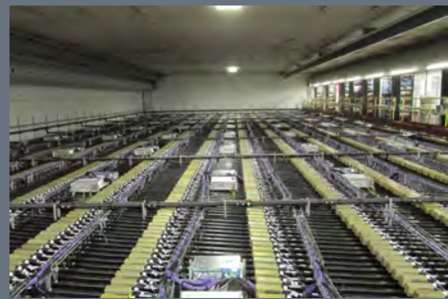
Neutrino Oscillations at Work



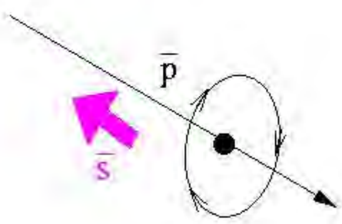
- Introduction to neutrino oscillations
- Recent results from around the world
- CHIPS : towards the precision solution
- Summary and Outlook

Building Blocks of Nature

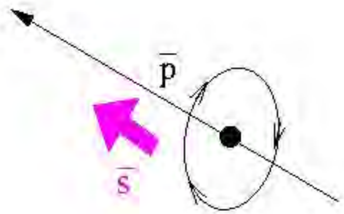
- Quarks have fractional charge
  - proton=uud (d=-1/3, u=+2/3)
  - Neutron=udd
- Leptons have unit charge
  - Electron = -1
  - Muon = -1 (heavier than electron)
- Gauge bosons carry the forces
  - Strong, Weak and Electromagnetic
  - Photon = EM Force
  - Gluon = Strong Force
  - W^{+-},Z = Weak Force

NEUTRINOS

- Neutrinos only interact with the weak interaction.
- They are fermions (spin ½) like quarks, and charged leptons
- When starting out studying neutrinos, we need to look first at what we know about the weak interaction
- Its very weak, and makes measuring neutrino properties quite difficult
- It is also quite unique: it violates parity…



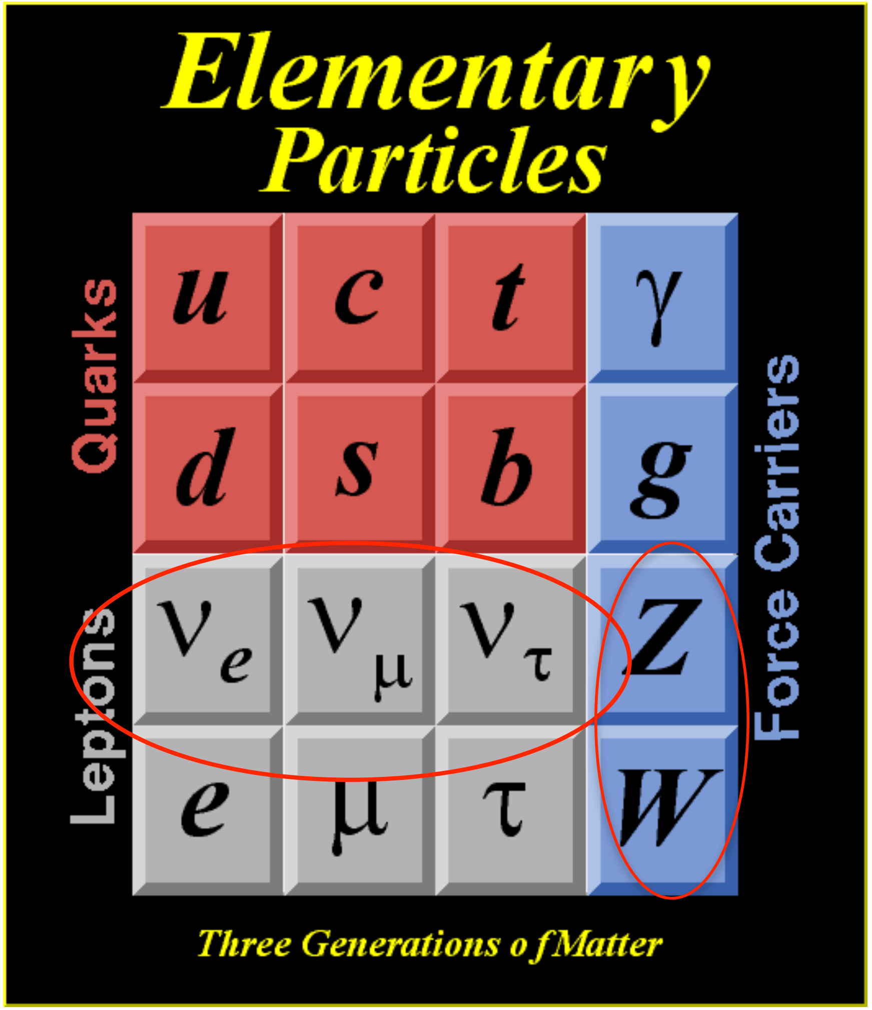
negative helicity



positive helicity

The Standard Model

- The SM is the most exquisitely tested theory known to man
  - 3 generations of quarks and leptons and 3 forces mediated by Gauge Bosons
  - Each family separated by ΔQ=1
- Neutrinos are the only neutral fermions and that makes them special
- Recently discovered Higgs particle leaves no doubt over its correctness
  - Gives mass to the Gauge Bosons
- One (gaping) hole remains in the SM : neutrinos must be massless, but they are not!



+ Higgs

PARITY VIOLATION

- The weak interaction only “sees” left handed fermions, and ignores right handed ones.

Parity Violation

- The weak interaction is parity violating. Yang and Lee predicted it, CS Wu 1957 proved it
- Life imitates science

- Only the men were "seen" by the Nobel committee
- Like the left-handed particles are only seen by the weak interaction

POPULARITY CHART OF THE FERMIONS

Fermion	Strong	EM	Weak
L.H. Quarks	X	X	X
R.H. Quarks	X	X	
L.H. Charged leptons		X	X
R.H. Charged leptons		X	
L.H. Neutrinos			X
R.H. Neutrinos			

- We do know that weak force only "sees" left-handed helicity states
- Connection between helicity and mass well known and general
- Leave out the RH neutrino (missing in weak interaction) by forcing the mass to zero

- We DON'T know
  - The neutrino state (Dirac or Majorana)
  - The masses of the three neutrino states
- But oscillation phenomenon tells us much more
  - Mass hierarchy
  - Do neutrinos violate Charge-Parity symmetry?

Weighing a neutrino

- OK, so why not just measure its mass?

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$p^+ \rightarrow n + e^+ + \nu_e$$

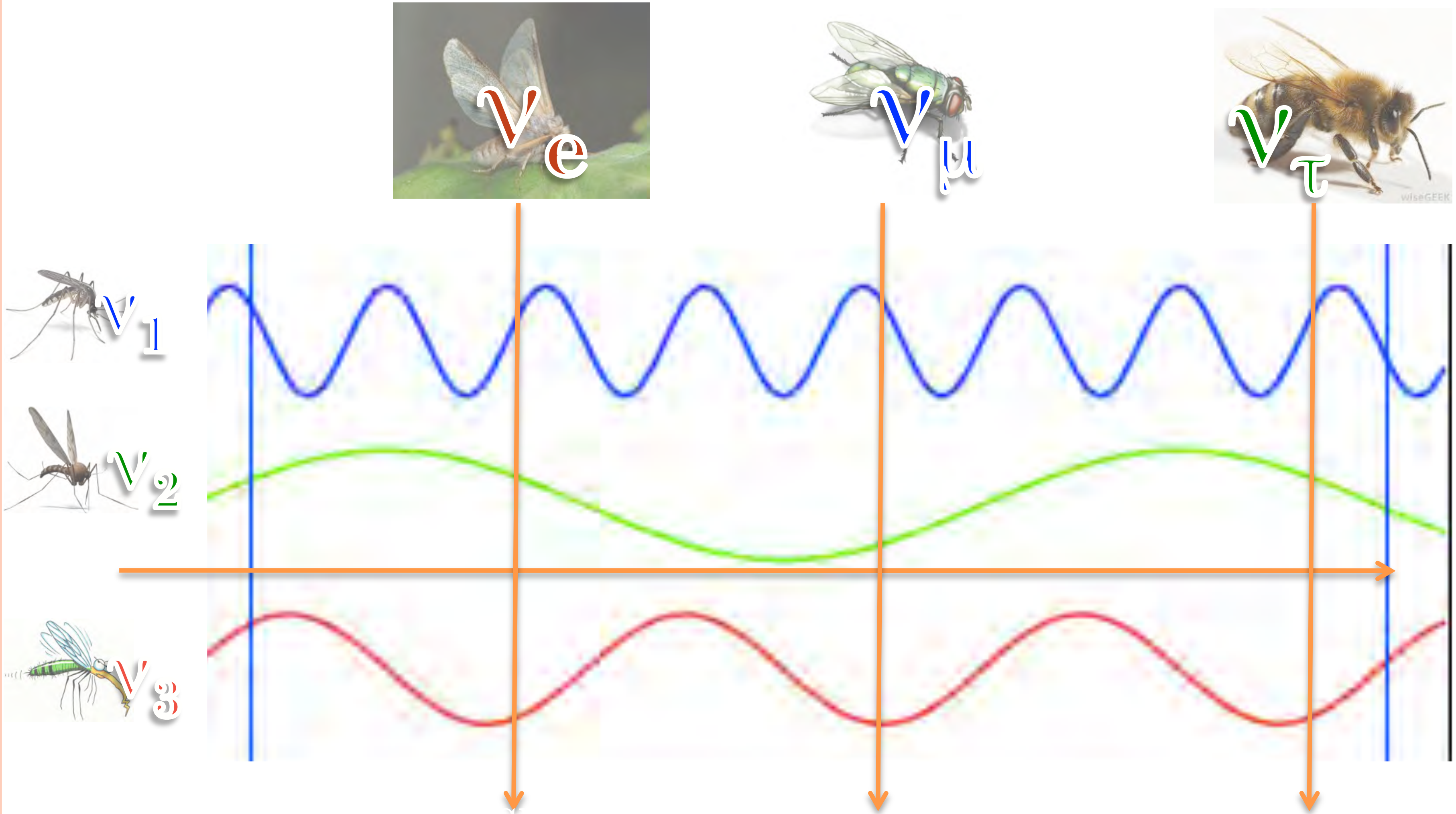
WEIGHING A NEUTRINO

ν_μ

Dynamic Range
Limitations

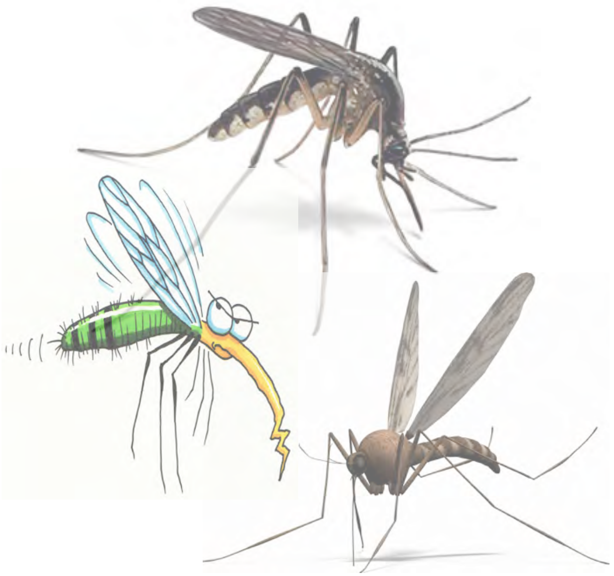
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Insect Oscillations



Wing beat BEAT frequency = weak state

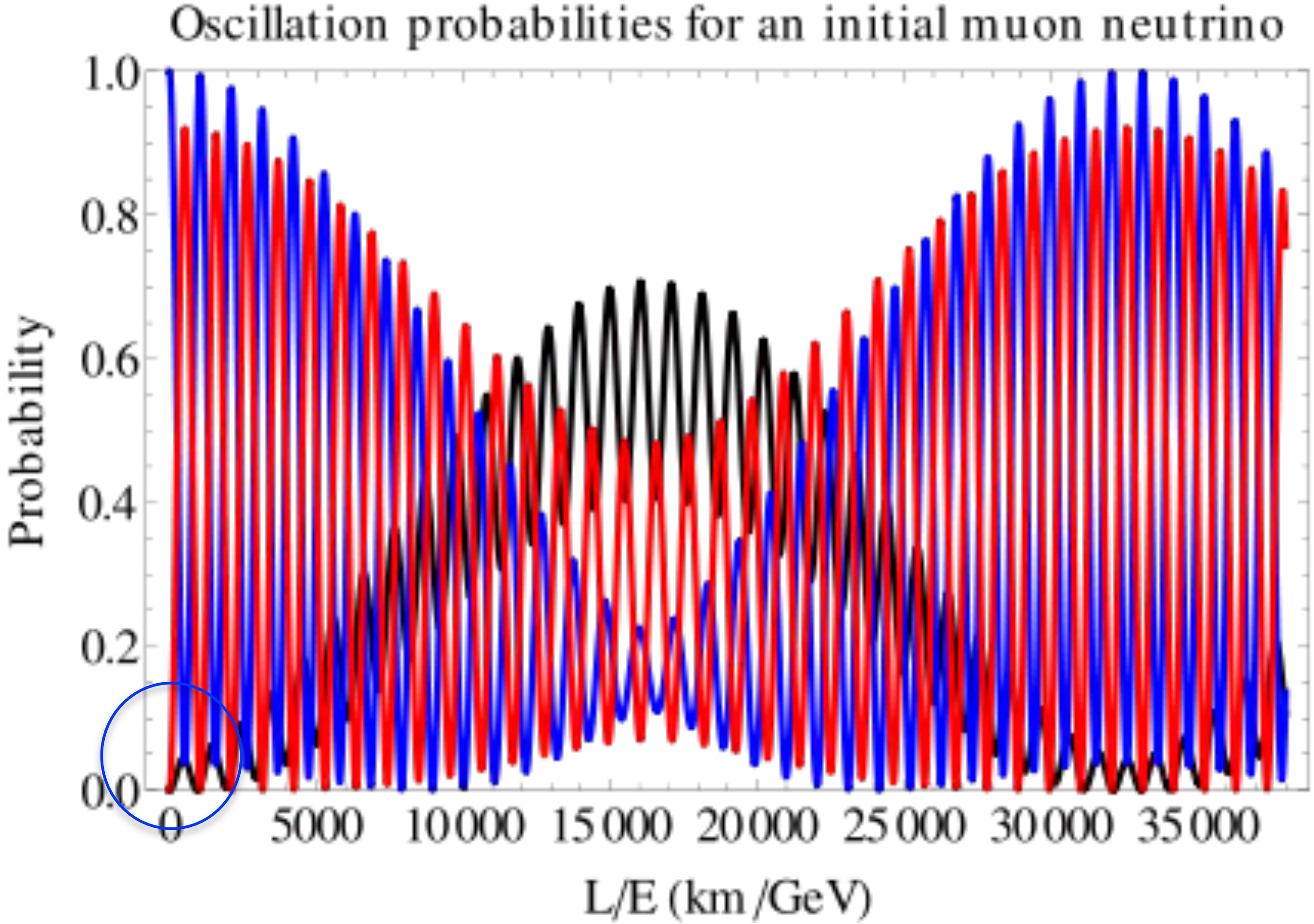
Leggit-Garg Inequality Violation



- MINOS data has evidence for the L-G inequality violation!
  - Formaggio, Kaiser and Murskyl, Phys. Rev. Lett. 117, 050402 (2016)
- The mosquitoes come in a group, and don't change from one to another en-route!
- Like Schroedingers cat is dead and alive all at the same time

NEUTRINO OSCILLATIONS IN REALITY

- The **disappearance experiments** start off with $\boldsymbol{\nu}_{\mu,e}$ and look for disappearance of $\boldsymbol{\nu}_{\mu,e}$ (no CP violation allowed)
- The **appearance experiments** start with $\boldsymbol{\nu}_{\mu}$ and look for appearance of $\boldsymbol{\nu}_{e}$ (CP violation IS allowed)
- L/E is (time) the experiment variable, for the known Δm^2s as shown



Reminder of the approach

Pontecorvo–Maki–Nakagawa–Sakata

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

- Looking at disappearance probability of ν_μ (or ν_e)

$$|\nu_\mu(t)>=U_{\mu 1}e^{-iE_1 t}|\nu_1>+U_{\mu 2}e^{-iE_2 t}|\nu_2>+U_{\mu 3}e^{-iE_3 t}|\nu_3>$$

Time evolution

$$\mathrm{P}(\nu_\mu\to\nu_\mu)=<\nu_\mu(0)||\nu_\mu(\mathrm{t})>$$

$$E_i=p+\frac{m_i^2}{2p}$$

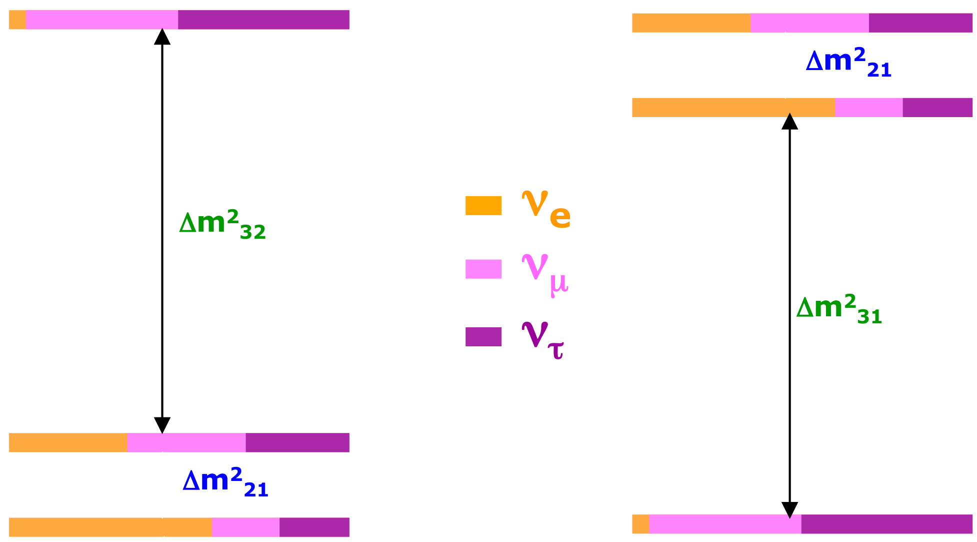
$$=U^*U(1-cos^2(E_1-E_2)t)+U^*U(1-cos^2(E_1-E_3)t)+U^*U(1-cos^2(E_2-E_3)t)$$

$$P(\nu_\alpha\to\nu_\beta)=\left|\sum_{i=1}^{3}U^*_{\alpha i}U_{\beta i}e^{-im_i^2 L/2E}\right|^2$$

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

Looking more closely

Pontecorvo–Maki–Nakagawa–Sakata

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

- Looking at **disappearance** probability of ν_μ (or ν_e)

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

- $\Phi_{32} = \Delta m^2_{23}$
- 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 $\sin^2\theta_{13}$ and δ_{cp}

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

- 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}

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

- Combining appearance and disappearance measurements tells us about the octant

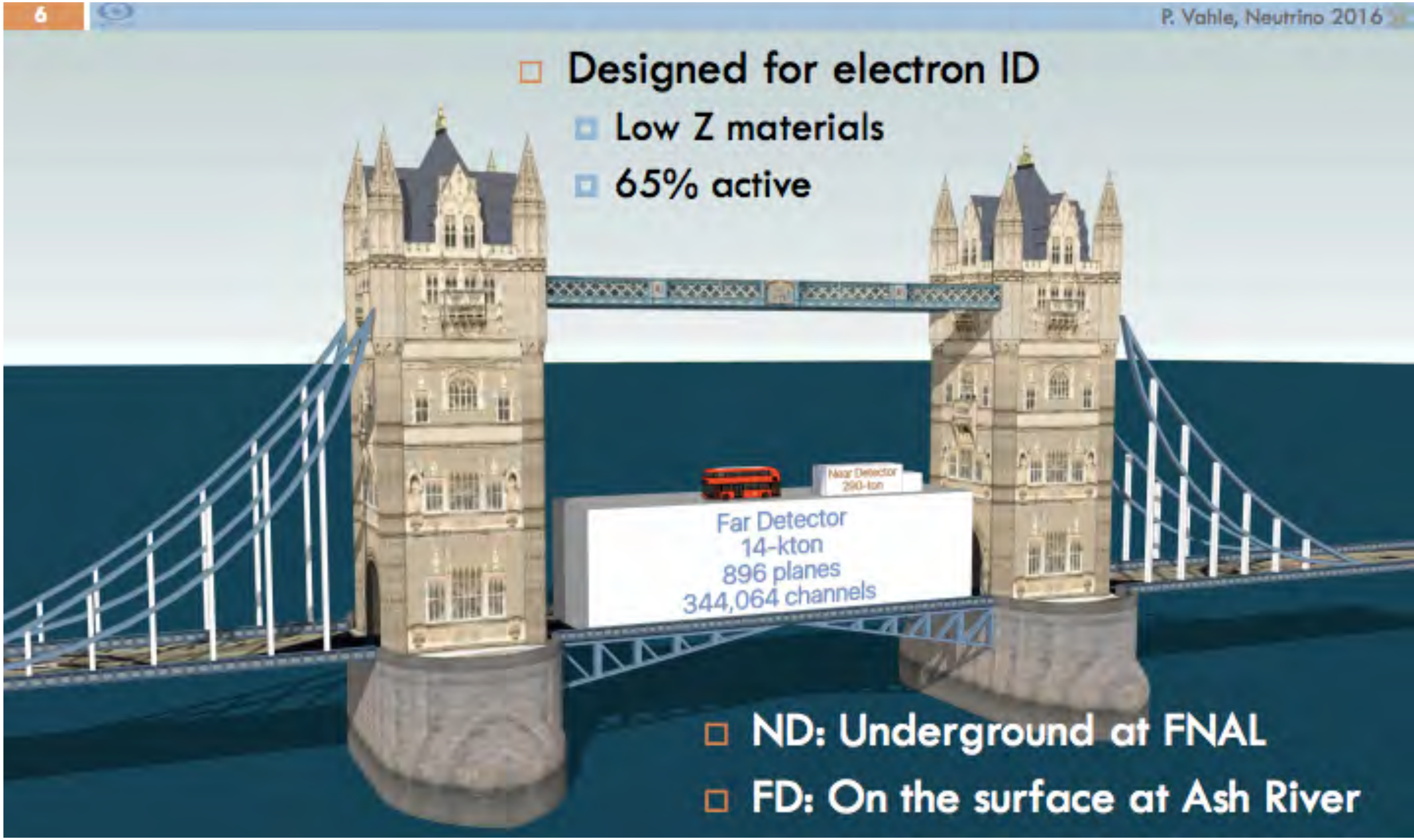
So why do we care?

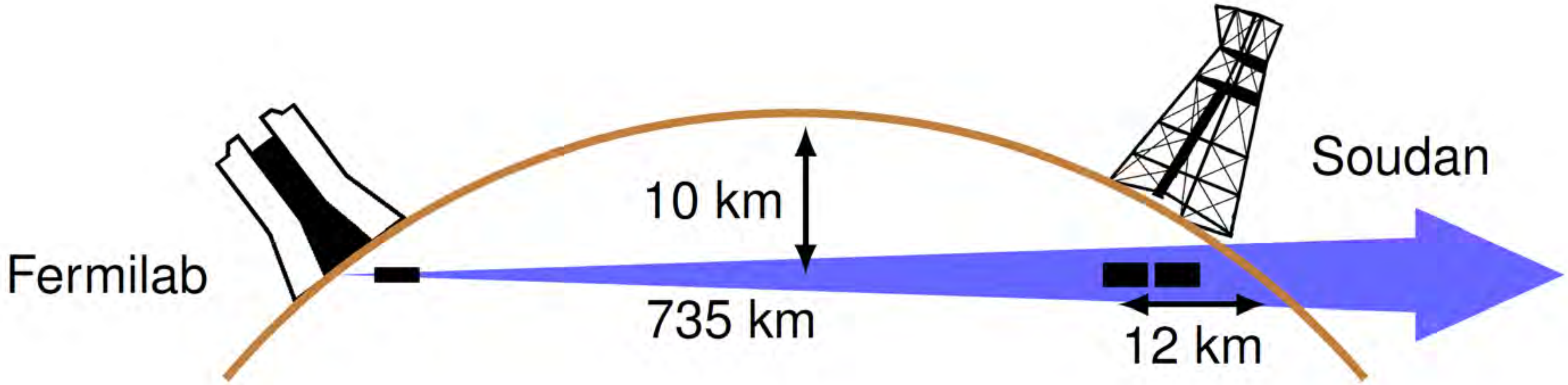
- Neutrinos are the most abundant of fundamental particles after photons
- The universe it full of them, and so is your head
  - Contribute to the mysterious dark matter
- Could they violate Charge Parity symmetry?
  - Neutrinos and anti-neutrinos behave differently
- They could have serious implications for cosmology
  - Baryon-anti-baryon asymmetry could be explained
  - Need L=2 transition allowed with Majorana Neutrinos

AROUND THE WORLD IN 15 MINUTES

All the new information about neutrino oscillation properties from the NEUTRINO 2016 Conference in London

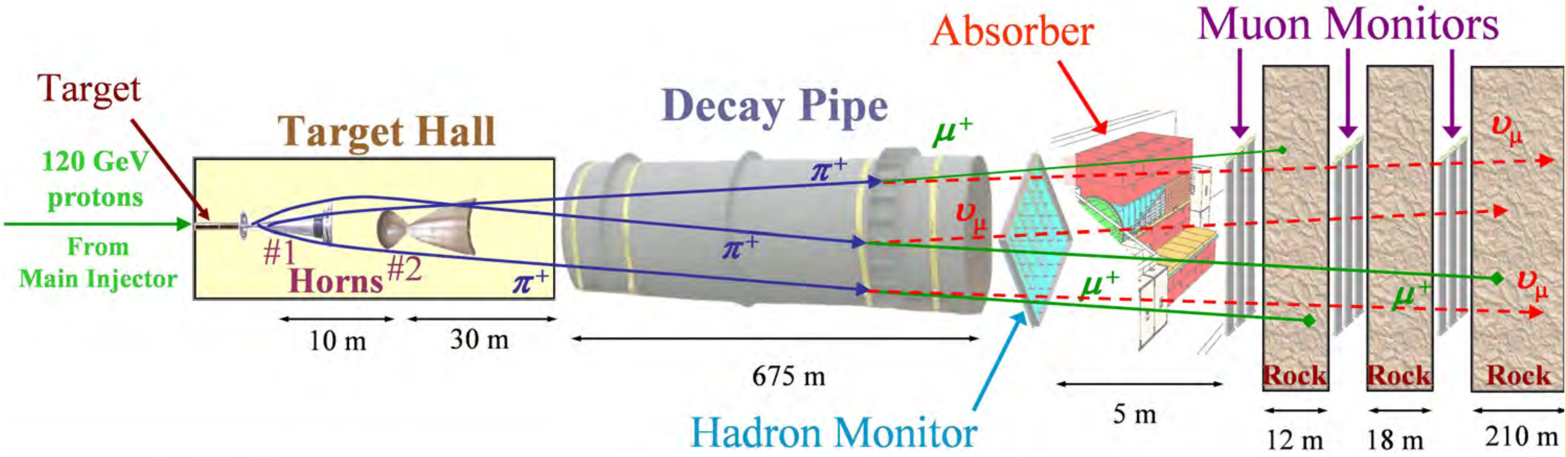
AT NEUTRINO 2016, LONDON
NOVA

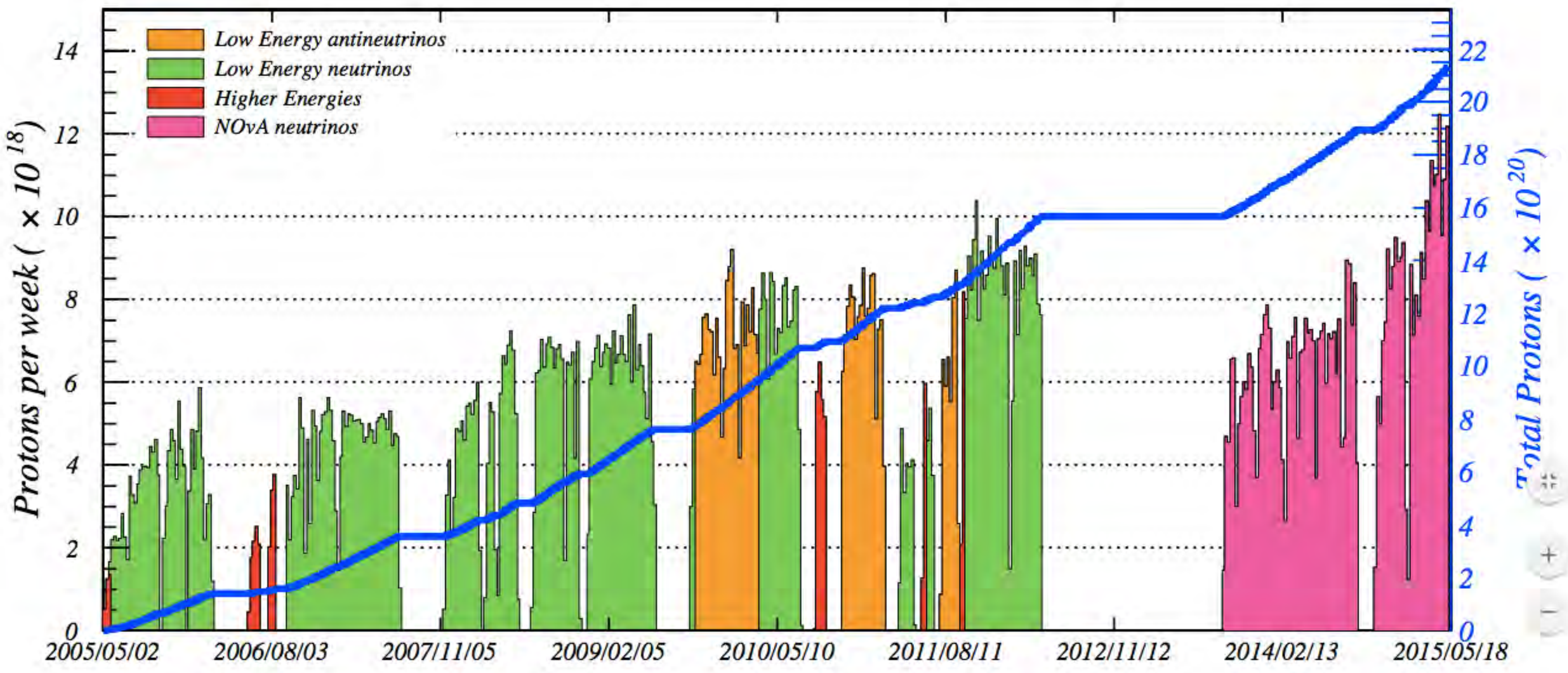




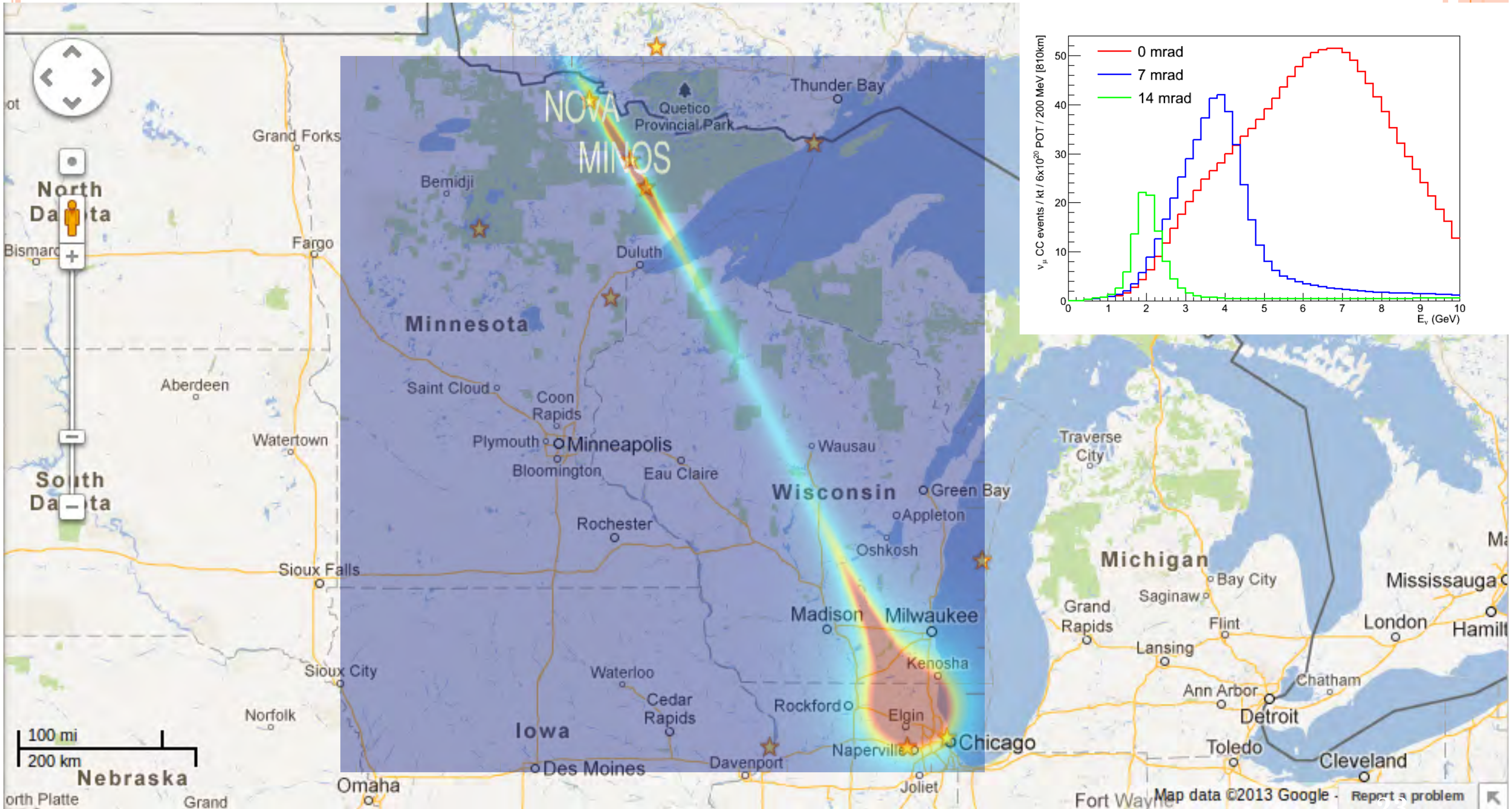
- Distances are macroscopic: 100s km for ν_μ, 100's m for reactor ν_e
- Neutrinos only interact weakly
  - Need massive detectors to find them
- Measure them at source, then at end
  - Compare to get oscillation signal

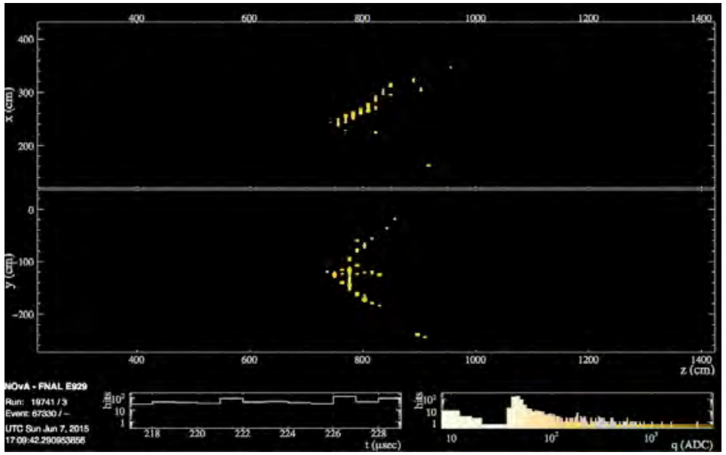
THE NUMI BEAM AT FERMILAB: BEST IN THE WORLD

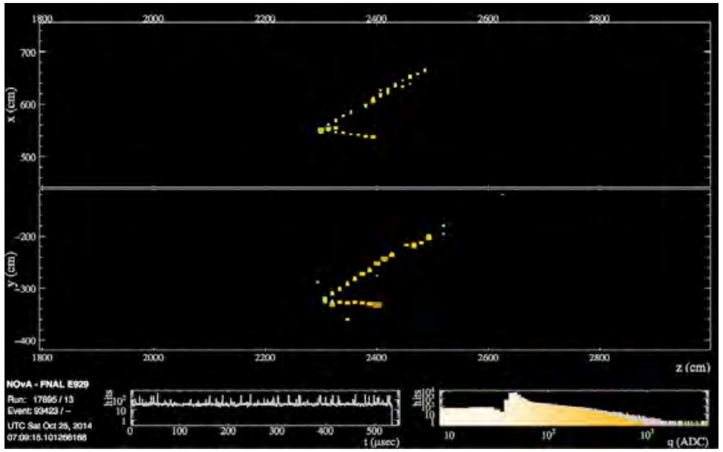


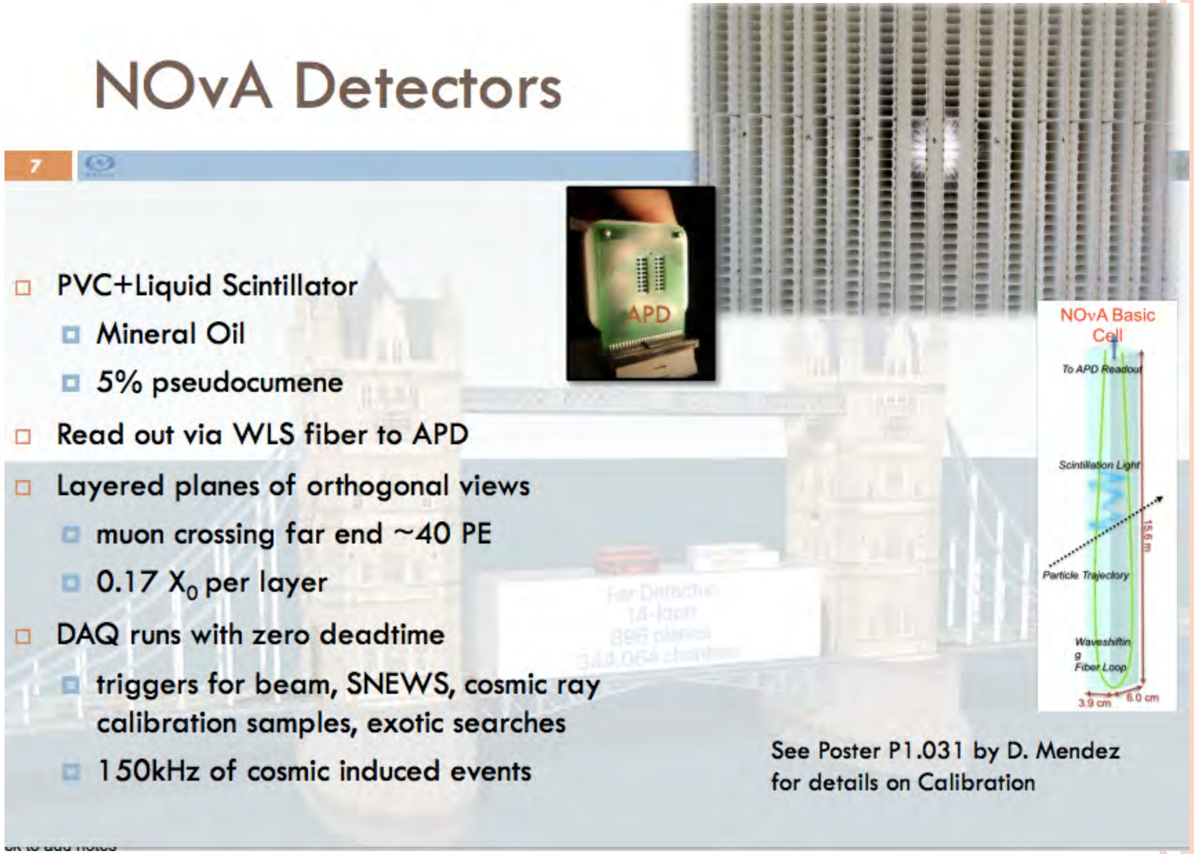


LOOKING AT THE NUMI BEAM : FLUX AT THE SURFACE









- NOνA event displays show very fine detail in this liquid scintillator detector
- Muon energy by range, 8% energy resolution

Disappearance

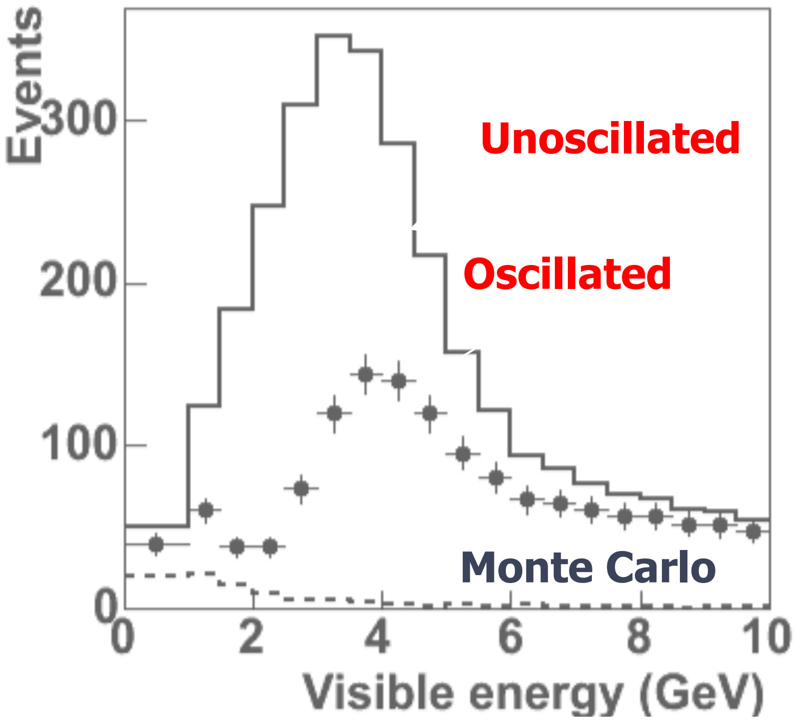
There's no CP violation in disappearance

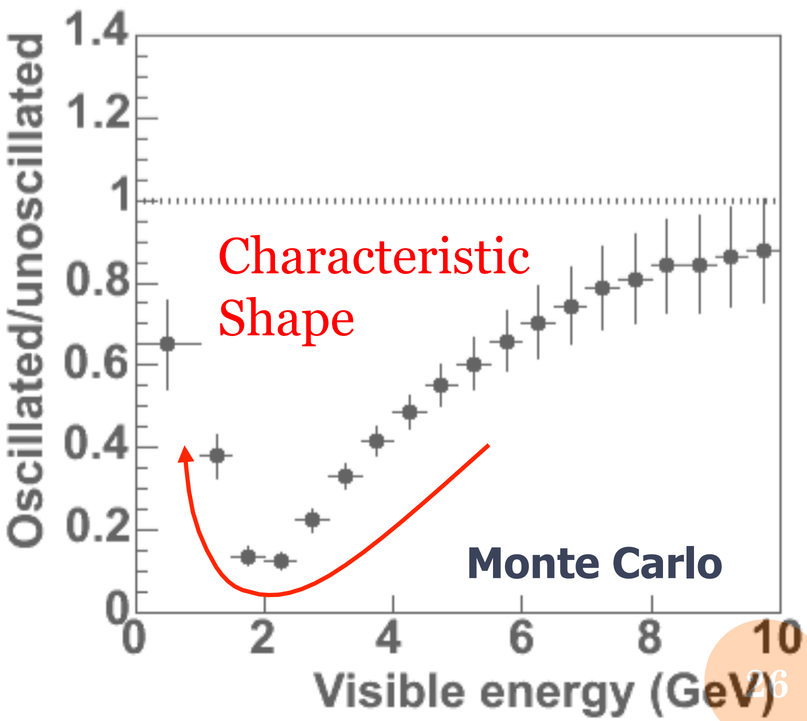
"there's no crying in baseball" : League of their Own

DISAPPEARANCE : 2 DETECTOR GOLD STANDARD

- Predict un-oscillated spectrum at the further detector using the nearer detector and knowledge of kinematics using 2-flavour approximation

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267\Delta m^2 L / E)$$





ν_μ disappearance

- Predict un-oscillated spectrum at the further detector using the nearer detector and knowledge of kinematics using 2- flavour approximation

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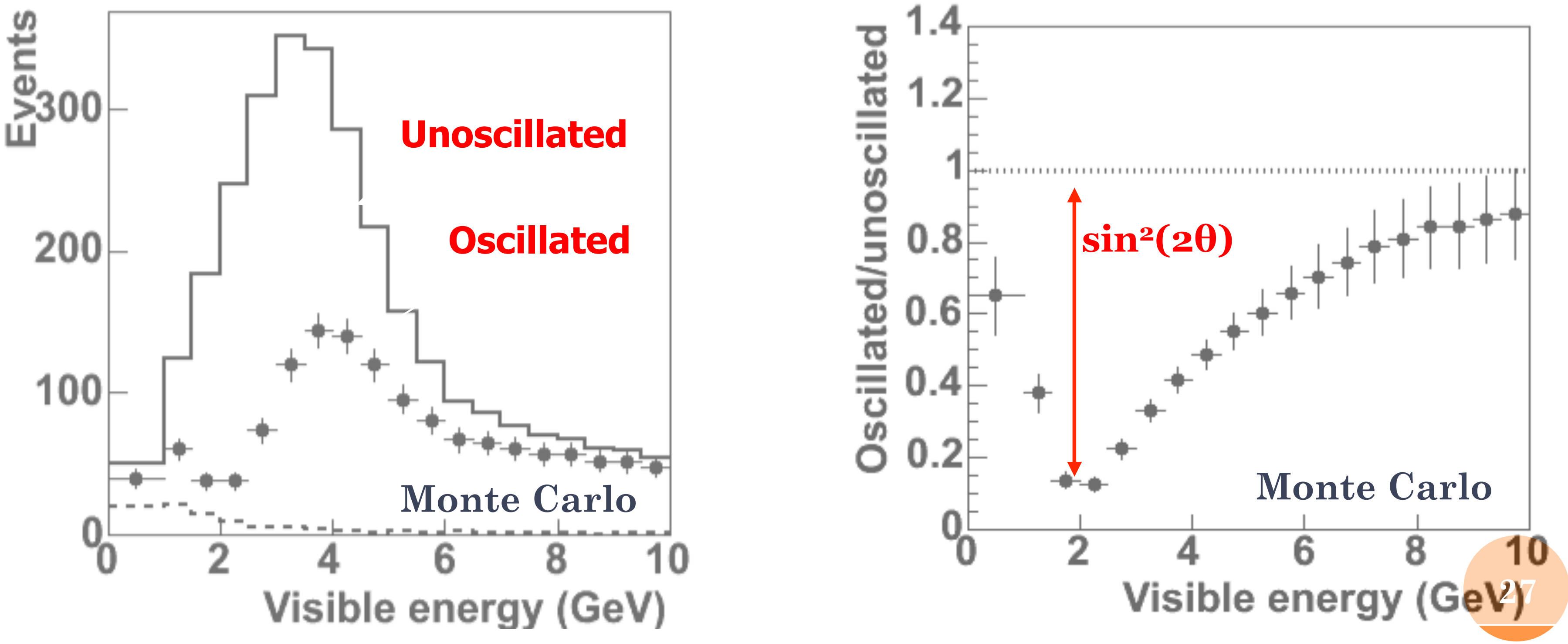

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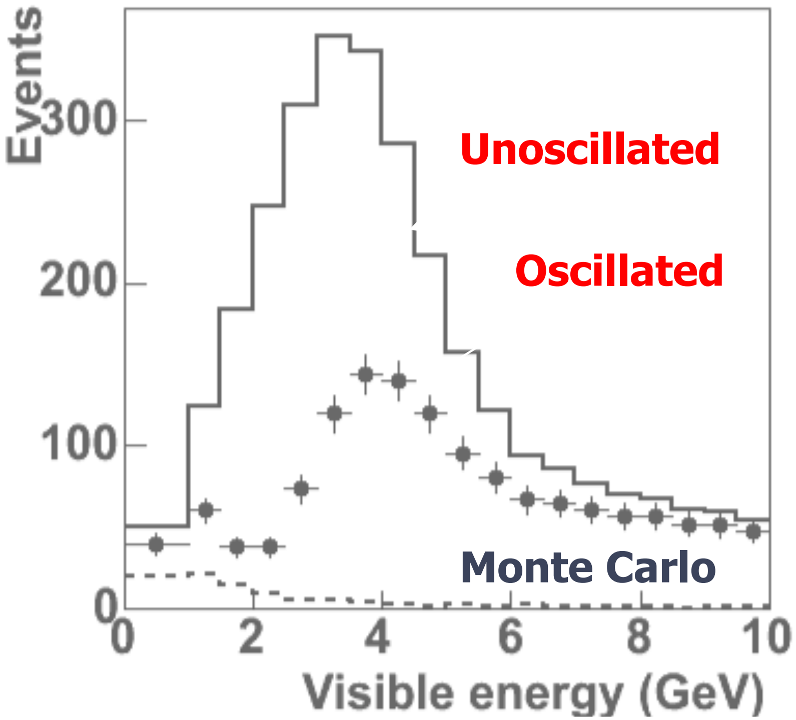
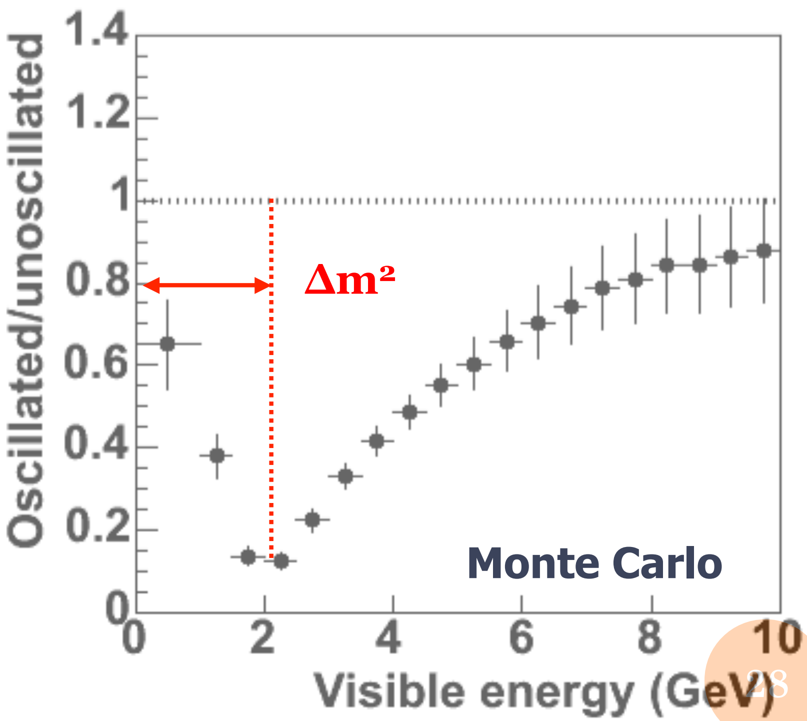




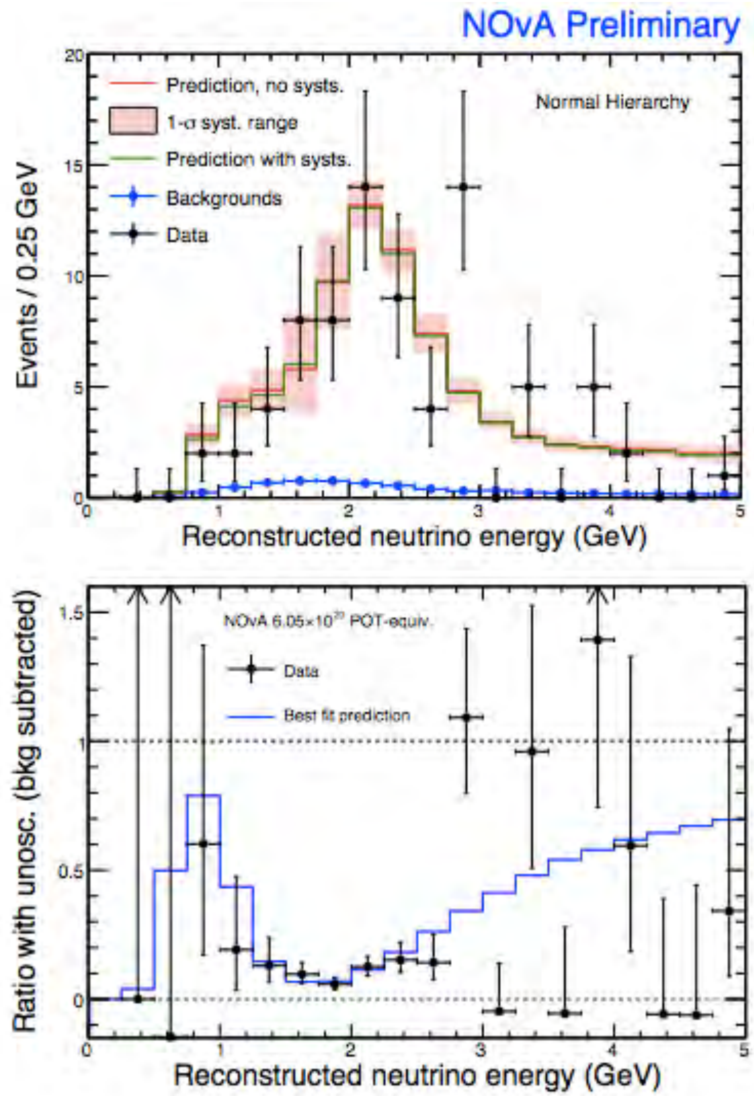
AT NEUTRINO 2016, LONDON

NOνA

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

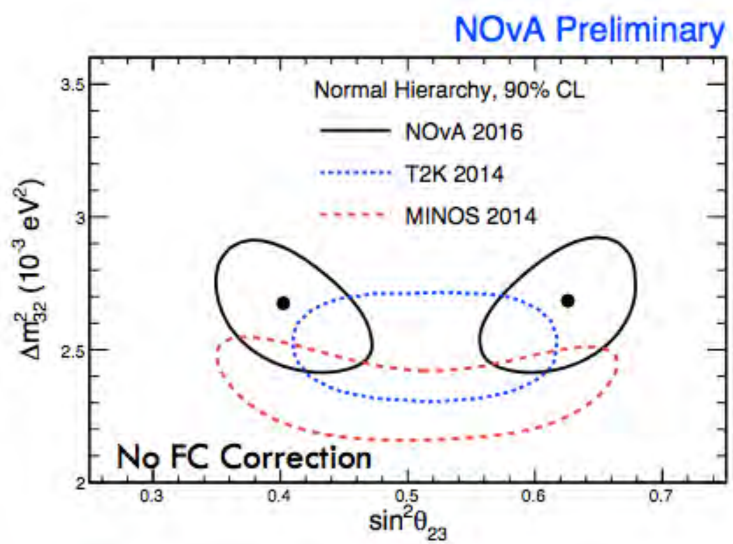
χ^2/NDF=41.6/17
Driven by fluctuations in tail,
no pull in oscillation fit

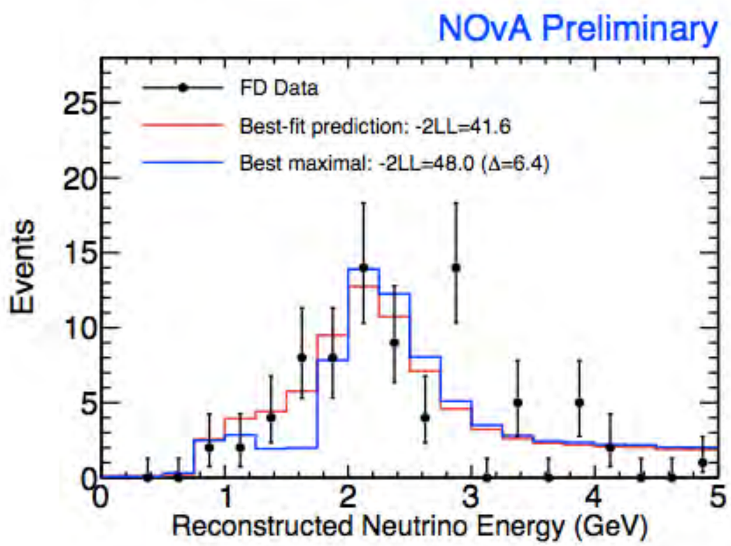


AT NEUTRINO 2016, LONDON

NOνA

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





Best Fit (in NH):

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

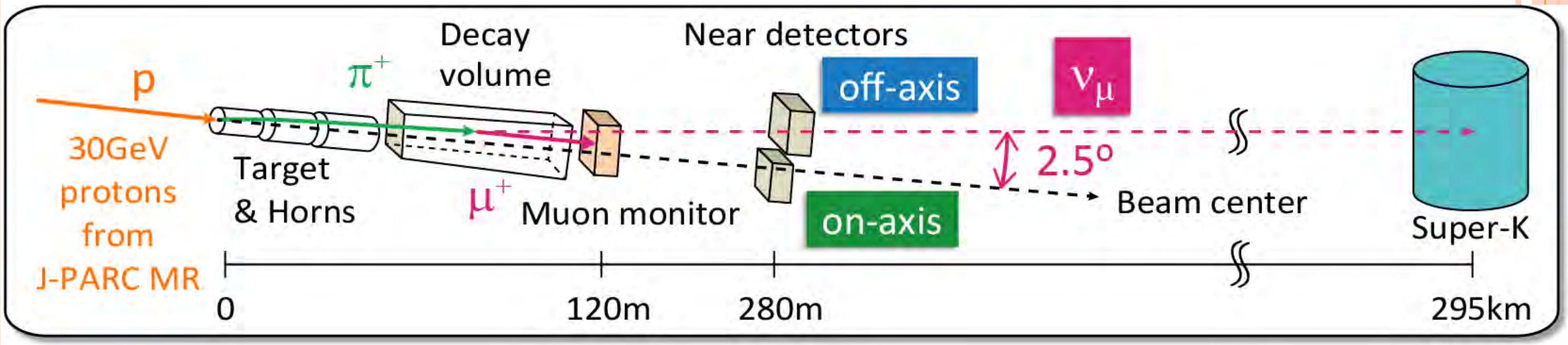
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

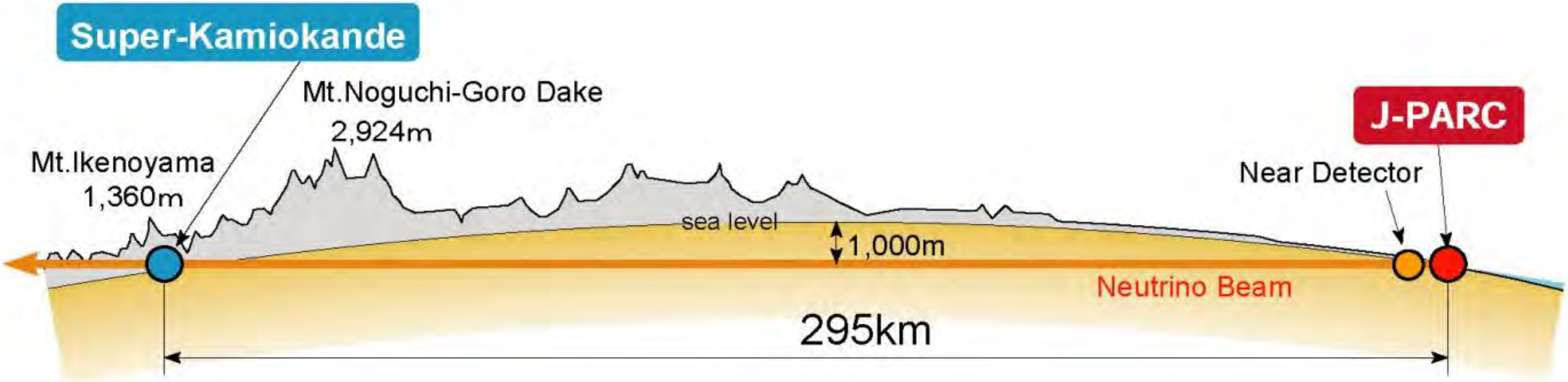
Maximal mixing excluded at 2.5σ

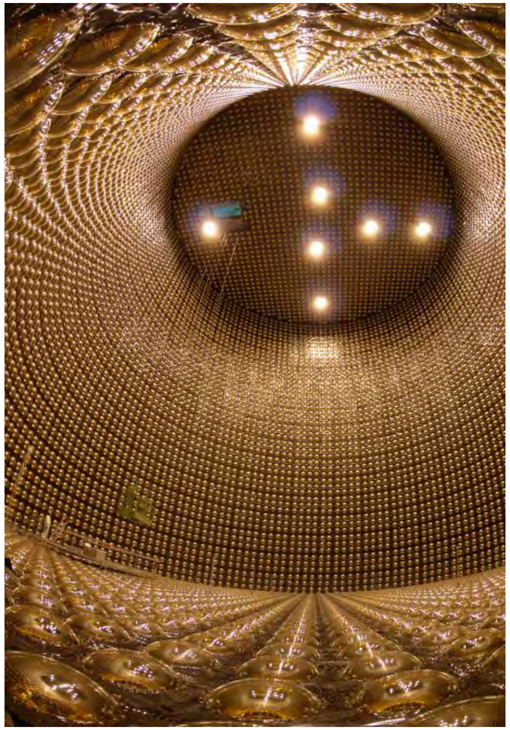
WHICH OCTANT? THE NEW PARAMETER OF INTEREST!

- 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?
  - Another running LB experiment in Japan

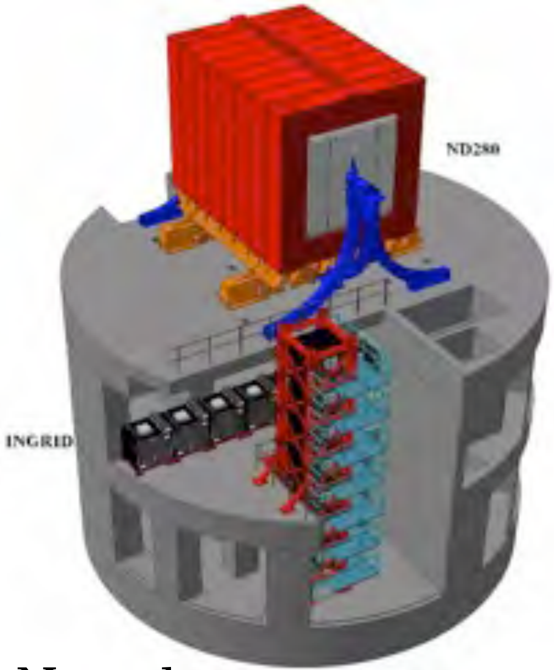
T2K EXPERIMENT IN JAPAN



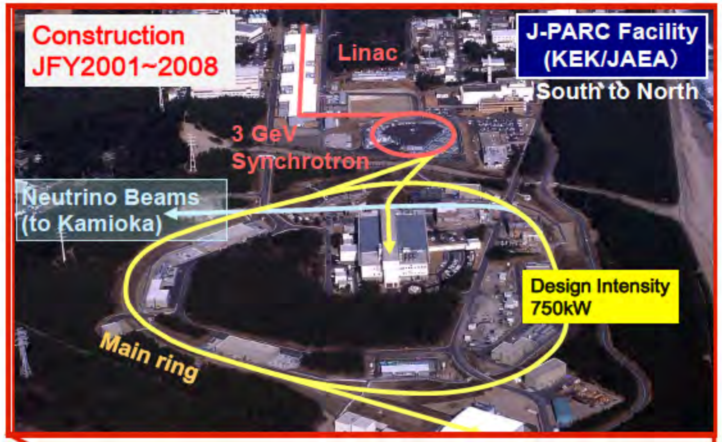




Far detector



Near detectors
Off-axis: ND280
On-axis: INGRID

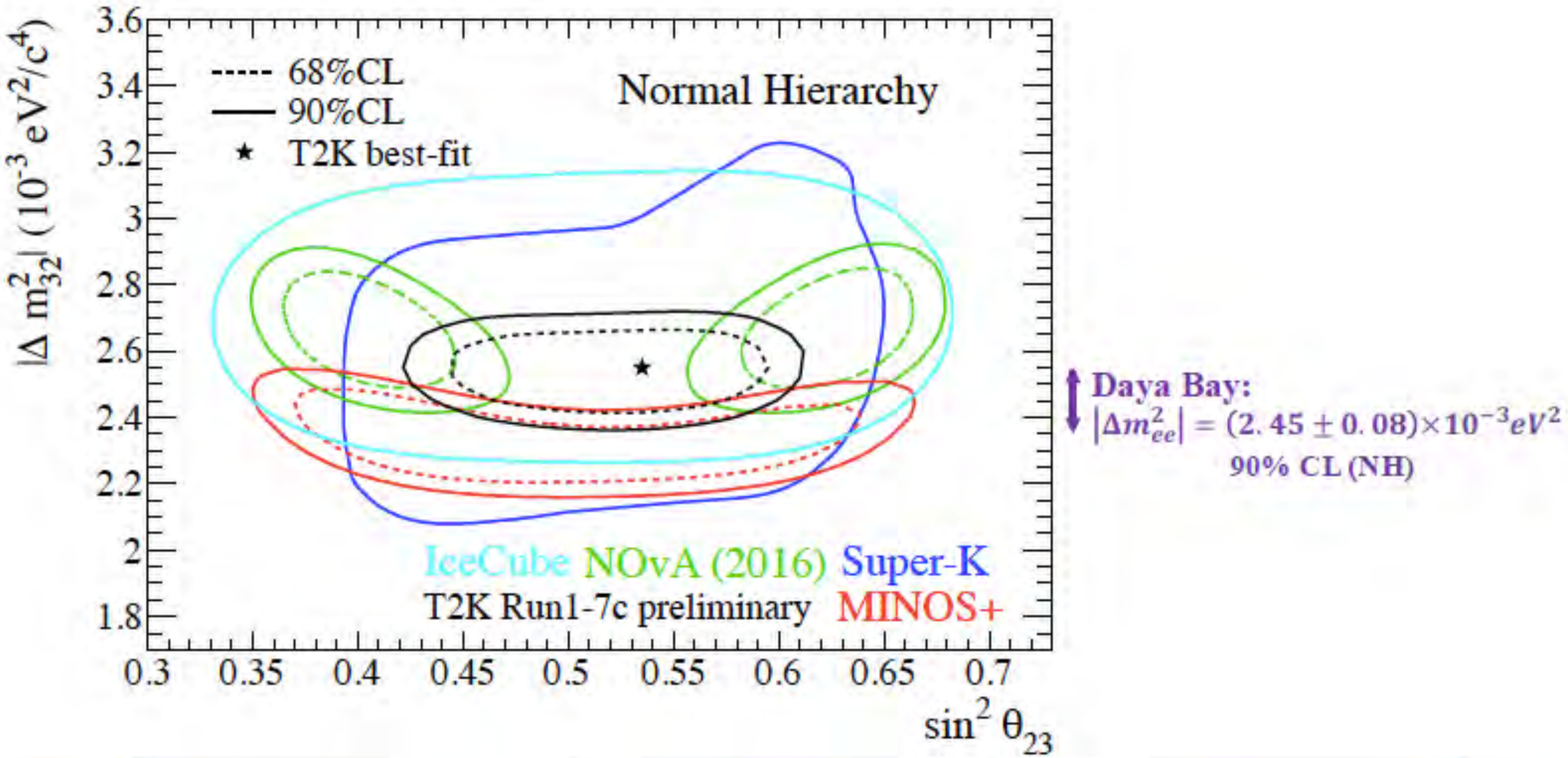


J-PARC accelerator

At ICHEP 2016, Chicago

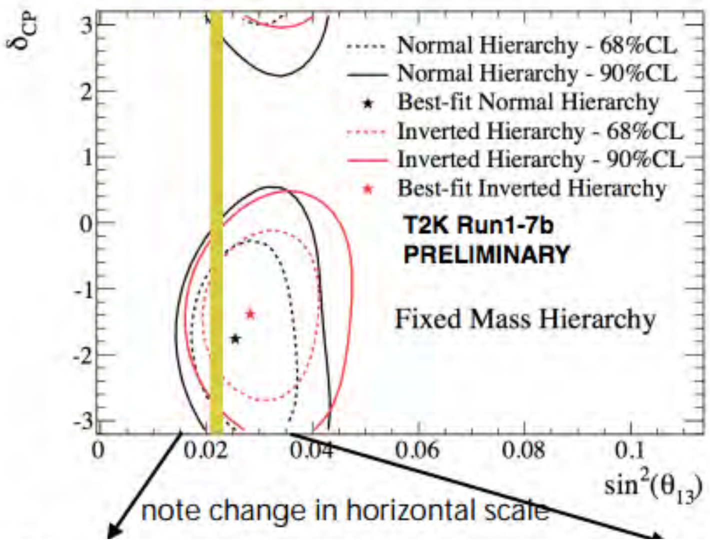
- T2K combination with anti-neutrinos, the tension mounts!

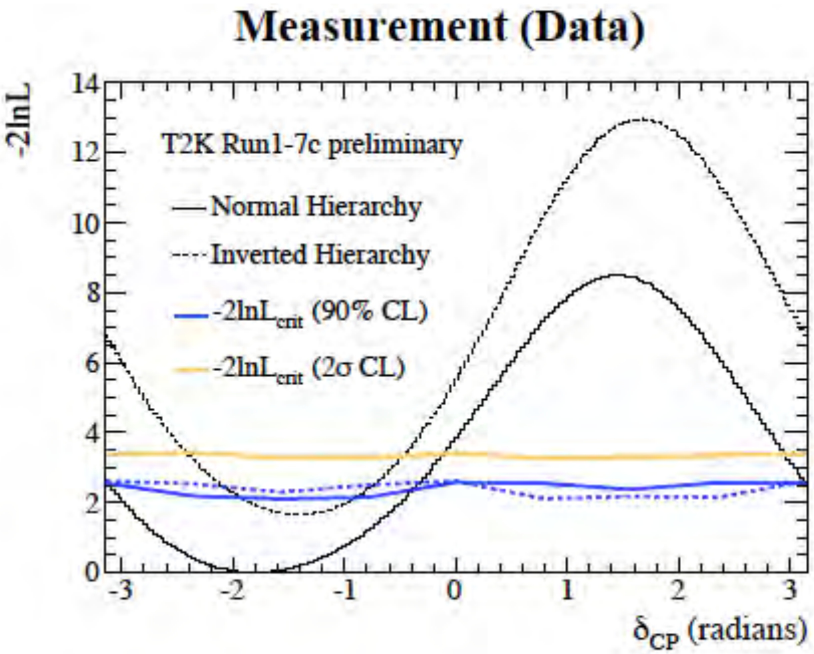
- Consistent with maximal mixing



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

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





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

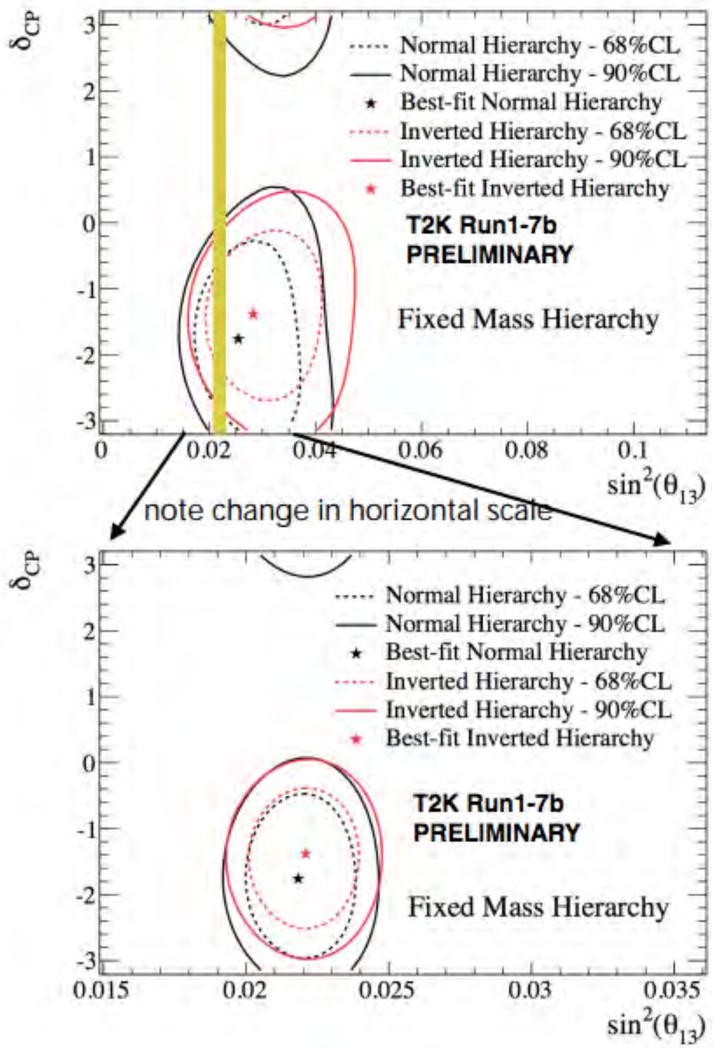
$$\cancel{+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}}$$

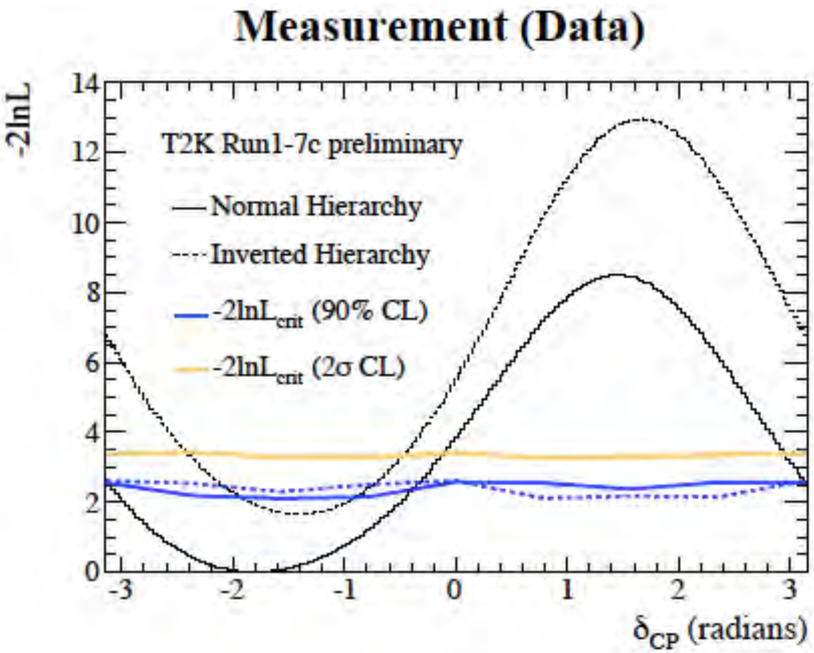
CPV

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

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

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



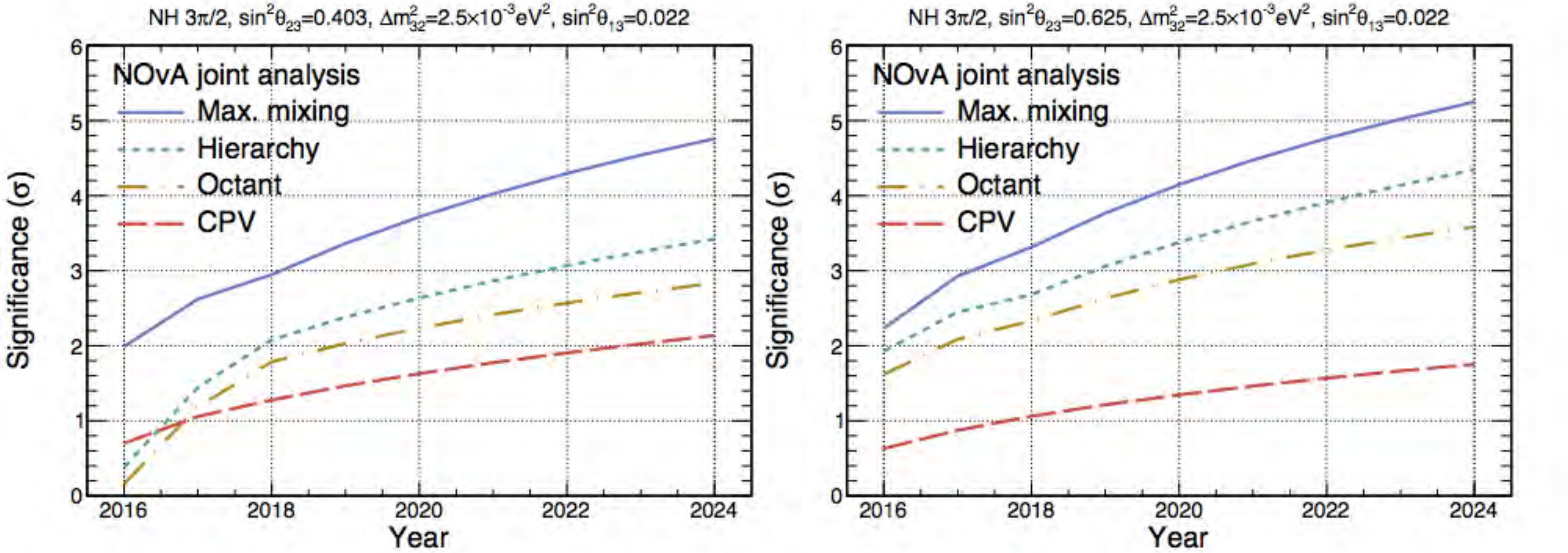


- T2K uncertainty on s^2_{23} is **very small** because its maximal
- This leads to significant reduction in δ_{cp} parameter space
- All other parameters are now marginalized over : progress

δ_{cp}=0 ruled out at 95% C.L!!!

Prognosis for mass hierarchy and CPV

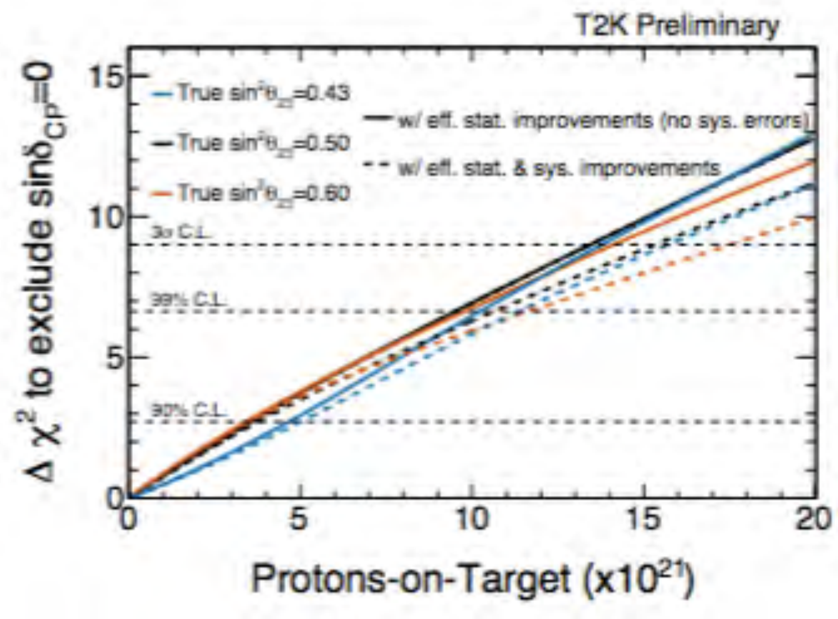
- Ultimate precisions depend on run strategy
- JPARC upgrade in 2018 is significant (run until 2025)



- 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

PROGNOSIS FOR MASS HIERARCHY AND CPV

- Ultimate precisions depend on run strategy
- JPARC upgrade in 2018 is significant (run until 2026)



T2K will exclude δ_{cp}=0 by 2026 at > 3σ

- T2K will exclude δ_{cp}=0 by 2026 at > 3σ if not before
- MH will likely be determined to 3σ by 2022 by NOνA even if θ_{23} not maximal
- Old sensitivities already somewhat overtaken by events

Into the future

Before I retire

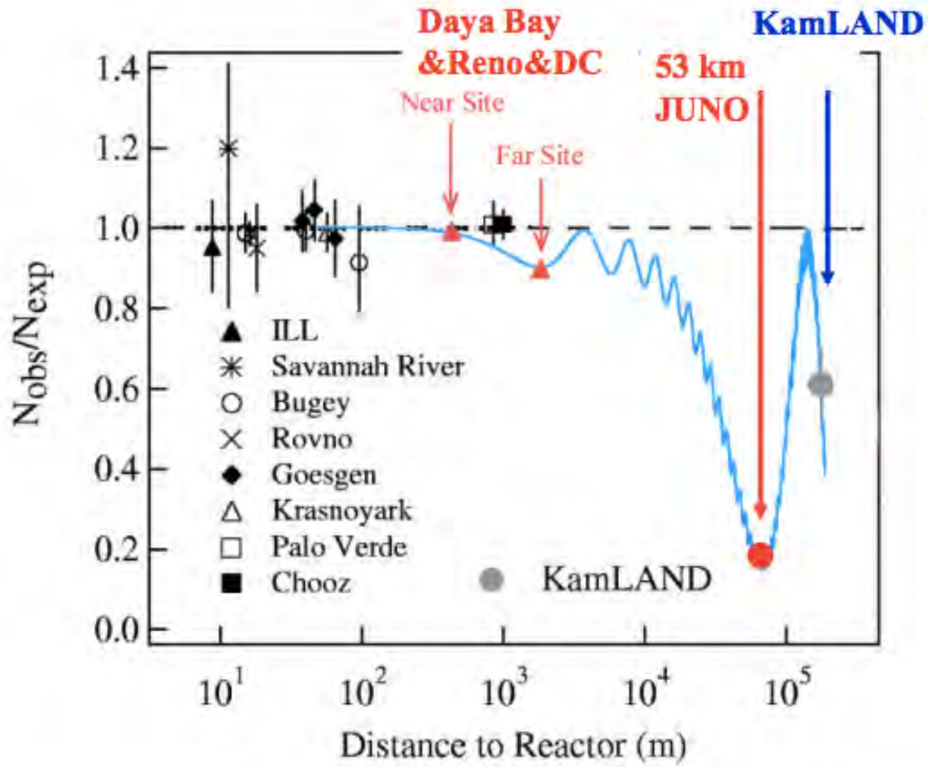
The future

- There are a number of projects on the horizon
  - JUNO : reactor experiment to study MH (start 2022 + 3)
  - LBNF : LB accelerator experiment (start 2026 + 6)
  - T2HK : “L”B accelerator experiment (start 2023 + 6)
  - PINGU : (2021+3)
- DUNE + LBNF
  - Remaining uncertainties on θ_{23} will likely be the most important to reduce

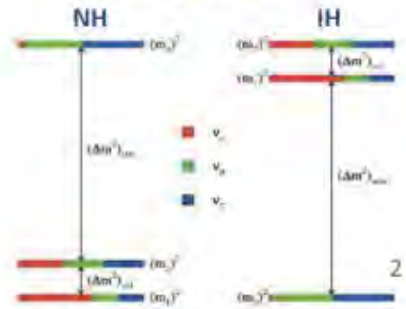
THE FURTHER FUTURE, JUNO, STARTING 2022

The precision frontier

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, 2022-26

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

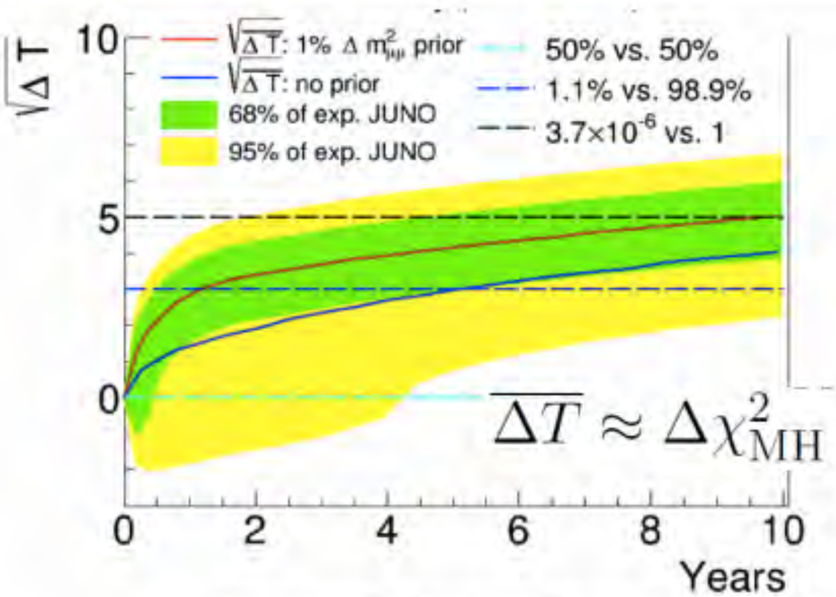
Fiducial Volume: 20 kt

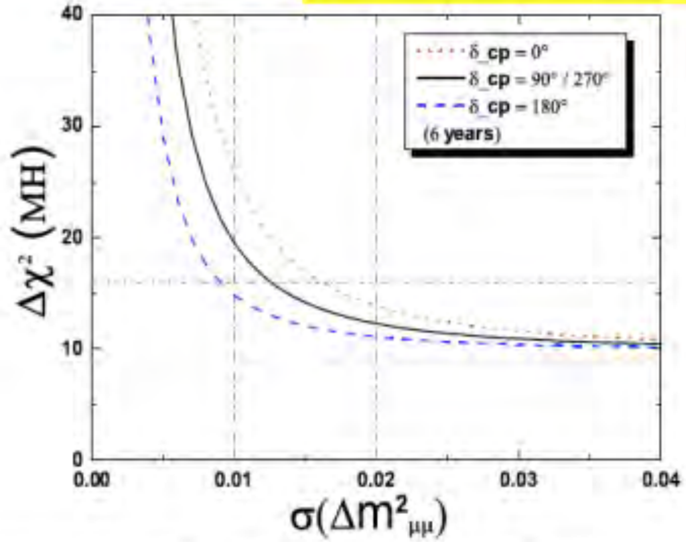
Thermal Power: 36 GW

Exposure Time: 6 years

Proton content 12%

en. res. 3%



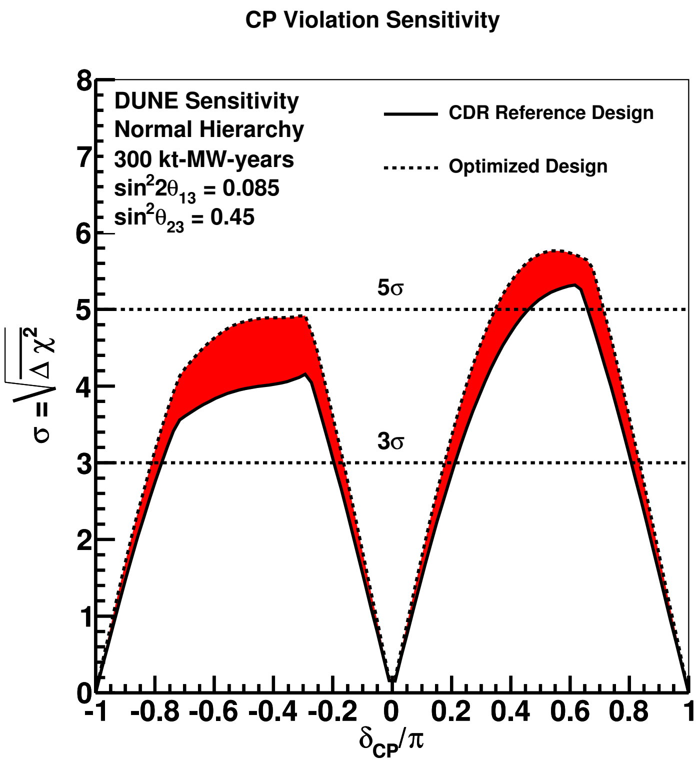


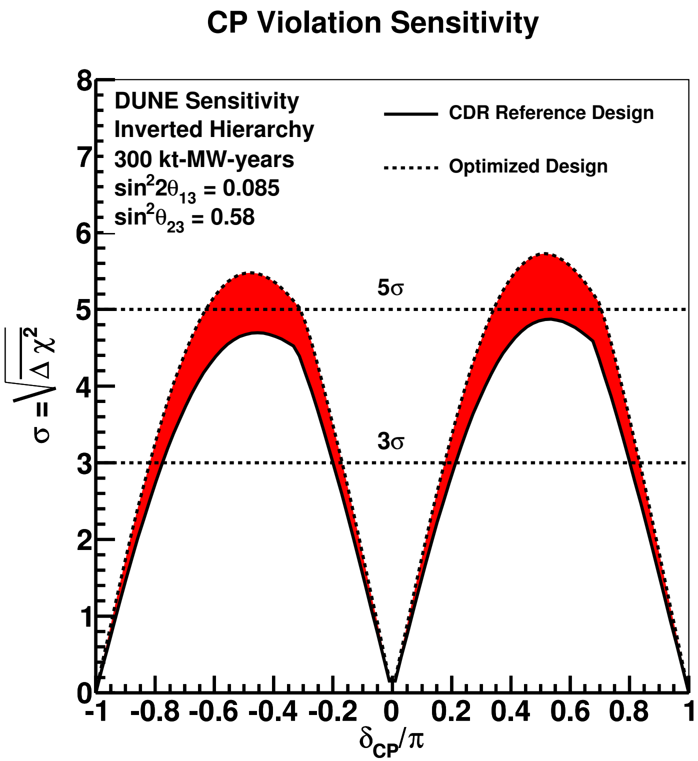
	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{\mathrm{MH}}$	+16	−4	−1	−0.5	−0.1	+8

DUNE Physics:
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)

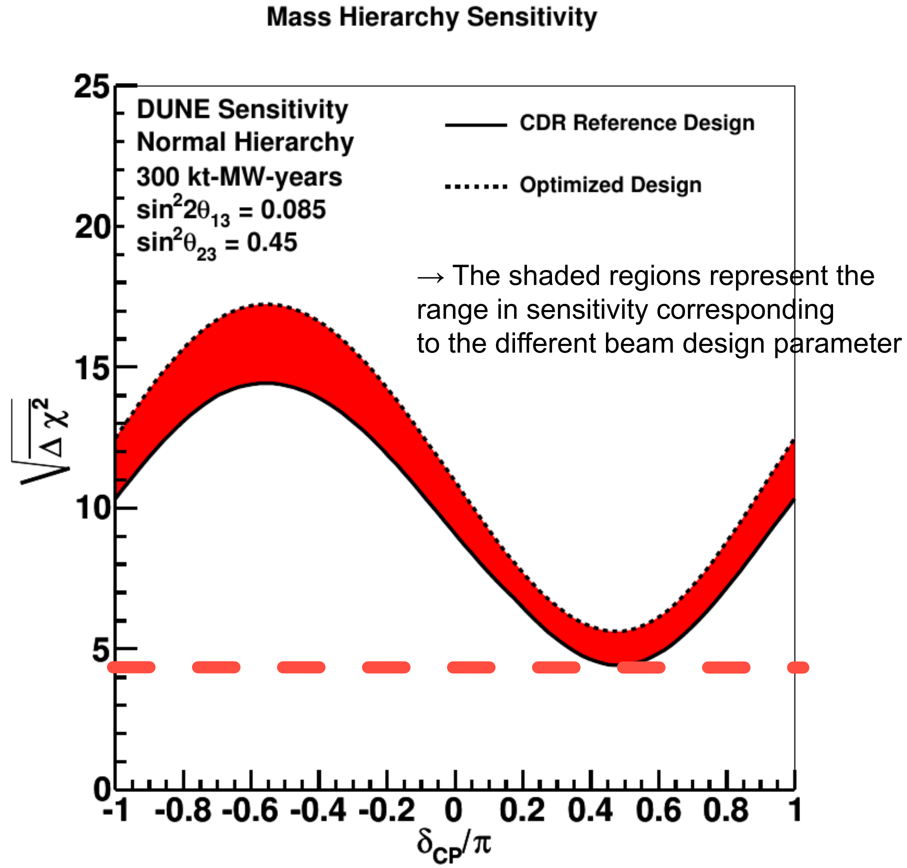


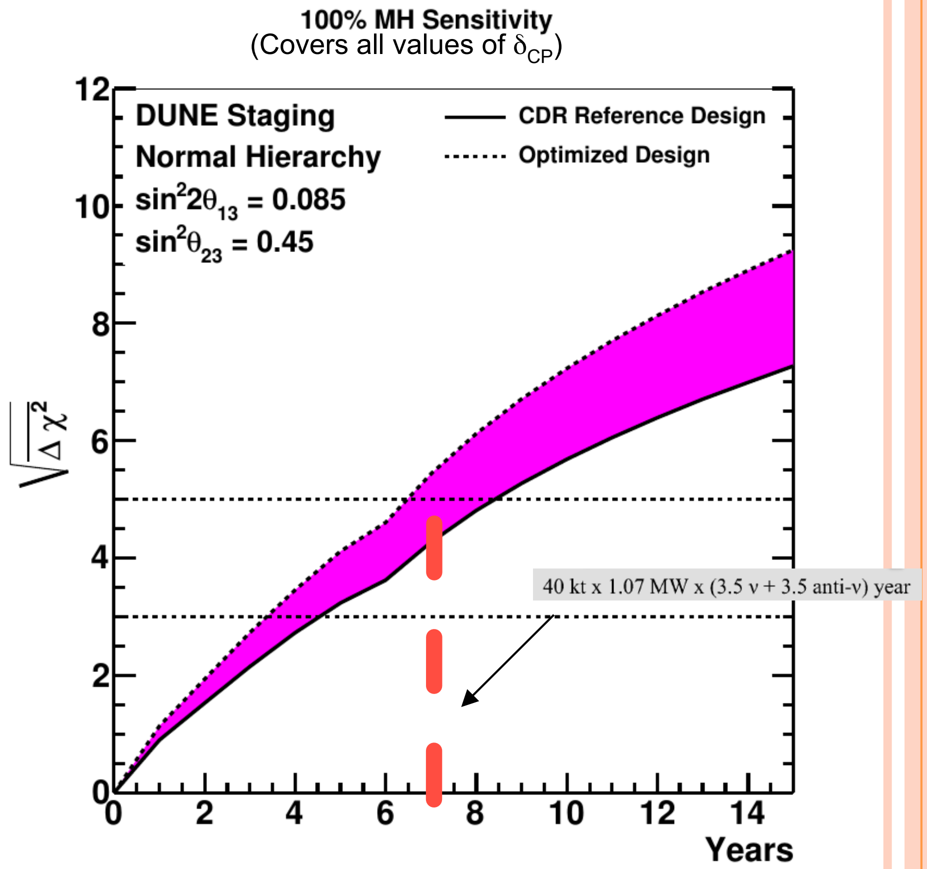


Official timeline : 2032 for this sensitivity

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).





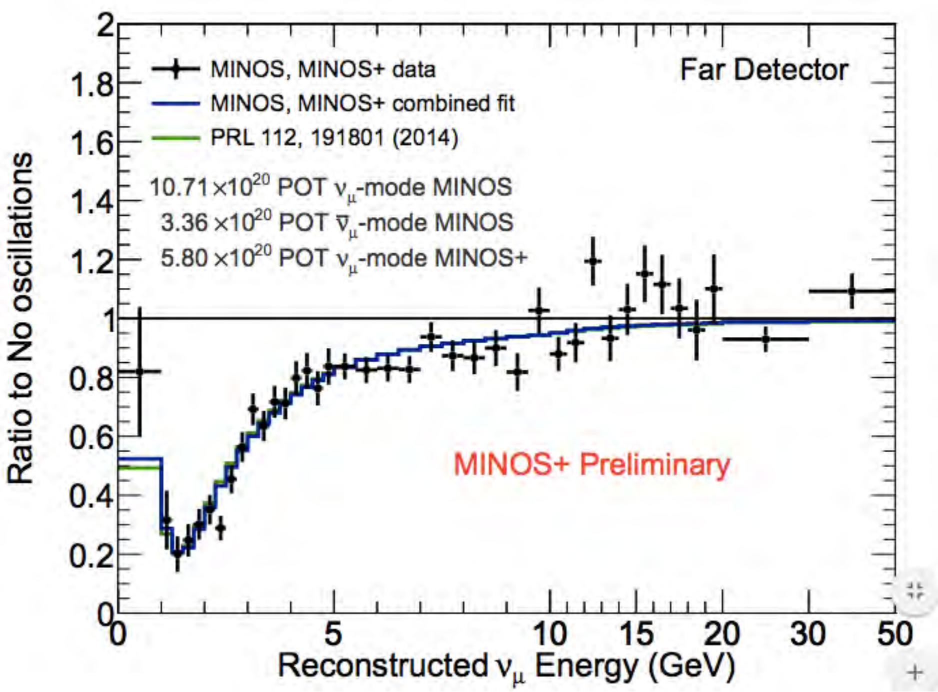
→ The minimum significance (the lowest point on the curve on the left) where the mass hierarchy can be determined any value of δ_{CP} as a function of years of running

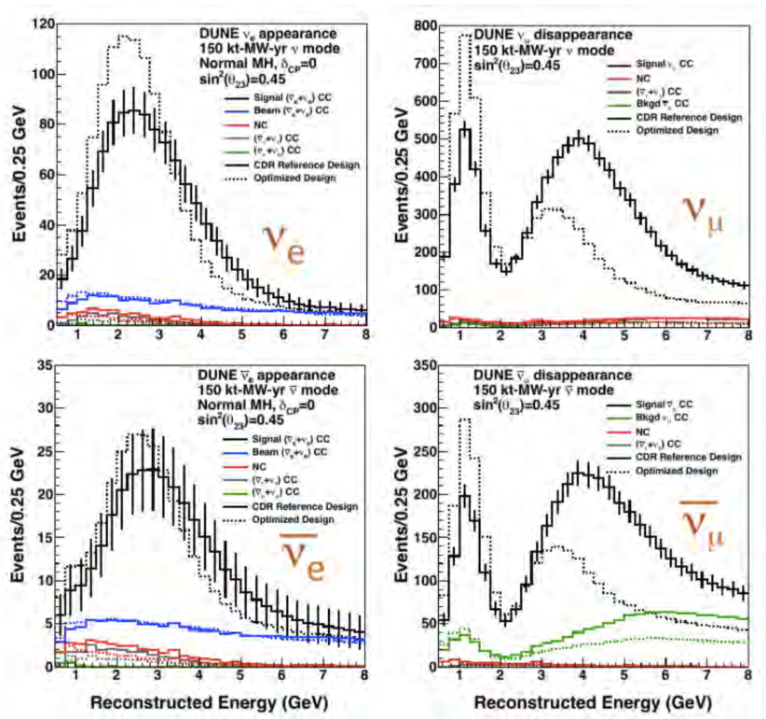
Official timeline : 2032 for this sensitivity

Future Projects

- There are a number of future projects in the pipeline focussing on δ_{CP}
  - JUNO : China, ground breaking reactor experiment
  - DUNE : USA, Liquid Argon detector in South Dakota
  - Hyper-K : 200kt Water Cherenkov detector in Japan
- There are the existing projects which continue to push on the result
  - NOVA
  - T2K
  - Daya Bay
- Then there is a new project which is happening now!

- FNAL has the best neutrino oscillation beam for the coming 30 years (NuMI now and LBNF starting 2026)
- **WE NEED BIGGER DETECTORS** to make measurements in a human lifetime
  - Maybe factor 2 from beam power in the future
  - With present detector ideas, measurements will be **statistics limited** for a very very long time
  - But we will know all the low hanging fruit: need to look with precision for new things
    - **Like MINOS+ ?**





- **WE NEED CHEAPER DETECTORS** because our physics is presently **limited only by money**
  - CHIPS combines the idea of a cheaper design and a huge mass

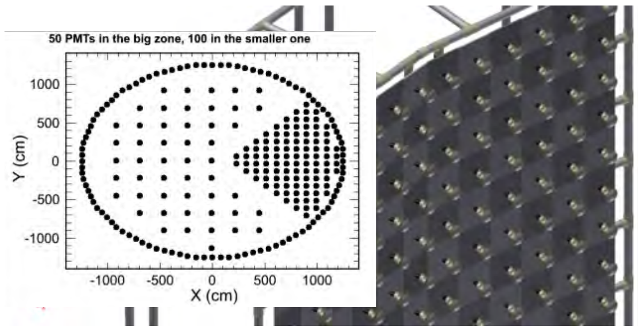
CHIPS P-1051
CHERENKOV DETECTORS IN MINE PITS

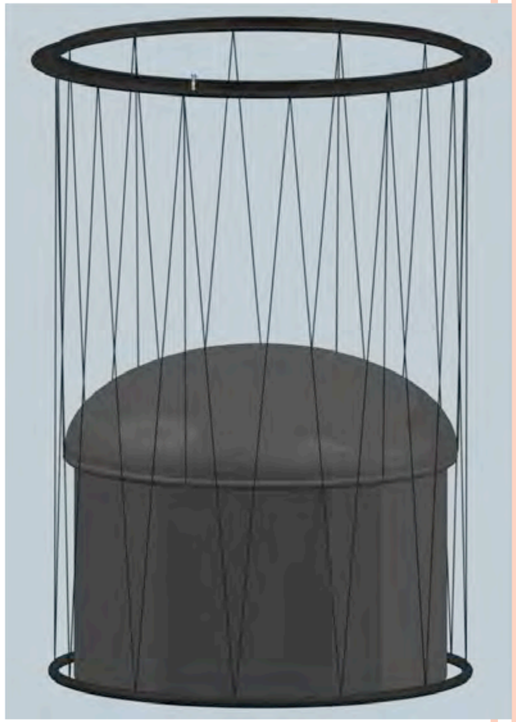
- Physics soon and Physics later R&D 3-5 year program

δChiPs

ORIENTATION

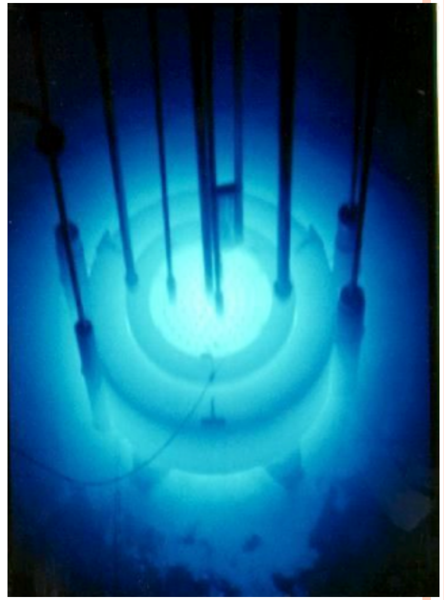
- The CHIPS goal is to prove that a water Cherenkov detector can do oscillation physics for a fraction of the cost of its competitors in LBNE, and also to constrain δ_{CP} using NuMI neutrinos now
  - to $200k/kt (presently $1M/kt water, $10M/kt Liquid Argon)
- CHIPS is a water Cherenkov detector which will be sunk in a flooded mine pit in the path of the NuMI beam : water will provide mechanical support
- Placement of PMTS and electronics developments make further cost reductions
- It starts with 5-10 kt deployed in 2018, funded by ERC



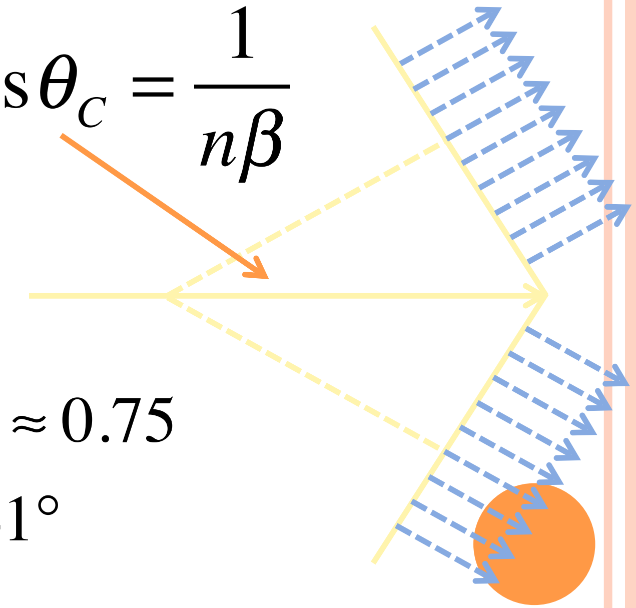


The Cherenkov Effect

- CHIPS relies on the Cherenkov effect
- Charged particles from neutrino interactions moving faster than the speed of light in the medium emit a cone of light
- The cone of light forms a ring on the detector wall
- In water, for a particle travelling with v = c:



$$\cos\theta_C = \frac{1}{n\beta}$$

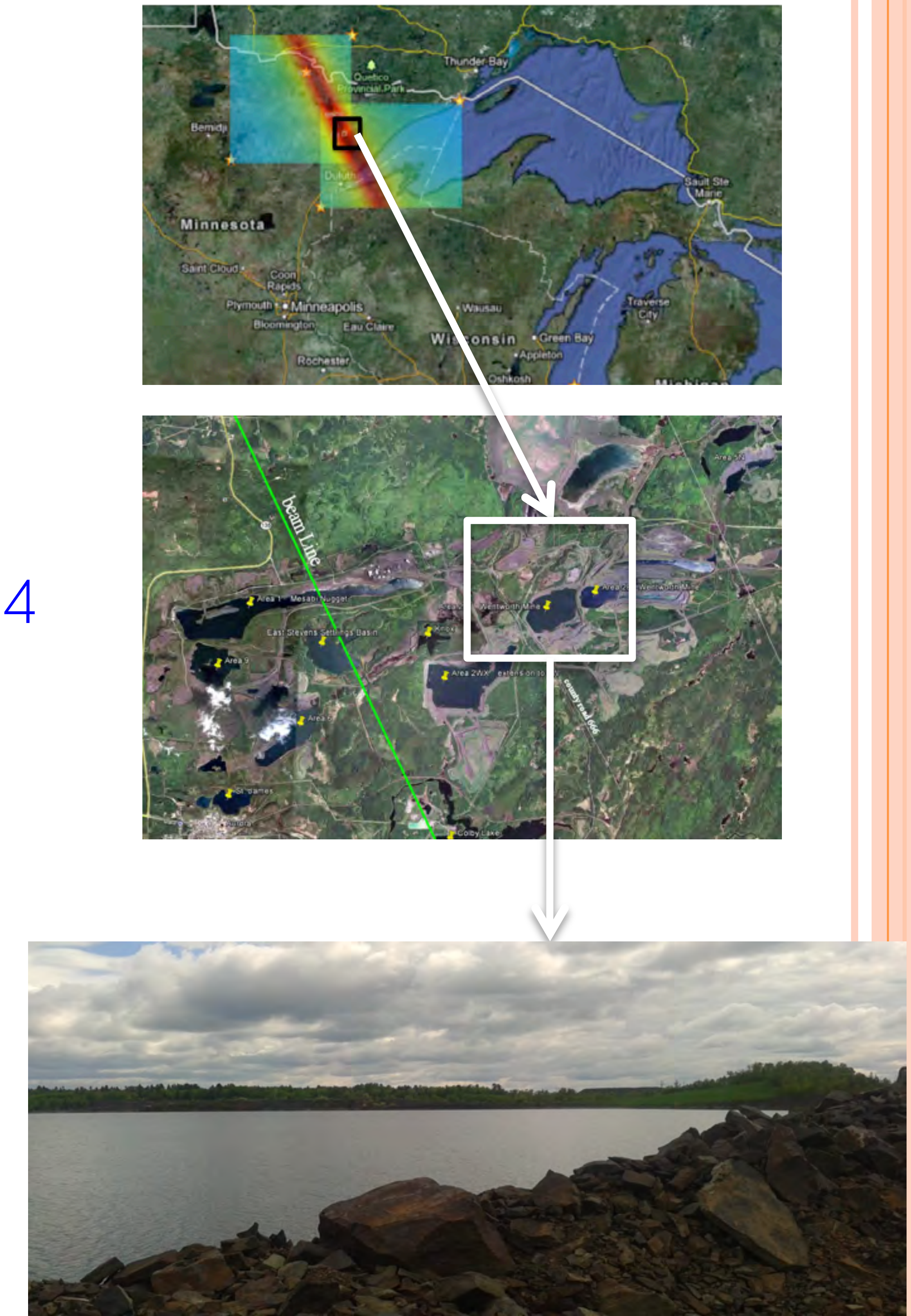


$$\cos\theta_C \approx 0.75$$

$$\theta_C \approx 41^\circ$$

CHIPS : INGREDIENTS

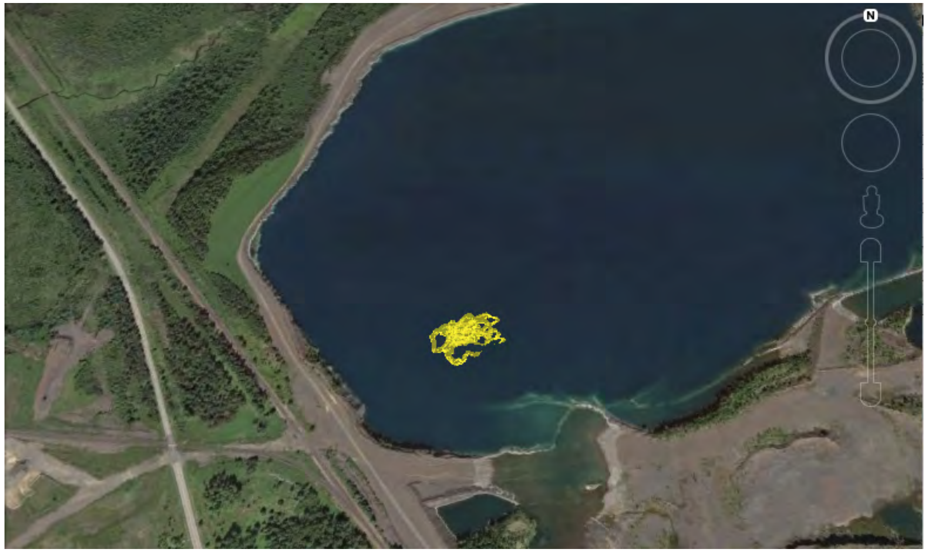
- Deep lake or body of water
- High energy neutrino beam
- Secure environment
- At 7mrad off axis
- Wentworth 2W is the solution
- CHIPS-M (mini) prototyped in 2014 and 2015

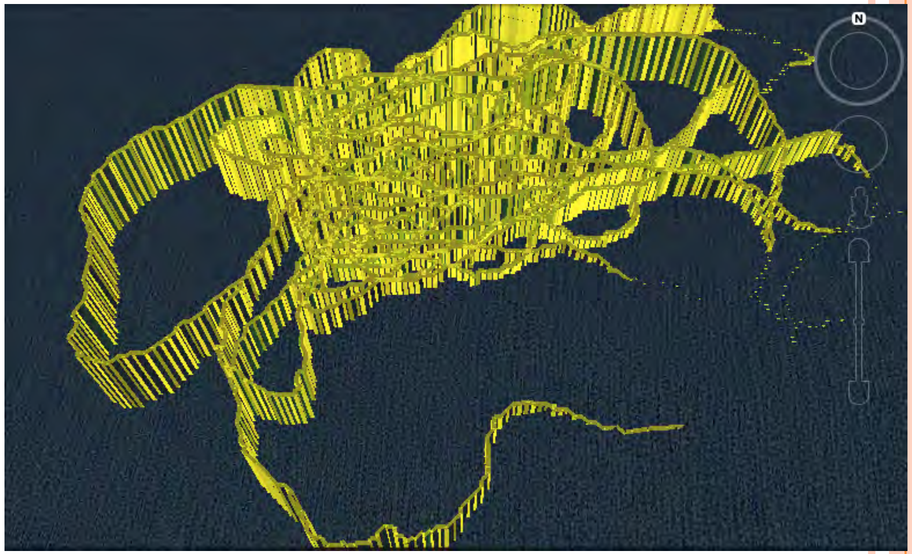


CHIPS-M BEING CONSTRUCTED

- Parts built at W&M, constructed in Soudan surface building
- Dedicated team of youngsters :2 postdocs, 3 grad students, 8 undergrads

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 ←←←←
- Being raised after one year under the water in 2015 →→→

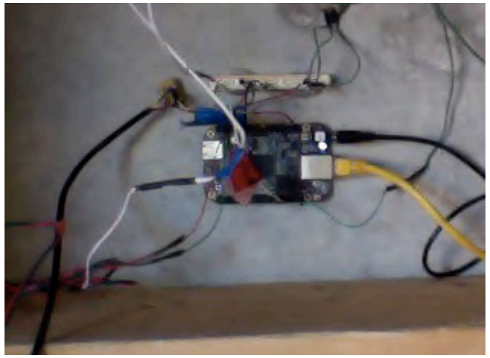
- Liner is robust, light-tight and was mostly pristine after a year under the water
- Sealing method is robust

Water Studies

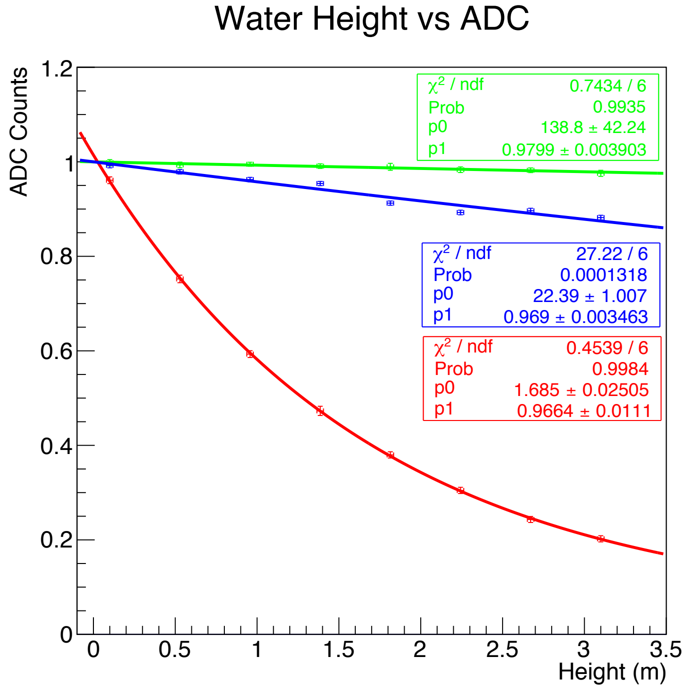
WATER CLARITY

- CHIPS has advantage of being under about 6 bar pressure and at 4°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 carbon filter to eliminate life + a UV sterilizer to make sure
- We have small model of CHIPS-M (micro-CHIPS) on surface
  - Using 405nm laser and 3m upright column, we have been watching the water clarity over the last 2 months
  - This will likely be worse than in reality because it is not pressurized
- Needed to know how clear we can make the water with simple filtering, for simulation benchmarking, and for system design

WATER STUDIES

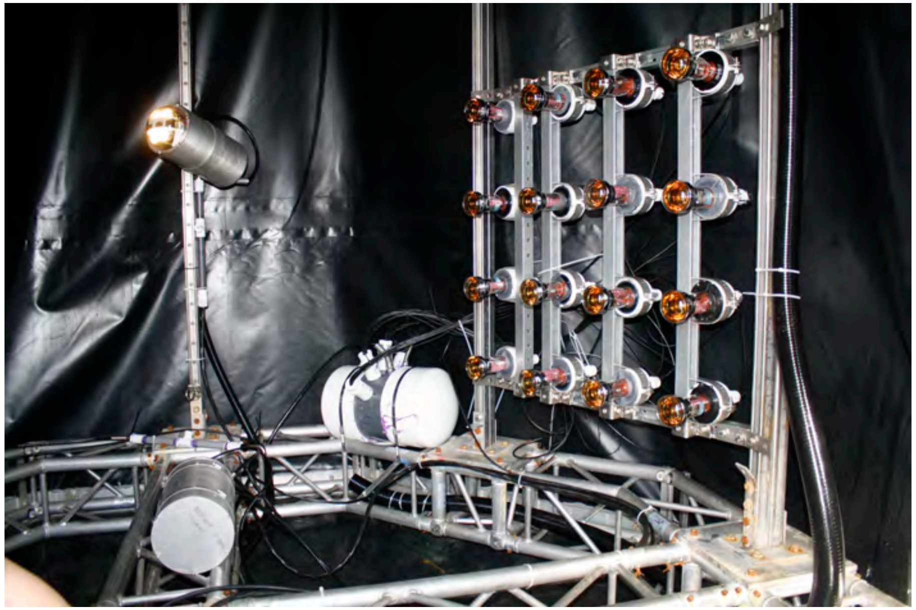


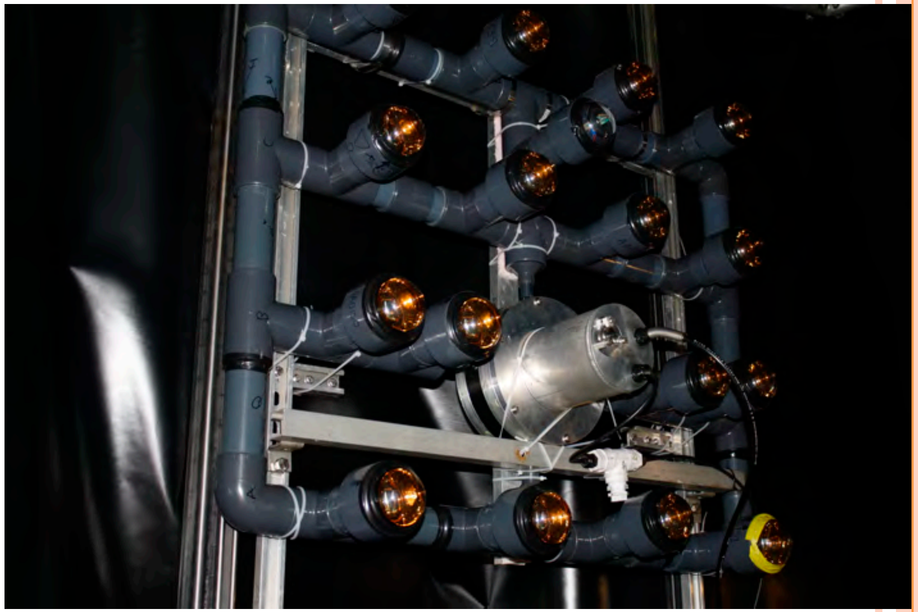
- Automated attenuation length measurements using BeagleBoneBlack, servos, relays etc.
- PIN diode at top and 405nm laser at base provide the baseline : simple op-amp circuit to get correct voltage for the BB
- 50 gallons of pit water circulated at equivalent of 4gpm in CHIPS-M
- UV sterilizer, 0.5μm + carbon, 0.2μm filters
- Full recycle time of about 10 days
- Water pumped into column once per day for measurement



The Detectors

PROTOTYPES (MADISON AND NIKHEF)

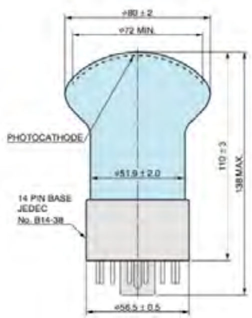


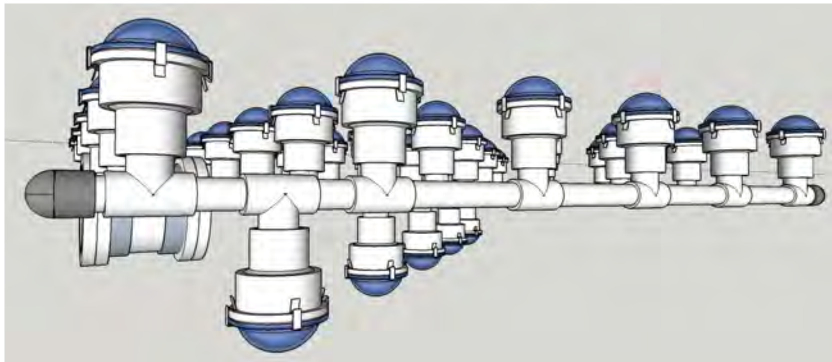


- Cheap and easy, no potting
- All cables and PMTs inside commercially available PVC pipe with acyrillic domes
- One cable in brings low voltage (from central DC/DC converter inside the detector), one fibre out brings time-over-threshold on Ethernet to the surface

- UW Madison with ParisROC readout.

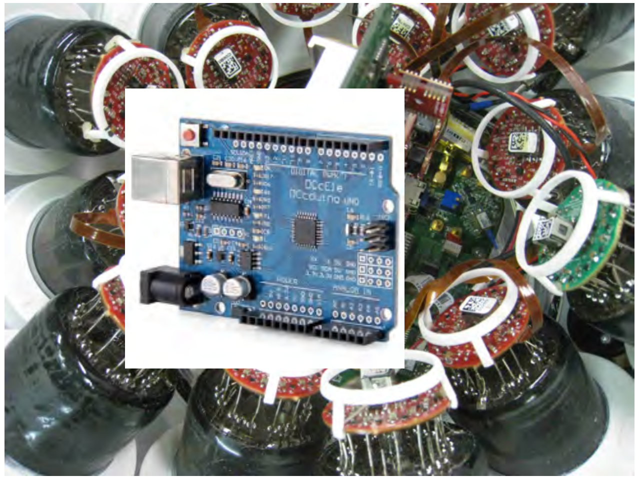
•13 stage 3" Hamamatsu tubes with flat glass withstand pressure without acryllic domes
•400-900 loaned to us from CNRS
•Potting of HV chip and cables on plane
•Standard uni-strut frame





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



Developers are like the Borg: and **resistance is futile..**

- Side comment: Industrially available ASICs in version 100 (ish): home grown electronics typically in version 2-5
- Combination of cheap processors such as Raspberry Pi, BeagleBone and Arduino combined with the WWW means progress goes incredibly fast as solutions are known almost instantaneously

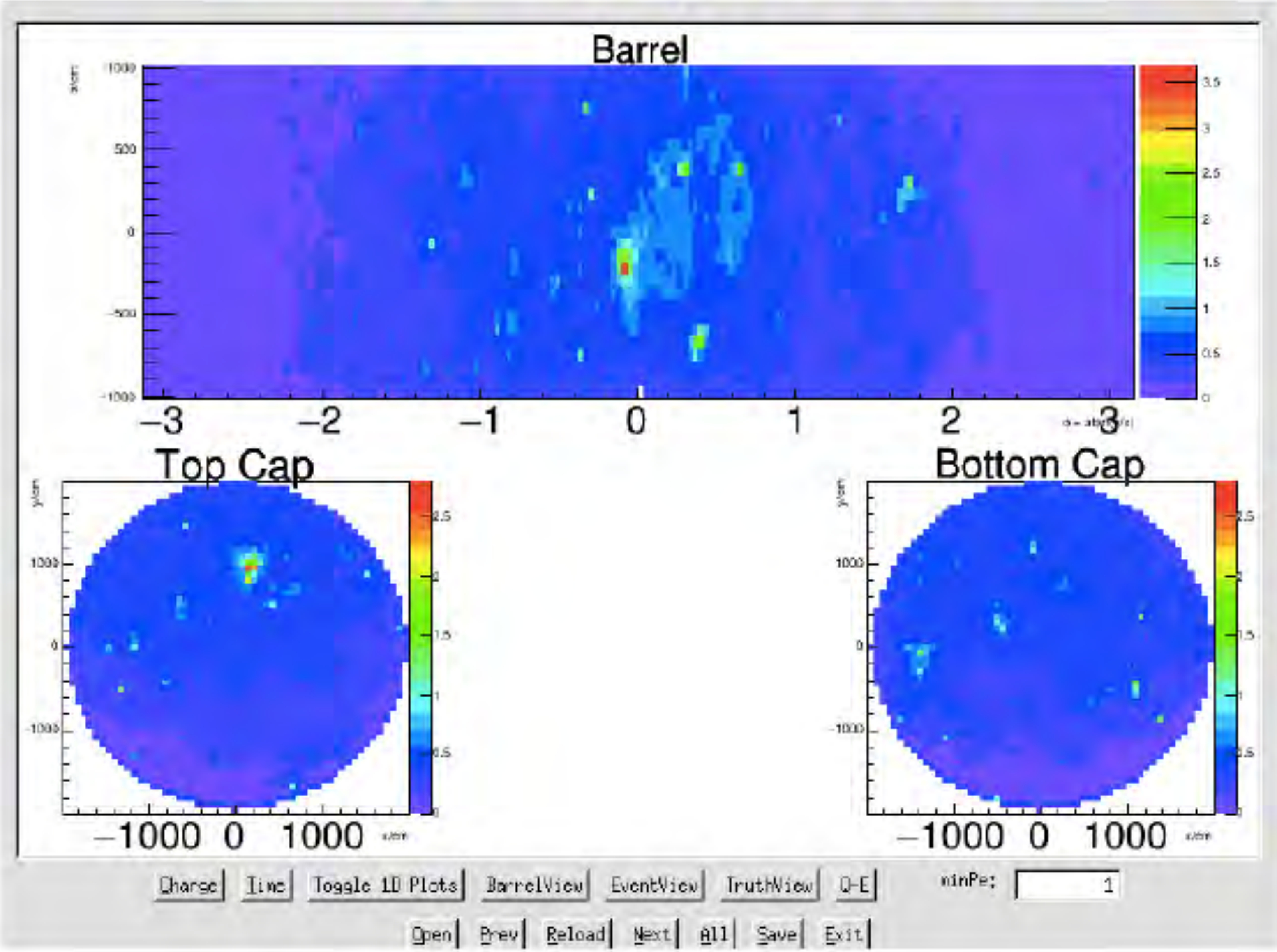
CHIPS-10KT

The near future

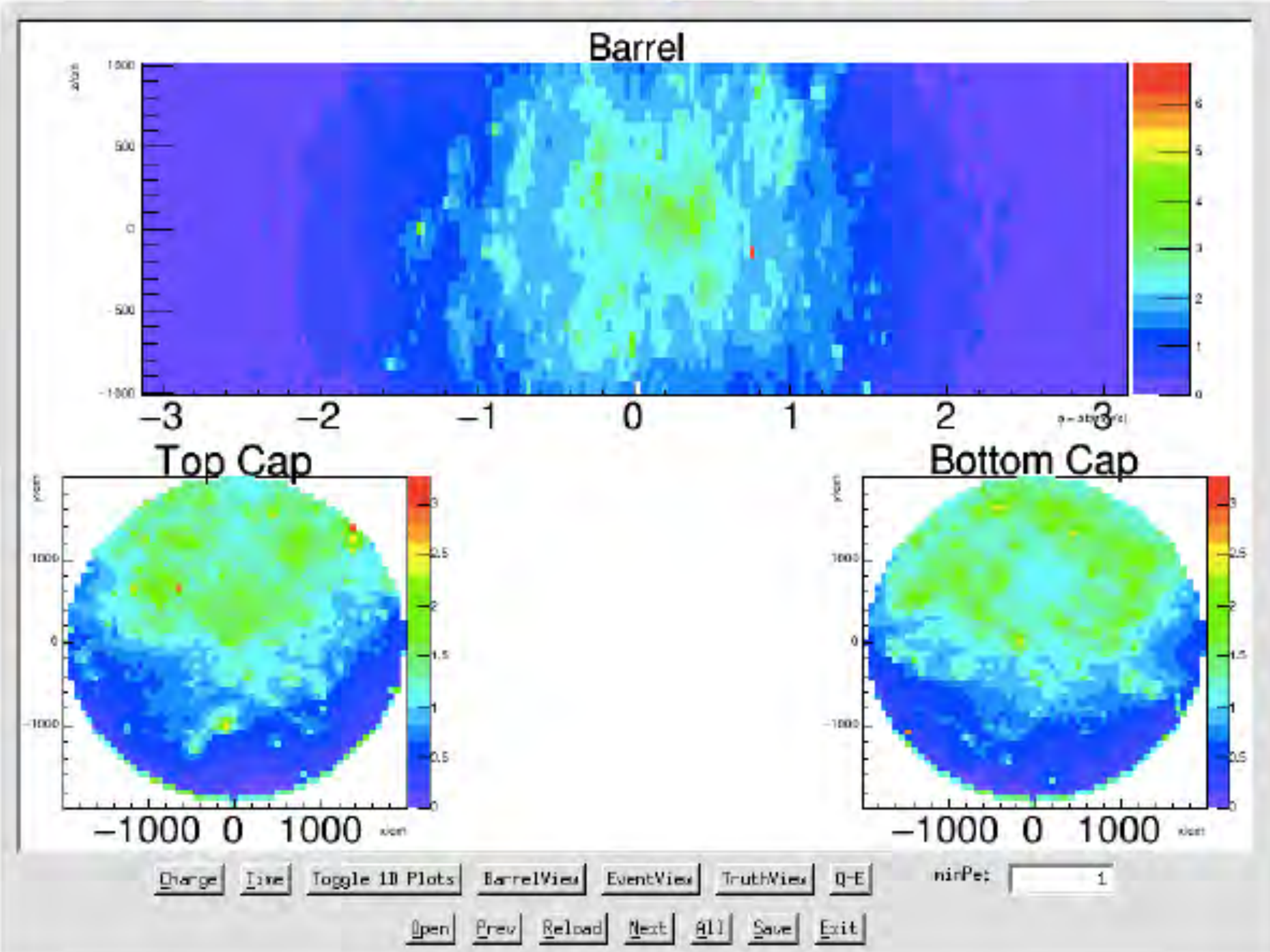
SIMULATION

- 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

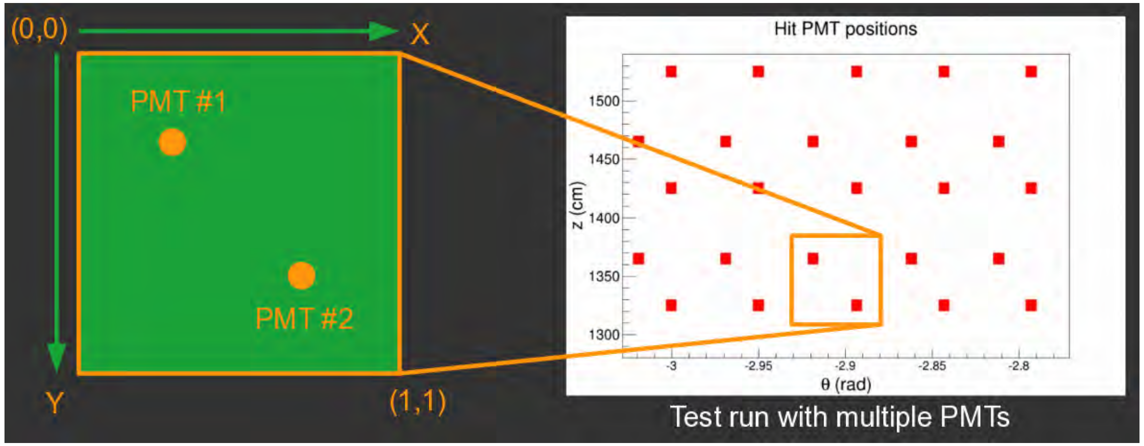
Hit Map 2000 ν_μNC Events

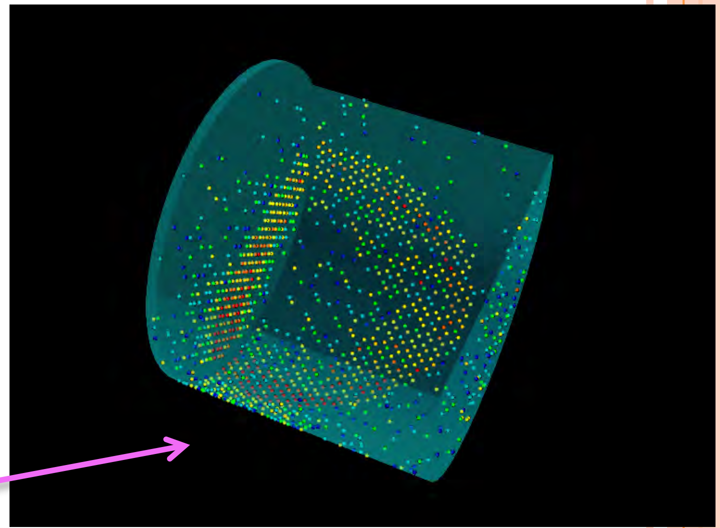


Hit Map 2000 ν_eCC Events

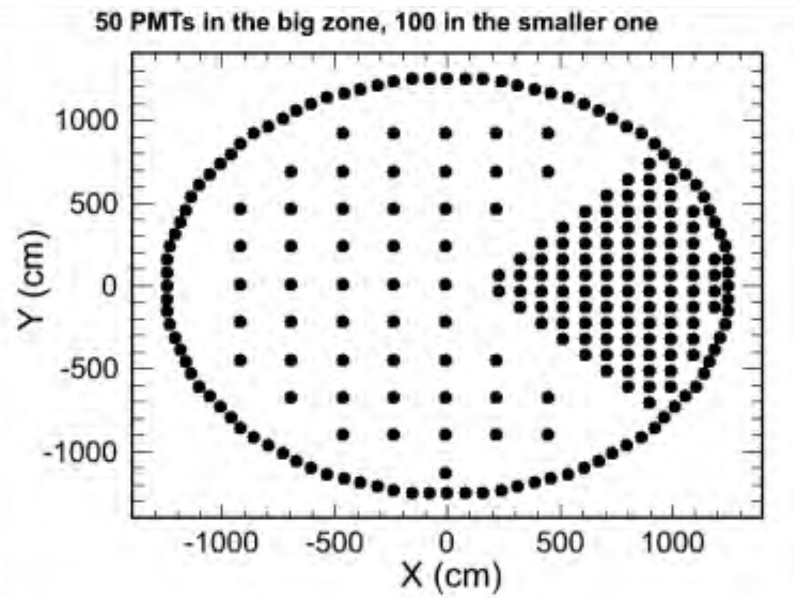


PMT Layout

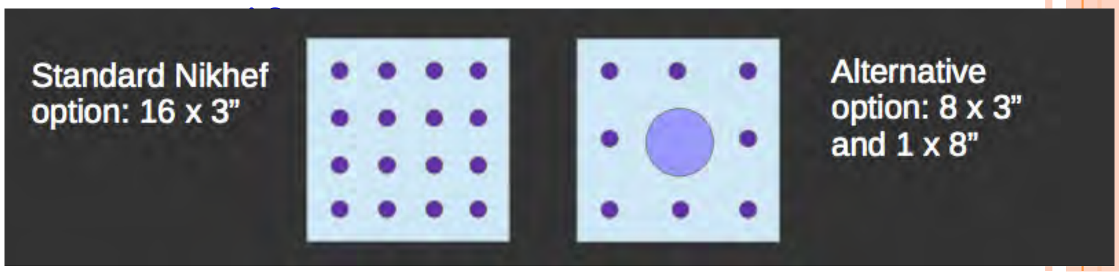


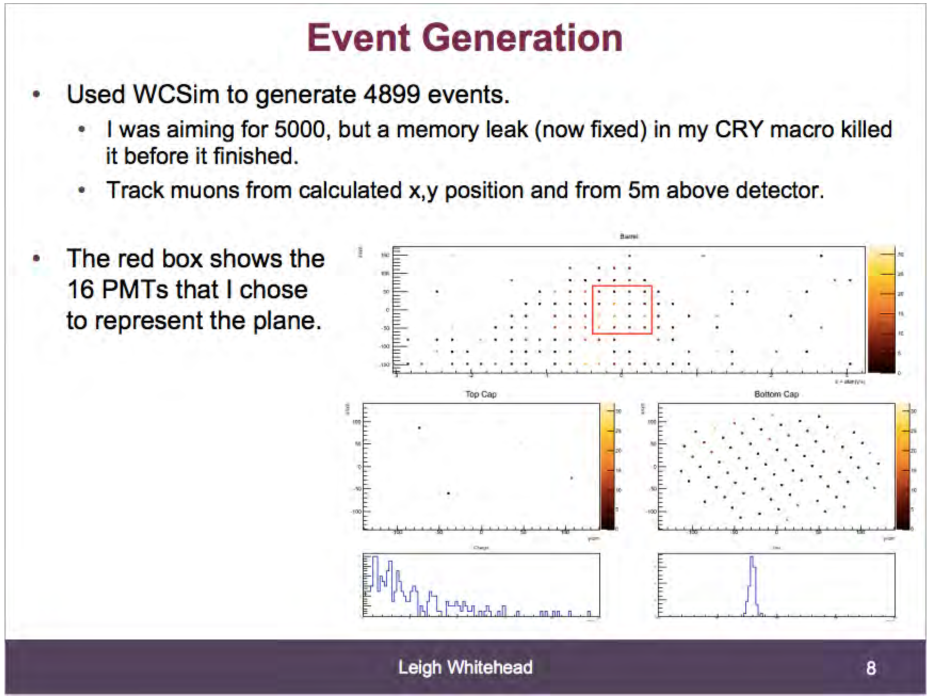


ν_μ CC event with the 2 PMT per cell layout

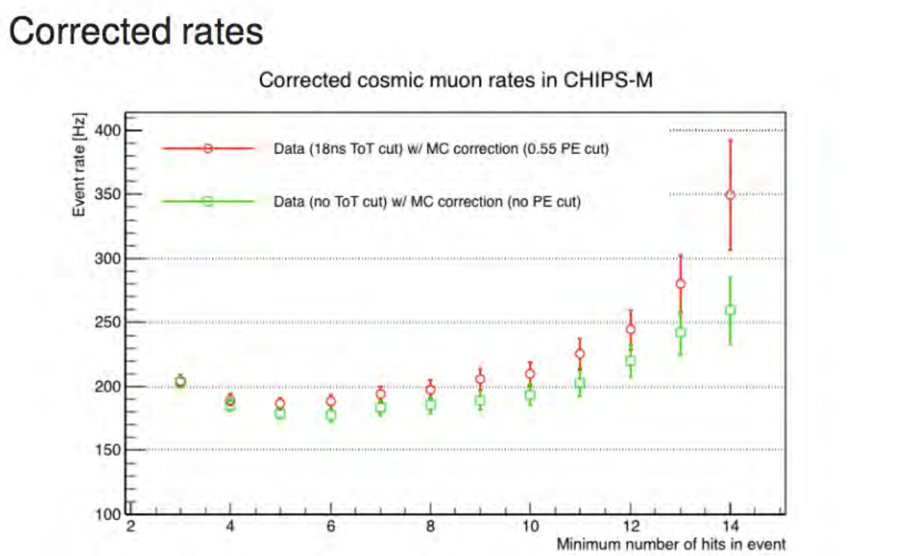


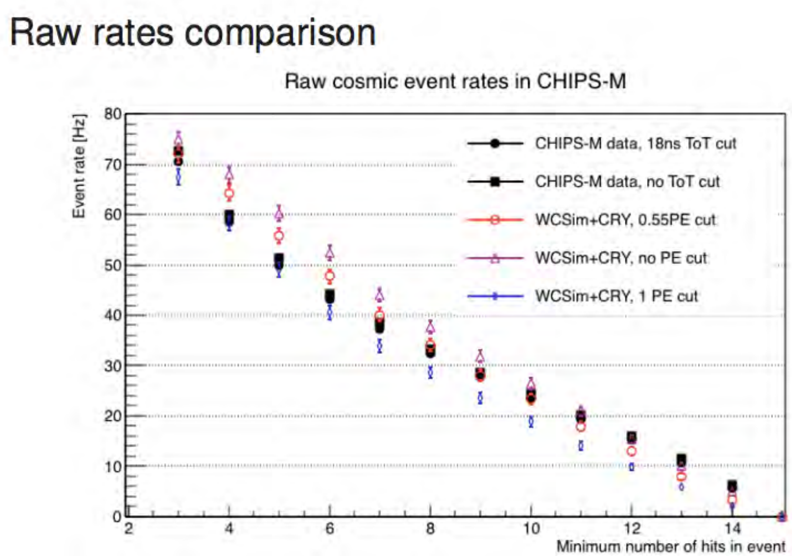
- New feature to lay out PMTs in more complex patterns
- Model the effects of different-sized PMTs side-by-side
- Model the efficiency of non-





- CRY cosmic package generates cosmic flux at earth with GEANT energy loss in water
- MC/Data shape (events vs number of PMTs) agree well, overall rate is higher in data
- Use this to calculate number of events which will be present in a 10μs NuMI spill for a 10kt CHIPS = 0.14
- Total cosmic rate in CHIPS-10 is 14.4kHz
  - Larger detector would have directional capability to reduce this further
  - Also veto PMTs to extract 200ns time window around cosmics

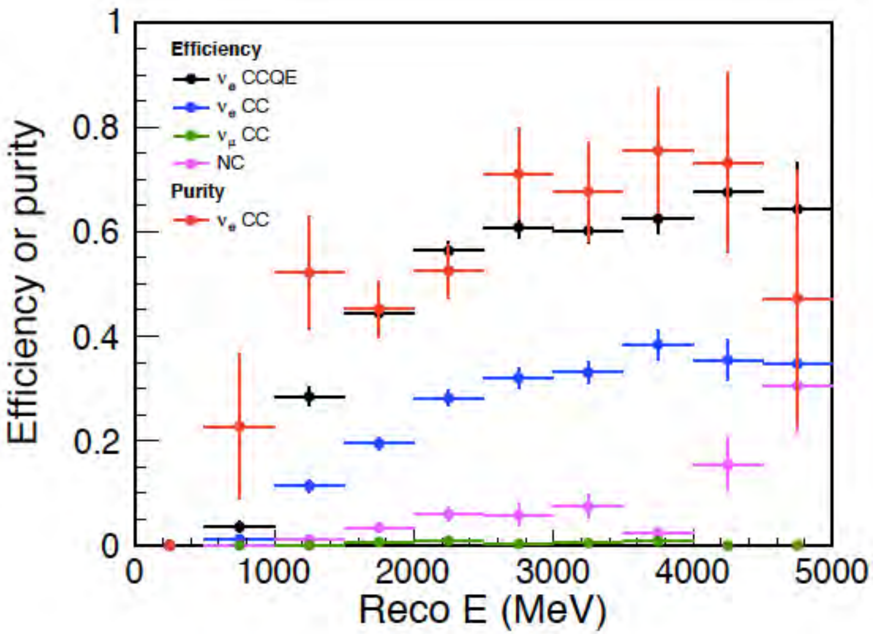


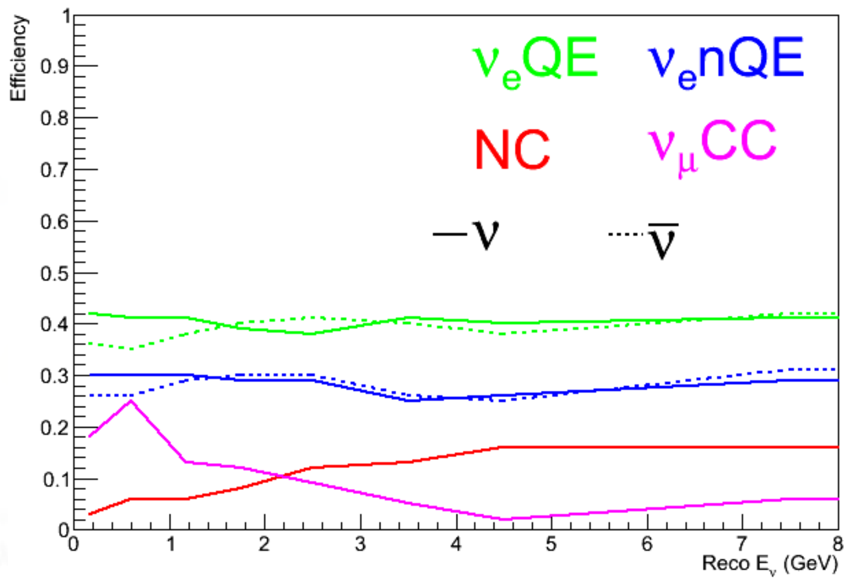


Reconstruction Bottom Line

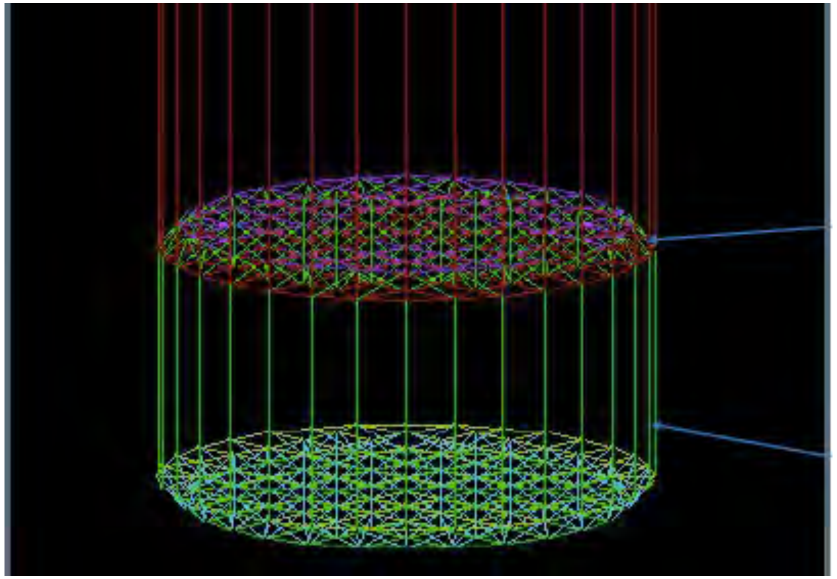
Table 1. The resolutions of various reconstructed parameters from single ring electron (muon) track fits to a sample of CCQE ν_e (ν_μ) interactions with energies following those expected from the NuMI beam.

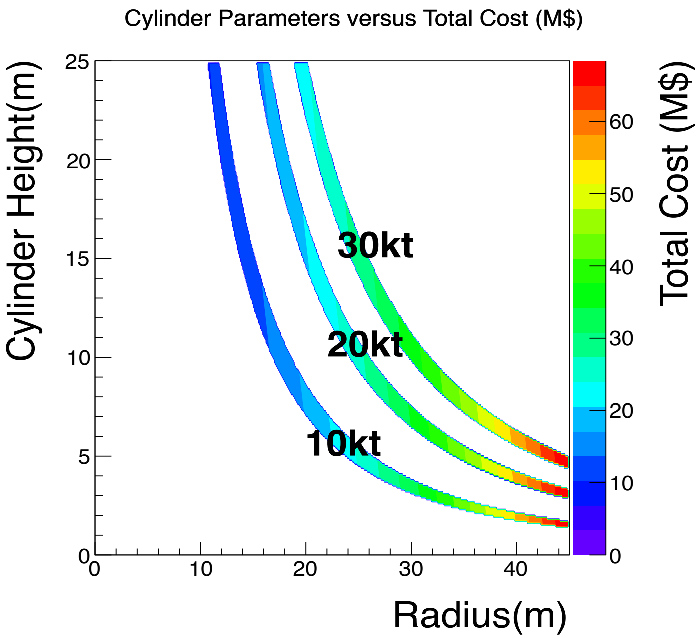
Sample	Geometry	Reconstruction Resolution Position (cm)	Time (ns)	Direction (°)	Energy (MeV)
CCQE ν_e	10 inch, 10%	35	0.9	2.1	208
	3 inch, 10%	35	0.84	1.9	210
	3 inch, 6%	38	0.89	2.1	211
CCQE ν_μ	10 inch, 10%	47	1.35	2.6	113
	3 inch, 10%	44	1.14	2.7	110
	3 inch, 6%	51	1.28	3.0	113





Mechanical Structure





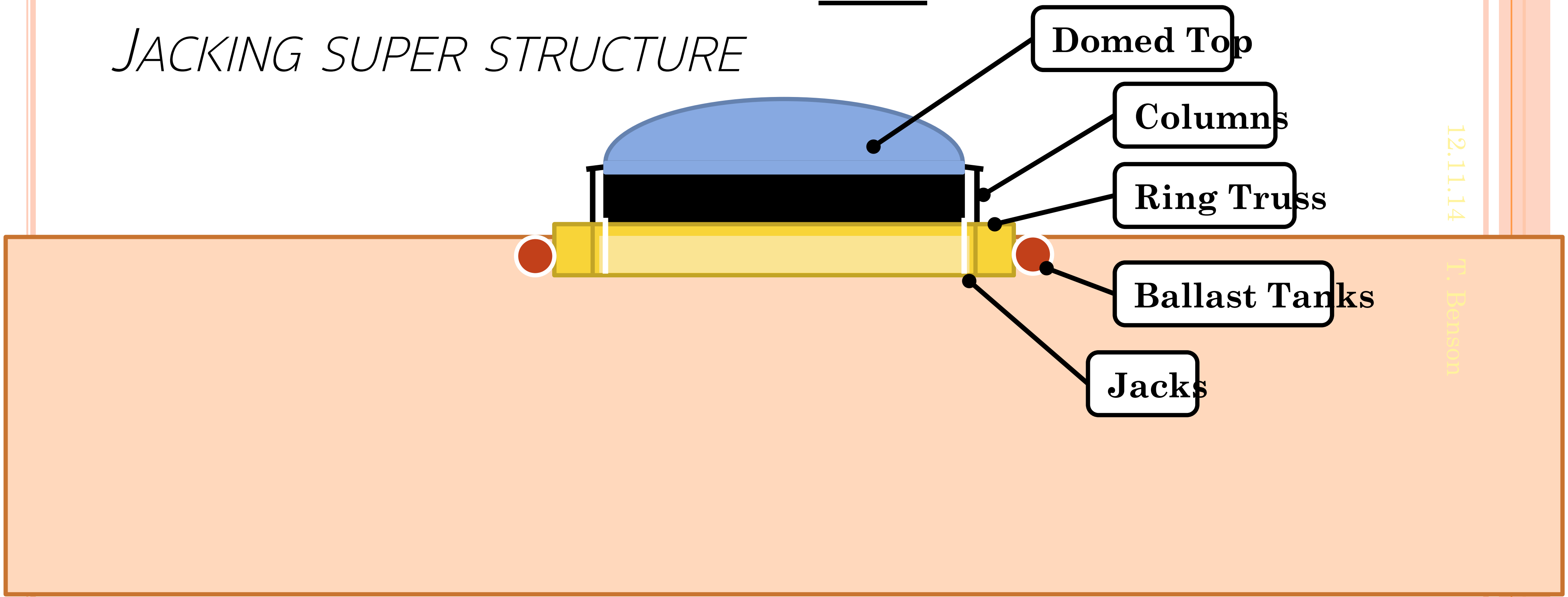
- New idea is to hang bottom spaceframe end cap from top one with Dyneema ropes (used in Km3Net)
- Allows volume to grow if more PMTs are available
- Saves 50% cost of the spaceframe sides
- PMT planes attached to ropes
- Make footprint large enough: bang for buck is impressive for walls

Mechanical Design

- Work on going on the mechanical design
  - Separate planes of PMTs easily attached
- Structure will be built on a semi-dry dock and floated
  - 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-M over-engineered for its size
  - CHIPS-10 will have a 25m diameter footprint

SPACEFRAME AND LINER: TOP

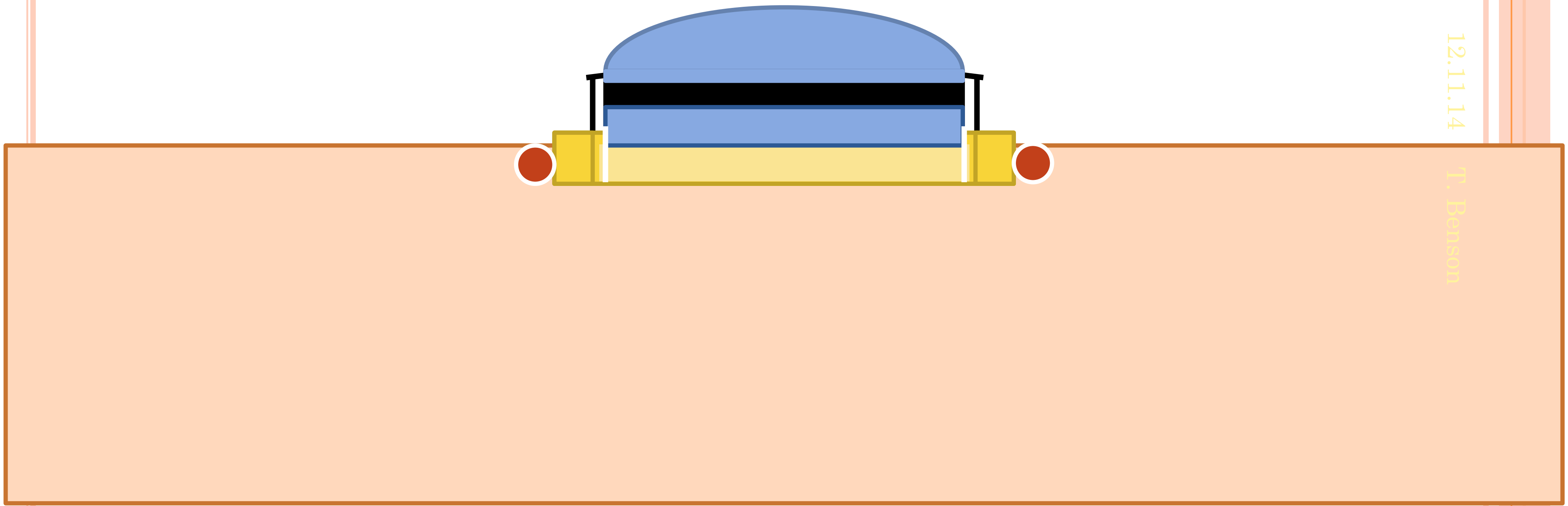
JACKING SUPER STRUCTURE



- 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

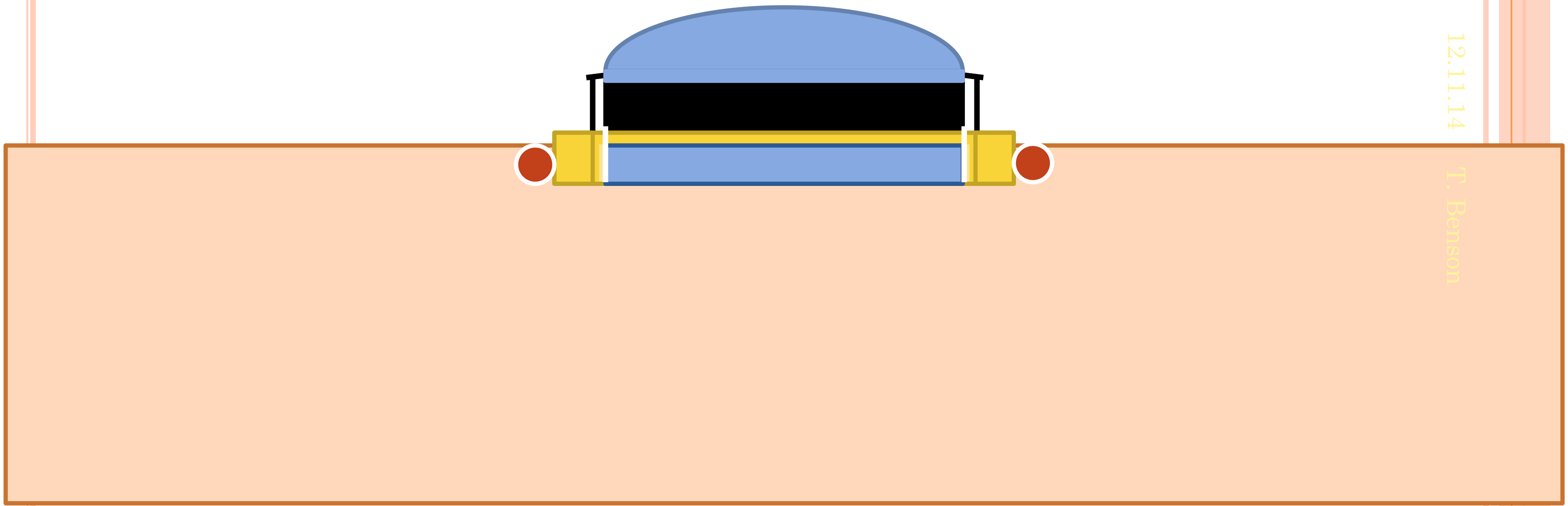


Assembly sequence on water

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

SPACEFRAME AND LINER: TOP

JACKING SUPER STRUCTURE

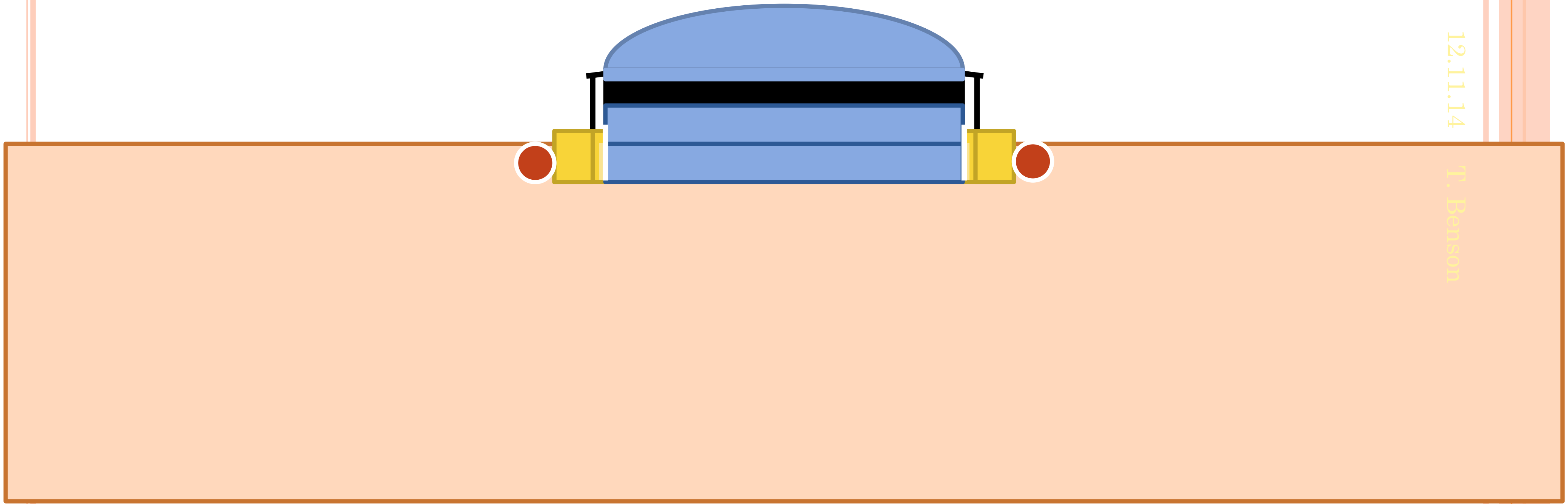


Assembly sequence on water

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: TOP

JACKING SUPER STRUCTURE

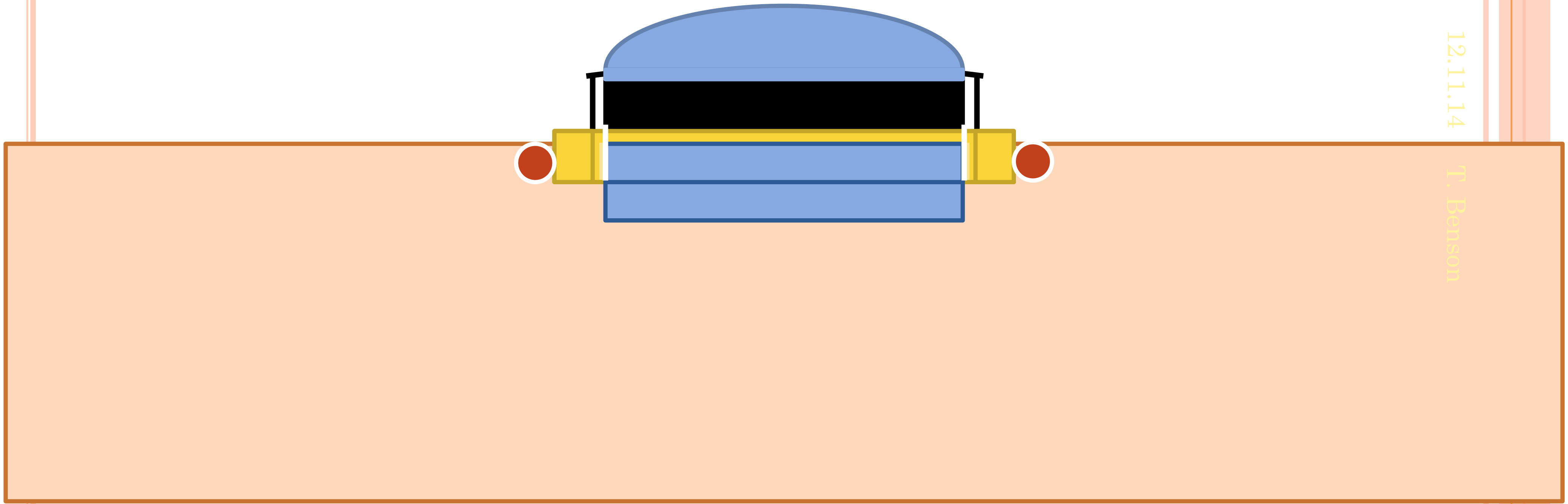


Assembly sequence on water

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.
3. Build second wall layer.

SPACEFRAME AND LINER: TOP

JACKING SUPER STRUCTURE



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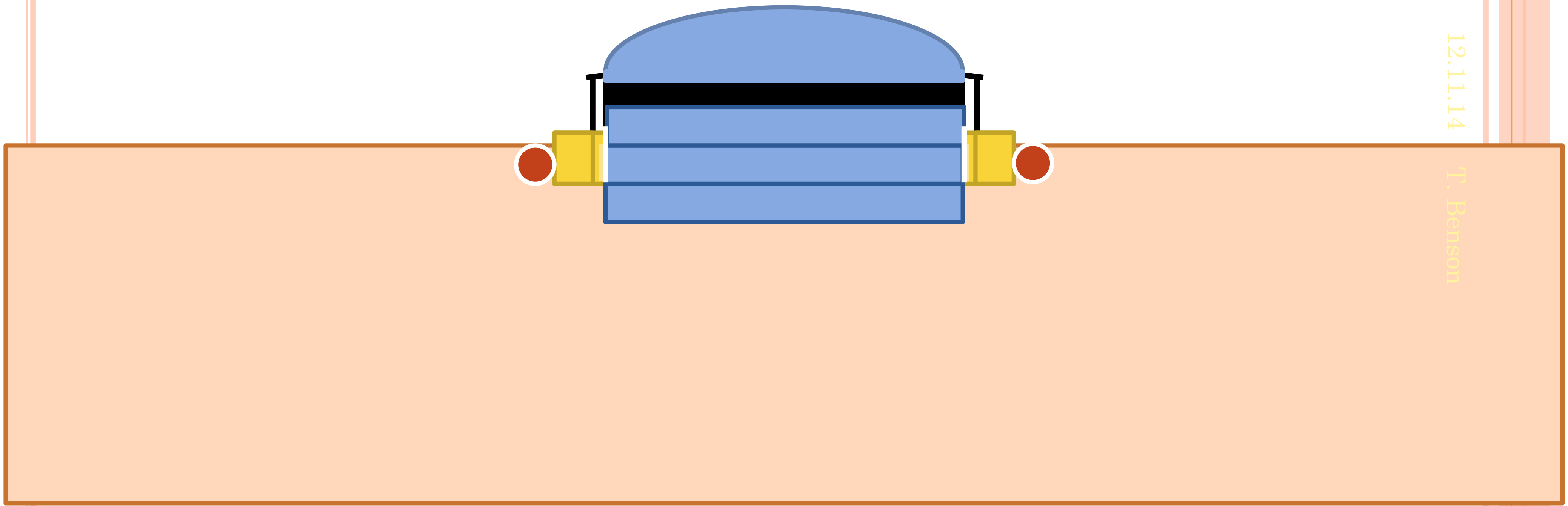
3. Build second wall layer.
4. As layers are added the floor and wall assembly successively climbs down.

SPACEFRAME AND LINER: TOP

JACKING SUPER STRUCTURE

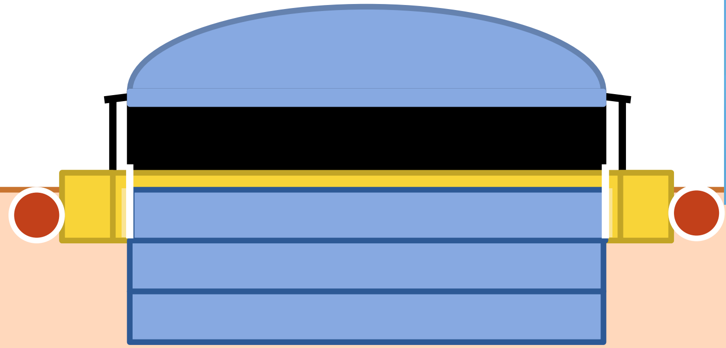


Assembly sequence on water

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.
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



Similar to how a tower crane assembles itself

T. Benson

Assembly sequence on water

1. Build floor and first wall layer. The wall layer also attaches to the floating ring.
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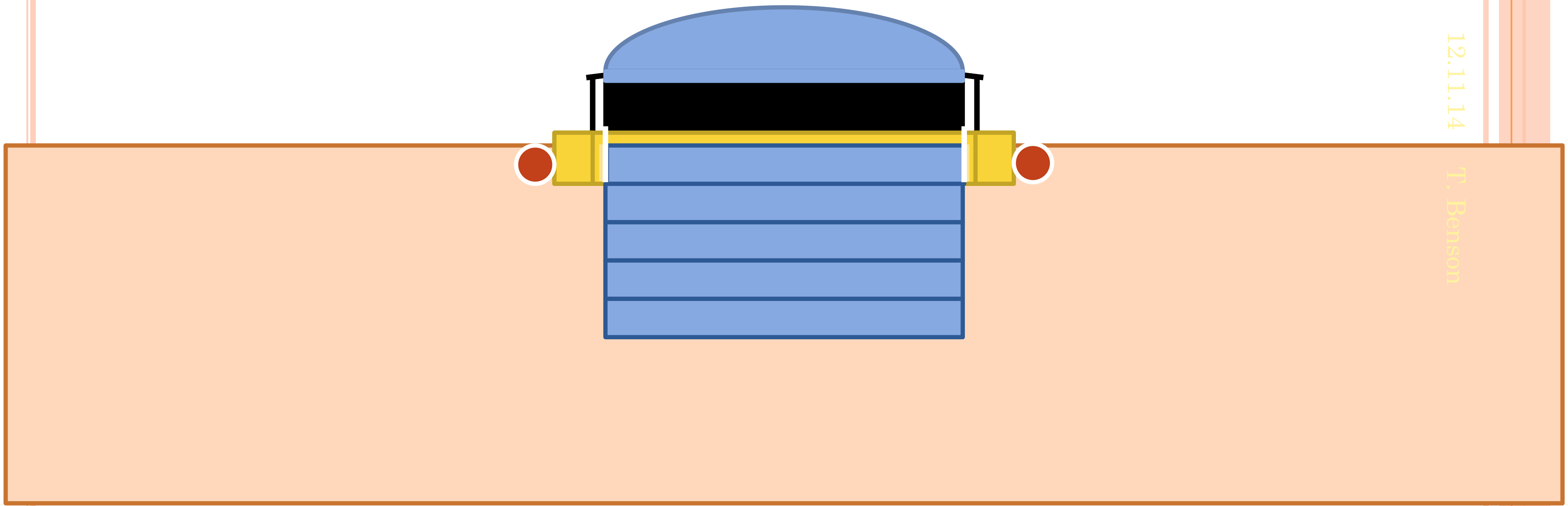
SPACEFRAME AND LINER: TOP

JACKING SUPER STRUCTURE



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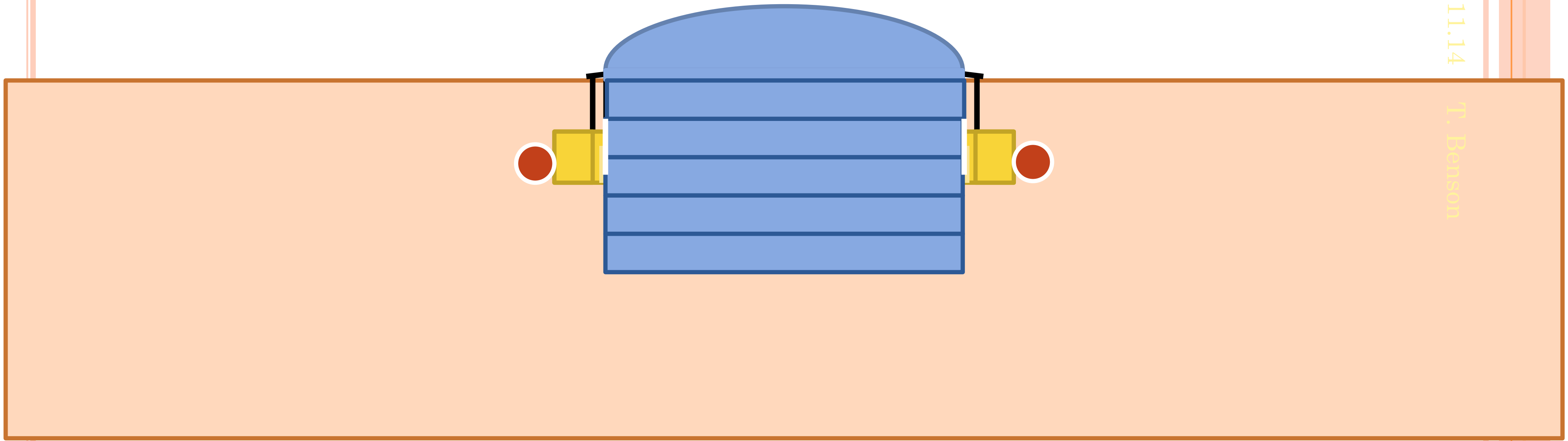
JACKING SUPER STRUCTURE

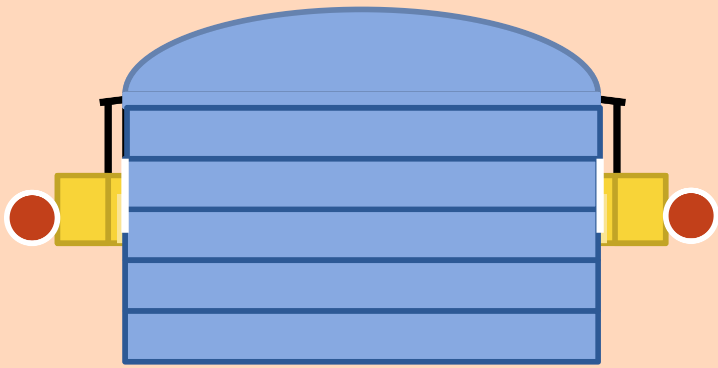


Assembly sequence on water

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.
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.

Status of the project today

- US, UK, Holland, Canada about 35 people
  - Looking for collaborators interested in WC development
  - Leverhulme 5 year grant awarded in UK for personnel
  - ERC AdG awarded to UCL and Nikhef (€3.5M)
  - Large contribution from UW
  - Pledged 900 3" PMTs from IN2P3
- Deployment of 3-5kton detector starts 2018
  - Additional resources being requested to double the volume
- If successful, will prove that WC can be built for \$200-300k/kt
  - Mton would likely comprise 20-30 separate ~30-40m diameter x 20m high detectors : total cost about \$200M
  - Every member of the collaboration could have their own detector!

SUMMARY

- Neutrino oscillations have moved from discovery to tool
- In the future we are going to learn about the mass ordering of the neutrinos and whether they violate CP symmetry
  - Huge impact on our understanding of the Universe
- Lots of new results coming in the next 3-6 years
- The scientific landscape is exciting, with the best neutrino beam in the world at FNAL for the forseeable future
  - Without huge detectors, learning anything beyond the standard model of neutrinos will be very difficult









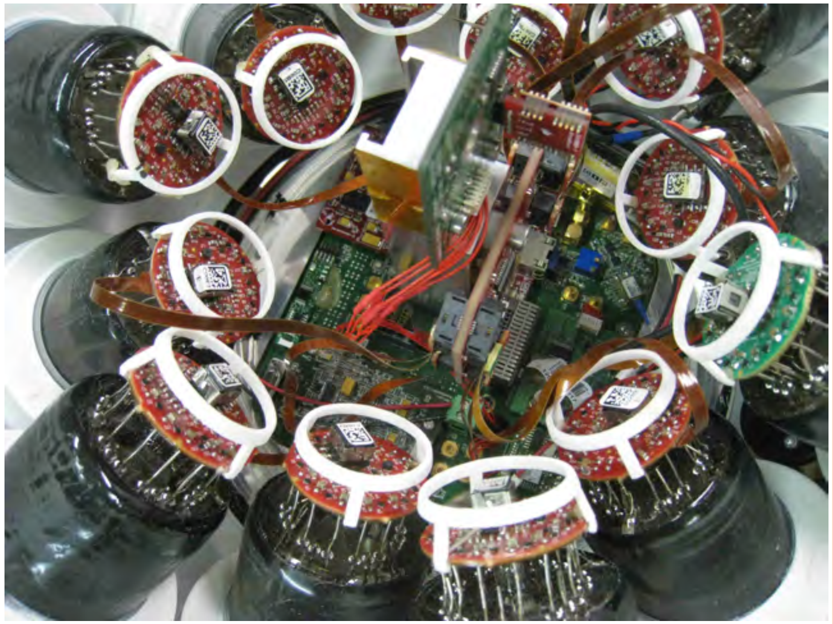
bobcat

BACKUP SLIDES

BACKUP SLIDES

STEALING FROM KM3NET

- 31 PMTs of 3in diameter :
- About the same cost as 11” (per unit photocathode area)
- Euro 150 each
- Low-power Cockroft-Walton HV generator
- PMT signals processed locally using a specially developed ASIC and FPGAs.
- Time-over-threshold instead of waveform digitization
- Two wires (power), one fibre
- The PMT-base developed at Nikhef, CLB at Genova (board layout) and Nikhef (fpga firmware) and Saclay contibuted CLB prototypes.



Why do we care?

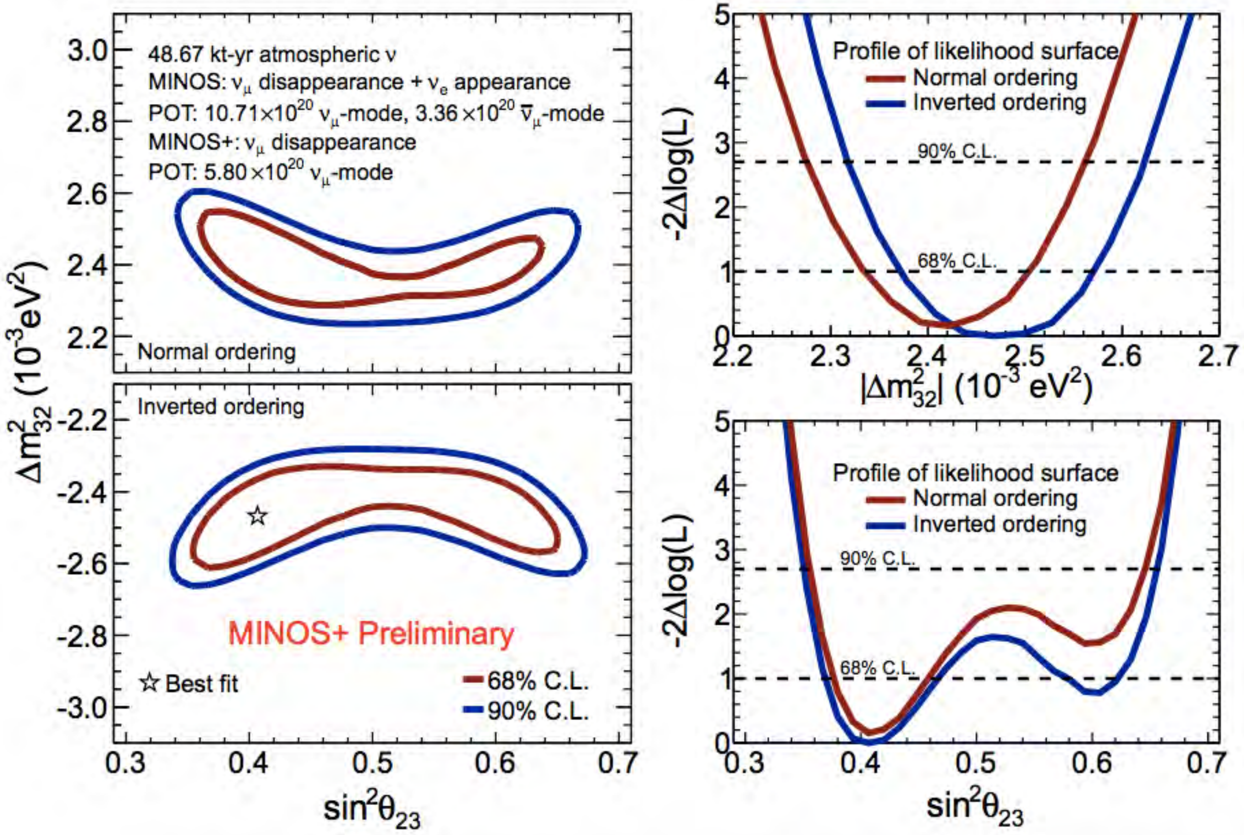
- There are 300 neutrinos in every cm^3 of the universe
  - Left over from the big bang
  - Coming from the sun
  - Coming from supernovas
  - Coming from cosmic rays
- $65 \times 10^9/cm^2/s$ just from the sun
- Compared to baryons its huge! you would be lucky to find 1 proton/m^3 but billions of neutrinos
- 10^{89} total neutrinos in the universe
- So, even if they have a tiny mass, they could have a big impact on cosmological calculations
- So where do we get them from to study?
  - ν_e from sun
  - ν_μ, ν_e from cosmic rays
  - ν_μ from accelerators
  - Anti-ν_e from reactors
  - ν_e from radioactive sources

CHIPS-M : WHAT WE LEARNED

- Liner is robust and totally light tight
- Water can reach >~50m attenuation length (at 405nm)
- 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 <1% dead-time 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

AT NEUTRINO 2016, LONDON
MINOS/MINOS+

- Combination of disappearance and appearance, slightly disfavours higher octant

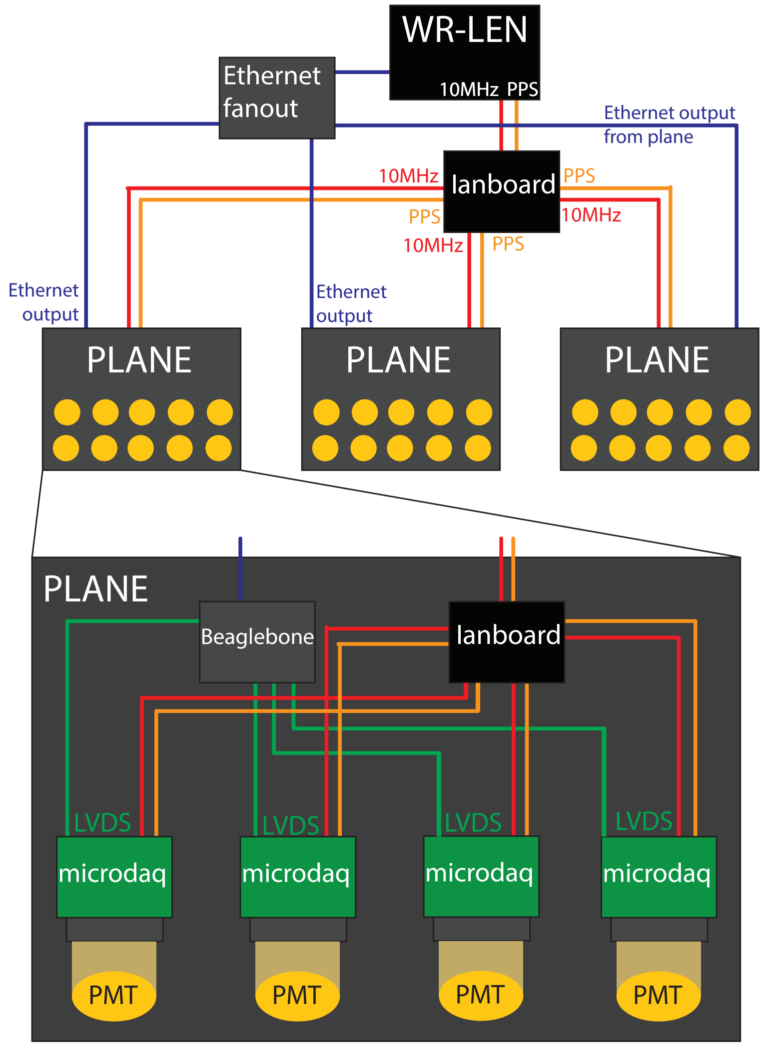


$$\Delta m^2_{32} = \begin{cases} 2.42 \pm 0.09 \times 10^{-3}\,\mathrm{eV}^2 \text{ Normal} \\ -2.48^{+0.09}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2 \text{ Inverted} \end{cases}$$

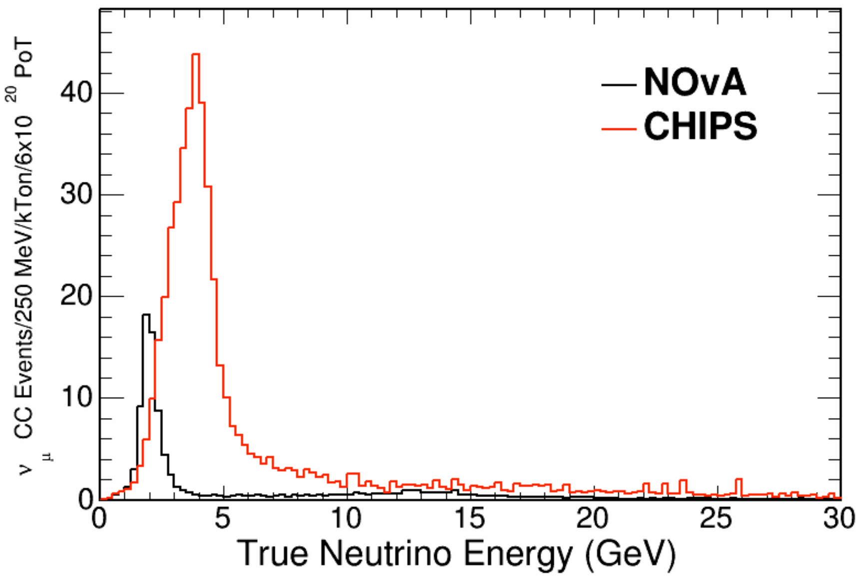
$$\sin^2(\theta_{23}) = \begin{cases} 0.35\text{–}0.65\ (90\%\ \text{C.L.})\ \text{Normal} \\ 0.35\text{–}0.66\ (90\%\ \text{C.L.})\ \text{Inverted} \end{cases}$$

DAQ Development : iPHONE and ARM Madison

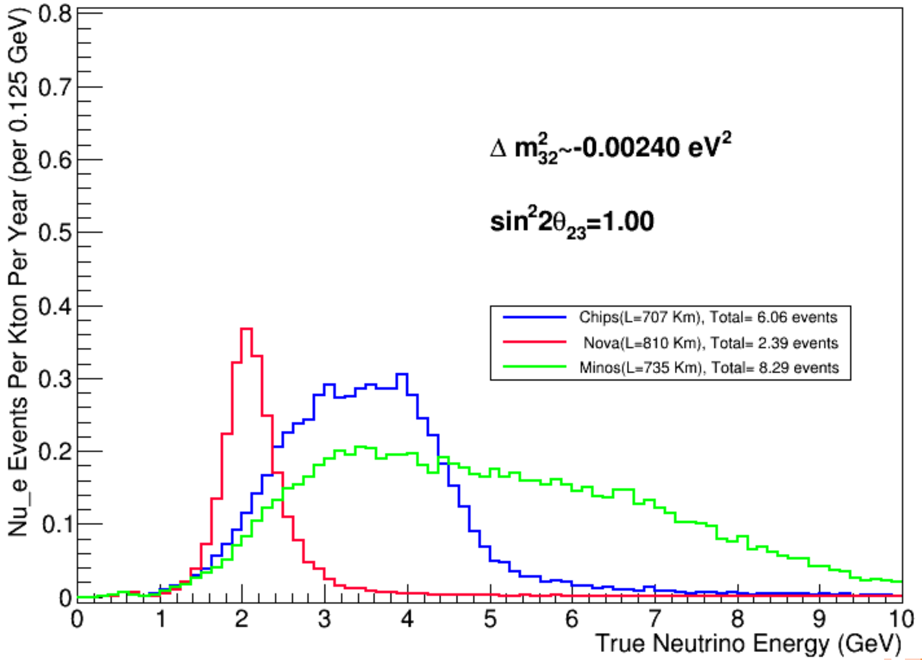
- Working in conjunction with IceCUBE IceTop and HAWC @ Madison
- Micro processor on PMT
- TOT to ~waveform from series of delays
- 1ns absolute timing
- WR provides clock
- BBB builds events
- Ethernet back to WR switch and the world
- +ve CW base being fabricated for all donated PMTs



NuMI Energy Spectrum (~7mr, 5km OA)

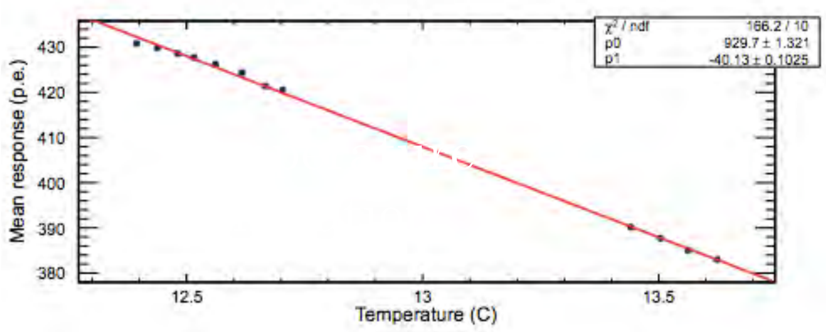


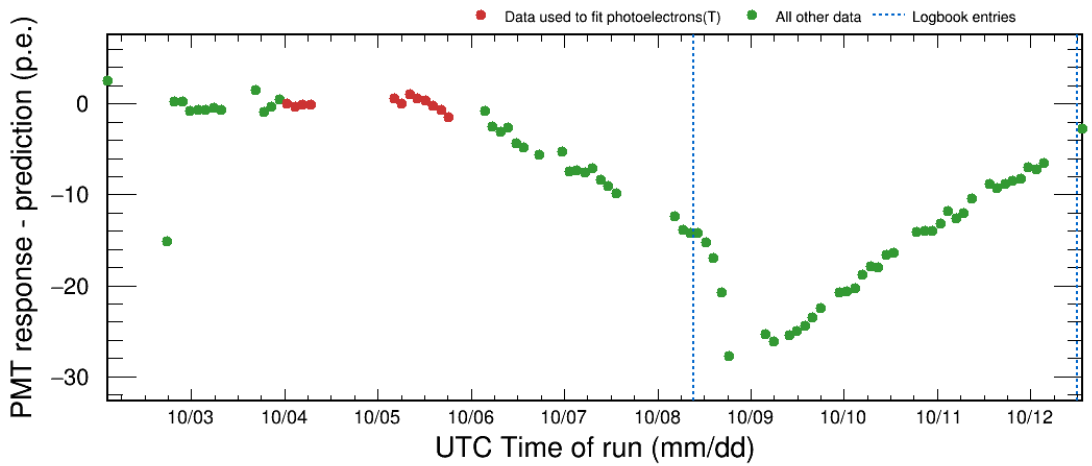
- Key is good identification of the events
- They are there for the taking in the NuMI beam!



WATER STUDIES

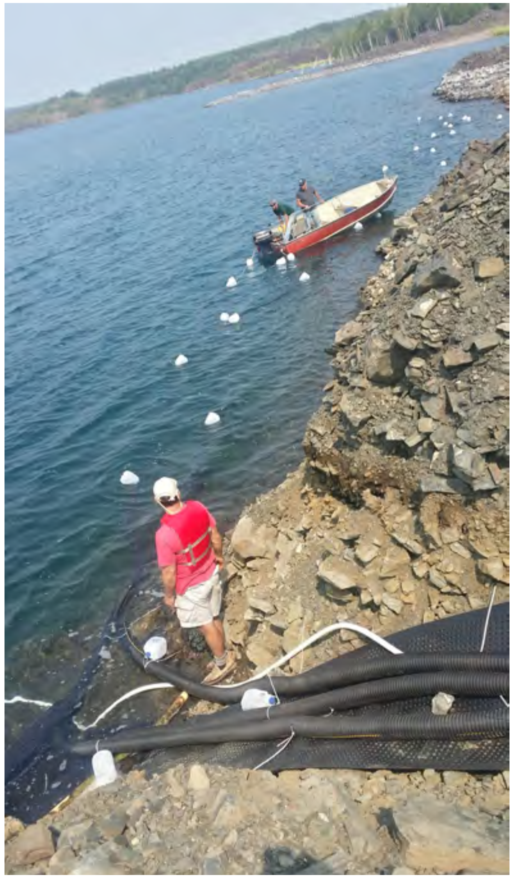
- The water used to fill CHIPS-M was put through a reverse osmosis filter and stored in a container before deployment
- Attenuation length after storage was about 3m
- Water started cooling as soon as the detector was submerged
- Plot shows the DOM response after temp correction to LED flasher as a function of circulation time

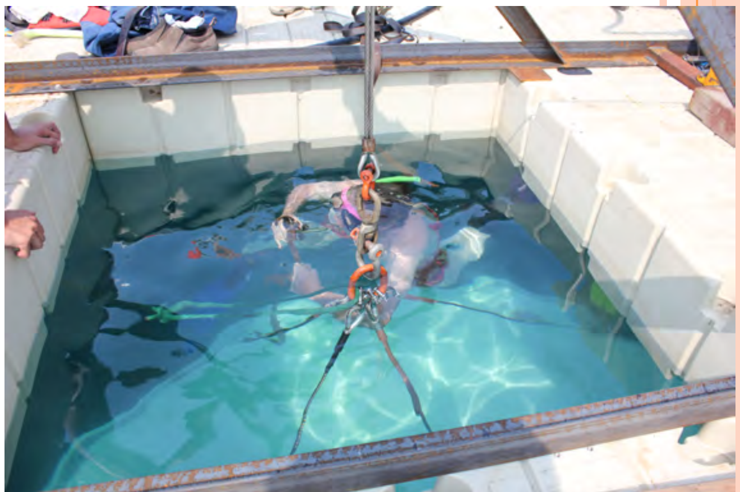


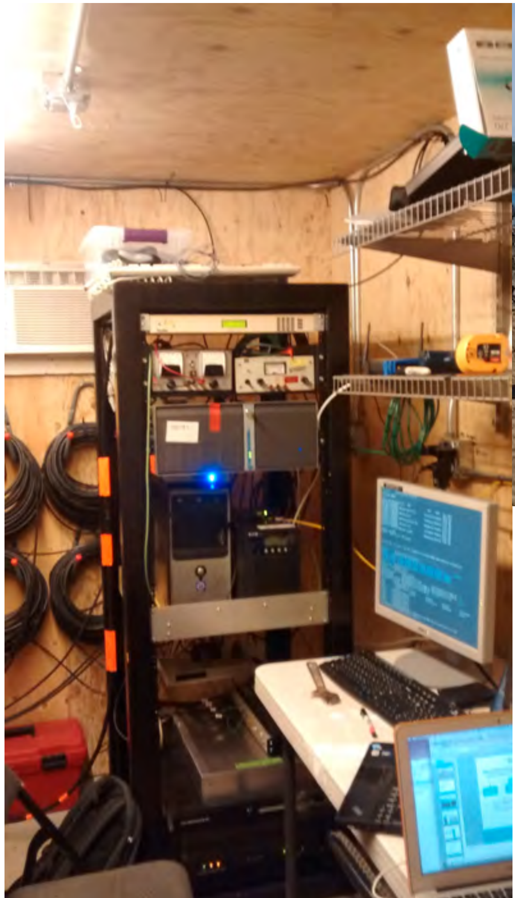


- CHIPS detector was not that clean, water initially got dirtier before it started raking out the debris inside the detector with the filters
- Not possible to get an absolute attenuation length from this monitoring measurement, so we took some water back to the lab to continue to clean it and see how well we could do

Deployment Day



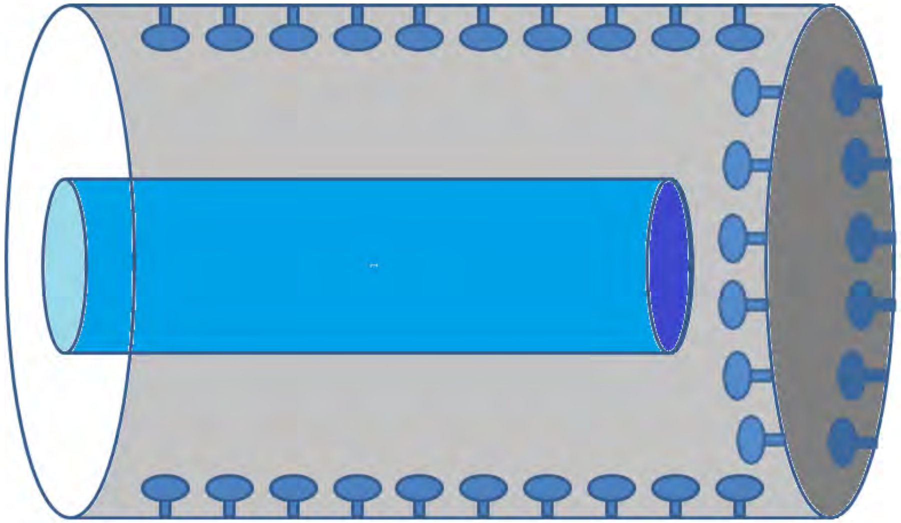





LAKES GAS


POLICE PUBLIC CALL BOX

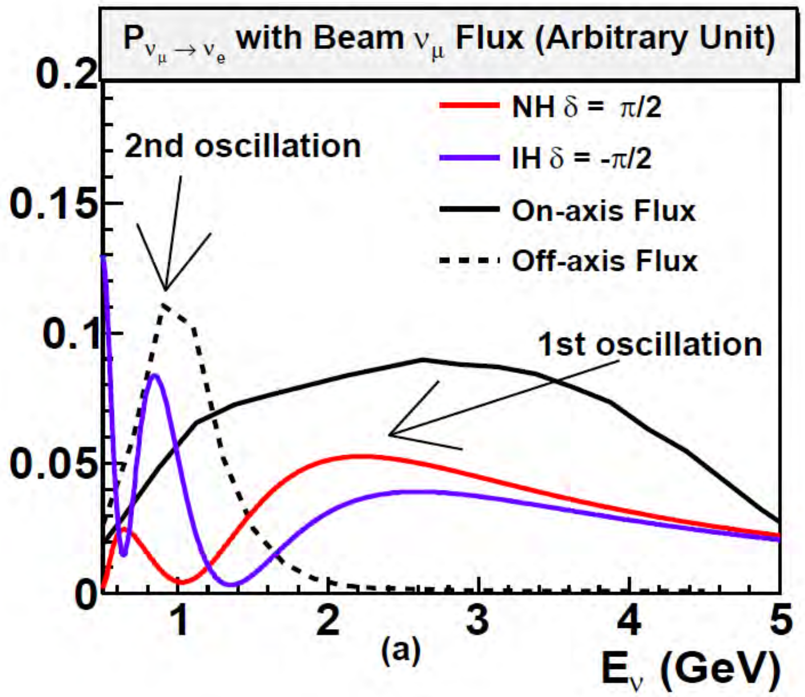
Near Detector Concept



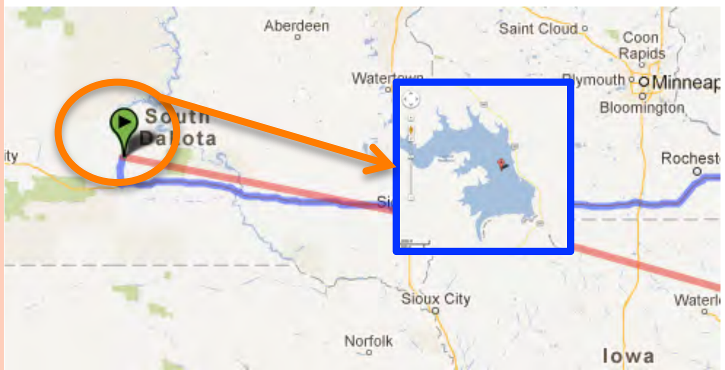
- Minerva with water target might be another option
- Need to understand exactly what ND would be used for

- Potential use for fast PMTs here...
- Small water volume leads to small number of events per spill
- MINOS ND as muon catcher
- MC must model ND performance : this true in any case
- Lots of interesting development to be done

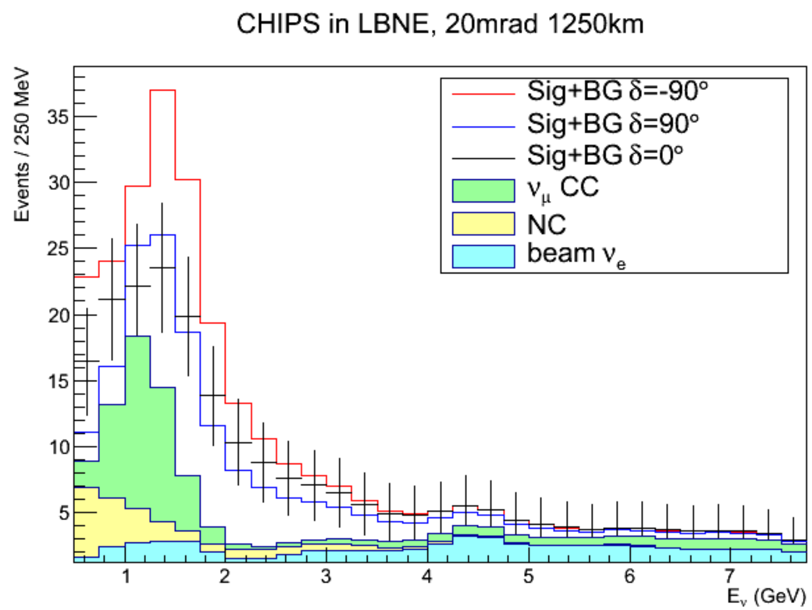
CHIPS@LBNE (20MR OFF AXIS)

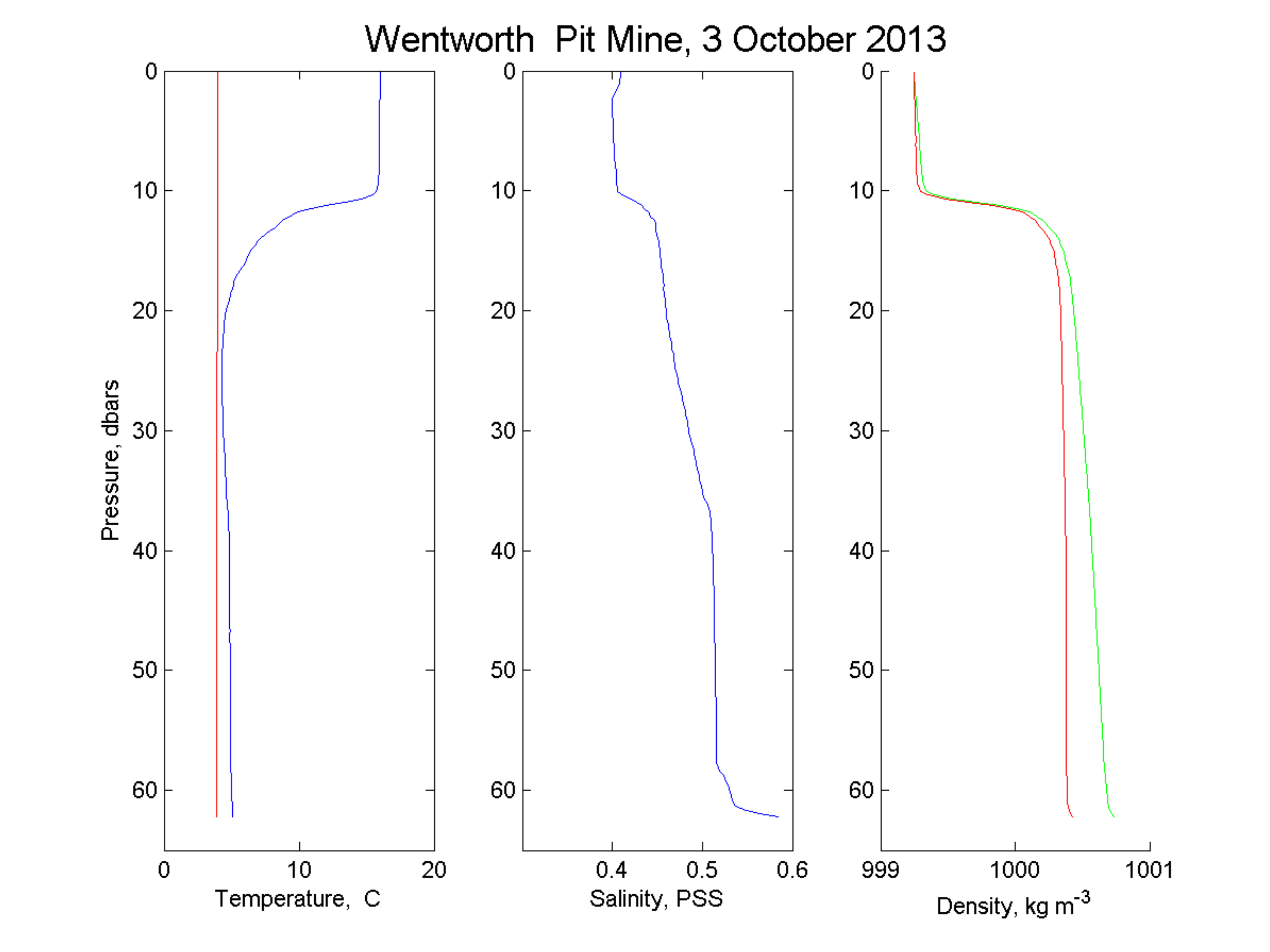


- There is (at least) one (40m depth) reservoir in the beam line @ 20mr (Pactola Resevoir, SD)



- 2nd oscillation maximum located around 0.8 GeV
- Large quasi-elastic x-section
- Suitable for water Cerenkov detector
  - High efficiency for QE events
- 2nd oscillation maximum is a necessary upgrade/augmentation path for LBNE





Recording probe results at the anchor site.
Note the water temperature change at 10m

A Big Question

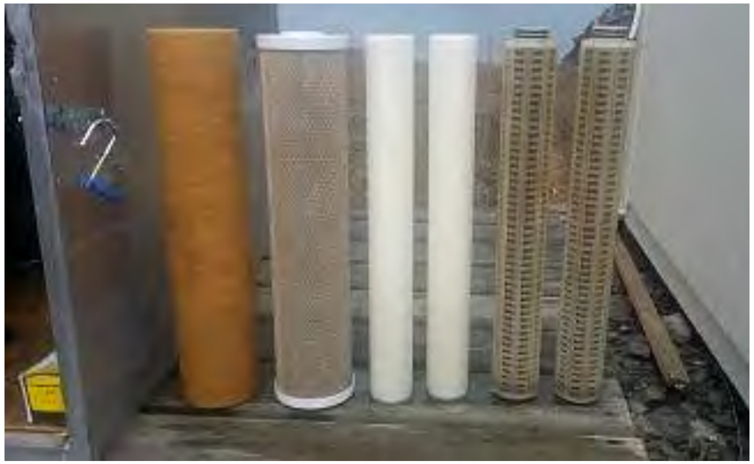
- Our Universe appears to be made predominantly of matter
  - Yet the big bang would have created matter and anti-matter in equal portions
  - CP violation allows for the rate of a process to be different for a particle and its anti-particle
  - This means that as the universe expanded, an asymmetry could be formed where the reverse process was no longer possible and a small amount of matter was “stranded” without its anti-matter partner
  - Lepton CP violation can transform into a baryon asymmetry via the Sphaeleron process
    - conserves B-L, the only anomaly-free global symmetry
  - Neutrinos have L=2 transition if Majorana

NEUTRINO OSCILLATIONS

- Once established, the neutrino oscillations can be used as a technology
  - Just like using interference to learn more about the original sources
- We are now in this era of oscillation technology
  - Over the last 15 years neutrino oscillations have been established and measured
    - SuperK,Kamland,SNO,MINOS,T2K,DayaBay,Reno,DoubleChooz
- What is the remaining information we still don't know?
  - Which neutrino mass eigen-state is the heaviest
  - Do neutrinos violate CP symmetry
    - And does that tell us about the matter-antimatter asymmetry of our universe
  - Are neutrinos their own antiparticle?
    - Search for double beta decay is hard but ongoing
    - Oscillations have put hard base of 50meV^2 on Δm^2

The Water System

- UV Sterilizer + series of filters down to 0.2microns
- Carbon filter to eliminate life
- Circulates at 3-5 gpm from shed down 200m of hose and back



At neutrino 2016, London
NOVA

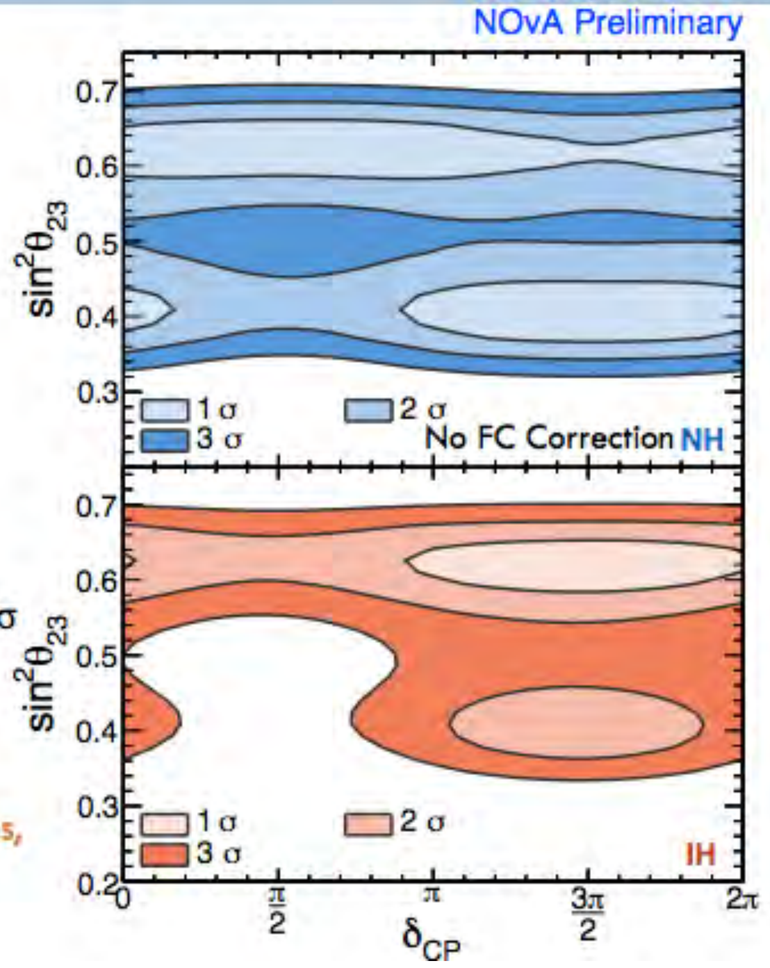
Contours

27 P. Vahle, Neutrino 2016

- 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