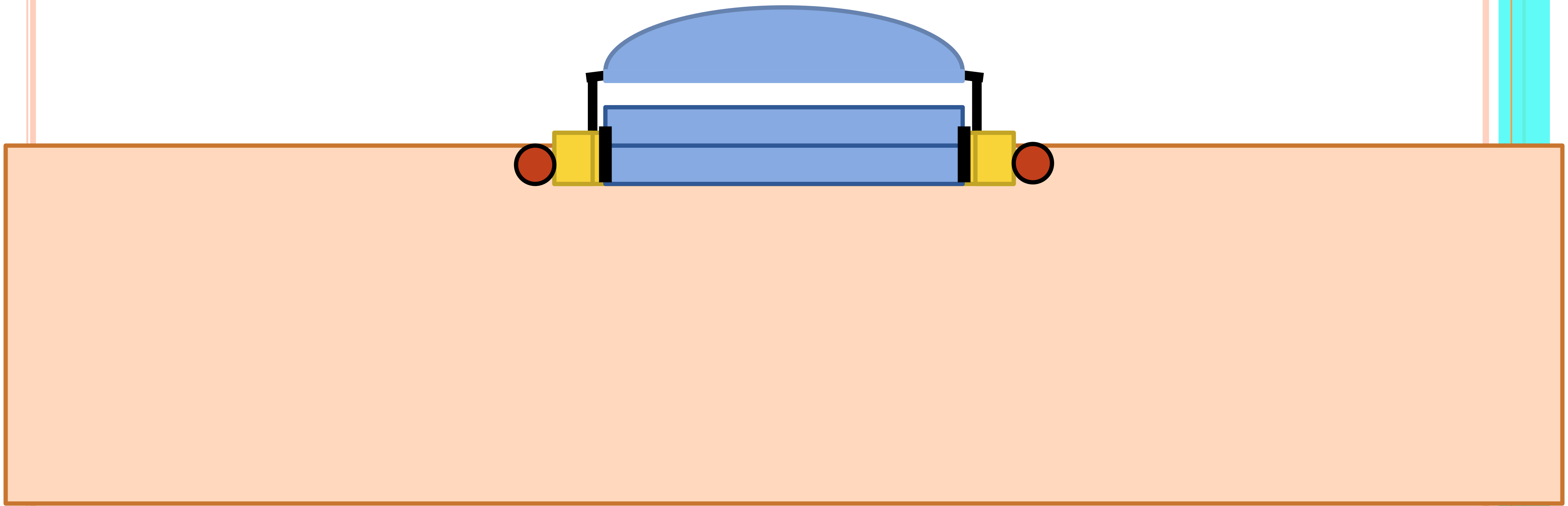


Assembly sequence on water

1. Build floor and first wall layer. The wall layer also attaches to the floating ring.
2. First wall layer "climbs" down the floating ring into the water as it is filled.

SPACEFRAME AND LINER: <u>TOP</u>

JACKING SUPER STRUCTURE



Assembly sequence on water

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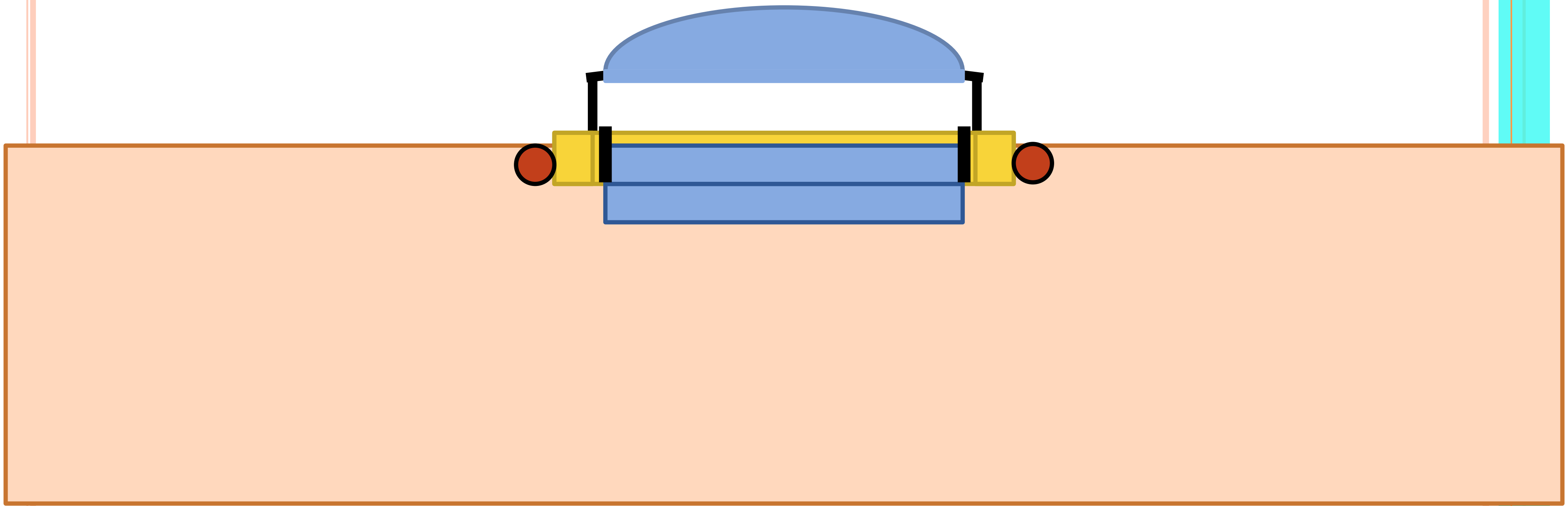
3. Build second wall layer.

SPACEFRAME AND LINER: TOP
JACKING SUPER STRUCTURE



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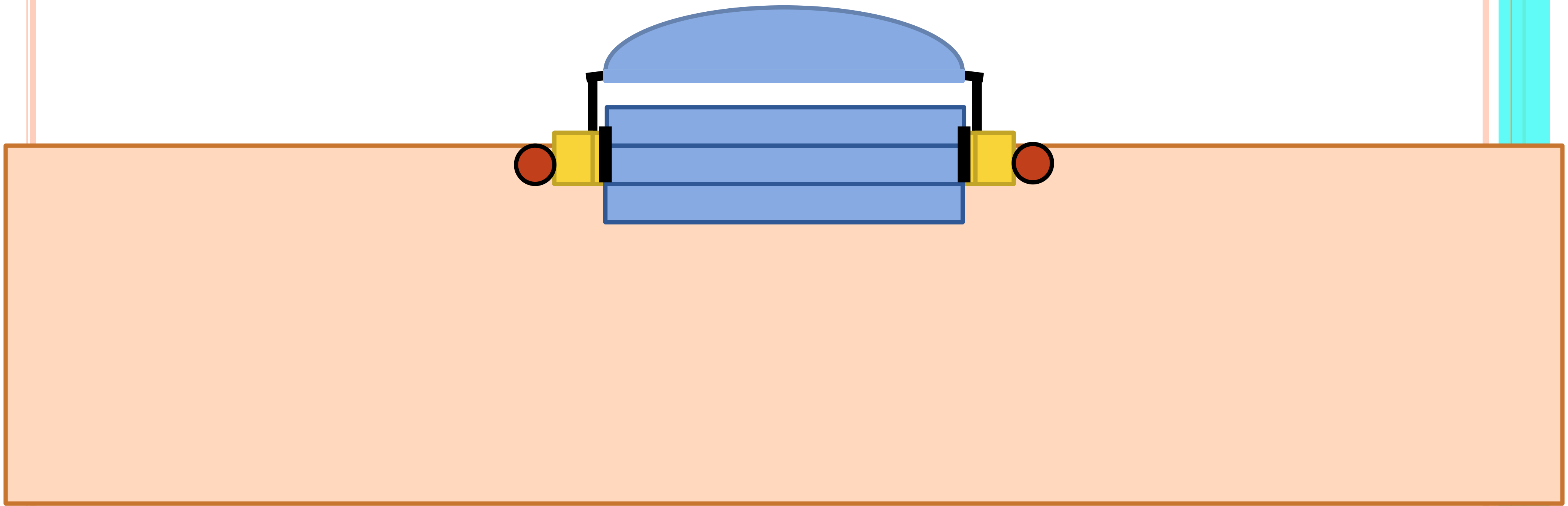
3. Build second wall layer.
4. As layers are added the floor and wall assembly successively climbs down.

SPACEFRAME AND LINER: TOP
JACKING SUPER STRUCTURE



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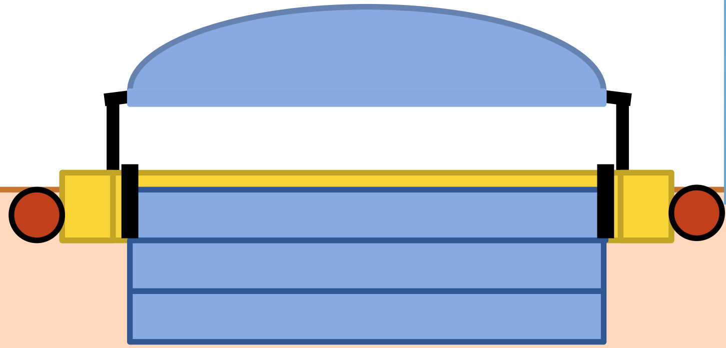
SPACEFRAME AND LINER: TO

JACKING SUPER STRUCTURE



Similar to how a tower crane assembles itself

Assembly sequence on water

1. Build floor and first wall layer. The wall layer also attaches to the floating ring.
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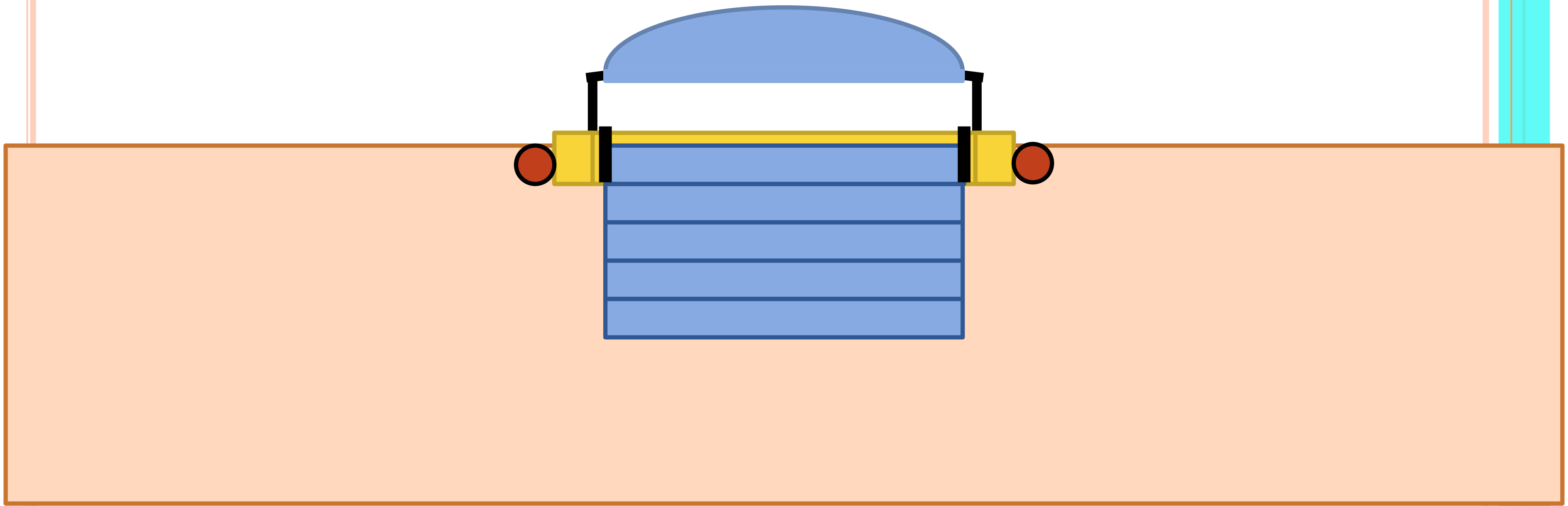

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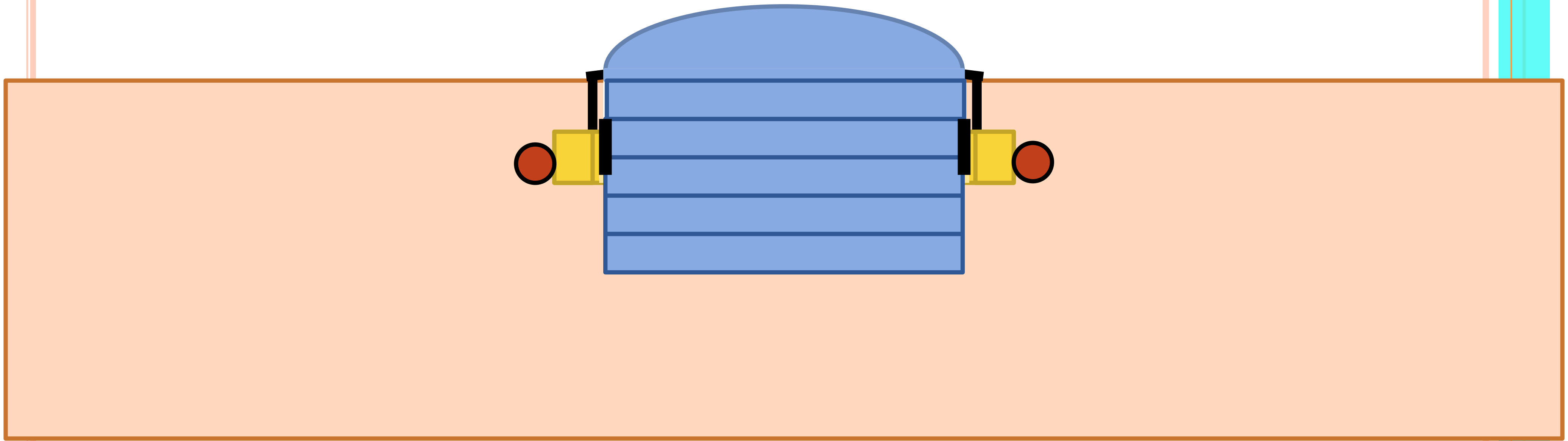

Assembly sequence on water

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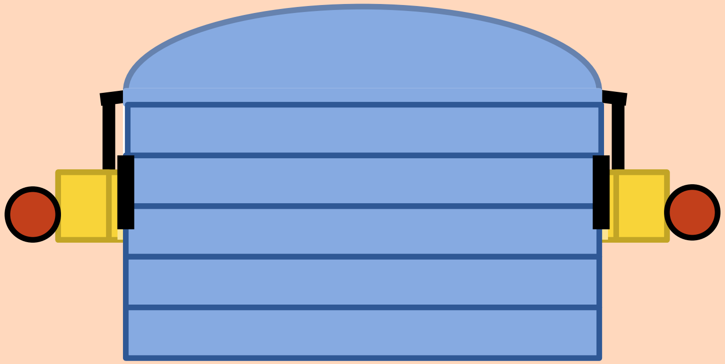
2. First wall layer "climbs" down the floating ring into the water as it is filled.
3. Build second wall layer.
4. As layers are added the floor and wall assembly successively climbs down.
5. After all wall layers are assembled, ballasts are adjusted and the ring and top climb down the wall. A seal is made at the perimeter seam.

SPACEFRAME AND LINER: TOP
JACKING SUPER STRUCTURE

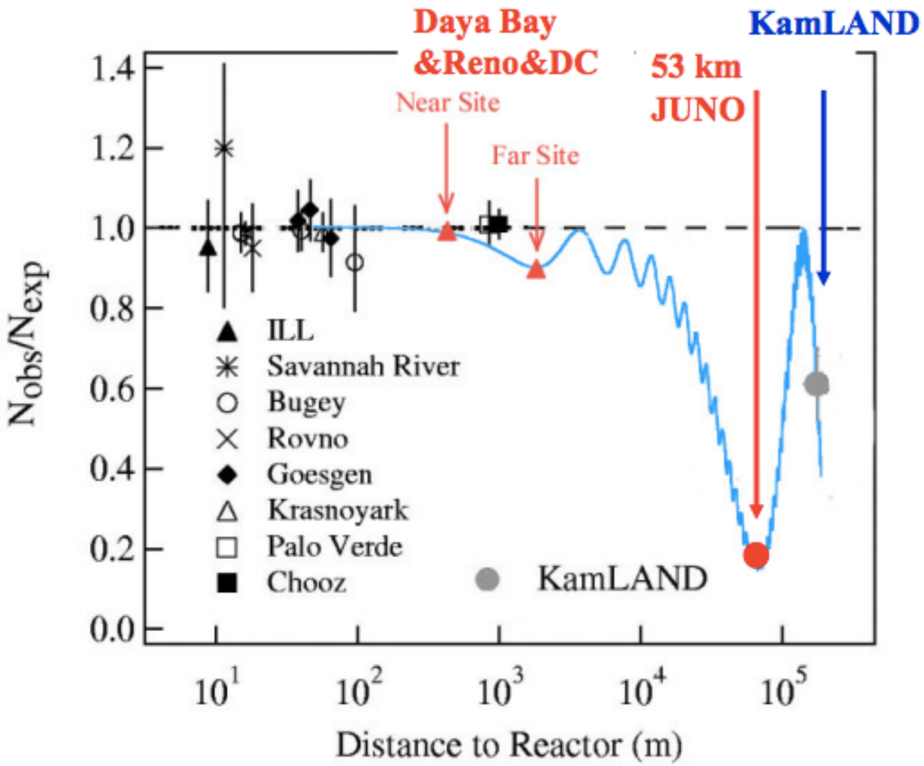


(Lowering)

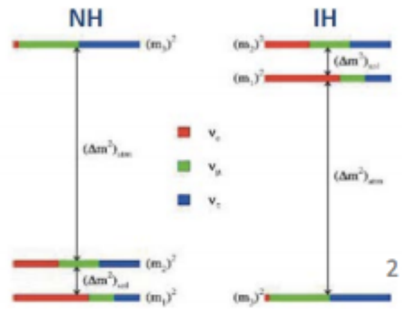
Additional comments
- The ring truss may also be used for rigging and mooring.
- A top dome that emerges above the water line will require a spaceframe or geodesic dome structure – despite wall design choice – due to large self-supporting span.

THE FURTHER FUTURE, JUNO, STARTING 2022

JUNO physics summary



- **20 kton LS detector**
- **~3 % energy resolution-the greatest challenge**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 3 mixing parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Sterile neutrino**
  - ⇨ **Atmospheric neutrinos**
  - ⇨ **Nucleon Decay**
  - ⇨ **Exotic searches**



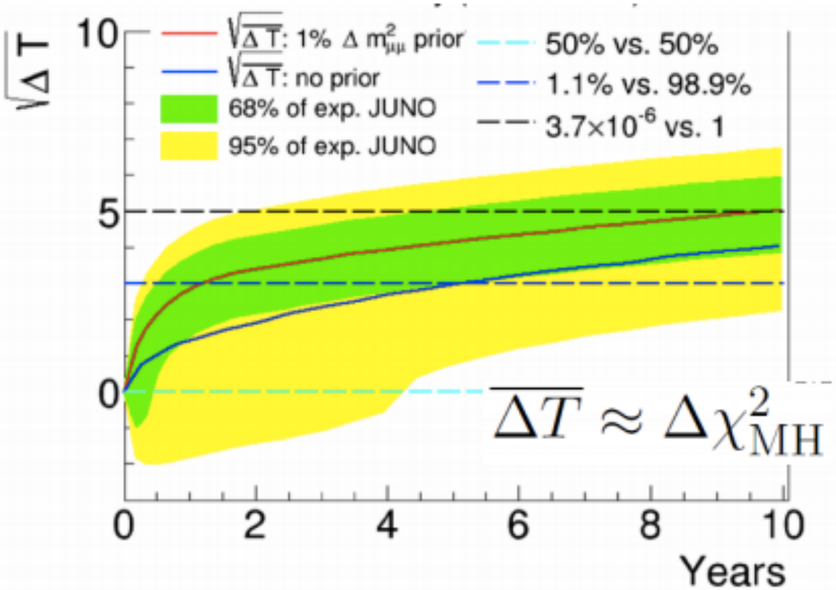
Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

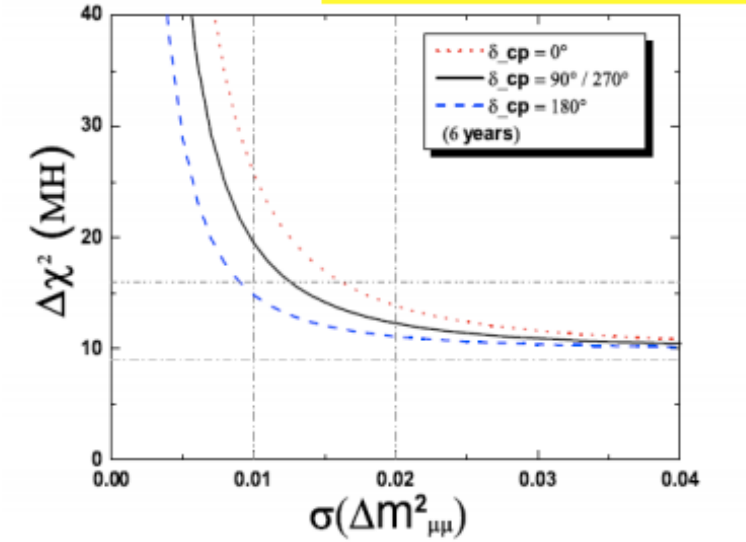
THE FURTHER FUTURE, JUNO, 2022

Summary of MH Sensitivity

PRD 88, 013008 (2013)	Relative Meas.	$\Delta m^2_{\mu\mu}$ from LBL Expts
Statistics only	4σ	5σ
Realistic case	3σ	4σ

Baseline: 53 km
Fiducial Volume: 20 kt
Thermal Power: 36 GW
Exposure Time: 6 years
Proton content 12%
en. res. 3%



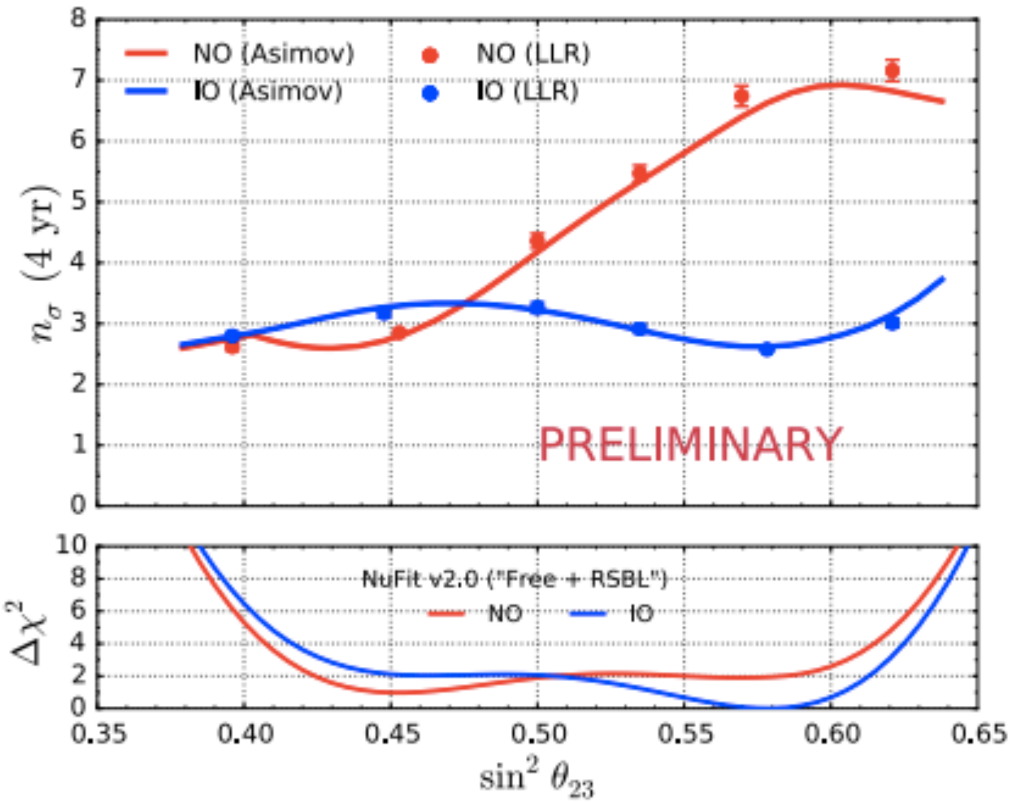


	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{\rm MH}$	+16	−4	−1	−0.5	−0.1	+8

Could be fast: depends on error on $\Delta m_{\mu\mu}$!

PINGU

- Independent measurement 5 years from start date, 2022-2027?
- 3σ in 4 years, or 3 years with external prior



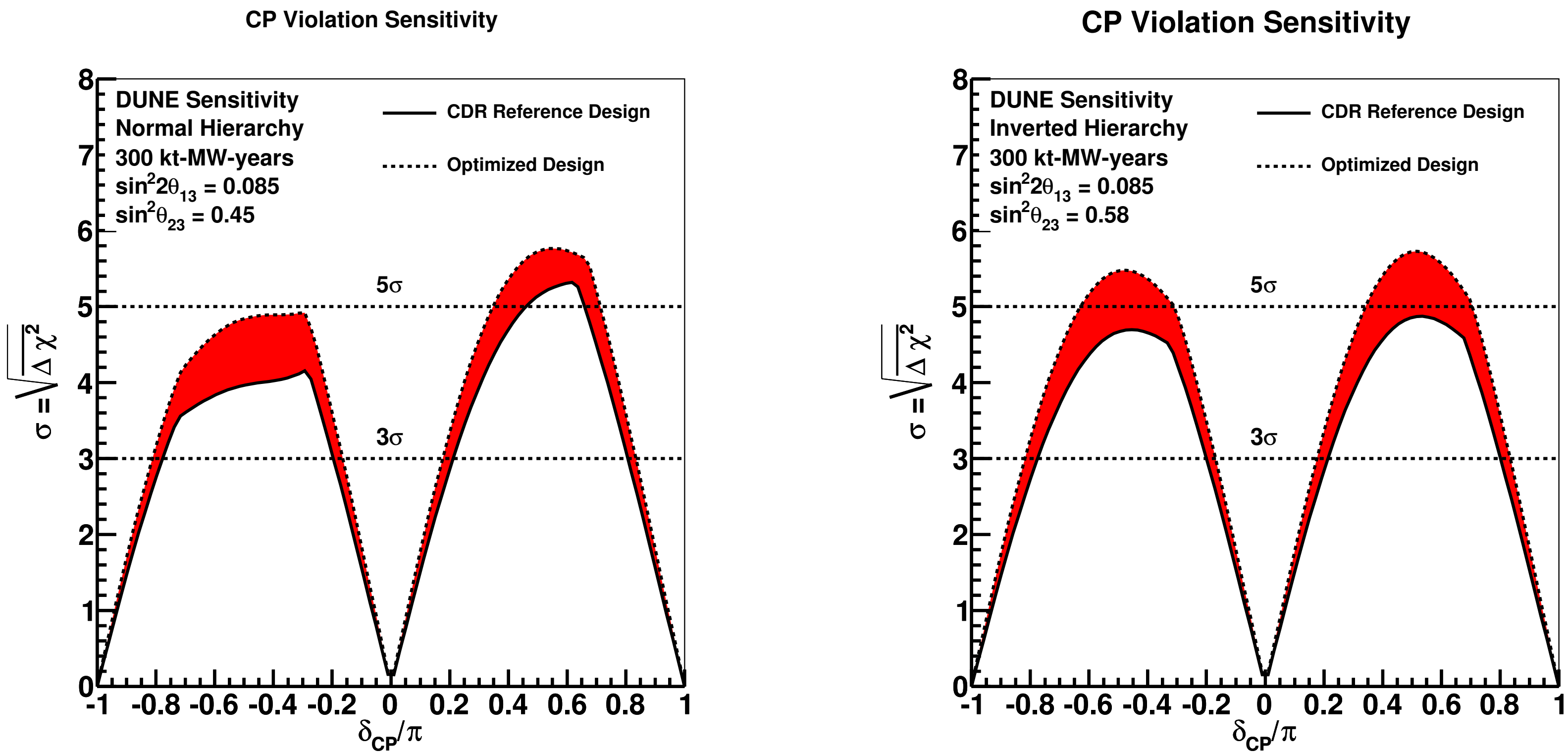
Fully deployed PINGU data only. Addition of partial deployment PINGU data and multi-year DeepCore data will improve sensitivity

- Combination of signal in track and cascade channel
- Sensitivity from pseudo-data set based log-likelihood ratio (LLR) and Asimov analysis methods are in good agreement

DUNE Physics: Official timeline : 2032 for this sensitivity
CP Violation Sensitivity

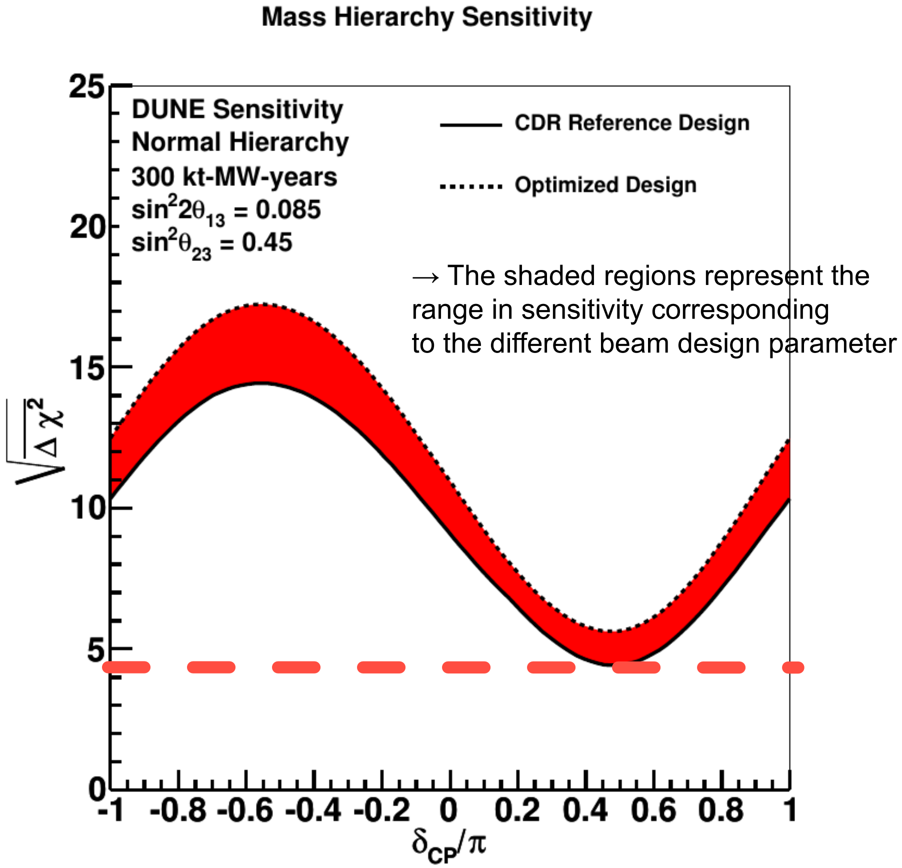
Sensitivity to CP Violation, after 300 kt-MW-yrs
(3.5+3.5 yrs x 40kt @ 1.07 MW)

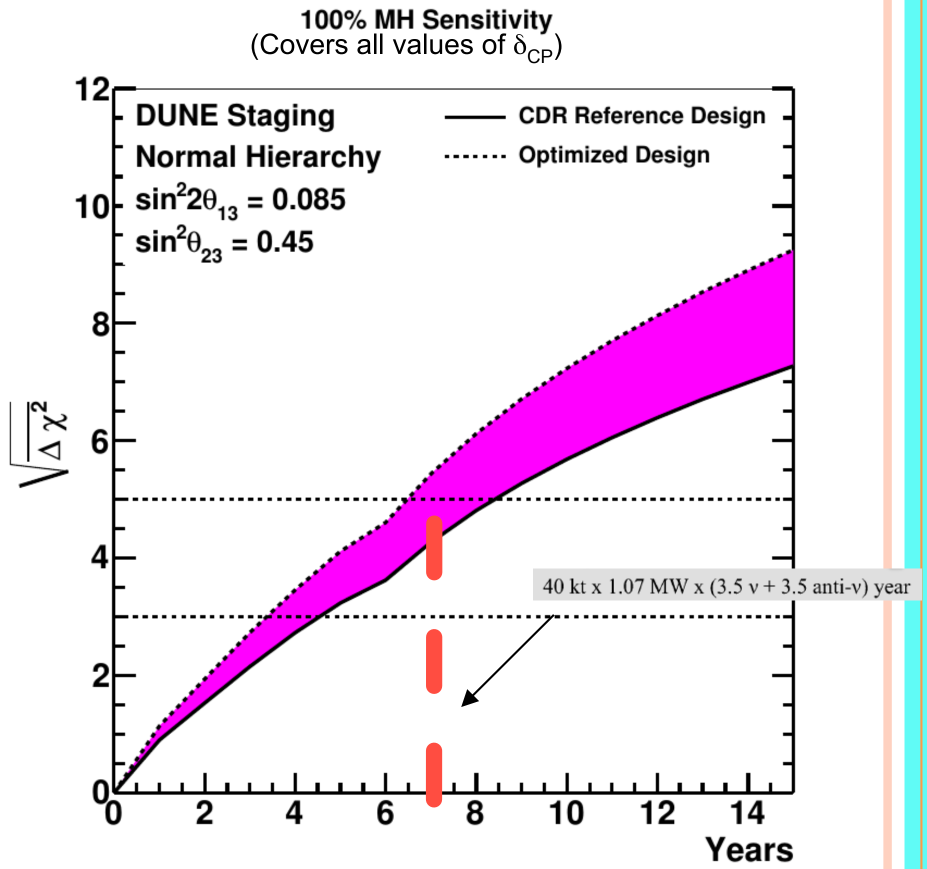
(Bands represent range of beam configurations)



DUNE Physics: MH Sensitivity

Discrimination (between NH and IH) parameter as a function of the unknown δ_{CP} for an exposure of 300 kt·MW·year (40 kt·1.07 MW·7 years).





→ The minimum significance (the lowest point on the curve on the left) where the mass hierarchy can be determined any value of δ_{CP} as a function of years of running

Official timeline : 2032 for this sensitivity

Summary and personal conclusion

- The neutrino oscillation parameter list is being ticked off very fast!
- Each new neutrino conference shows significant progress
- It looks like things could be wrapped up very soon wrt δ_{cp}
- Personal feeling is that by 2022 we should know the MH, and we should know that $\delta_{CP} \neq 0$ at (***at least***) 3σ
  - Impact of JPARC upgrade should not be underestimated
- Juno should confirm MH at 3-4σ by 2027, combination with NOνA and T2K could be 5σ
  - Also, great cross check of solar parameters in a completely different environment
- DUNE will confirm this all at 5σ by 2032
  - VERY exquisitely reconstructed events !

Where I hope to be in 2032