CHIPS AND THE NEW DEAL

- Introduction
  - Preamble
  - Intro to oscillations
  - What is CHIPS?
  - Why should you care about CHIPS?
- The fun part
  - Construction of the detector (life in the Gulag)
  - What to expect near term
- The future vision towards an array of detectors

April 17th

EXECUTIVE SUMMARY

- The Standard Model is a supremely successful theory of matter and describes three of the four Forces of Nature
- It underpins all of physical science but categorically forbids neutrinos to have mass
  - small details of the theory need tweaking? OR
  - our fundamental understanding of physics is wrong?
- We have developed a disruptive technology to enable a step change in precision measurements of neutrino oscillations
  - Technology push enables us to dream!
  - Allows us to imagine more than one huge detector at a time!
- We will develop the new vision of how to use this new tool for unprecedented precision measurements of neutrino characteristics

Introduction

GENERAL

- Neutrino oscillation study needs to measure neutrinos at-a-distance
- Neutrinos interact only with the Weak Interaction
- At low energy ($E << m_W$) the interaction x-sec rather low
- Need to increase the flux (beam) or increase the target mass (detector)
  - Increase flux by maximum factor 2 (1-2 MW) over present as its hard
  - Increase in mass is expensive (10M-100M money units/kton)

SPECIFIC

- Mass Hierarchy needs a long baseline to be accessible
- CP violation needs lots of events to be measured
- $\sin^2\theta_{23}$ remains the big uncertainty in trying to measure the first two
  - also potentially is the most interesting….maximal?

TO CATCH A NEUTRINO

- Pontecorvo first proposed the idea that neutrinos could “oscillate” in about 1957
  - His idea was they would transition between a neutrino and an antineutrino
- Maki, Nakagaw and Sakata (1962) proposed the flavour eigenstates would mix as they propagated as mass eigenstates
  - Their unitary matrix (squares of values in each row and column add to 1) is conveniently factorizable:

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

Super-K
MINOS
T2K

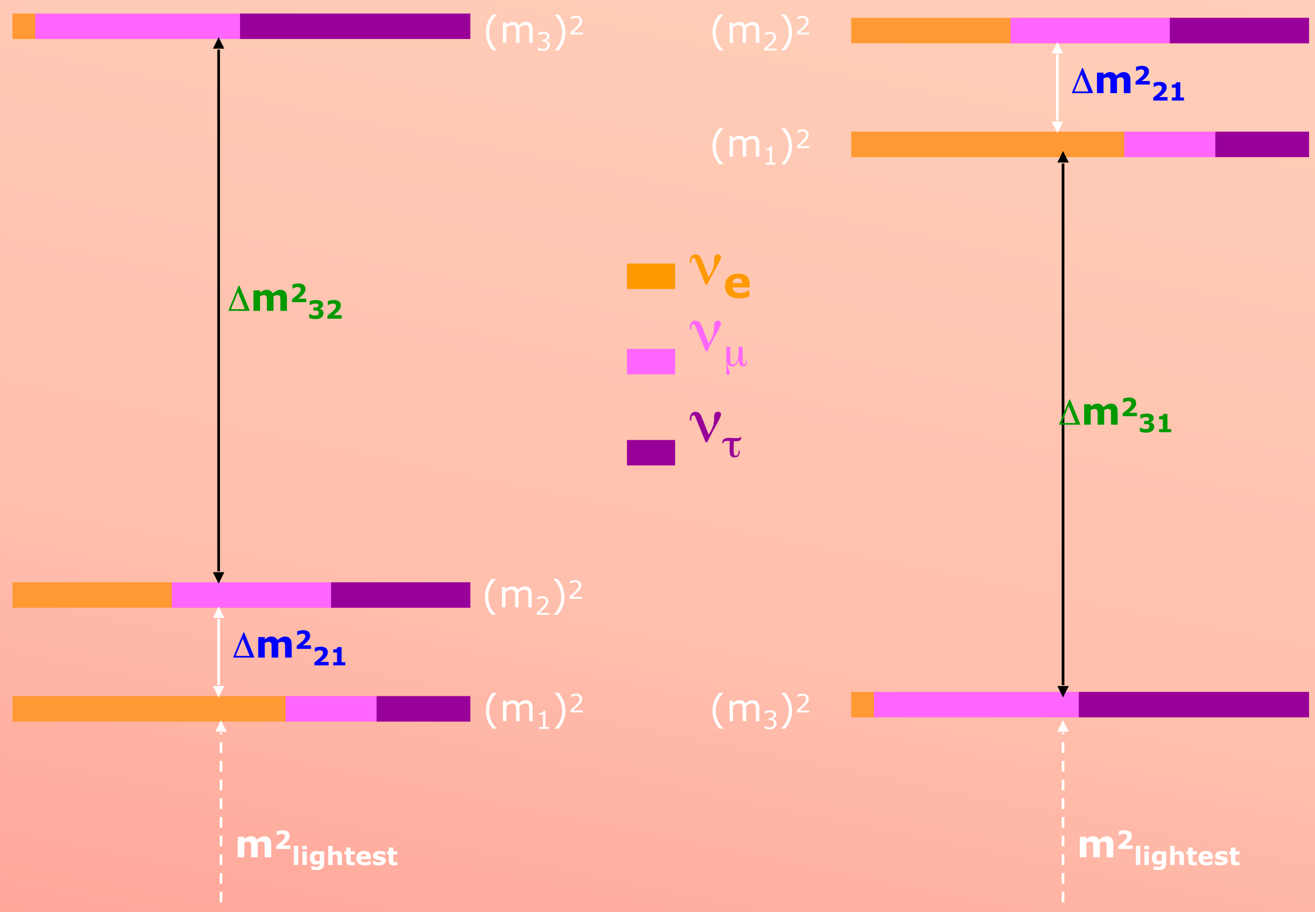
DayaBay
Reno

SNO,
Kamland

Reminder of the questions

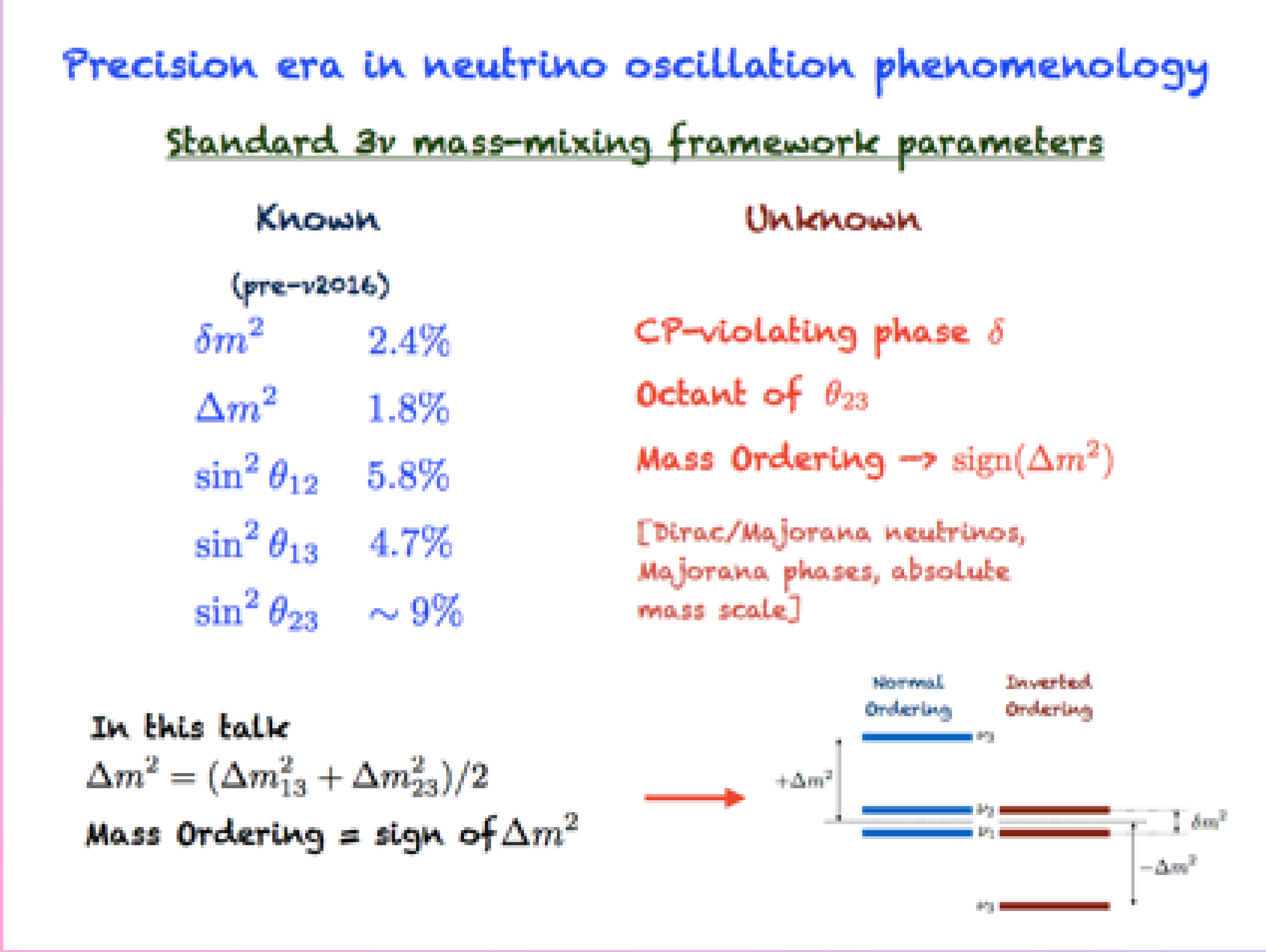
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

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 → $\mathrm{sign}(\Delta m^2)$
$\sin^2\theta_{13}$	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

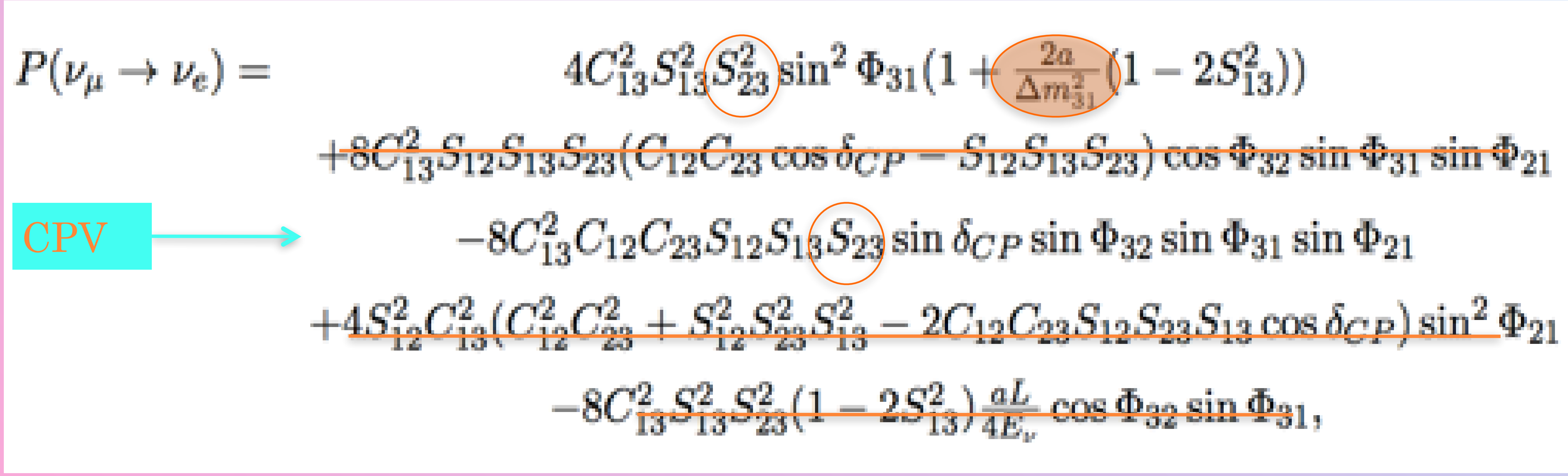
- Looking at disappearance of ν_μ

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

- First term depends on $\sin^2 2\theta_{23}$
  - $\phi_{32} = \Delta m_{32}^2 L/E$
  - Octant unknown
- 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

- Searching for electron neutrino **appearance** tells us about $\sin^2\theta_{13}$, mass hierarchy and δ_{CP}
- Leading term now relies on **$\sin^2\theta_{23}$** and **a**, related to density of electrons in the earth, leads to dependence on sign of Δm^2_{31}, octant of θ_{23} and value of δ_{CP} but all mixed together

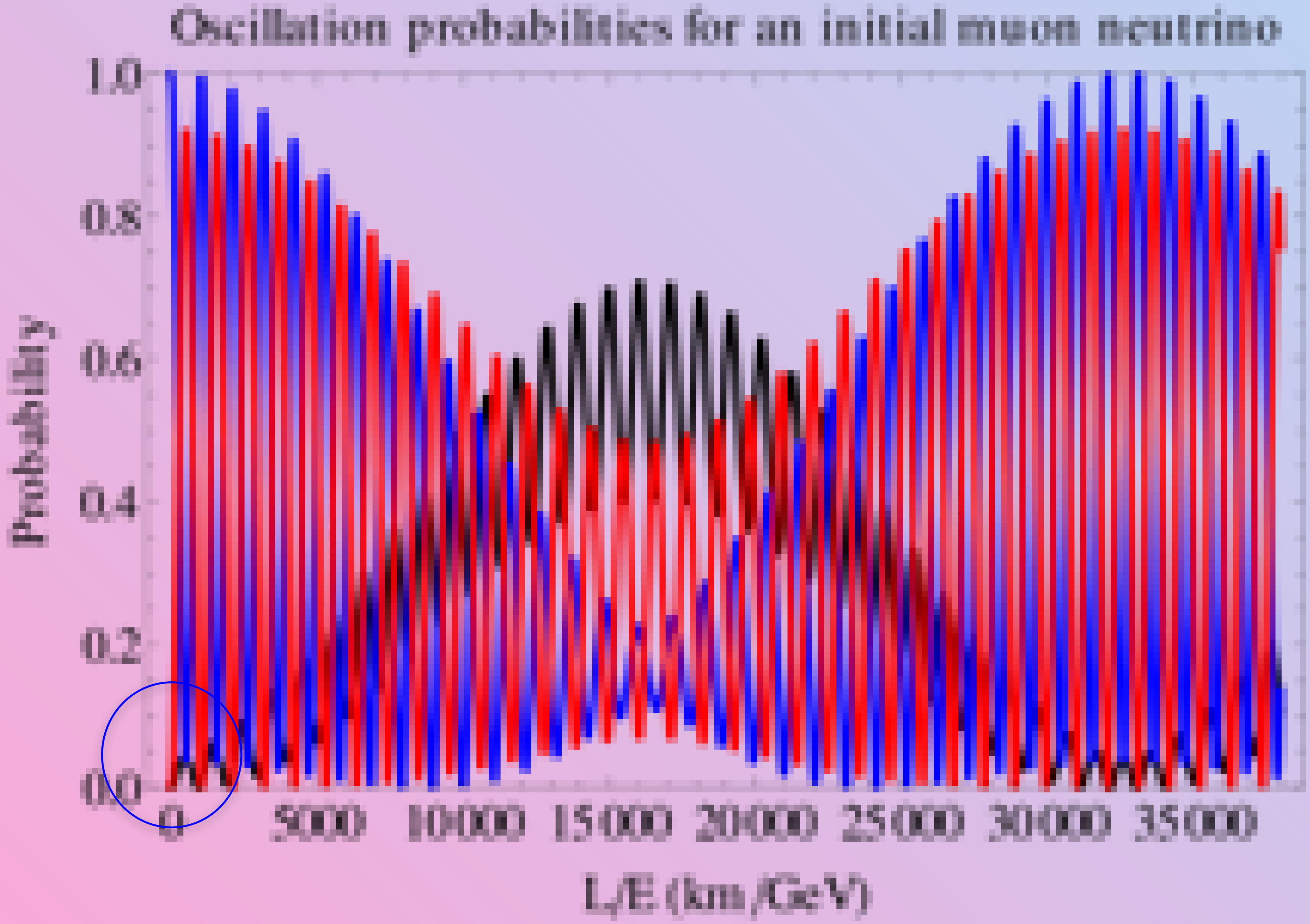


$$\begin{aligned} P(\nu_\mu \to \nu_e) = \; & 4C_{13}^2 S_{13}^2 \boxed{S_{23}^2} \sin^2\Phi_{31}\left(1 + \boxed{\frac{2a}{\Delta m_{31}^2}}\left(1 - 2S_{13}^2\right)\right) \\ & \cancel{+8C_{13}^2 S_{12} S_{13} S_{23}\left(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23}\right)\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}}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

- Running with anti-neutrinos changes sign of CPV term

Neutrino Oscillations in practice

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



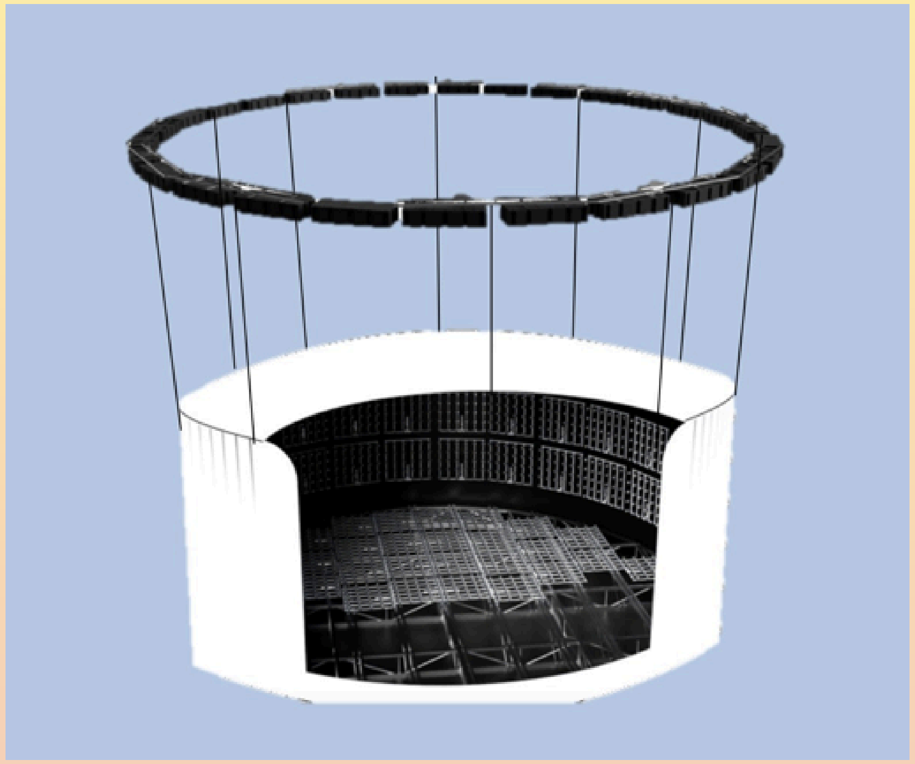
SOMETHING NEW AND RISKY

- Location
  - Sunk in a flooded mine pit in the path of the NuMI neutrino beam, will make use of the water for cosmic overburden and mechanical support
- Structure Design
  - Will allow it to grow in size with time but with no financial penalty beyond the instrumentation costs
- PMT Choice and Layout
  - 3"PMT's good position and time resolution and beam optimized layout
- Electronics
  - will make use of ubiquitous mobile phone and communications technology and already developed KM3Net Solutions
- Water Purification
  - Simple water purification plant will use filtering to maintain water clarity together with natural coldness of 4°C

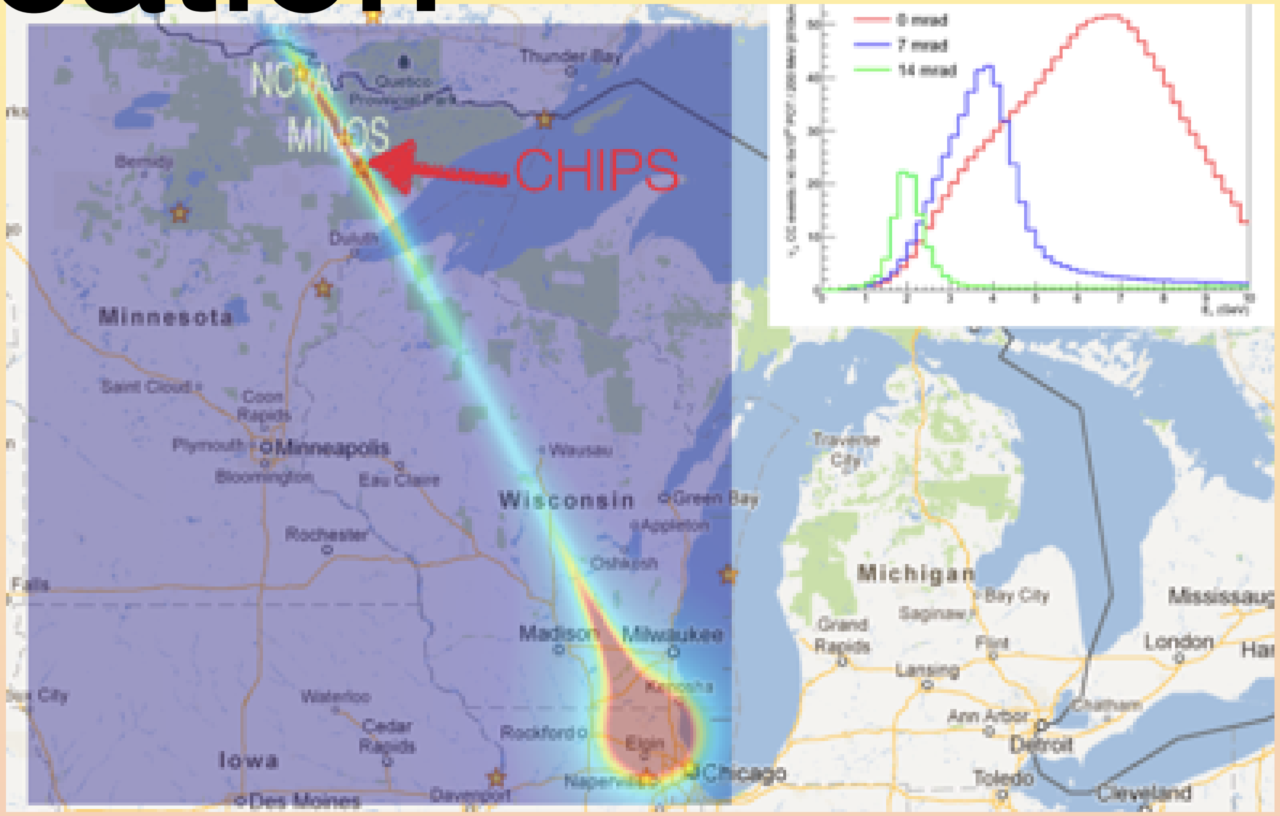
with support from ERC, Leverhulme Trust, UCL, UW, Nikhef, UMn, U.Alberta, UC, UMD, Marseille, MSU, Czech TU, W&M

CHIPS : Cherenkov Detectors in Mine PitS

- The CHIPS goal was to prove that a water Cherenkov detector can do oscillation physics for a fraction of the cost of present neutrino detectors
  - to $200k/kt (presently $2-10M/kt water, $10-50M/kt Liquid Ar
  - and with all the technical challenges that go with it
- ~5kt CHIPS was submerged (end last year) in a flooded mine pit in the path of the NuMI beam : in 4 months!



1.Location



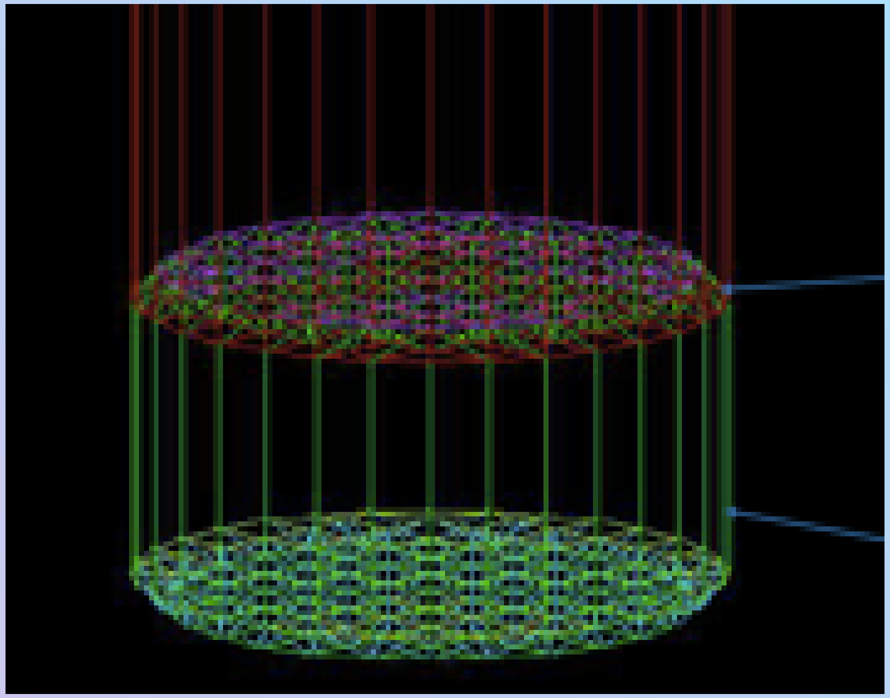
- Polymet Mining site, secure and friendly lab space in the main building
    - (reminds one of the twilight zone)
- Wentworth pit is ex-taconite flooded quarry
- 50-60m at deepest point
- 7 milli-radians off axis in the NuMI muon-neutrino beam

1.Location

May 29th

2.Structure

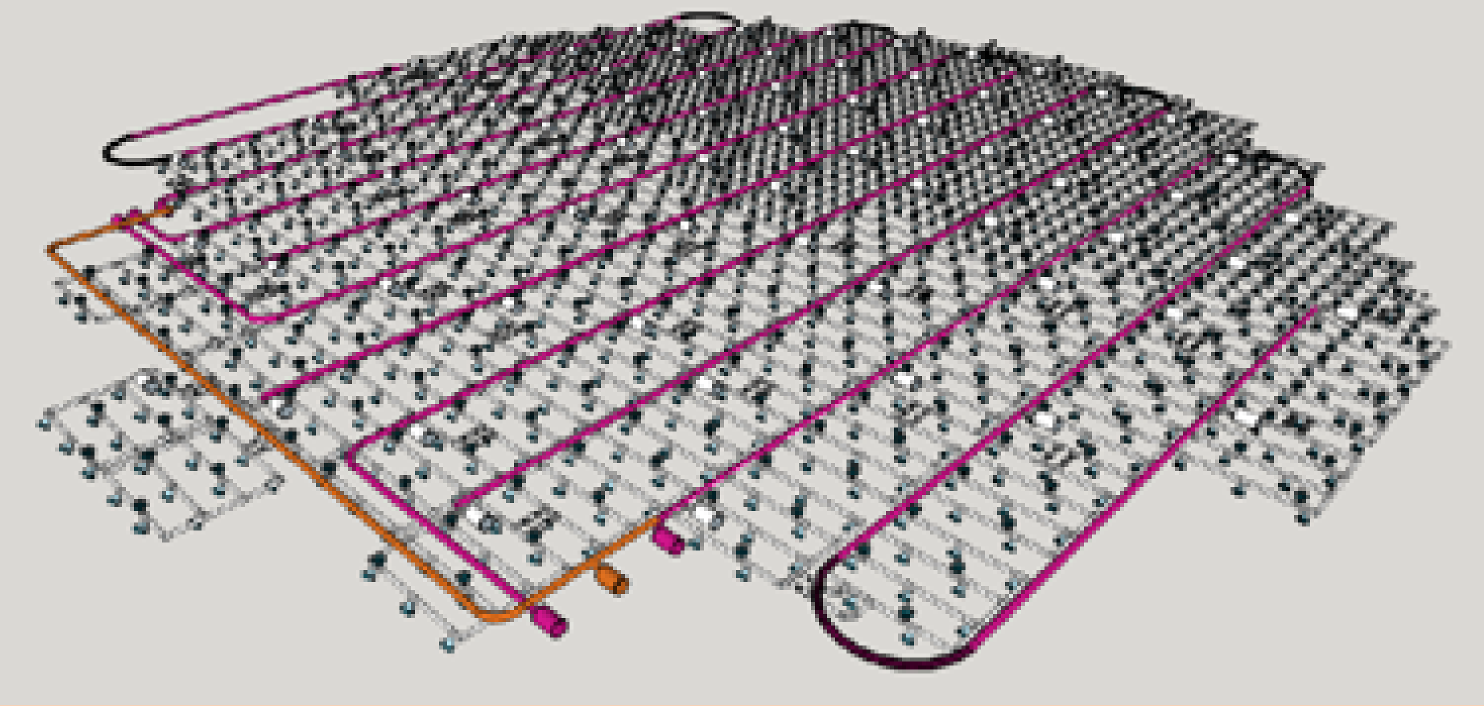
- Two 25m steel end caps are held together by Dyneema cables
- Detector can grow in height for cost of cables and instrumentation
- Top cap is buoyant wrt bottom cap
- Bottom cap will rest on ground
- Top cap will be held down by Dyneema cables

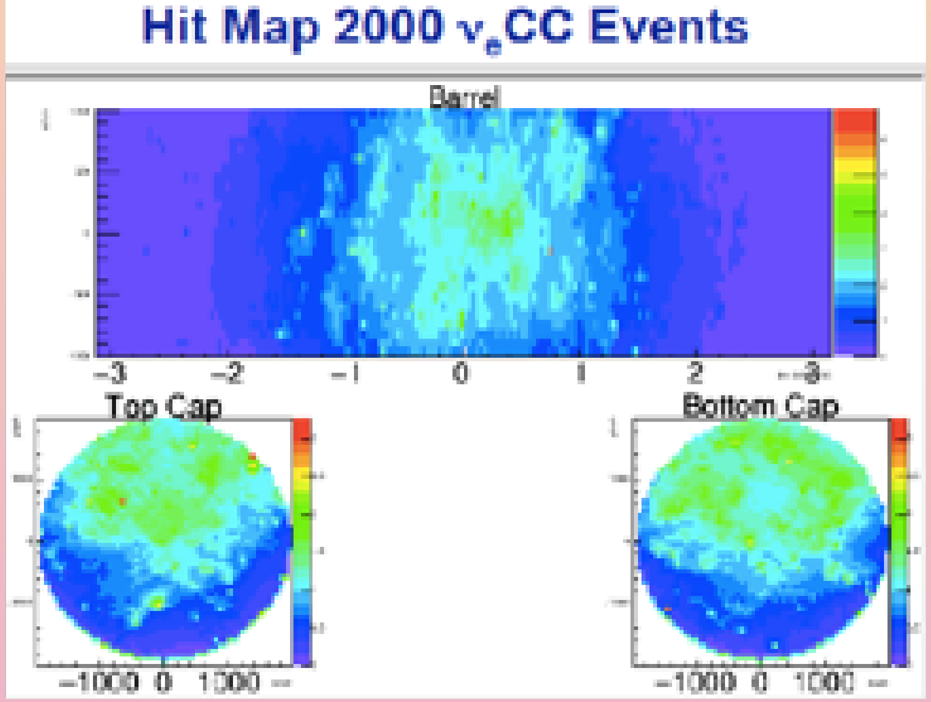



June 21st

3. PMT Choice and Layout

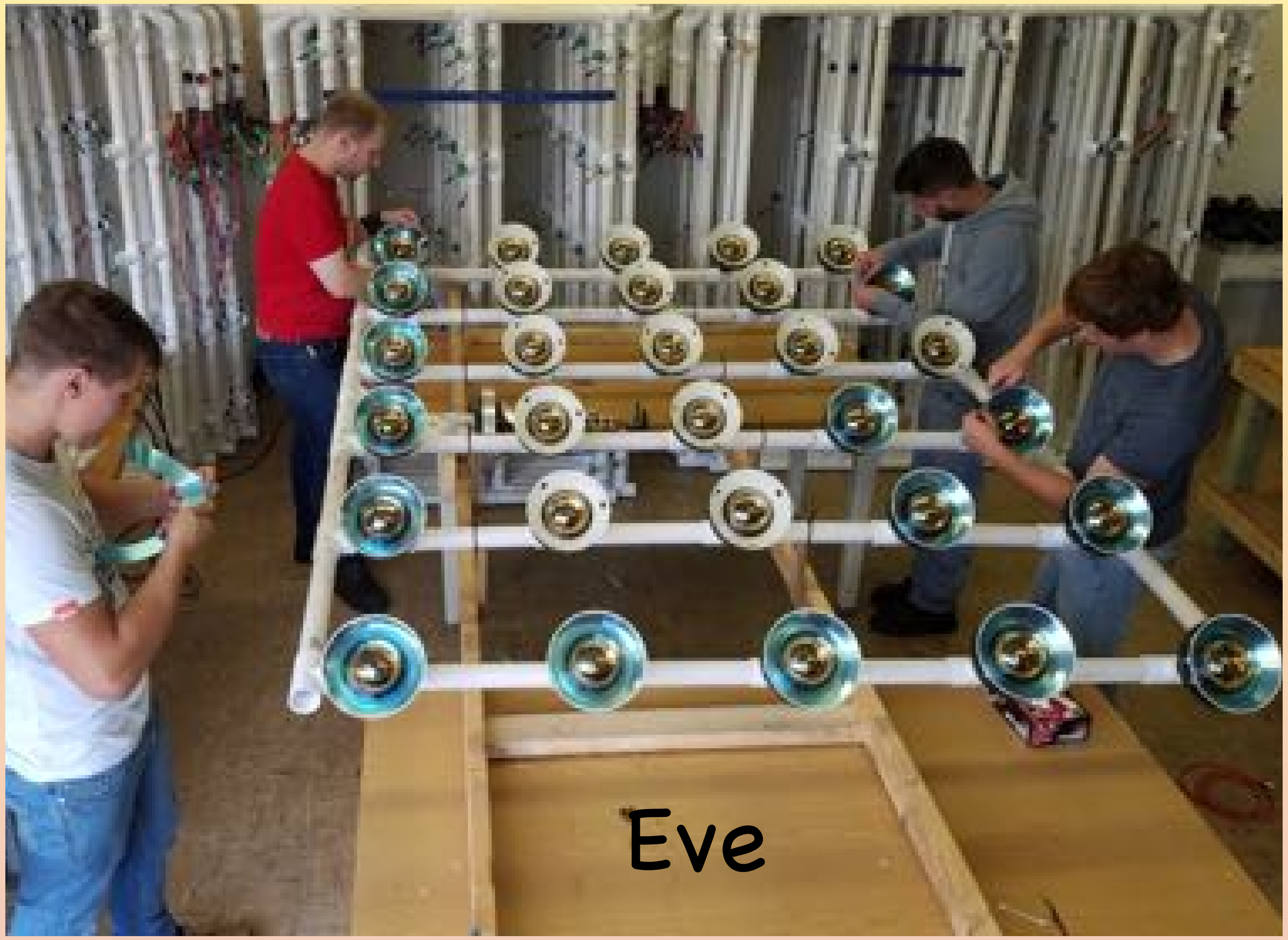
- Layout will involve high and low density planes
- A big part of the instrumentation will just implement (almost) KM3Net technology
  - HZC 3.5” PMTs at 6% coverage in front wall and front of end caps, and 4% coverage back end cap region
  - KM3Net uses -ve CW-HV base, PMTs must be protected from water
- Low density wall planes will be made with NEMO-III 3” PMTs and Madison electronics.
  - Old 3” PMTs at 4% coverage in back
  - Madison electronics uses +ve CW HV base, PMTs are in contact with water





- very good clarity achieved with the potting compound
- Only failure mode was flat cables to J45 connector
- Acrylic dome protects PMT from high pressure and also from contact with water

Detector Plane Construction (2018)

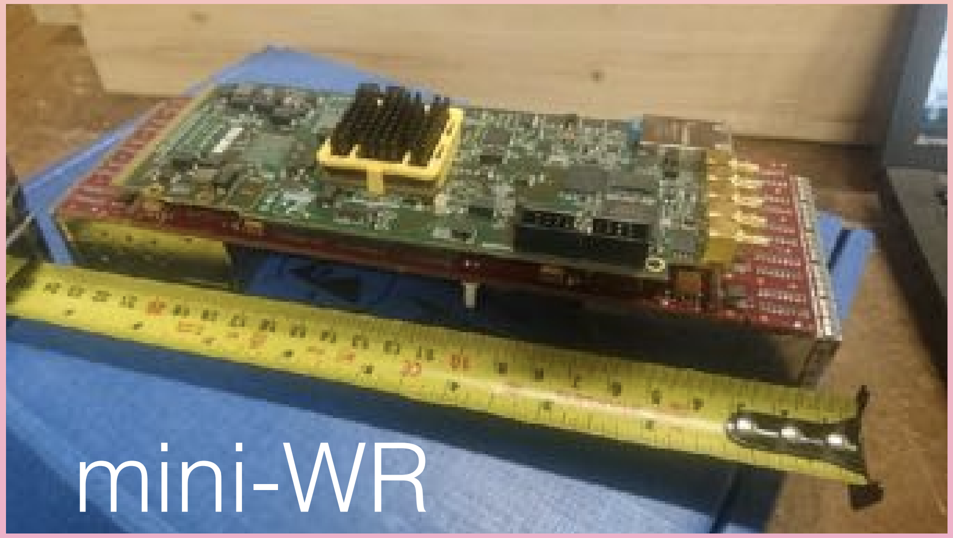


- Detector Planes made out of schedule 40 PVC, glued joints
- Keeps electronics dry, withstands 6 ATM (TBD!)
- Tested with air pressure (DO NOT DO THIS AT HOME)
- Inside cat-6 cables run though PVC pipe from PMT to Electronics
- Reflective (Winston approximation) cones increase light collection
- Undergrad involvement essential!!!
- 8 in 2018, 8 in 2019
- Planes built in just-in-time fashion as no storage possible

July 2nd

4.Electronics : Nikhef planes

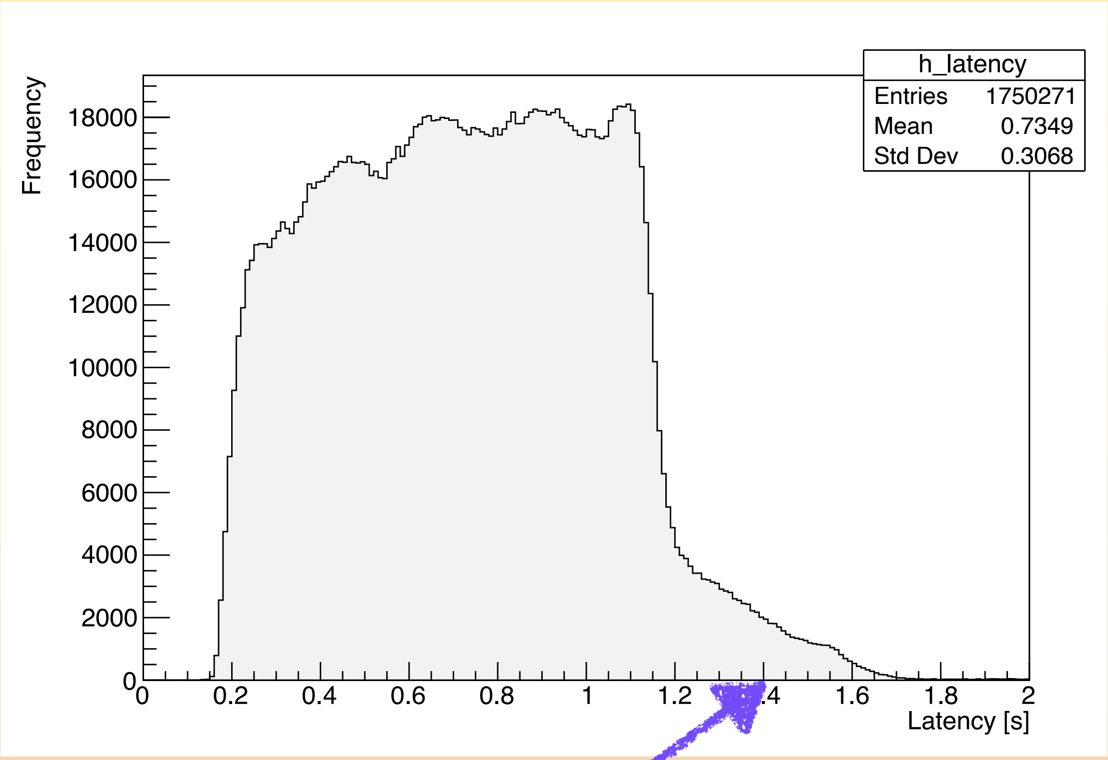
- KM3Net electronics takes advantage of some millions of euros of electronics design effort
- Blazes the trail of multi-small-PMTs : no long heavy cables, -ve HV CW bases
  - 30 PMTs talk to one central logic board (CLB), gets timing from CHIPS miniature White Rabbit timing board (1ns-over-ethernet)
  - CW uses 3.3V, AC/DC converter on CLB
  - All standard cat-5 interconnecting cables
  - CWDM (Coarse Wavelength Division Multiplexing) on fibres out of the planes
- SFPL (Small Format Pluggable Lasers) on WR at each fan-out box
- Power cable down, fibre cable up to surface via 5 fan-out boxes
  - Fanned out along manifolds between boxes and planes
- No other racks or modules!
- Spill time served over ethernet from MI $74 : trying to catch it in time for the spill but we will see

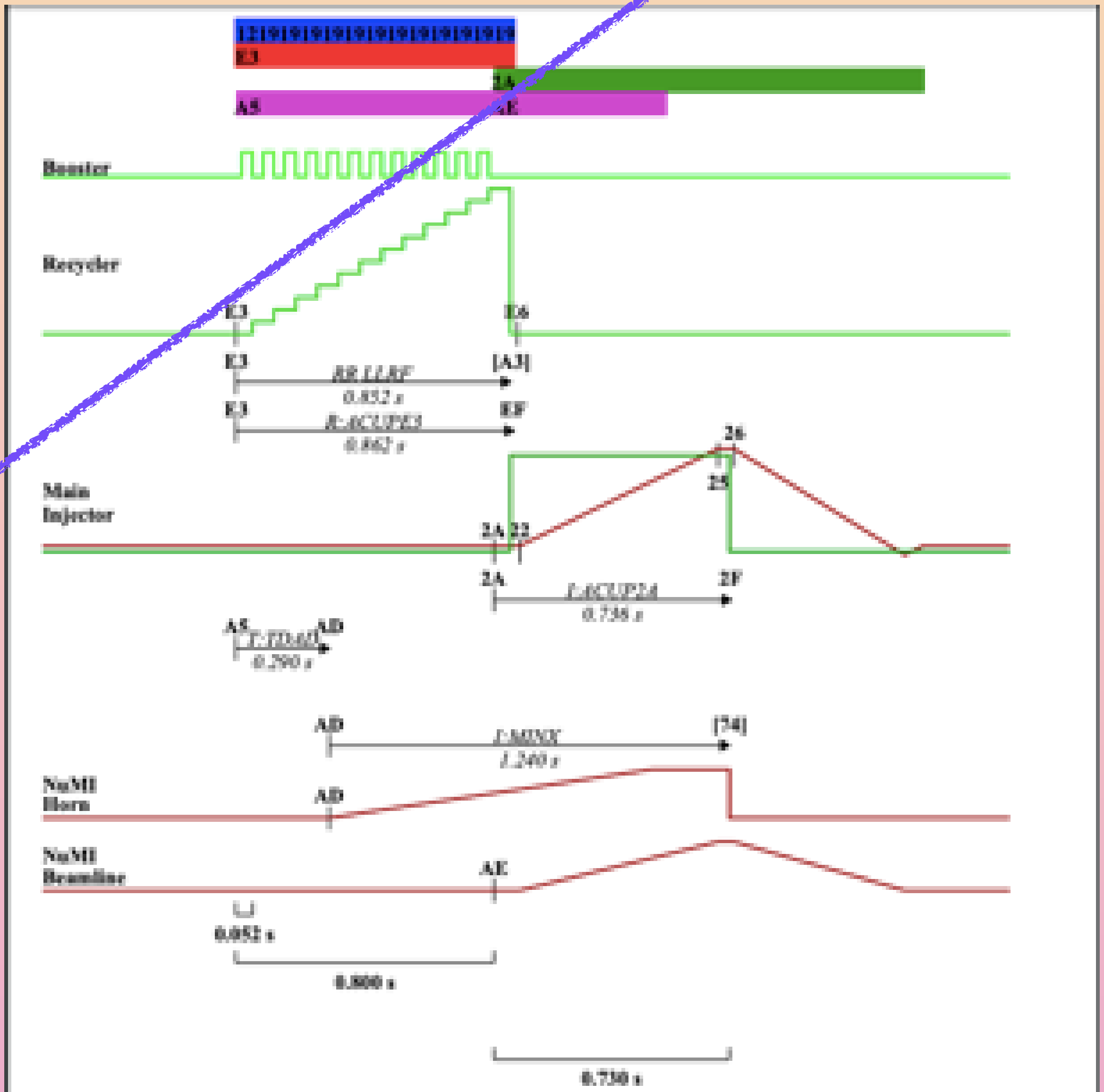


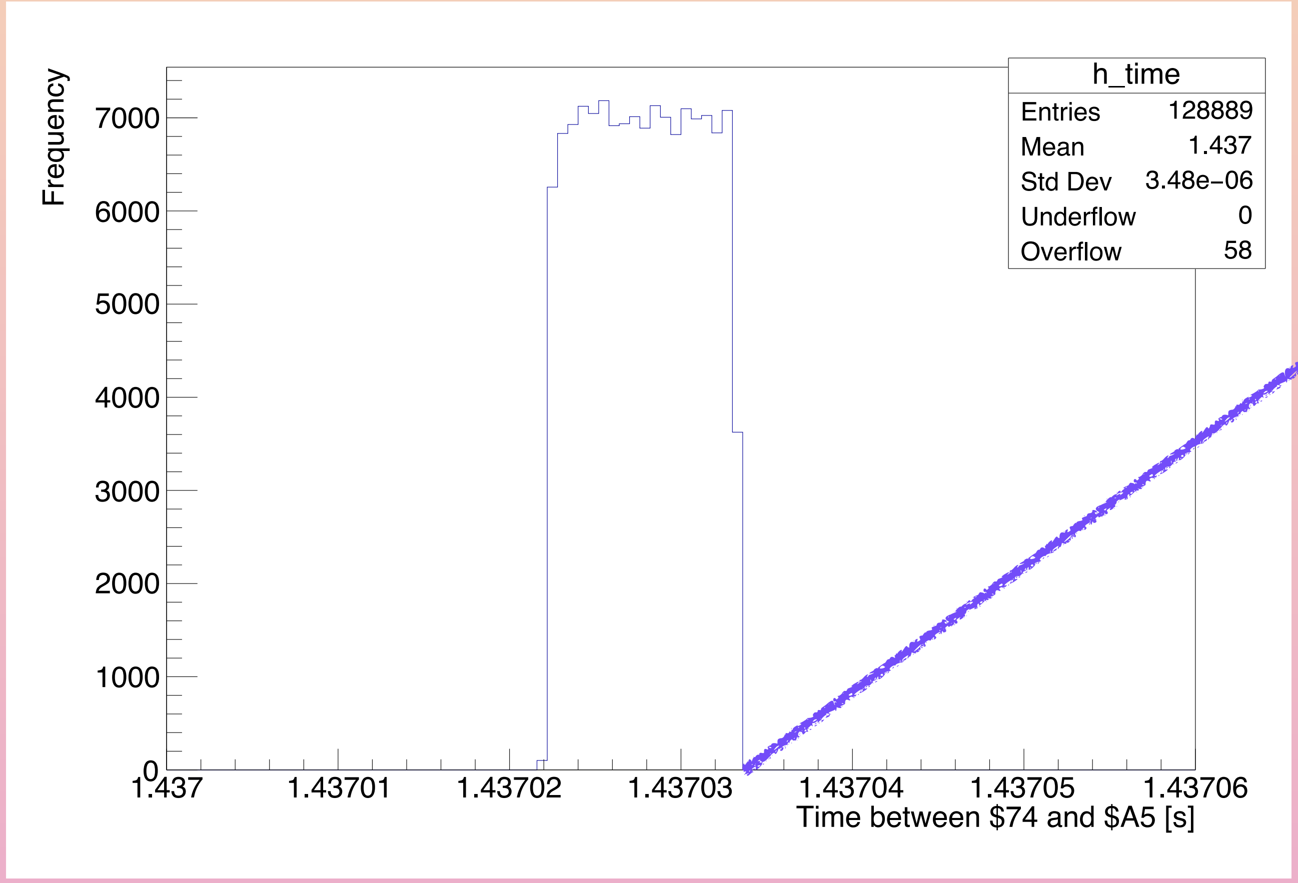
mini-WR

New! Spill Server results!

- Using NOVA TDU (Time Distribution Unit) we have served the spill from FNAL to the internet
- 95% of the spill signals arrive up at CHIPS within 1.3 sec (time from $A5 to $74 NuMI spill)
- Not the whole story, but proof of principle that we *COULD* get the signal in time for a trigger
- Jitter on $A5 compared to $74 is an issue
- Potentially useful for DUNE?



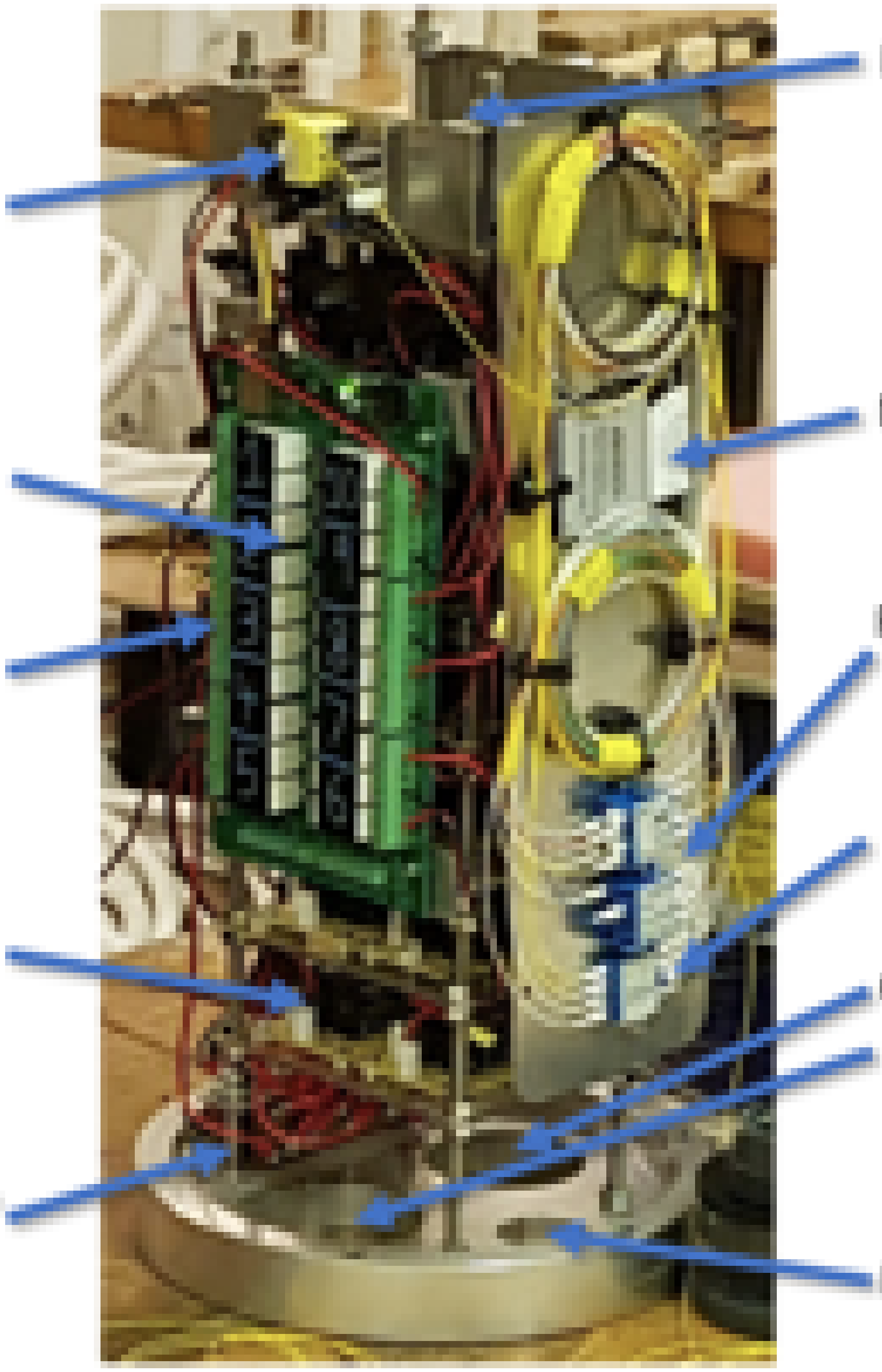




4.Electronics : Nikhef planes

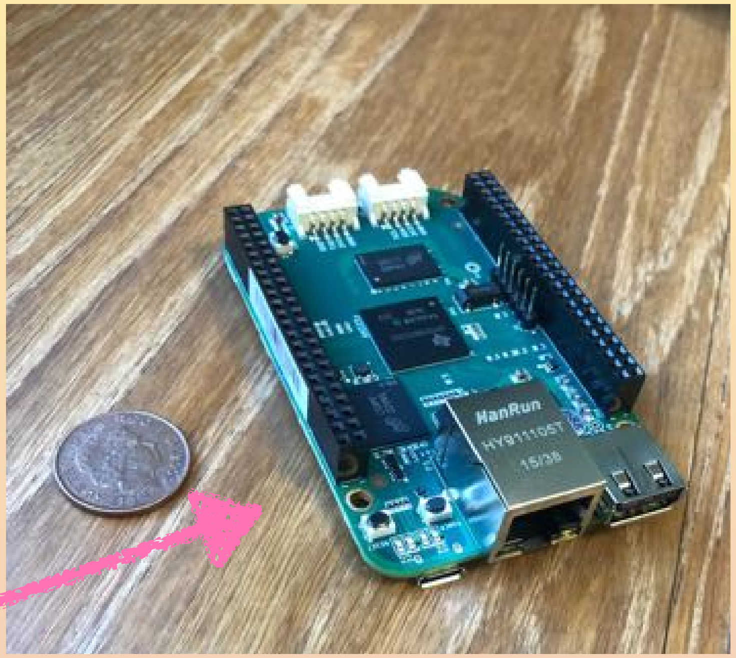
~~Junction~~ Box Jelly

The junction box takes both the power and fiber input from the shore hut and distributes these to the five Nikhef containers and single Madison container.



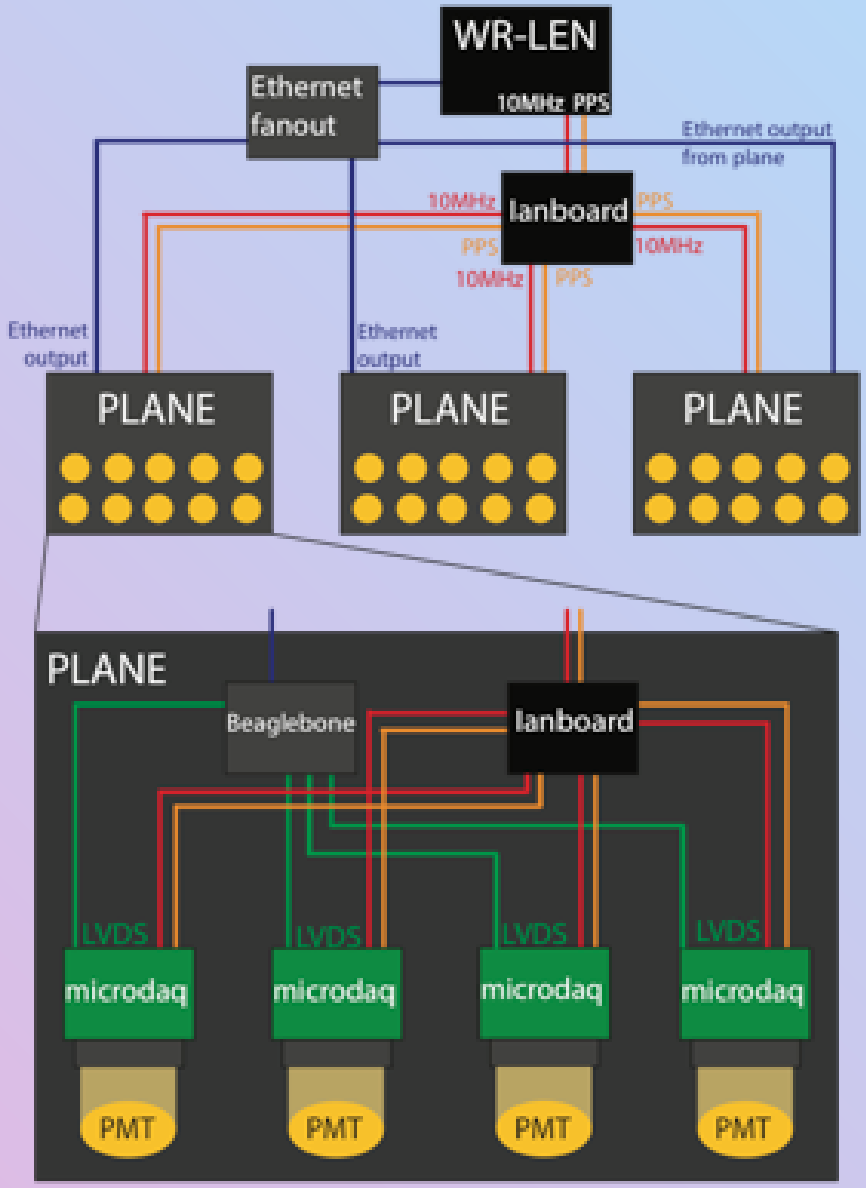
4. Electronics: Madison Planes

- We are riding a revolutionary wave in development
- Microprocessors on each PMT are possible, cheap and available!
- provide ToT and receive clock from WR system
  - Each PMT knows the time to 1ns
  - 24V, 10MHz, PPS and Ethernet all on the cat-6
- $40 for a BBG to collect (many) signals and transmit to Ethernet
- Reduce cost to minimum
- Designed at Madison, standing on giant shoulders



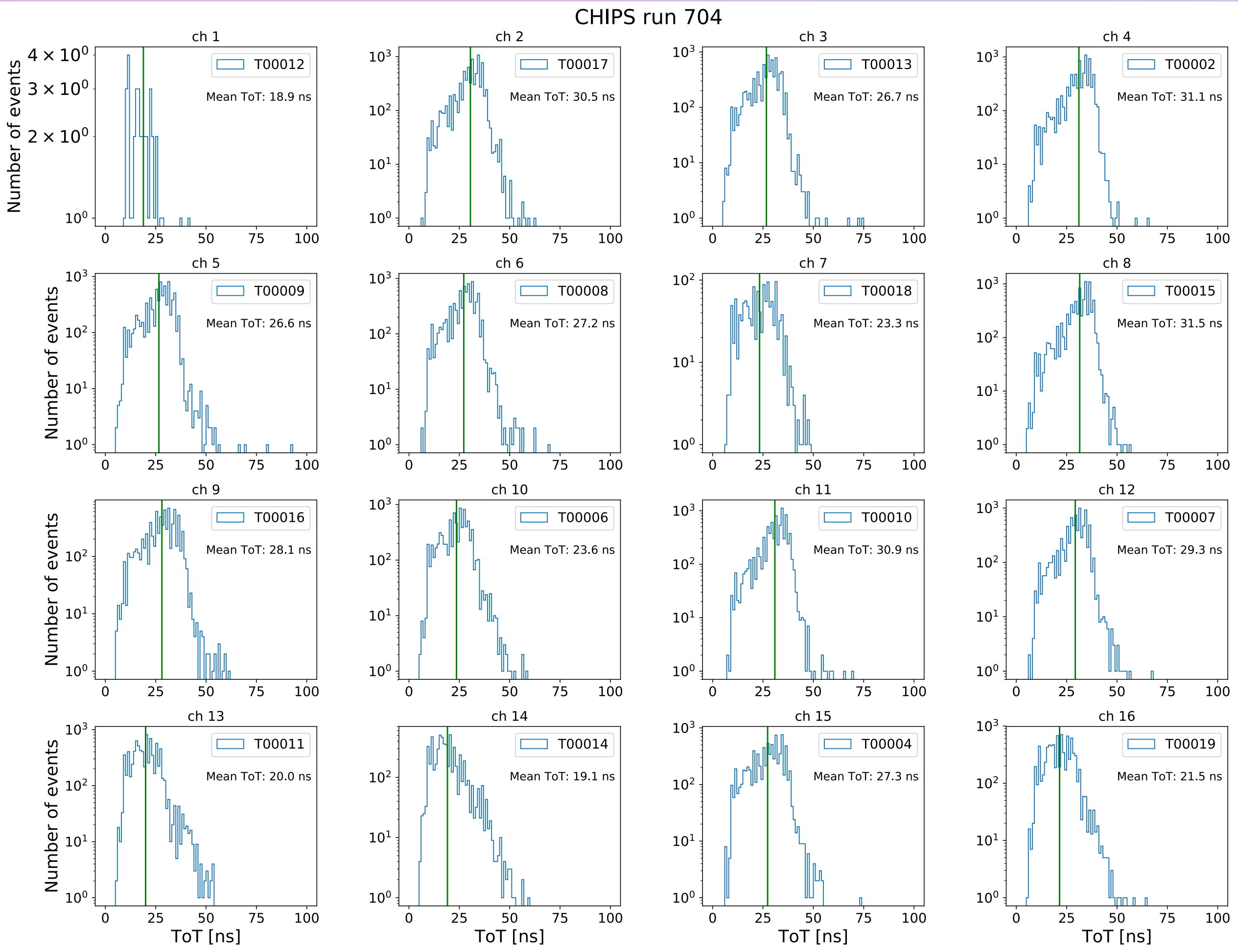
4.Electronics: Madison Planes

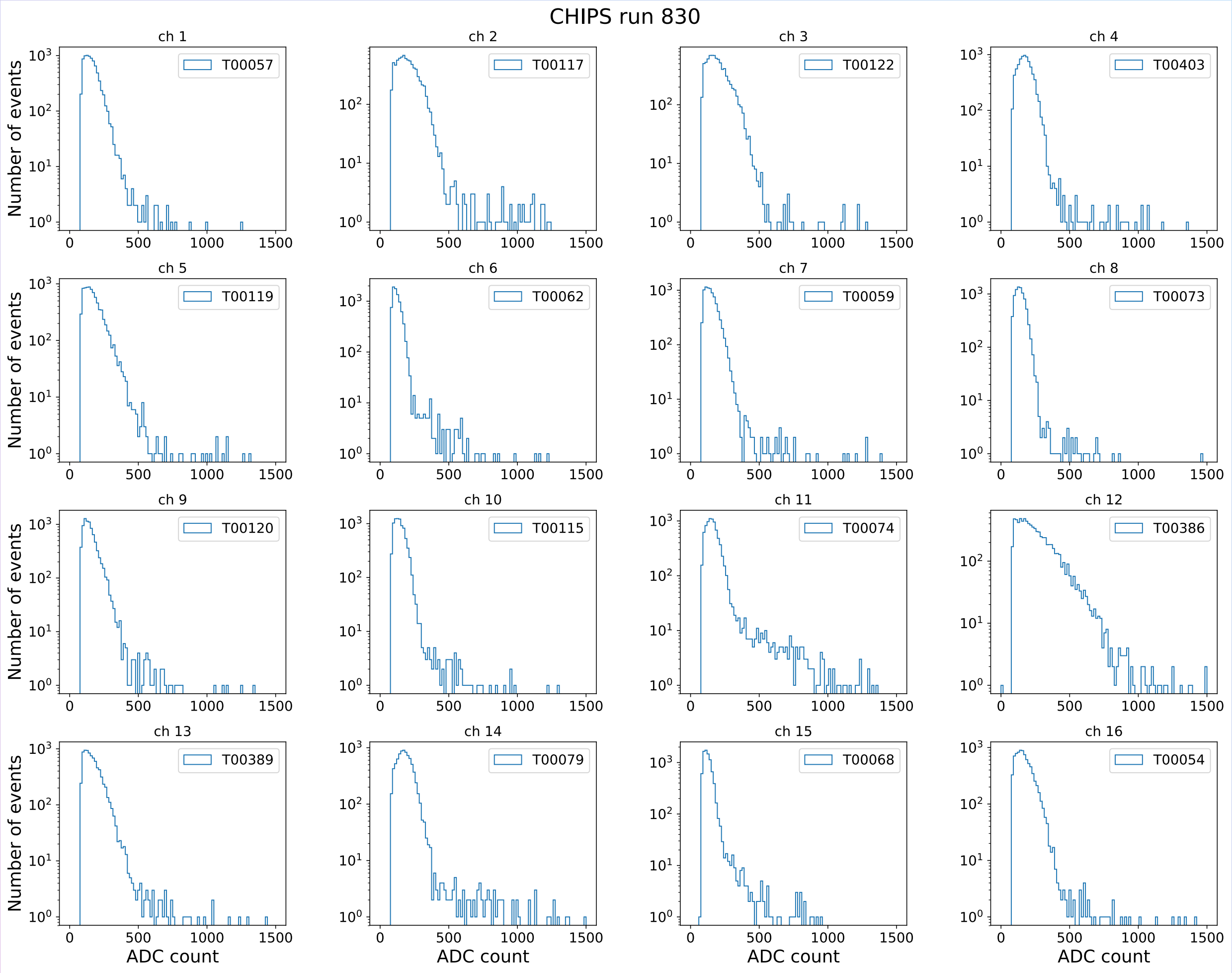
- Top level fanout provides power, 10MHz, PPS and ethernet on cat-6
- Communication software between BBG and micro-daq demonstrates 1Mbps on RS485/D
- Rate of 1-10kHz per tube means scope for local filtering (maybe) or at least buffering during spills
- Total cost, $25+PMT, data->disk



Madison Planes

- TOT or ADC, both available!
- Use low light LED flasher to identify 1 p.e. peak
  - set PWM frequency to set the CW HV so that TOT ~ 25

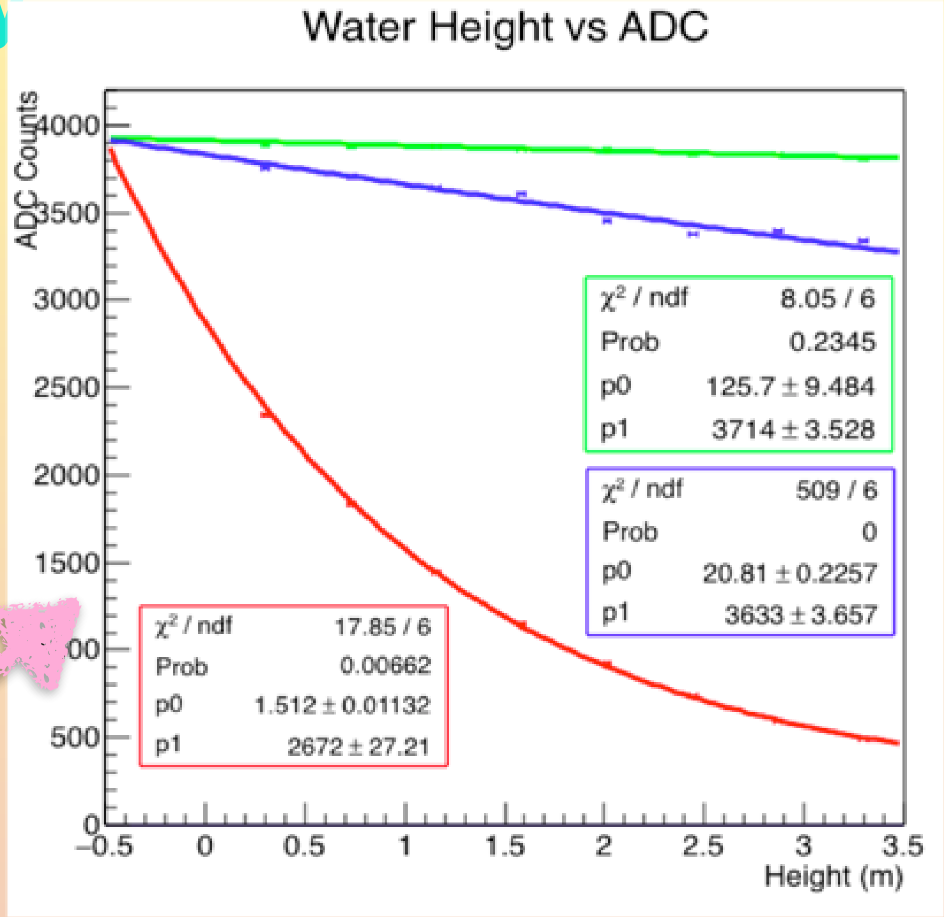




July 23rd

5. Water Clarity

- CHIPS has advantage of being under about 6 bar pressure and at 4-8°C :
  - Good for crushing bubbles and bacterial blooms respectively
- Filters provide
  - a raking of the particulates in the water down to 0.2 micron, bacteria mostly > 1 µm
- We used a small model of CHIPS-M (micro-CHIPS) on surface
  - Using 405nm laser and 3m upright column, we watched the water clarity over 3 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
- 60m attenuation length was attainable and reproducible



July 31st

August 9th

August 28th

August 28th

August 31st

CHIPS detector: September 2019

62 total detector planes installed in top and bottom end-caps

total of 1770 Photo-multiplier tubes

CHIPS detector: September 11th 2019

Buoyancy pipes hold top cap above the bottom cap via 28 dyneema strings

Veto PMTs look upwards

View from the air of CHIPS detector construction, September 2019

Water level was rising every day….October 6th

- This was a surprise, but everything was OK and we towed it back like an errant child with steel cable and the fork-lift

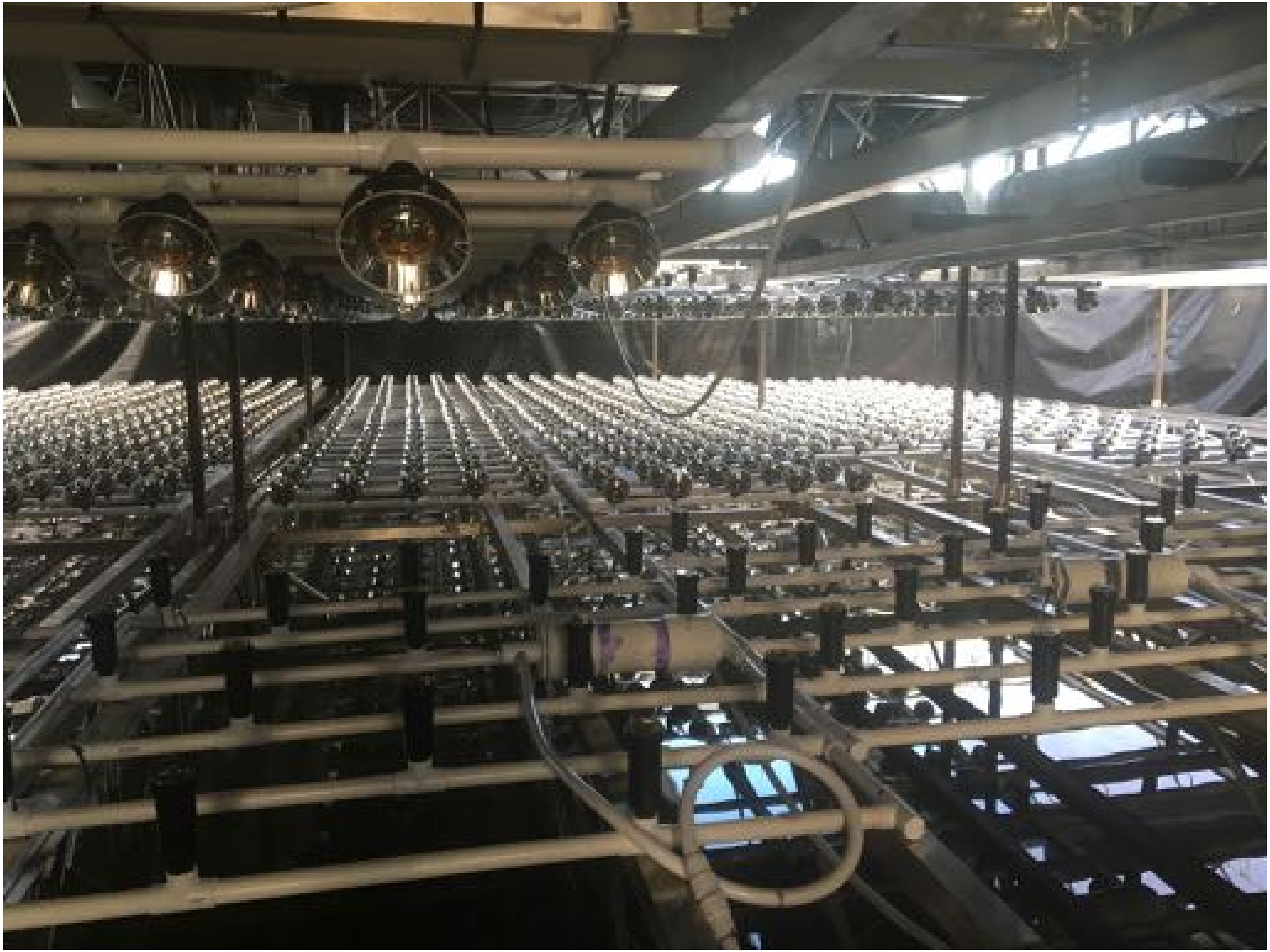
- she became anthropomorphic

CHIPS detector: October 10th 2019

62 total detector planes installed in top and bottom end-caps

total of 1770 Photo-multiplier tubes

will enclose ~5 kilotons of water

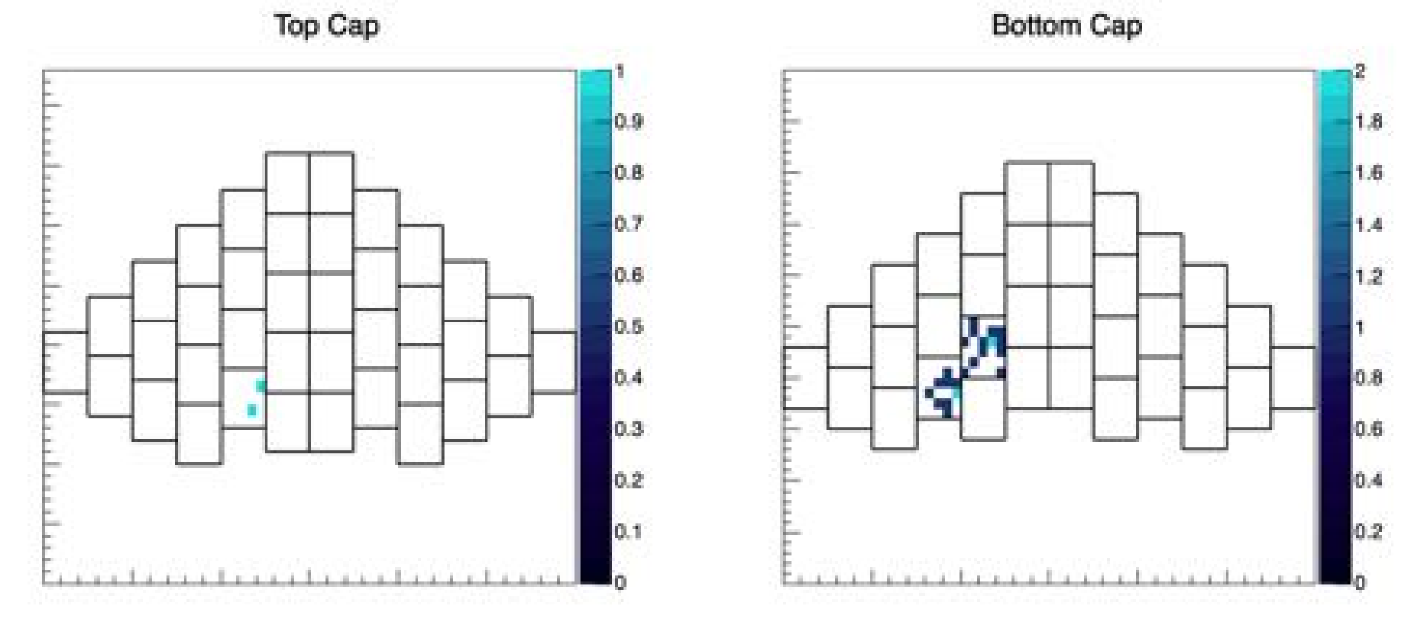


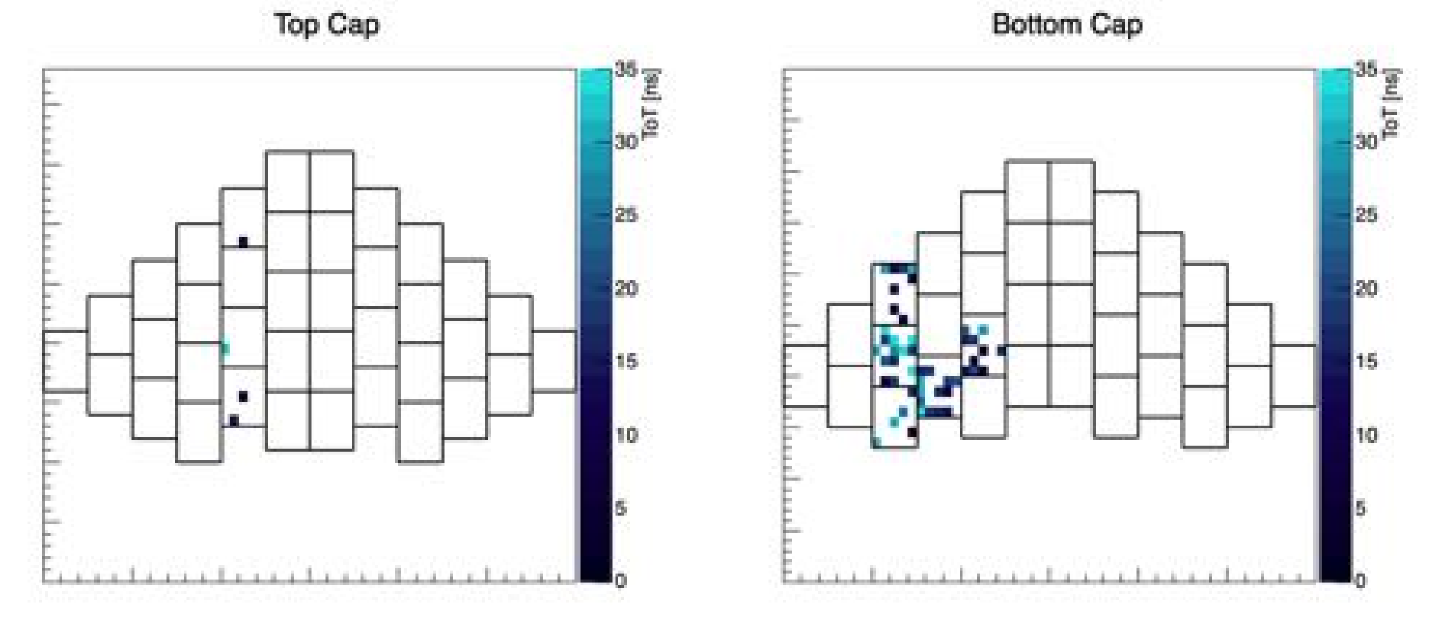
- CHIPS being towed out to position, October 14th 2019
- Finally was submerged 22nd November

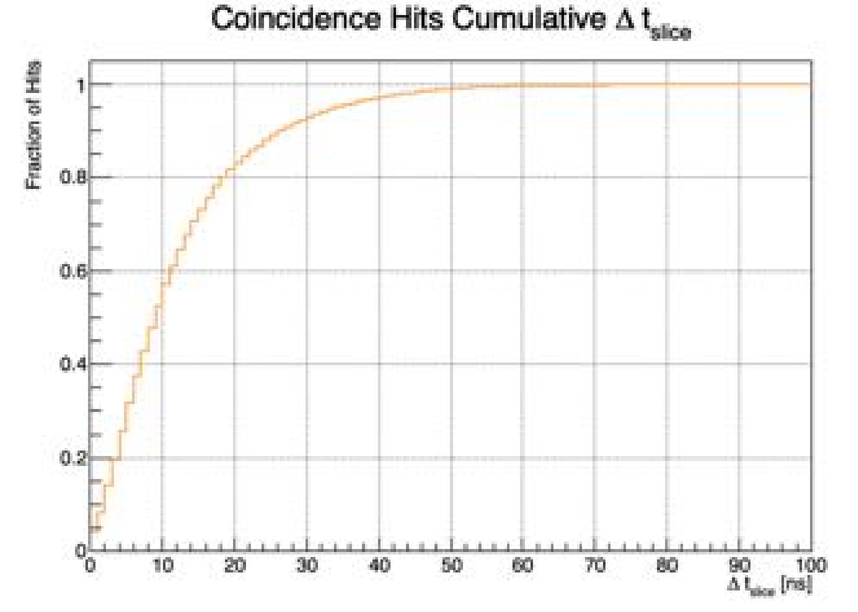

WYZE
2019-10-14 10:19:40

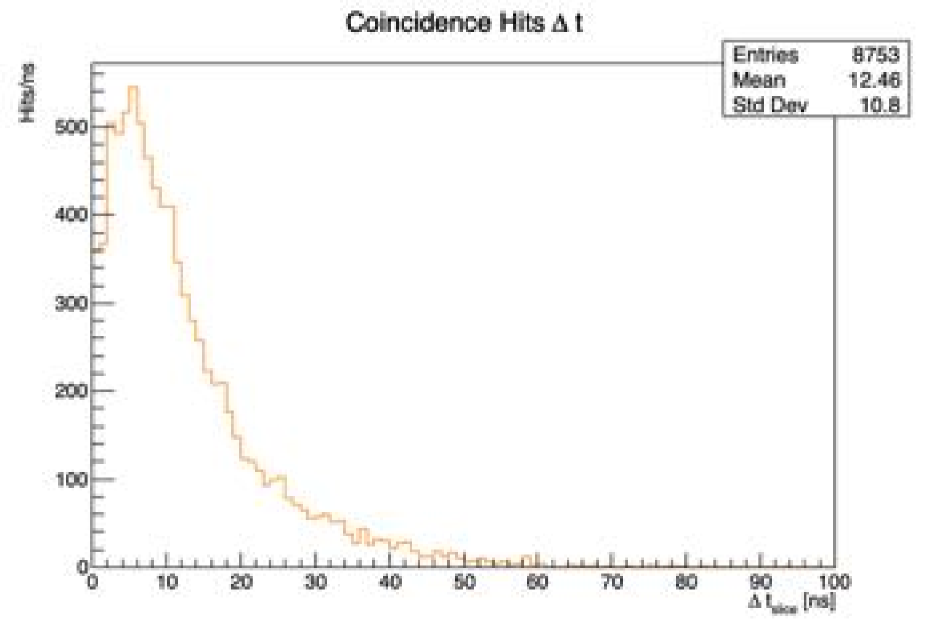
Some first events

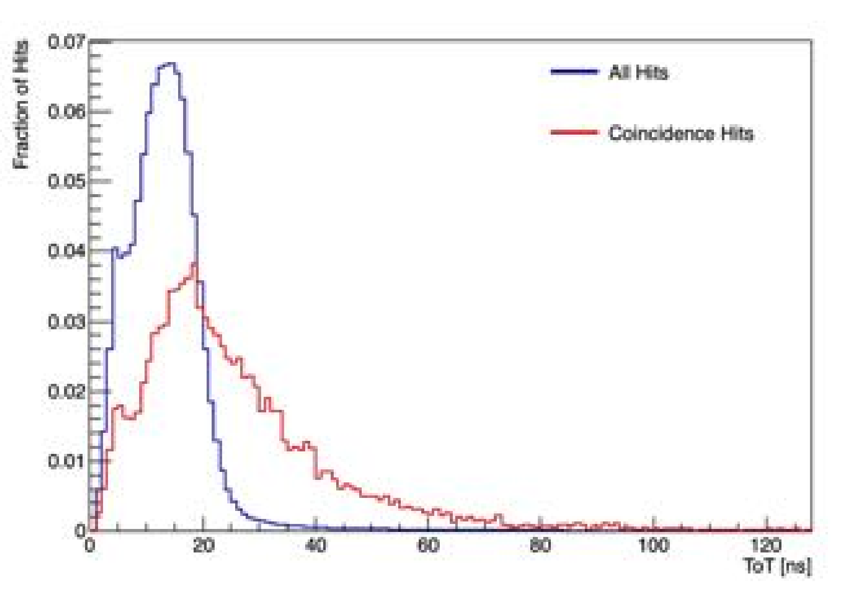
- First efforts to search for events in coincidence
- 35ns sliding window
- looks like we are seeing comics!







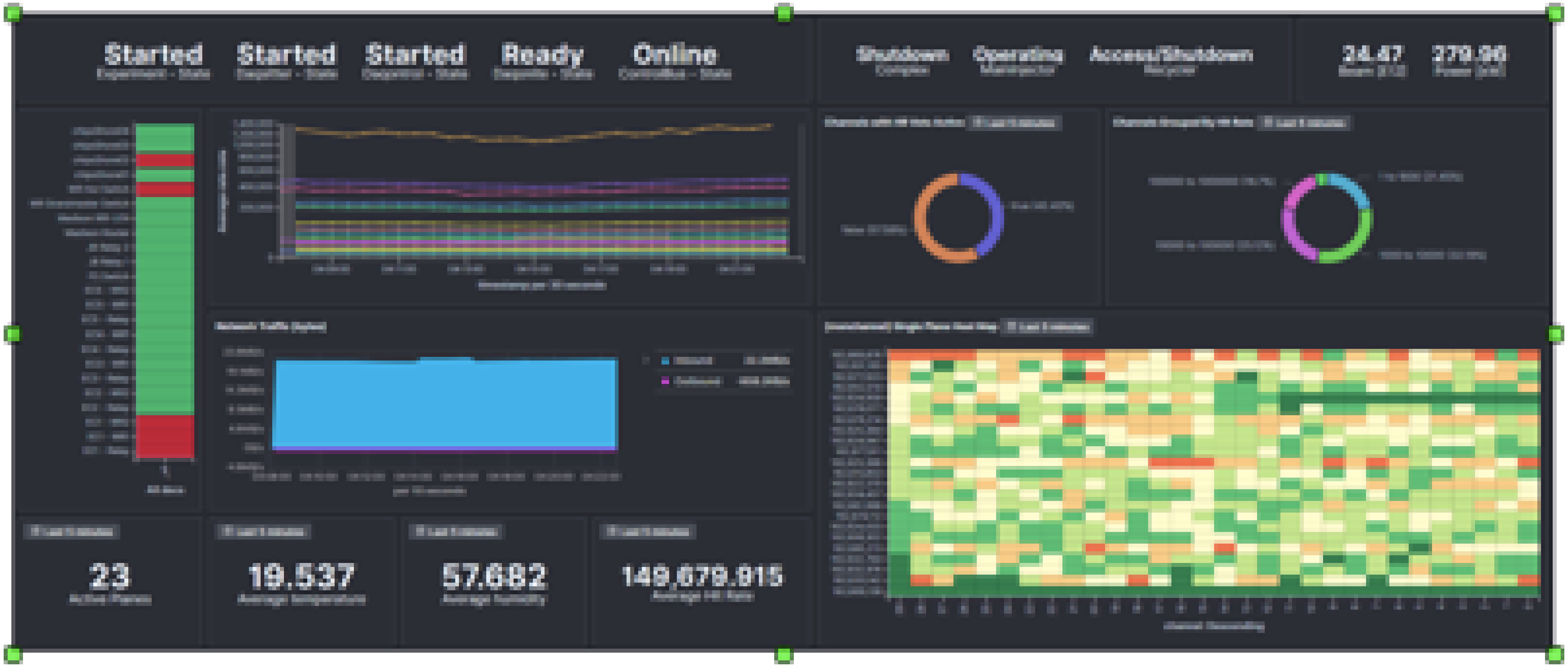




DAQ Monitoring

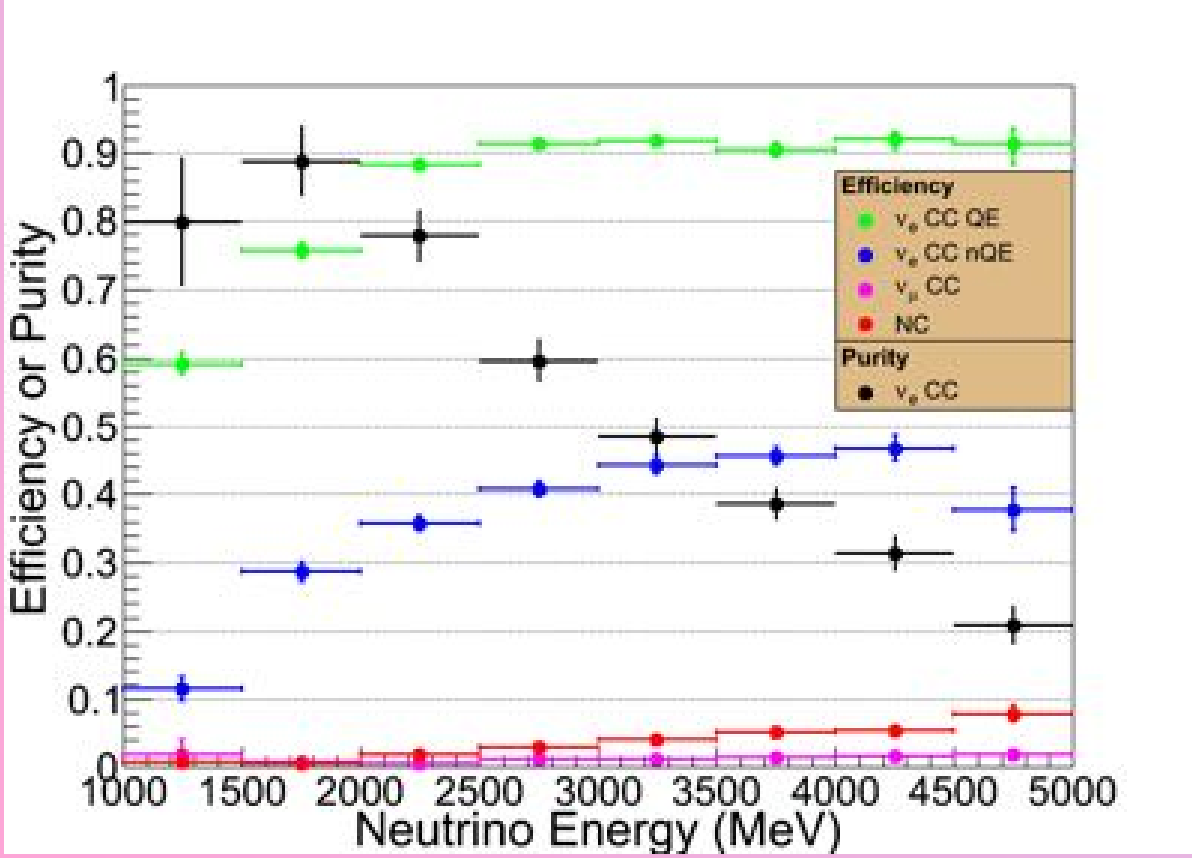
Monitoring

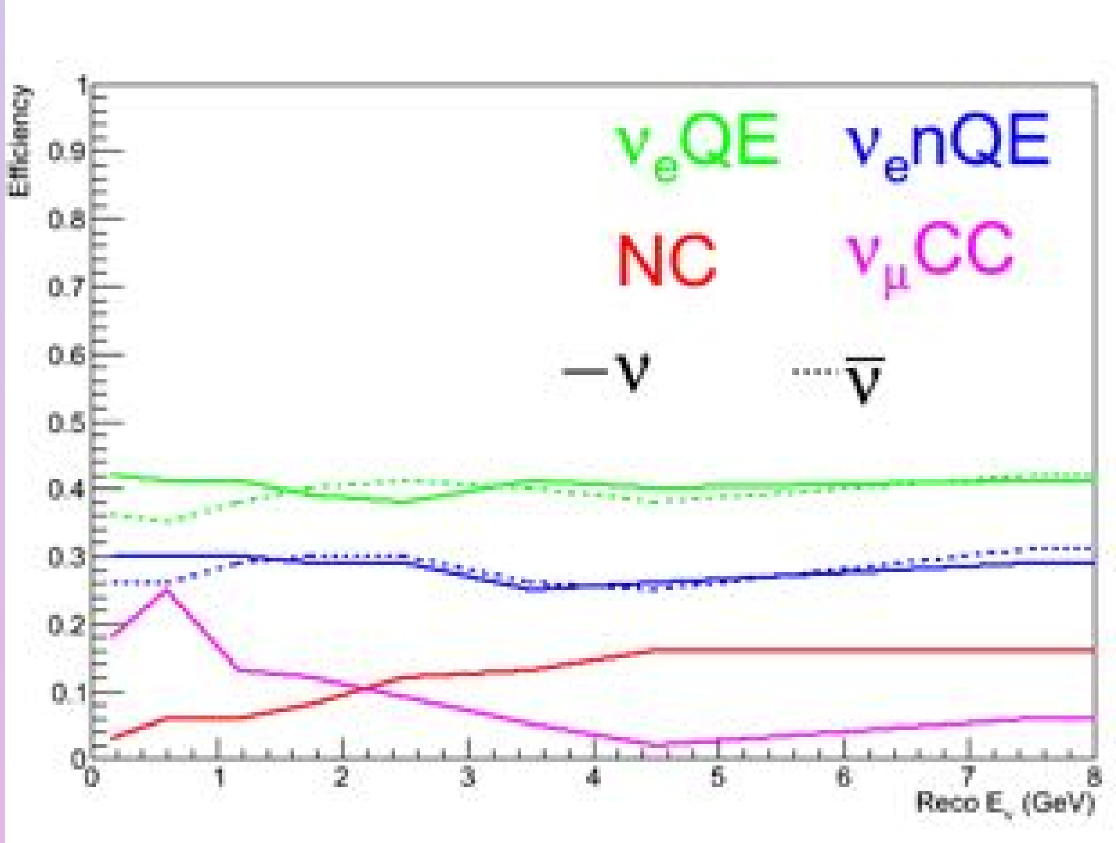
- All DAQ monitoring data (data quality, networking status, application status etc…) is stored in Elasticsearch, an open source, noSQL database, which accepts JSON data from many sources throughout the detector and DAQ machines.
- All monitoring is then done through a series of dashboards on the web based Kibana UI
- Flexible and extensible with plenty of extensions available for any input data type.



Reconstruction

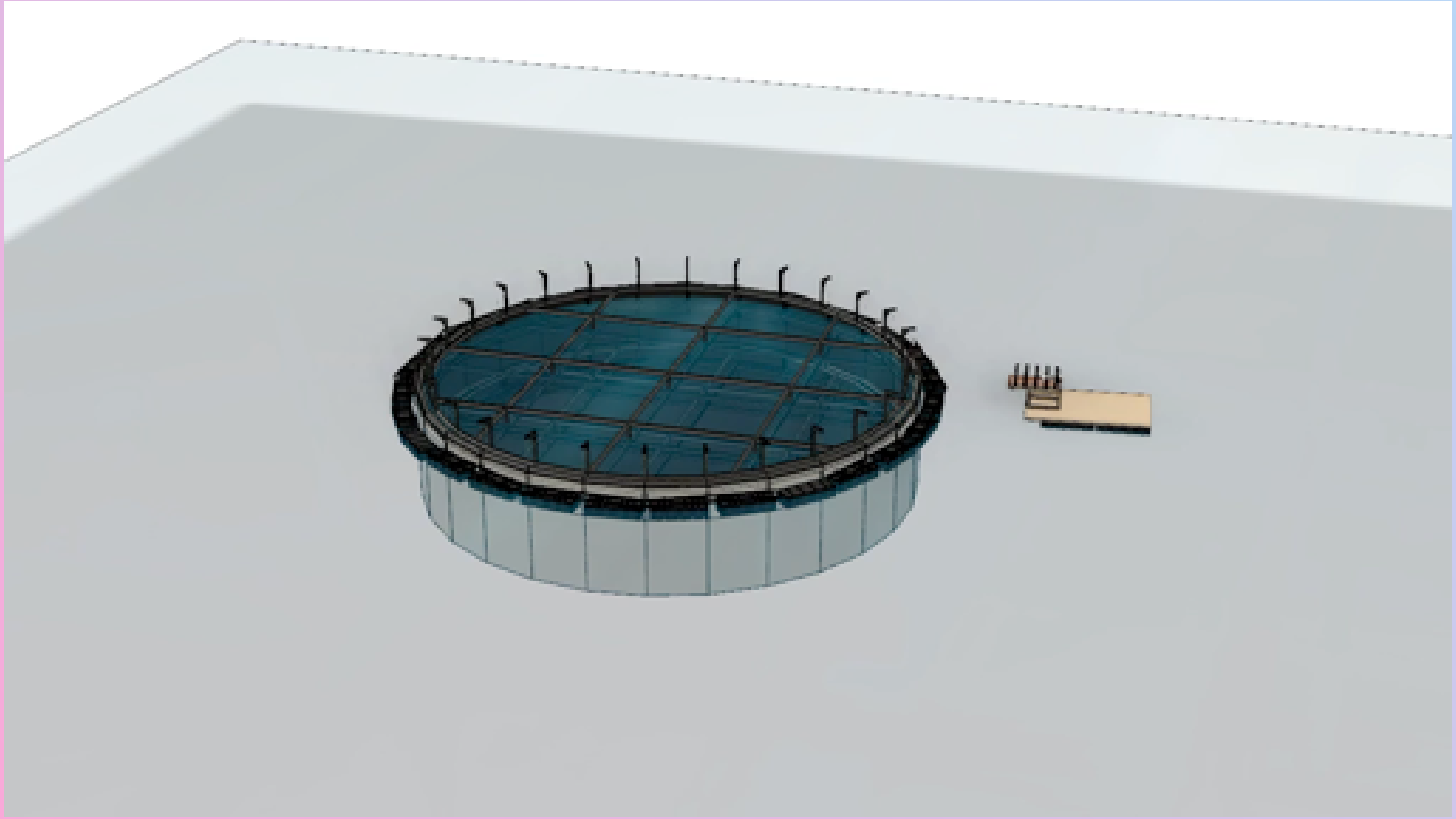
- Deep learning improved all aspects of the reconstruction to compete favourably (in simulations) with “old" Super-K reconstruction
  - No self-respecting new experiment will go without machine learning!
- Our first stab at this has improved our event efficiency and purity by 30% over old approach based on MiniBooNE algorithm
- It sped up the reconstruction from 2.5 minutes to 1sec / event!
- Pretty good basic bottom line so far, more improvements on the way



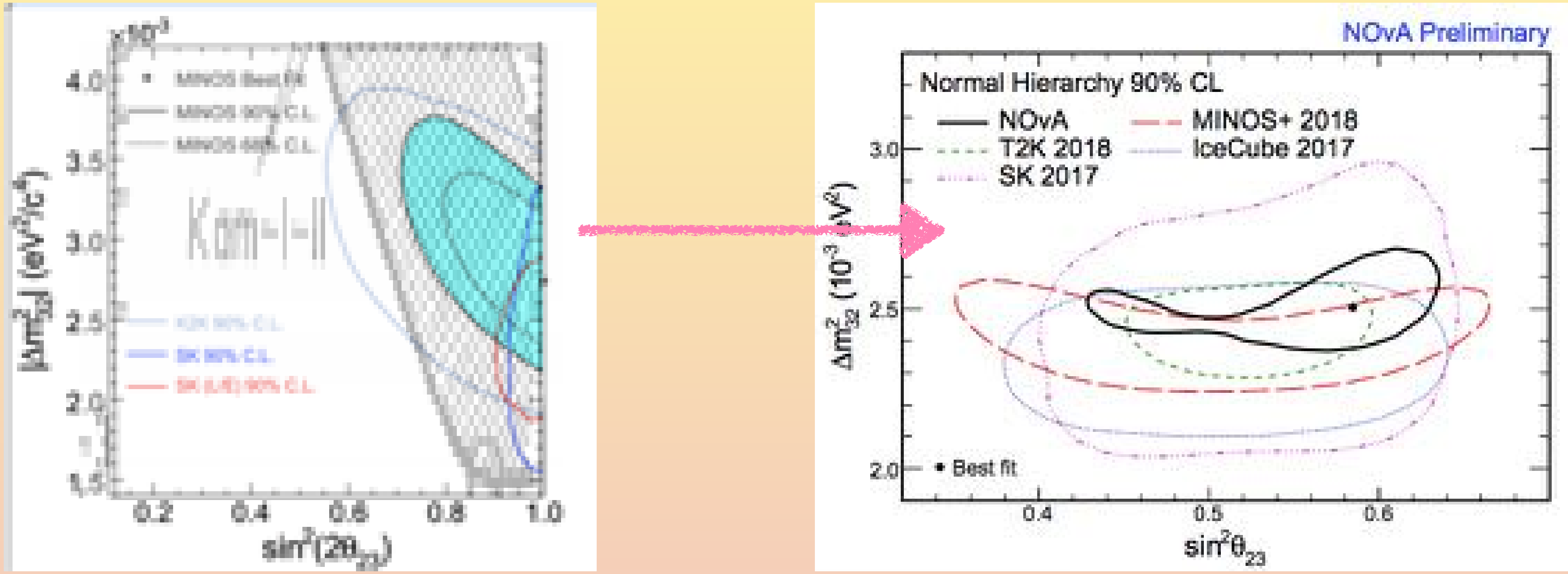


Next Steps at the Gulag

- Rebuild floating dock
- Add wall planes
- Extend to 10 kilotons?
- Take data.

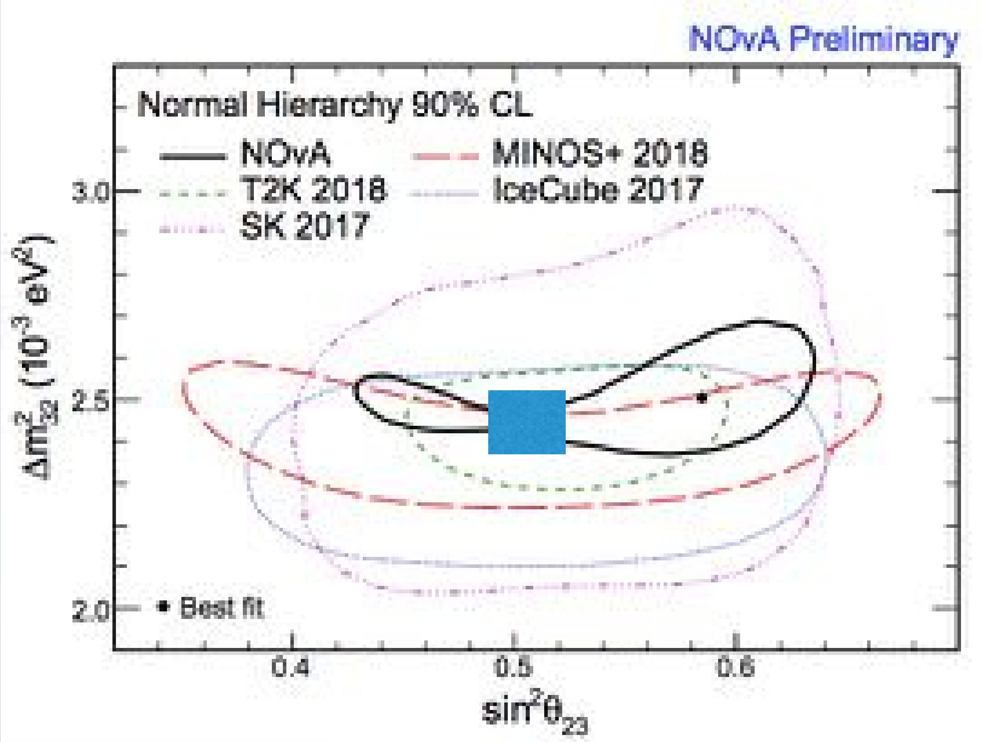


So what?

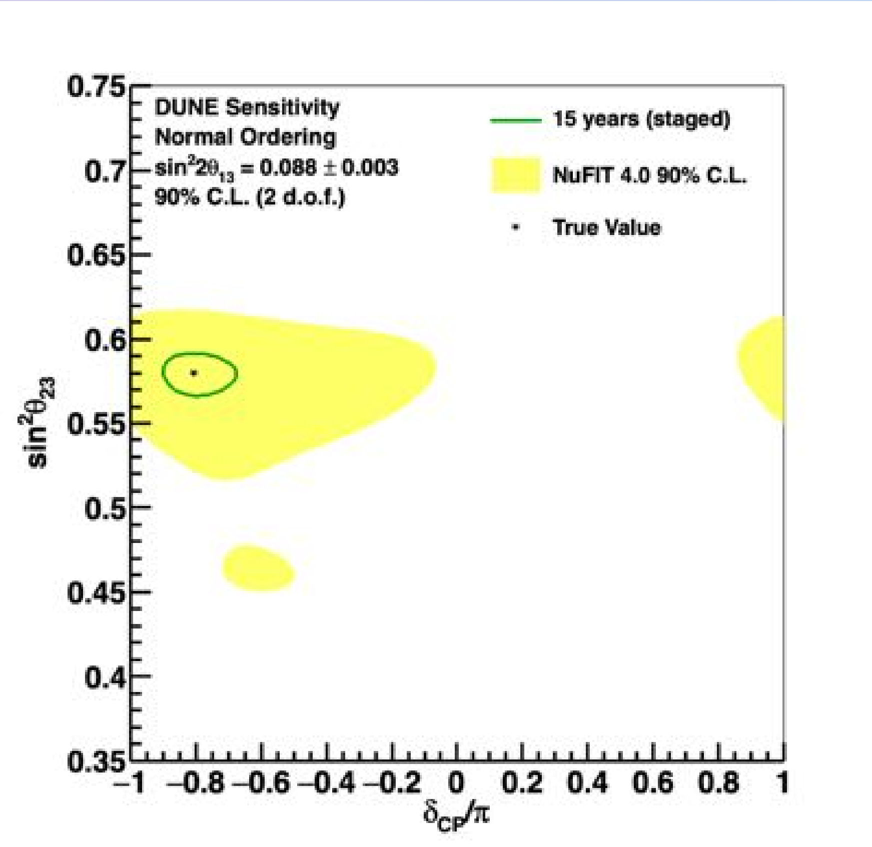


- This plot has taken more than 20 years to achieve (1994-now)
  - What is the next step?
- What if $\sin^2\theta_{23}$ is maximal?
  - Is this evidence of a new symmetry? A Big Thing?
  - Are there any theoretical insights that would tell us what to do next?

The potential for new insight

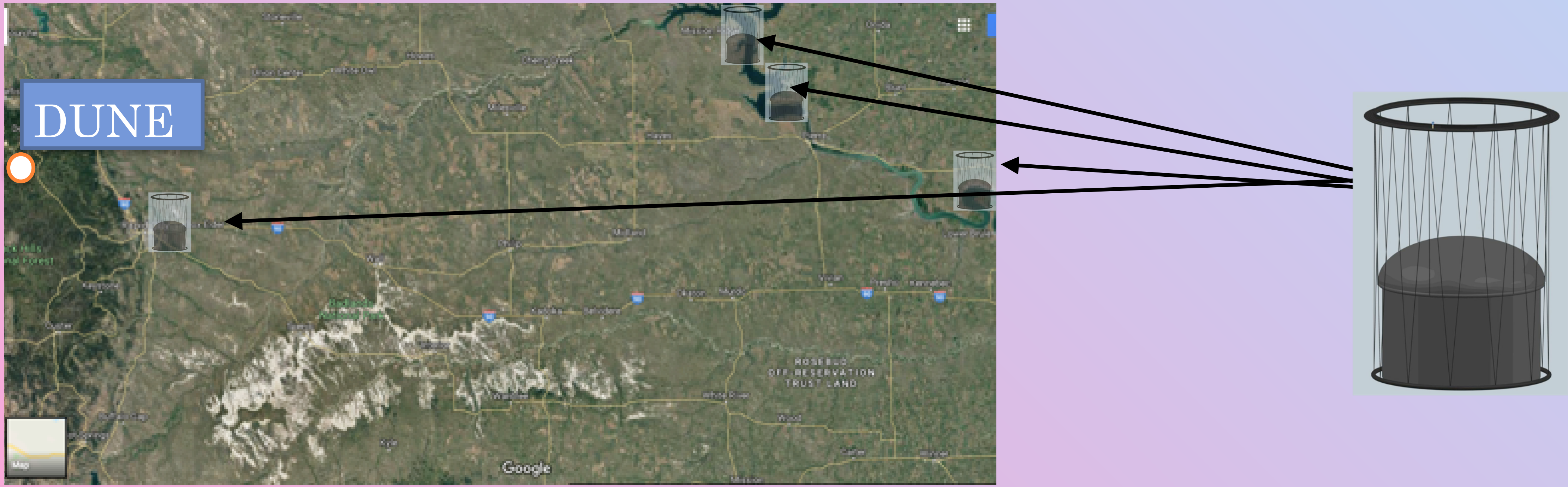


- DUNE can measure θ_{13}, θ_{23} to 1°
  - this is a $\sim 3\%$ total error
  - current experiments have $3\text{-}4\%$ systematic error also!
- Starts to be limited by systematics after “only” 400 kt-MW-years
  - that would be 2036 at the earliest
  - Its too late to realise we need more mass by then
  - About 10^{21} neutrinos will fly into space each year - a waste
- Will this be enough precision?
  - will we ever be able to say $\sin^2\theta_{23}$ is maximal and there is a symmetry that says so?
- What do the theorists say?
  - not enough on this topic IMHO



The new deal

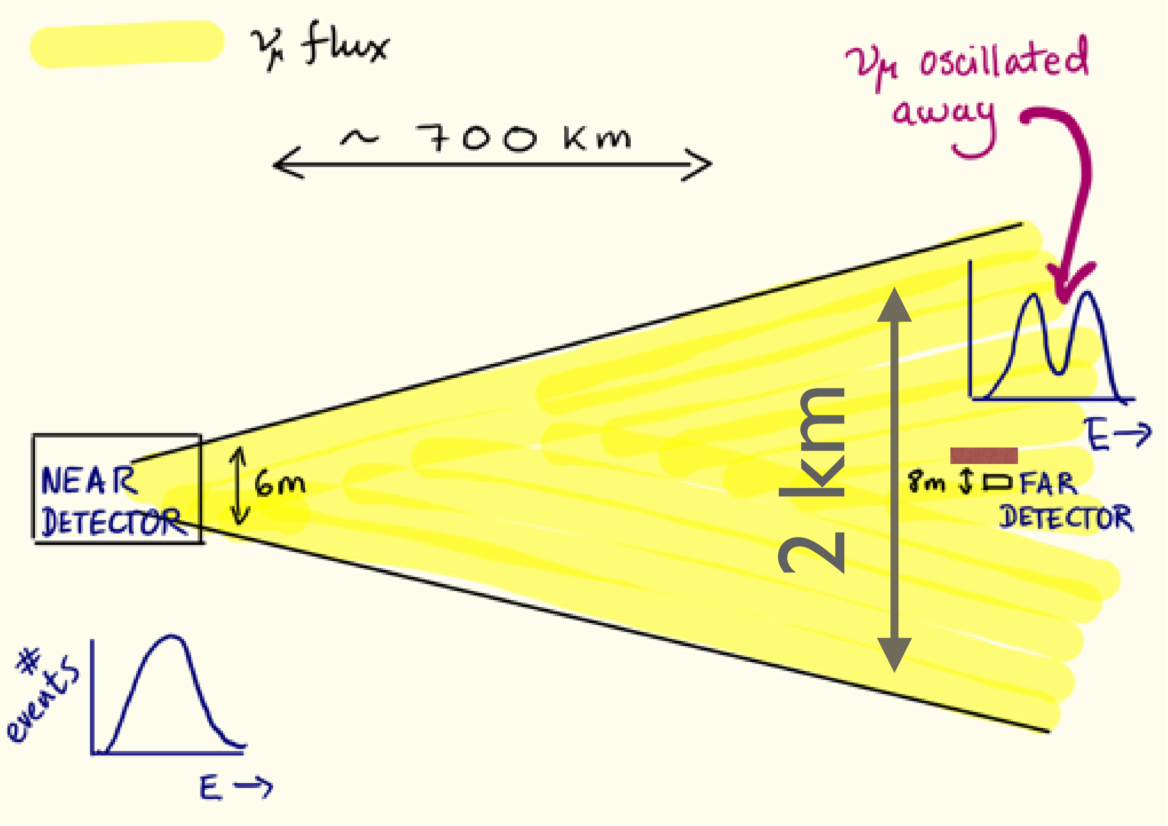
- Overarching idea is a Mton array of 100 kton CWCs (CHIPS Water Cherenkov) detectors
- Profit from systematics cancellation instead of systematics limitation
- Profit from large detector mass for “faster” measurements
  - nothing is fast in neutrino physics
- Profit from relatively simple and speedy construction
  - 14 people built first 5kiloton CHIPS in about 6 months
- Use reservoirs near Lead, S. Dakota (Oahe Lake, Pactola Lake as examples)
  - look for others when time permits (ROAD TRIP!!!!)



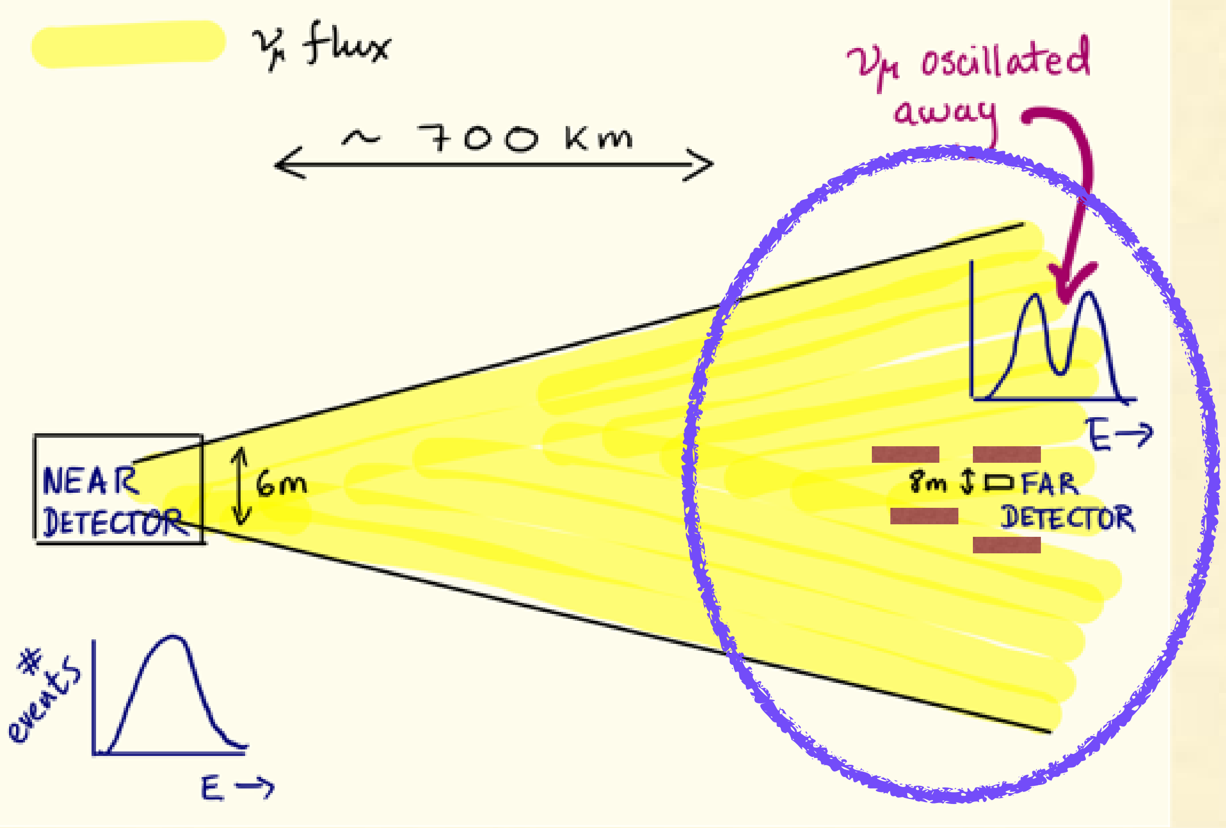
S.Dakota..scene of the new LBNF neutrino beam

… WE CAN DREAM!

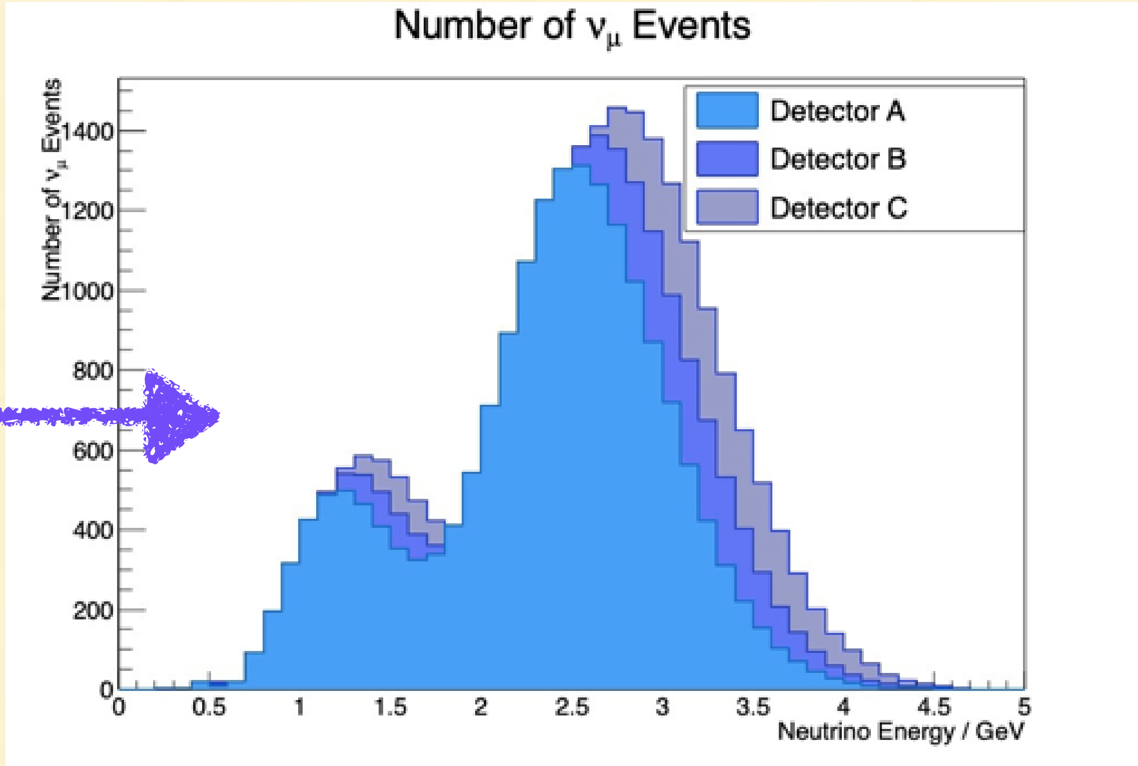
- The standard way to measure neutrino oscillations, pioneered by the MINOS experiment, was to have as-similar-as-possible near and far detectors, and look at the difference
- beam small compared to detector at ND, large compared to detector at FD
  - differences in flux, acceptance, reconstruction and energy measurement between the two detectors limit precision to ~4%
  - very high rate in ND requires different electronics and selection criteria and different detector technology at DUNE!
- This approach has outlived its usefulness : we no longer have to prove neutrino oscillations exist



NOW WE CAN DREAM!

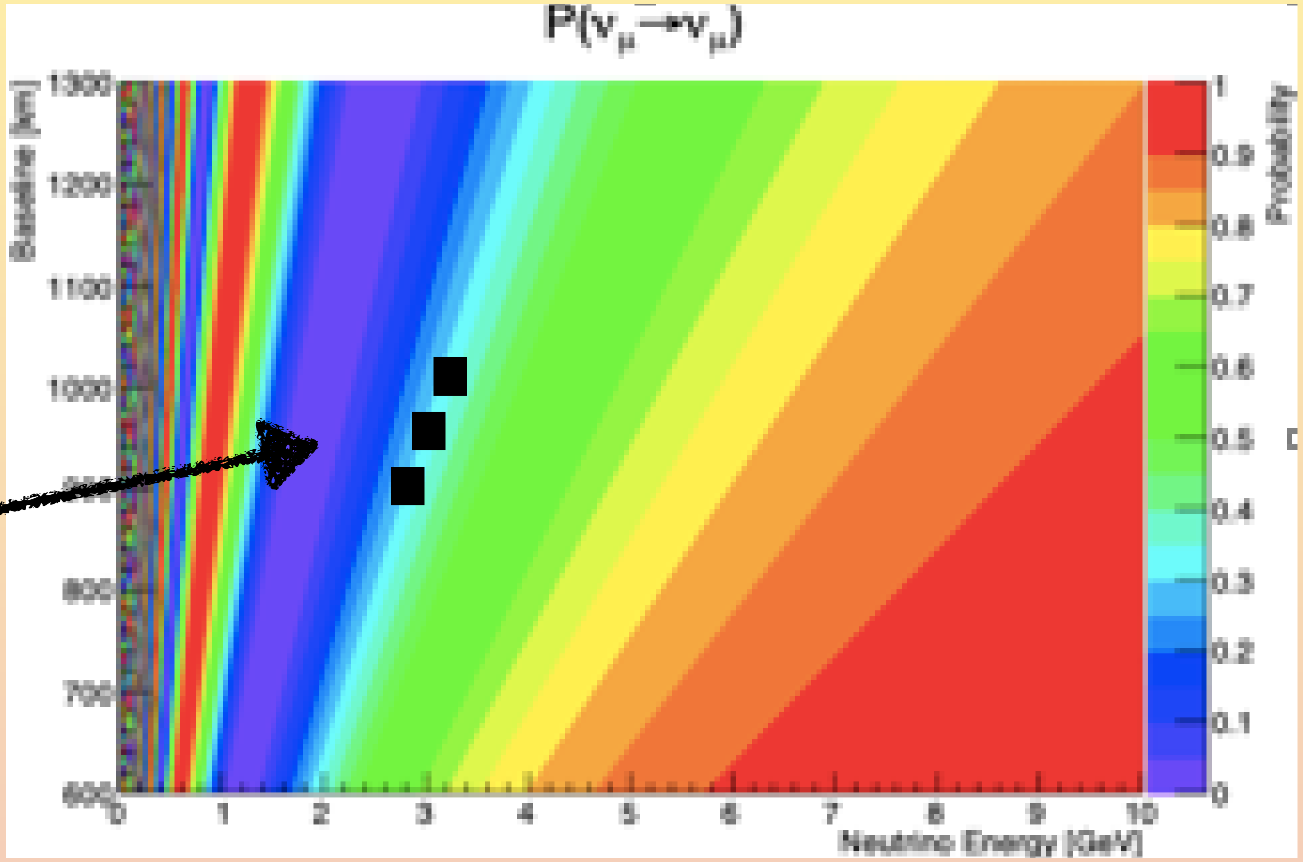


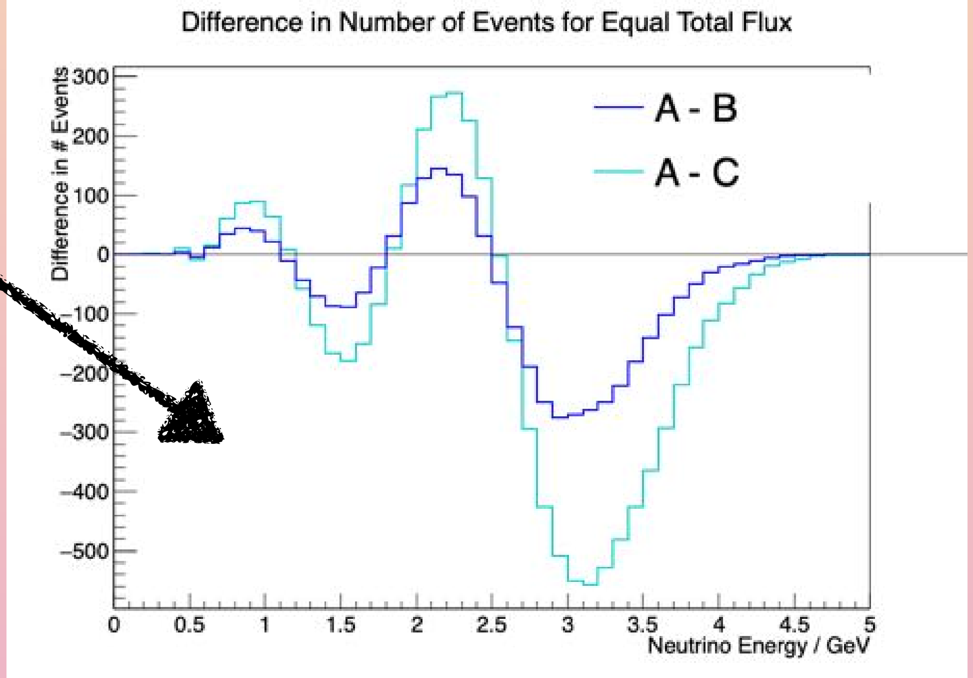
- Move to a new paradigm, where we accept oscillations take place and use an array of large identical detectors to measure small differences in oscillation in identical Far detectors, and *almost* identical beam
- These will **cancel** the dominant systematic errors, while at the same time record a very large number of events
- Using a 2 GeV Gaussian for the beam and 900, 950 and 1000km for the distances (at same off-axis angle of 7mrad)
- Only possible if cost of the huge (100 kilo-ton) detectors is low



CHIPS array @ LBNF

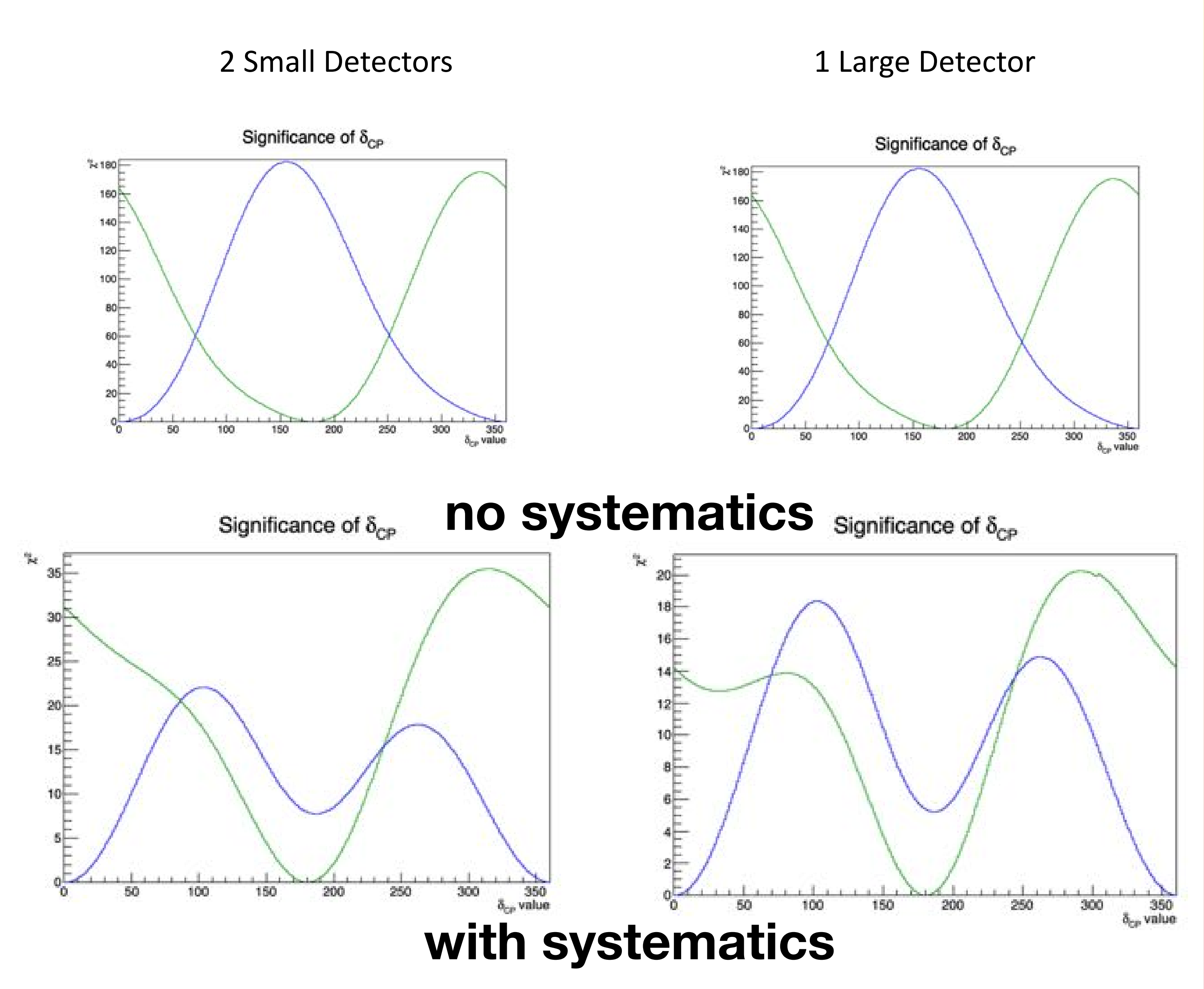
- Initial studies of the precision advantage of several identical detectors show promise
- Simple construction (always good) such that P_1-$P_2 = 0$, P_2-$P_3=0$, all systematics cancel
- Plot at right shows the difference between 3x100 kiloton detectors at 900km,950km,1000km, corrected for $1/r^2$
- Study is in its infancy, and implementation in GLOBES needs work
- We will see whether this can become a compelling argument for a complimentary detector (array) to DUNE





CHIPS array in principle: SANITY CHECK

- Look at 2 detectors compared to 1:
- Usual (GLOBES) approach is to add systematics in quadrature for different detectors
  - This isnt correct, as beam, x-sec etc are correlated
  - Could be for different detectors with different measurements
- More work to be done to make this argument concrete, sanity checks taking place now
- Checking this out with MINOS and NOVA
  - First look at two far detectors in the same beam



Summary

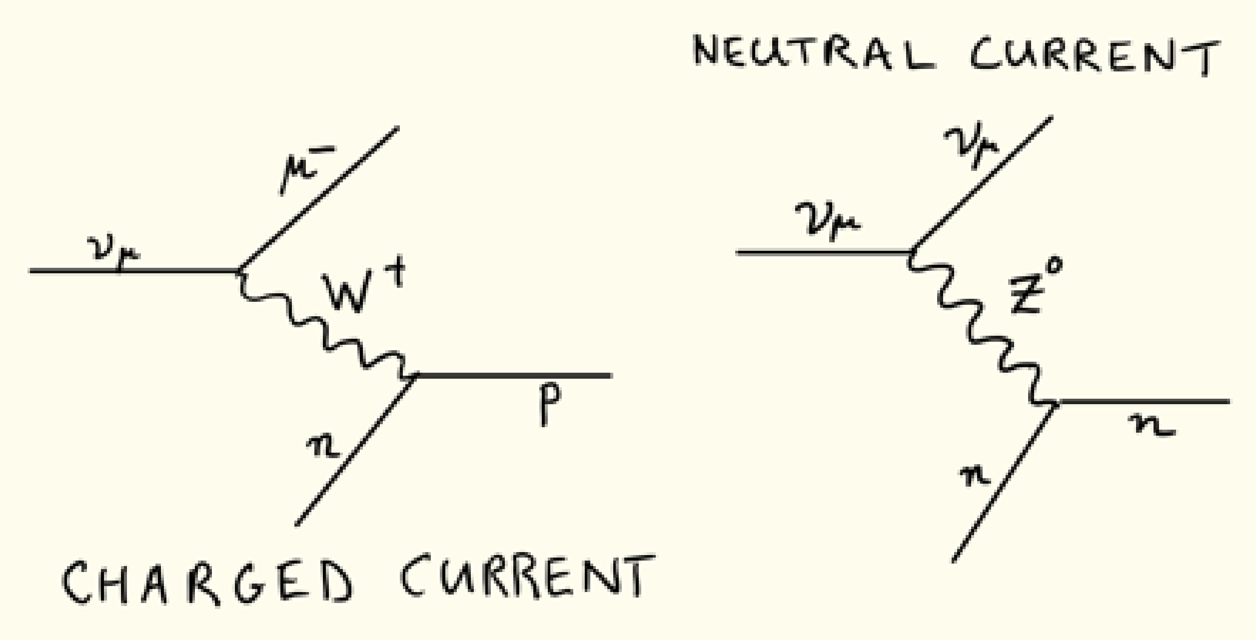
- If successful over the long term we will have shown:
  - \$200-300k/kton (compared to \$20M/kiloton)
  - Water-tight plane construction technique
  - Cheap electronics concept for distributed PMT systems
    - \$25/channel PMT to disk (excluding PMT of course)
    - development of small format White Rabbit module
    - Microdaq - microprocessor on a PMT
    - +ve HV miniaturized CW base
  - Low density coverage adequate for neutrino beam physics
  - Measurements along the way to help measure δ_{CP}
- To **learn** more we need to **be** more (massive) in the future
  - More mass, but smarter than just that
  - Is a detector array a better way to reach high precision?

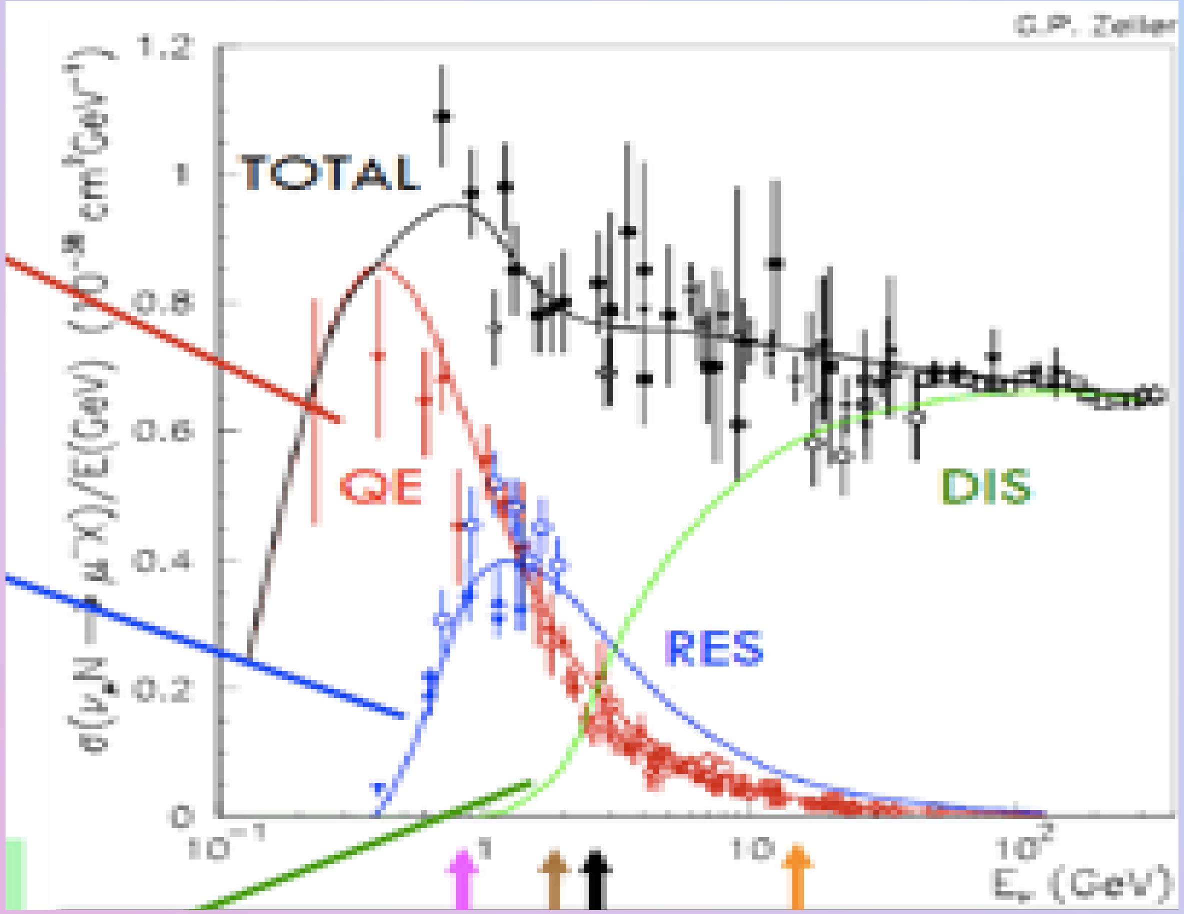
+Jerry

- We have 7 full time people
- 7 part time people
- 8 undergrad volunteers in 2019
- This group built the whole thing…
- I'm hiring postdocs @UCL too! : https://www.ucl.ac.uk/physics-astronomy/vacancies

TO CATCH A NEUTRINO

- Neutrinos are simple things
- They only have two types of interactions
- Its just they don’t like to have them
- You need LOTS of n and p if you want to catch a neutrino
- Steel and water are cheap and heavy
- But no amount of measuring them was going to ever give us the insight that their oscillations have





August 12th