Latest results of long-baseline neutrino oscillation experiments and (some) future perspectives

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Lepton-Photon 2017
Sun Yat-Sen University

8th August 2017

Reminder of the approach

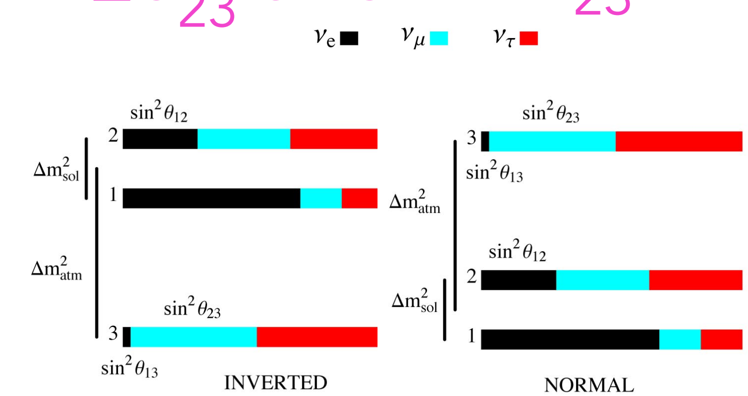
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12}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

How precisely do we know it?

Δm^2_{sol}	2.3%
Δm^2_{atm}	1.6%
$\sin^2\theta_{12}$	5.8%
$\sin^2\theta_{23}$	9.6%
$\sin^2\theta_{13}$	4.0%

F. Capozzi et al., Phys. Rev. D 95, 096014 (2017)

- ✦ Oscillations provide a tool to uncover characteristics of neutrinos that would be invisible if just measuring neutrino cross sections, no matter how many events you had
- ✦ All discussion here assumes we start with a muon neutrino beam
- ✦ Looking at disappearance of ν_μ we learn about $\sin^2 2\theta_{23}$ and Δm^2_{23}



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

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- Looking at electron neutrino **appearance** tells us about $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, sign of mass hierarchy and δ_{CP}

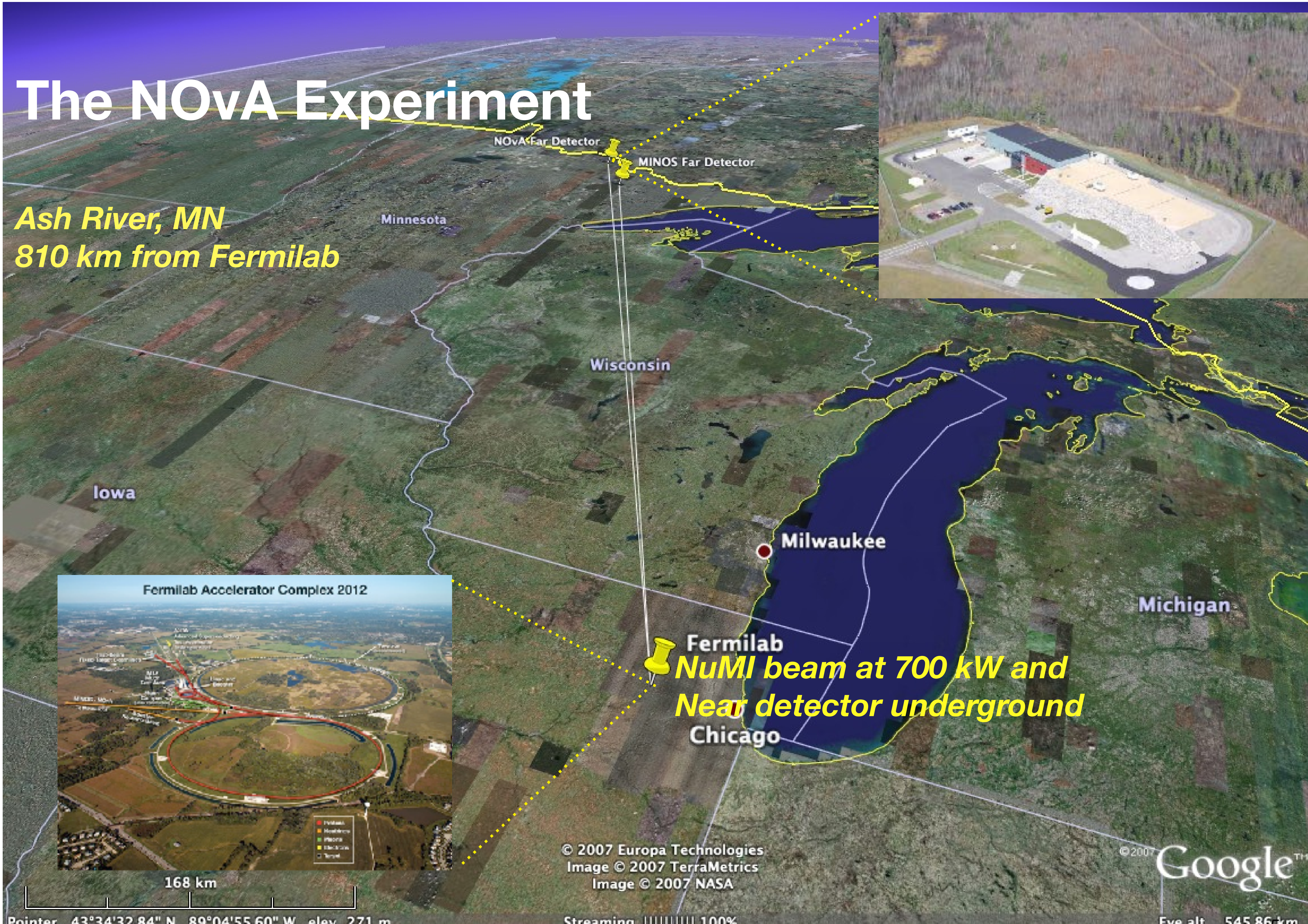
$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \\ & +8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\ & -8C_{13}^2 C_{12} C_{23}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

CPV →

- Running with anti-neutrinos changes sign of CPV term

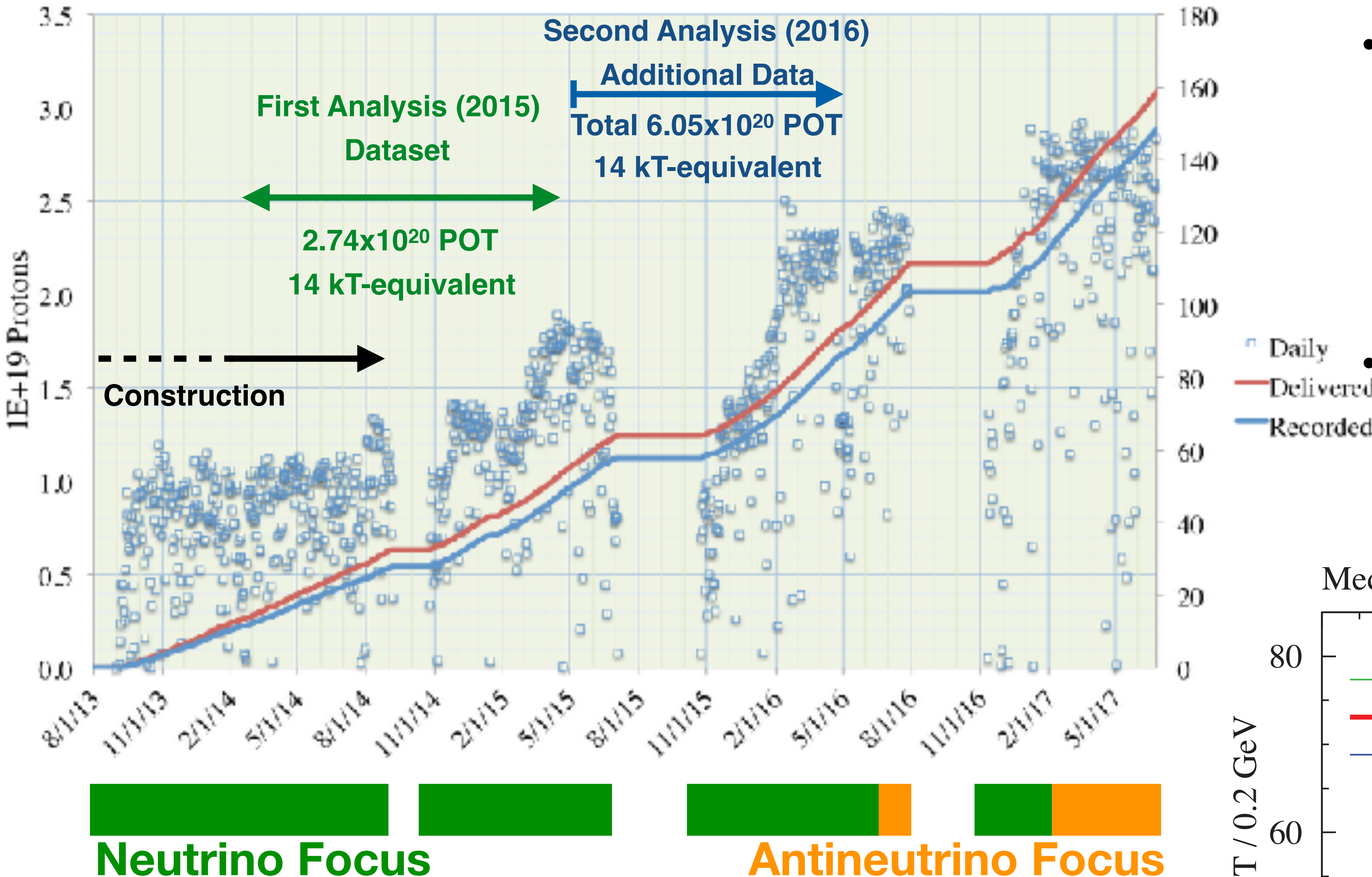
Outline

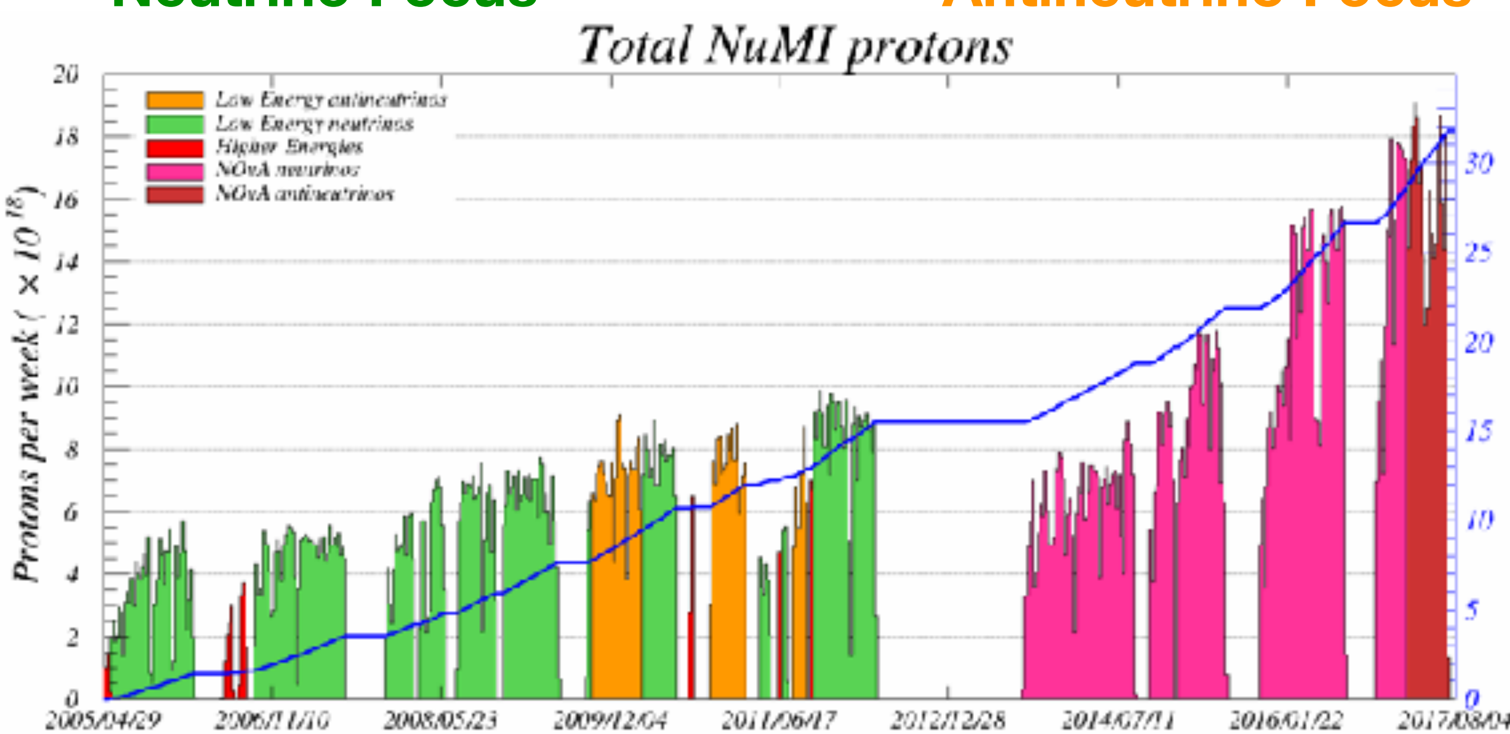
- There are four accelerator based long-baseline experiments presently producing results:
  - NOνA
    - goal to measure mass hierarchy, mixing angle $\sin^2\theta_{23}$, δ_{CP}
  - MINOS+
    - leading in the search for sterile neutrinos, $\sin^2\theta_{23}$
  - OPERA (CERN to GS beam)
    - has been mining their data since shut of in 2012
  - T2K
    - **New results** with improved neutrino statistics
- In the near future
  - CHIPS
- In the further future
  - DUNE, HYPER-K … dedicated talks on Saturday
- Messages for the future
  - Changing goalposts? Timescales? Flexibility?

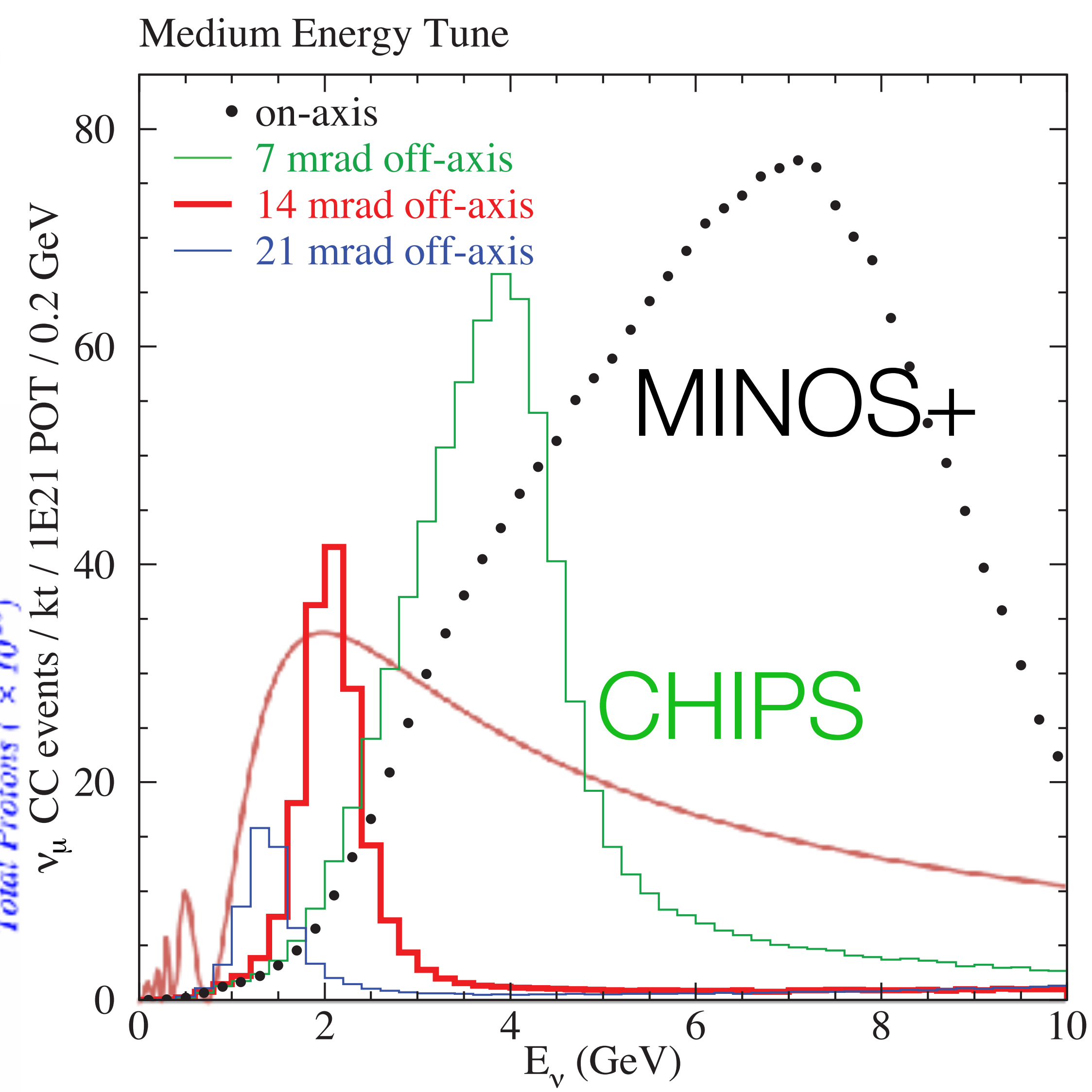

The NOvA Experiment
Ash River, MN
810 km from Fermilab
NOvA Far Detector
MINOS Far Detector
Minnesota
Wisconsin
Iowa
Milwaukee
Michigan
Fermilab
NuMI beam at 700 kW and
Near detector underground
Chicago
Fermilab Accelerator Complex 2012
168 km
© 2007 Europa Technologies
Image © 2007 TerraMetrics
Image © 2007 NASA
©2007 Google™
Pointer 43°34'32.84" N 89°04'55.60" W elev 271 m
Streaming |||||||||| 100%
Eye alt 545.86 km

NuMI Beam Performance

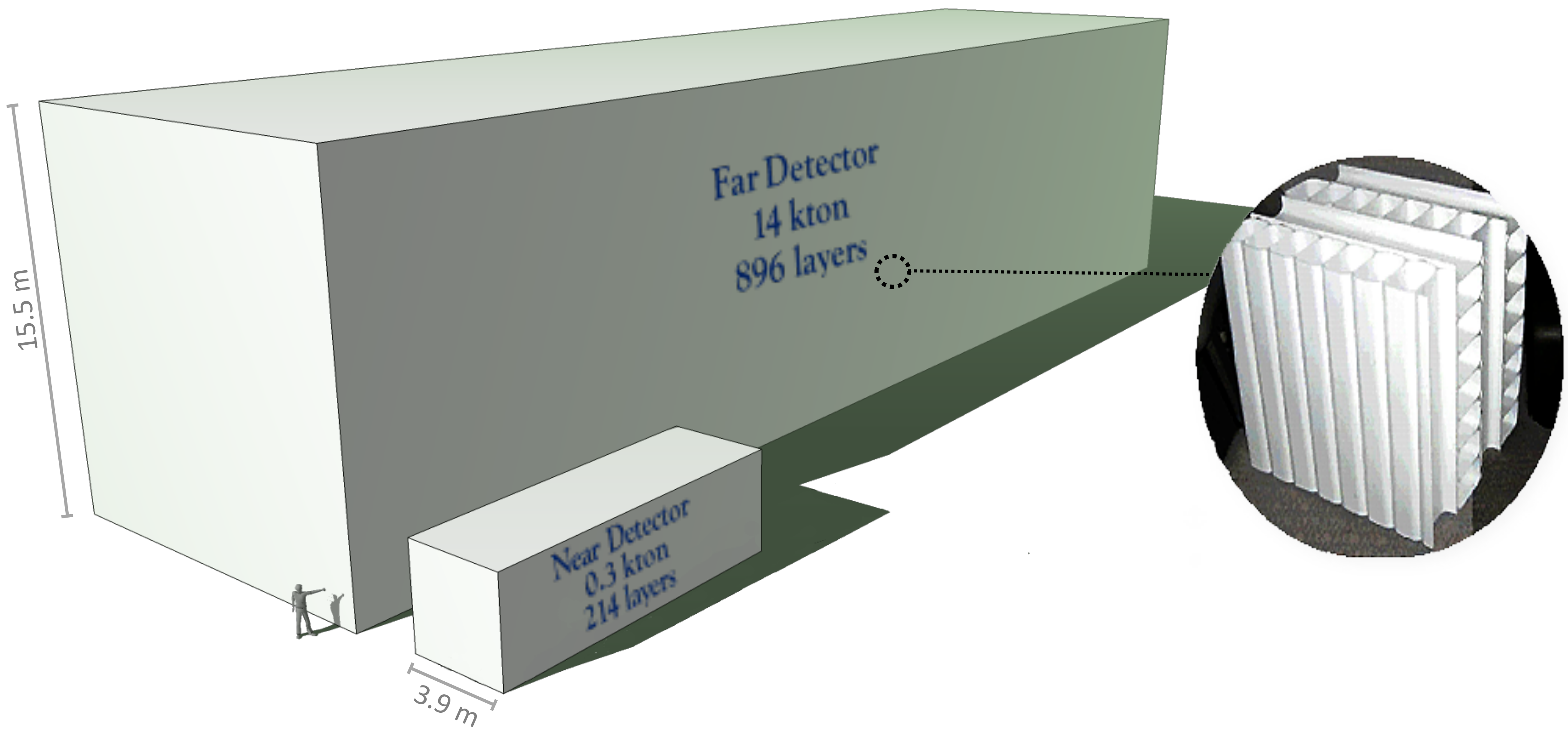
- **120GeV protons from the main injector**
- **Pions decay to produce muon neutrinos**
  - Decay kinematics mean a detector at 14.6 mrad sees a narrowly peaked energy spectrum
- **97.5% muon-neutrino, only 0.7% beam electron-neutrino (remainder wrong-sign) at NOvA**

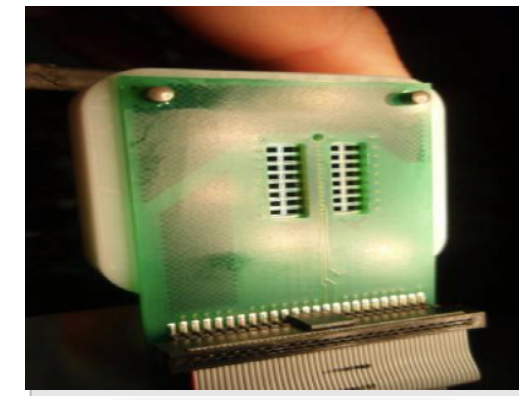


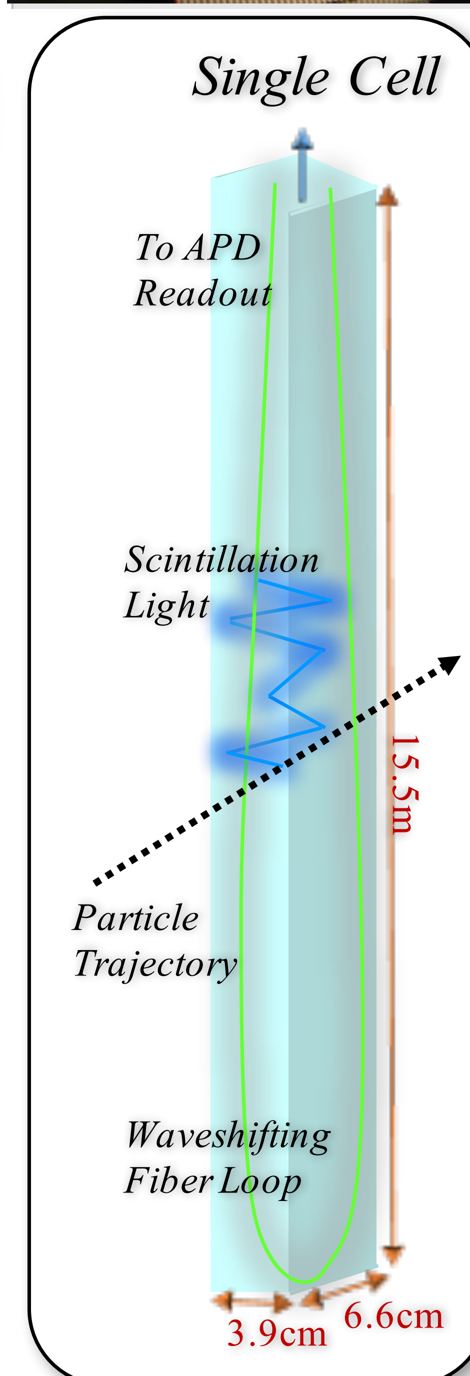




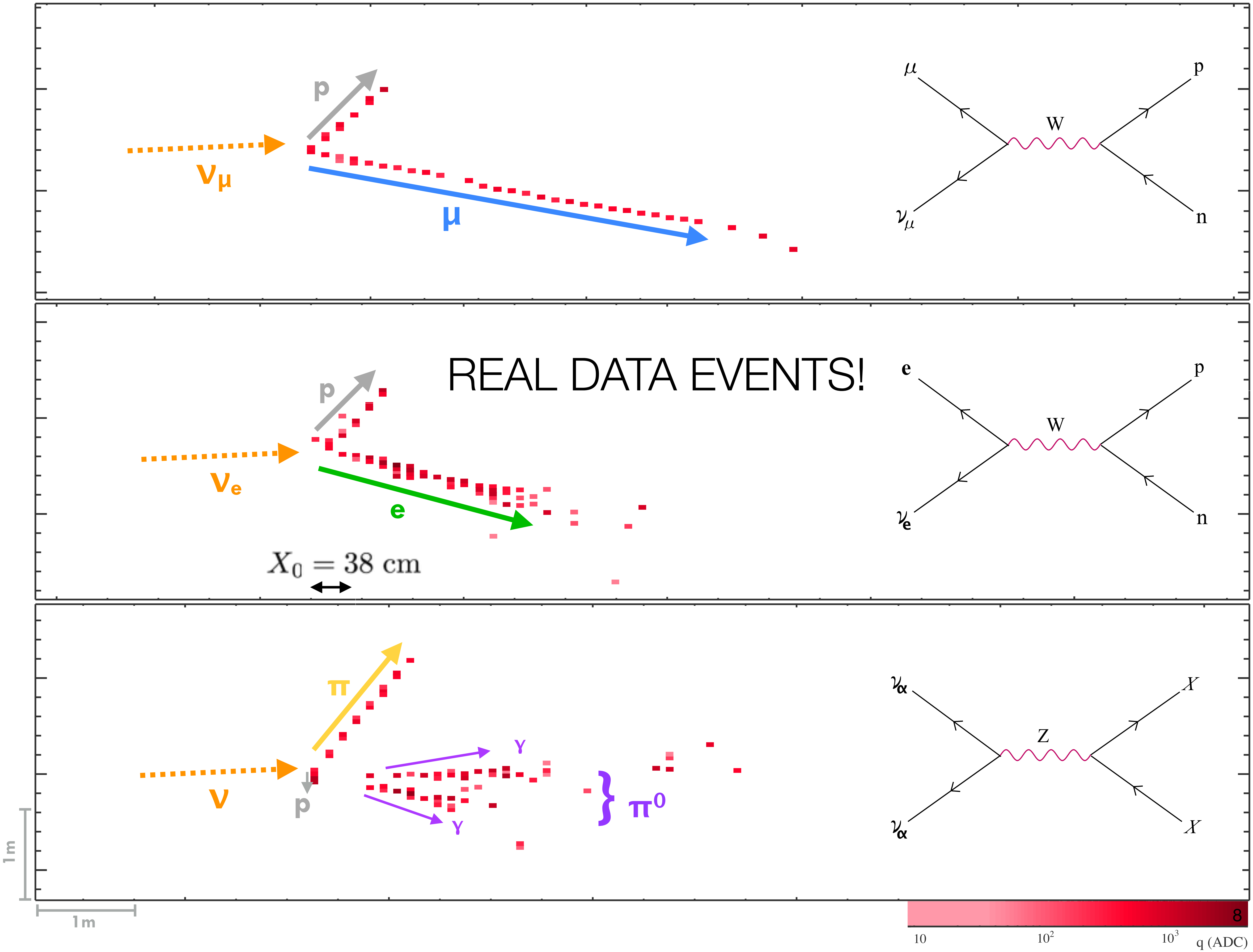
NOvA Detectors







- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator
- Charged particles passing through cells produce light which is collected by a wavelength shifting fibre and read out with an APD

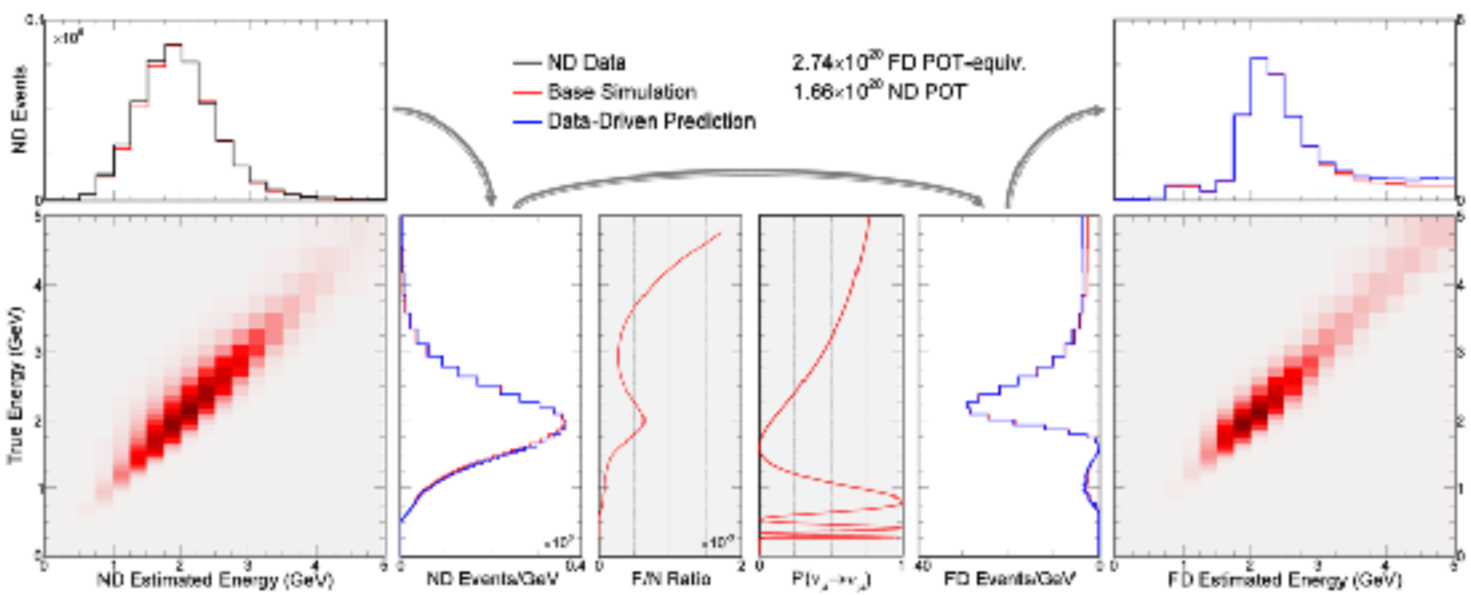


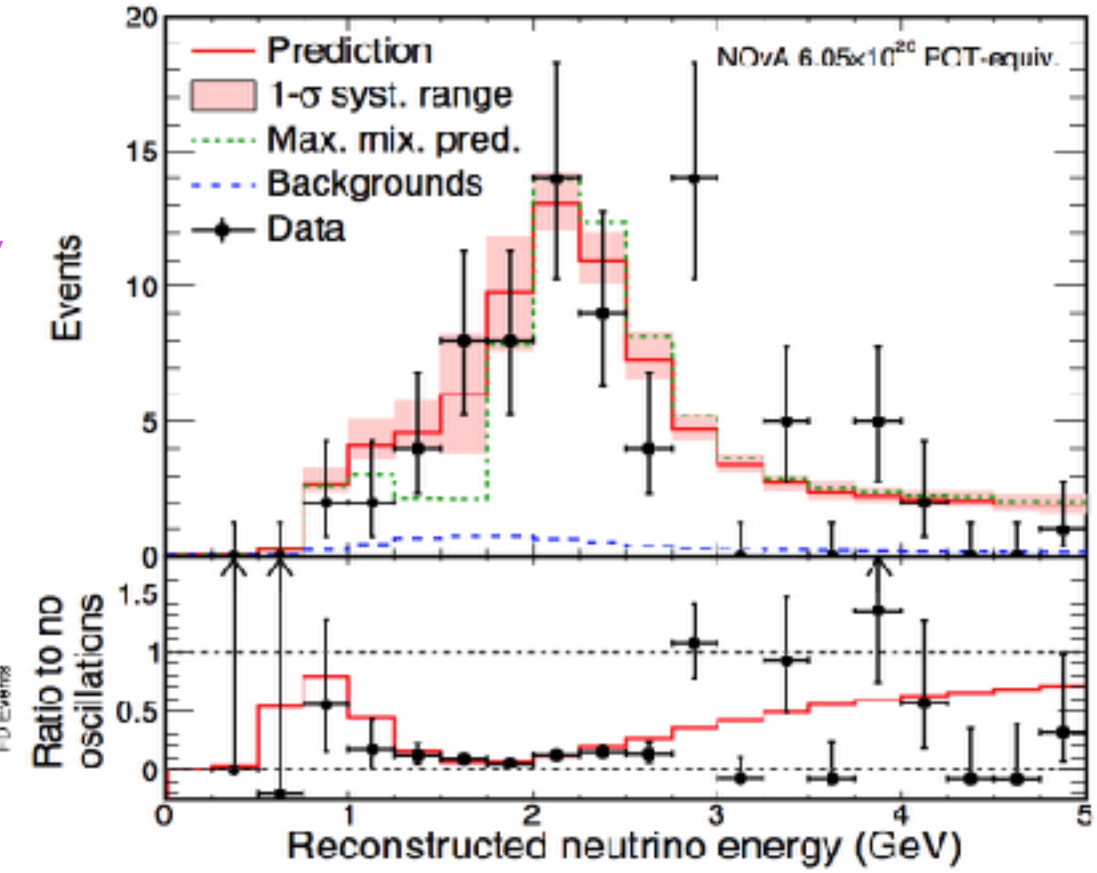
REAL DATA EVENTS!
ν_μ
p
μ
μ
p
W
ν_μ
n
ν_e
p
e
e
p
W
ν_e
n
$X_0 = 38$ cm
ν
π
p
γ
γ
π^0
ν_α
X
Z
ν_α
X
1m
1m
10
10^2
10^3
q (ADC)

PRL 118, 151802 (2017)

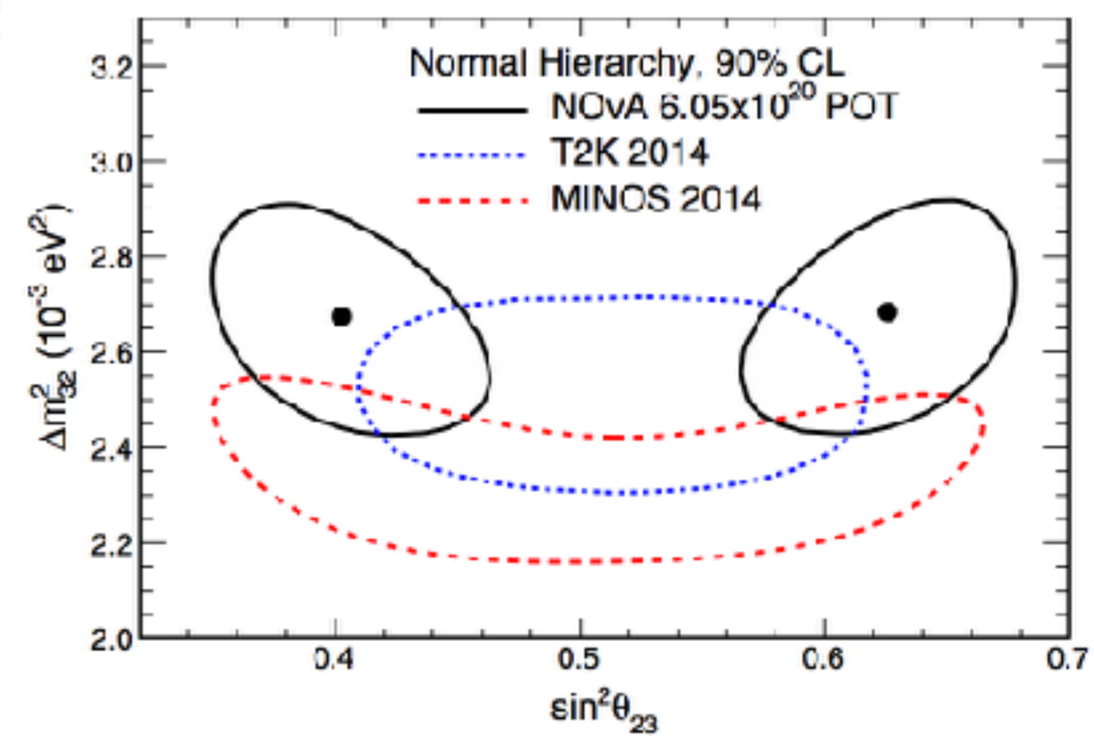
NOvA ν_μ Disappearance

- Use high statistics ND data/MC to adjust prediction at FD
  - Translate ND data/MC observation to true energy
  - Oscillate ratio to the FD
  - Smear back into reconstructed energy





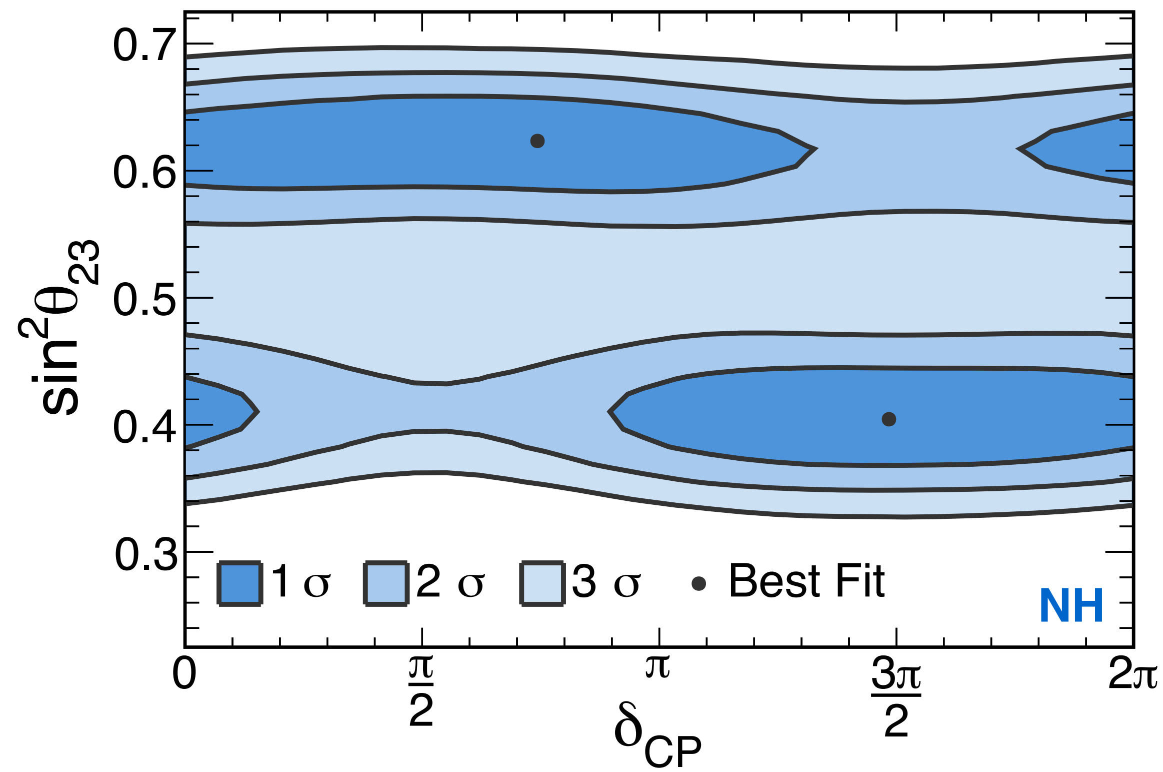
$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\text{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

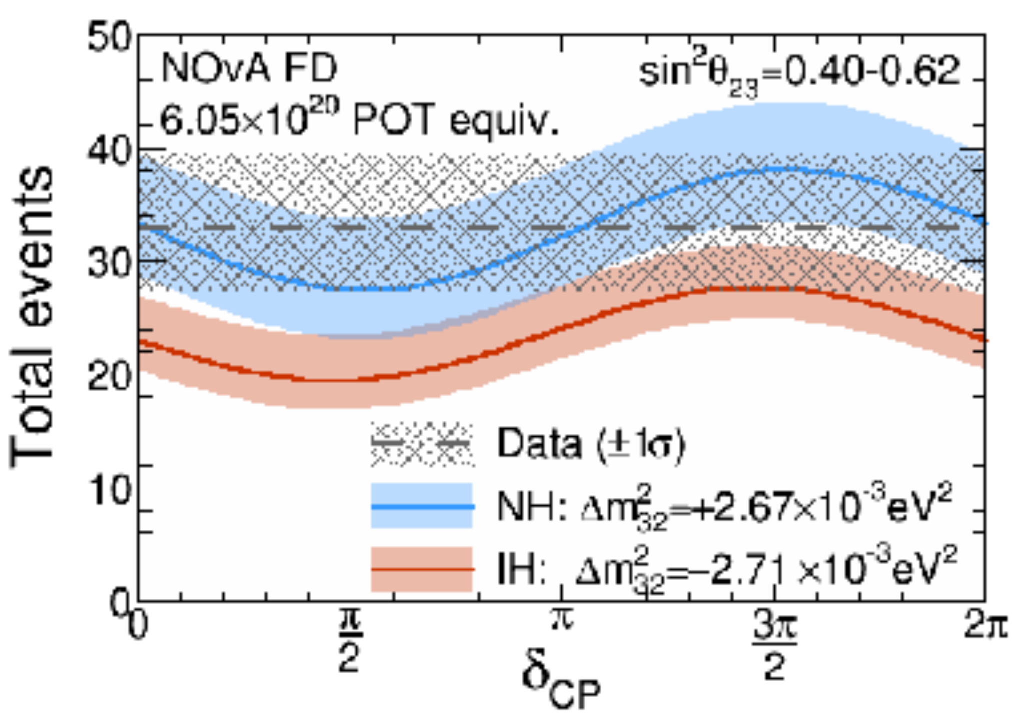


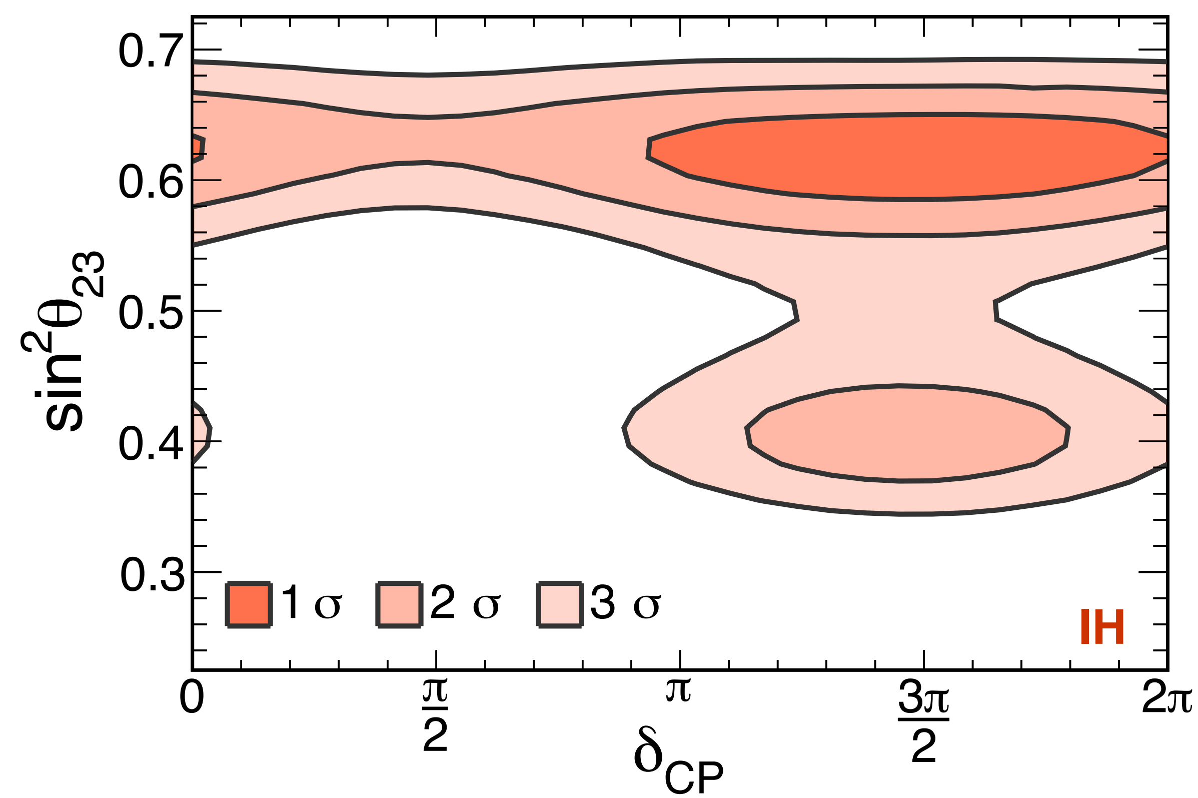
- Excludes maximal mixing at 2.6σ!

NOvA ν_e Appearance

- Update to Neutrino 2016 ν_e appearance
  - Observed 33 events on background of 8.2±0.8
  - **Full joint ν_μ/ν_e** fit constrains oscillation parameters
    - Lower octant/Inverted hierarchy disfavored at 93% CL for all values of δCP







Constraints on Oscillation Parameters from νe appearance and ν_μ disappearance in NOvA
PRL 118, 231801 (2017)

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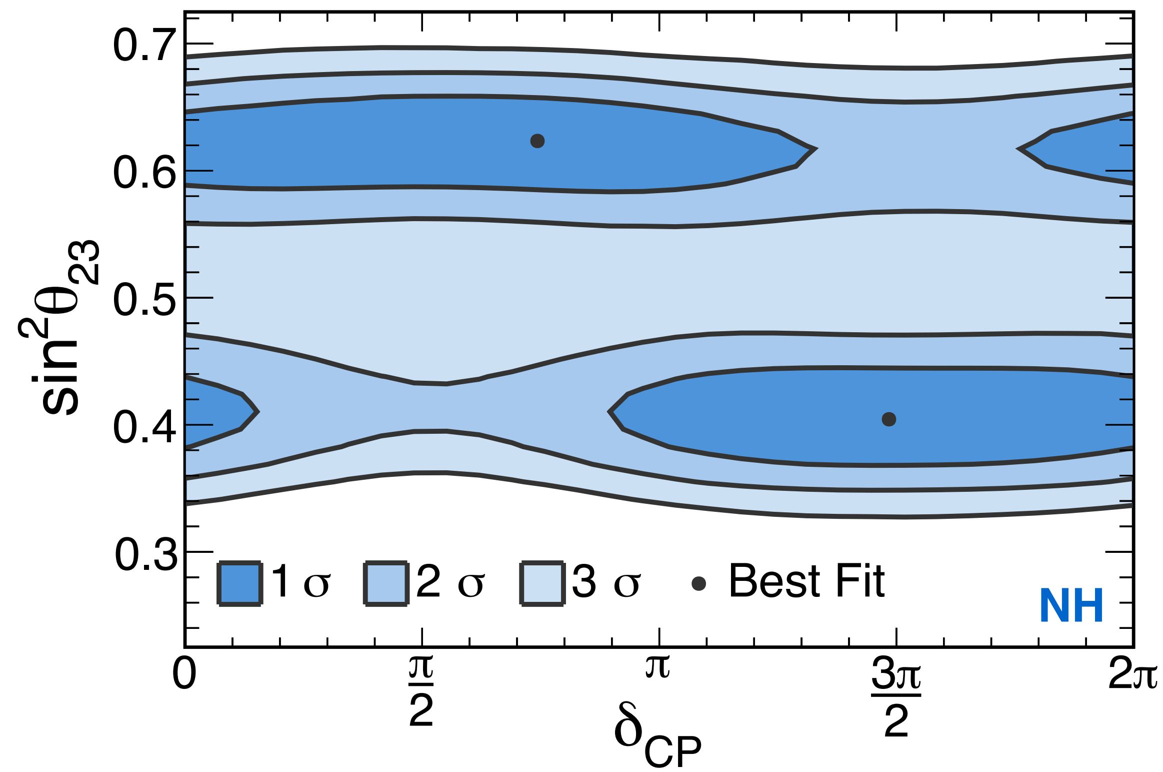

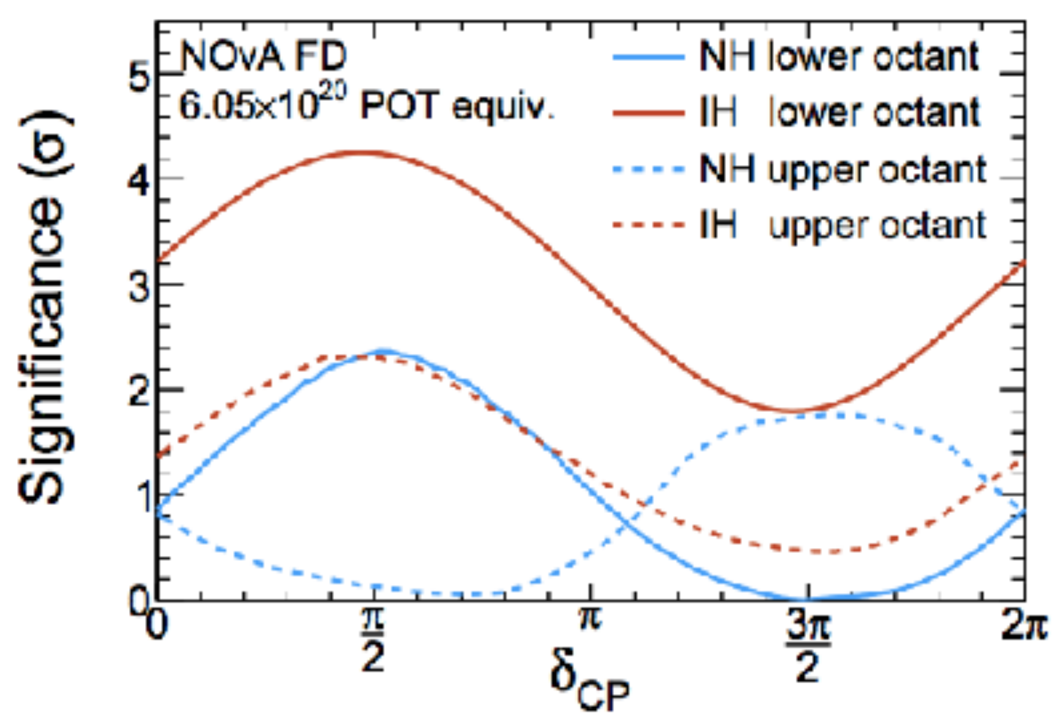

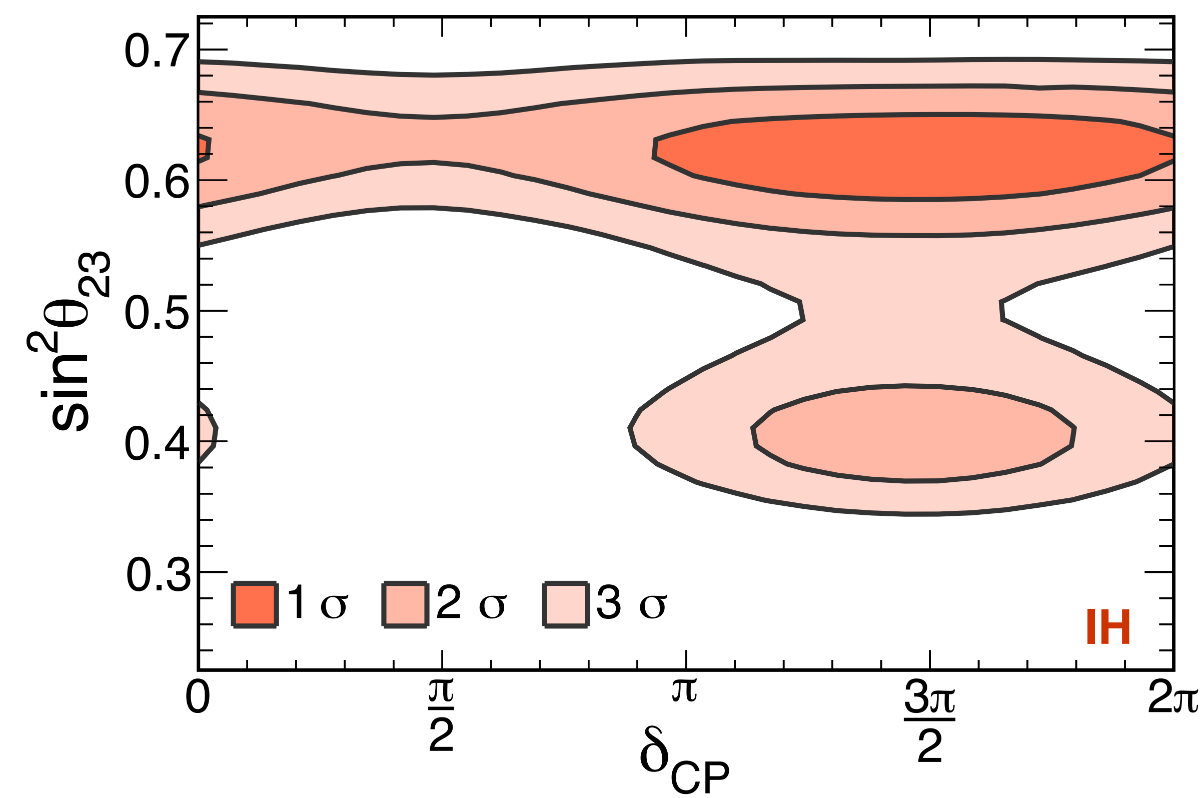

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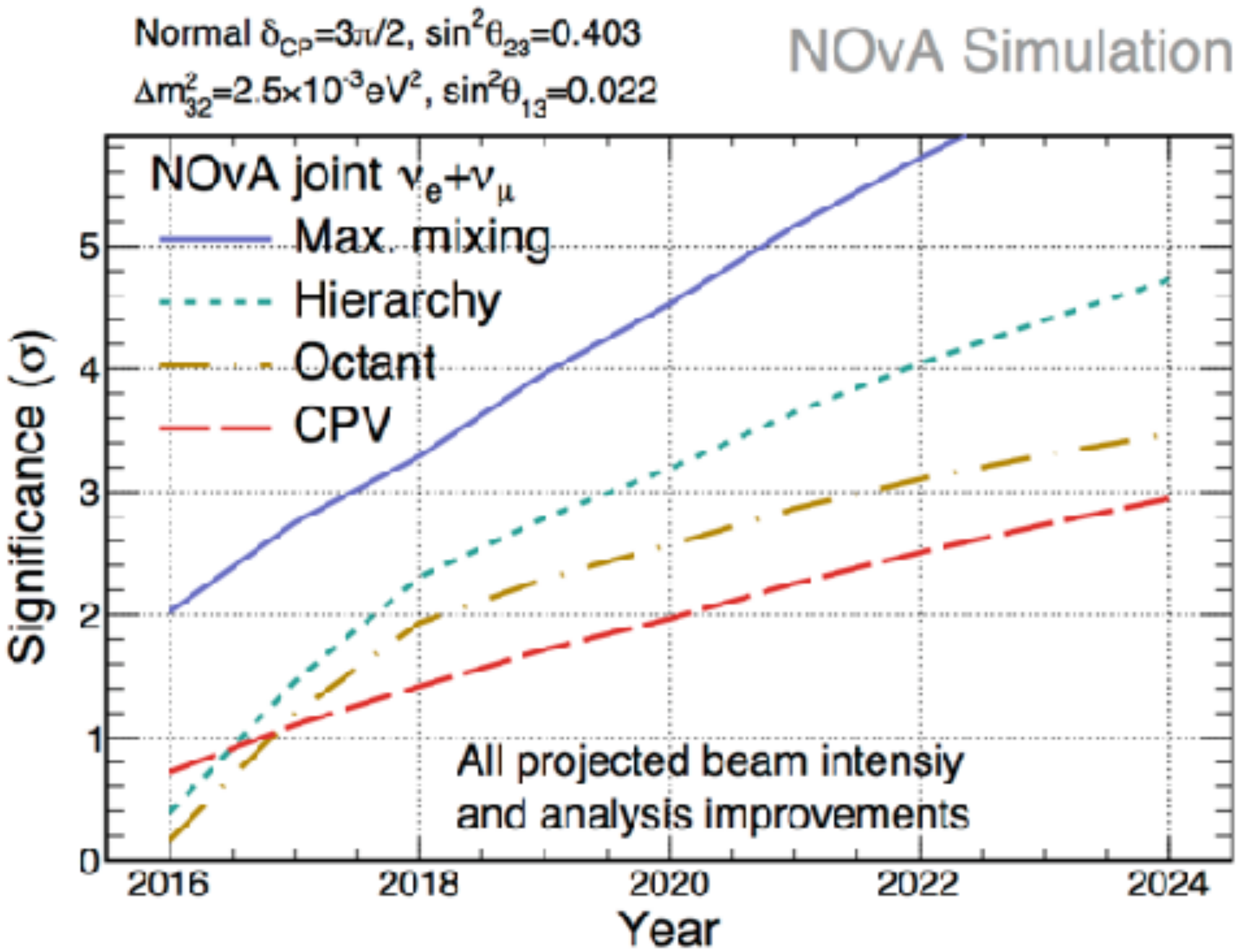
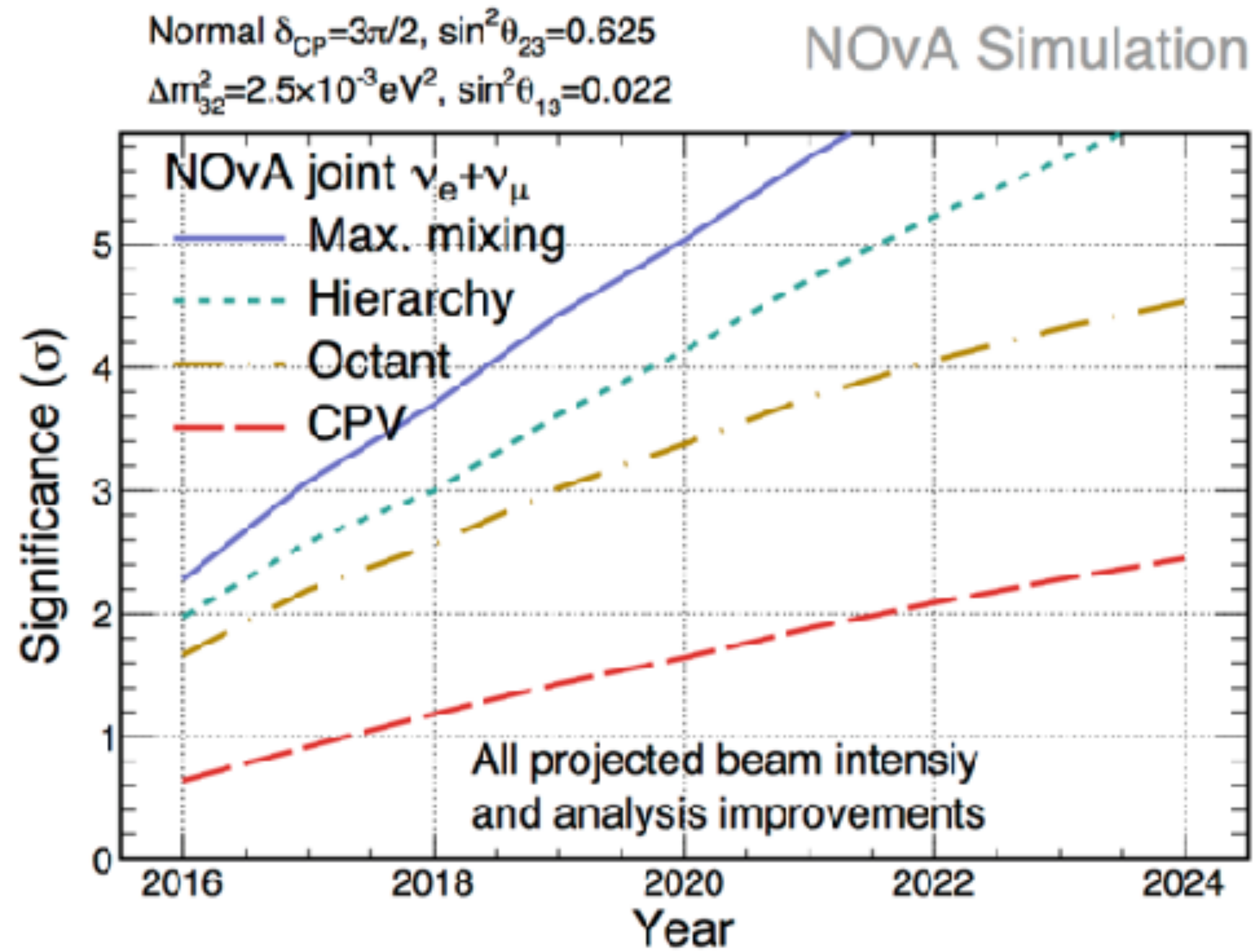
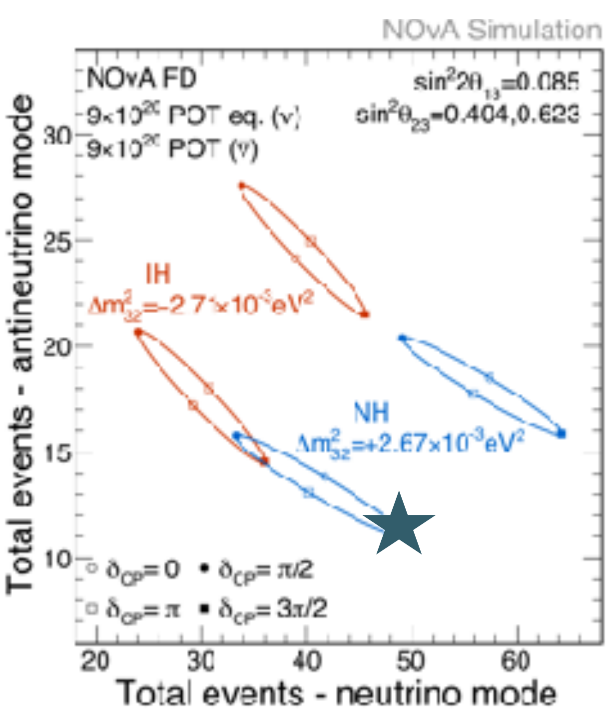
PRL 118, 231801 (2017)

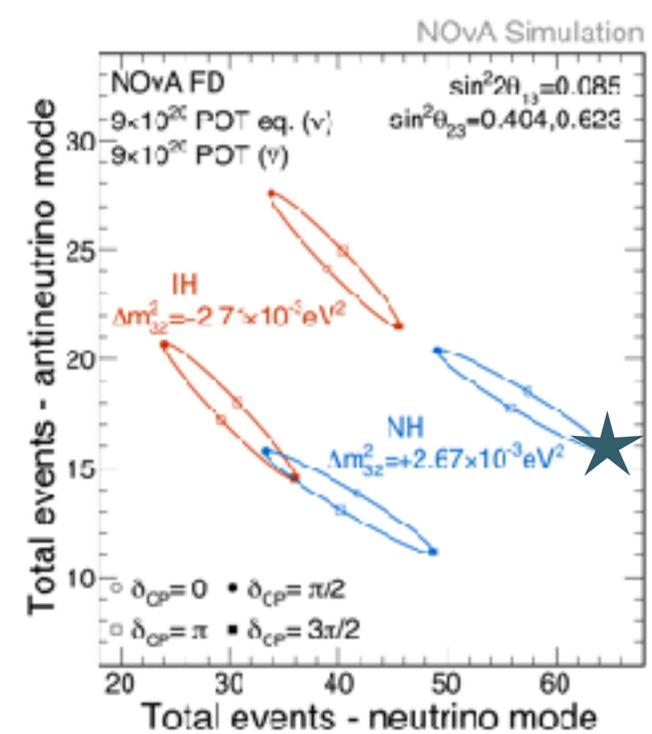
NOvA future reach







- NOVA Switched to anti-neutrino running in February 2017
- Plan to run 50% neutrino, 50% anti-neutrino after 2018
  - 3 σ sensitivity to maximal mixing of θ_{23} in 2018
  - 3 σ sensitivity to mass hierarchy in 2020
  - 3 σ sensitivity to θ_{23} octant by 2022
  - 2-3 σ sensitivity to δ_{CP} by 2024



The MINOS/MINOS+ Experiment

Far Detector
735 km from beam target
5.4 kton mass

Near Detector
1 km from beam target
1 kton mass

- MINOS/MINOS+ had two functionally identical, magnetised, tracking, sampling calorimeters.
  - Can distinguish muon charge from the curvature.
- Exposed to the NuMI beam at Fermilab.
- MINOS+ continued the running of the MINOS detectors into the NOvA era at FNAL.

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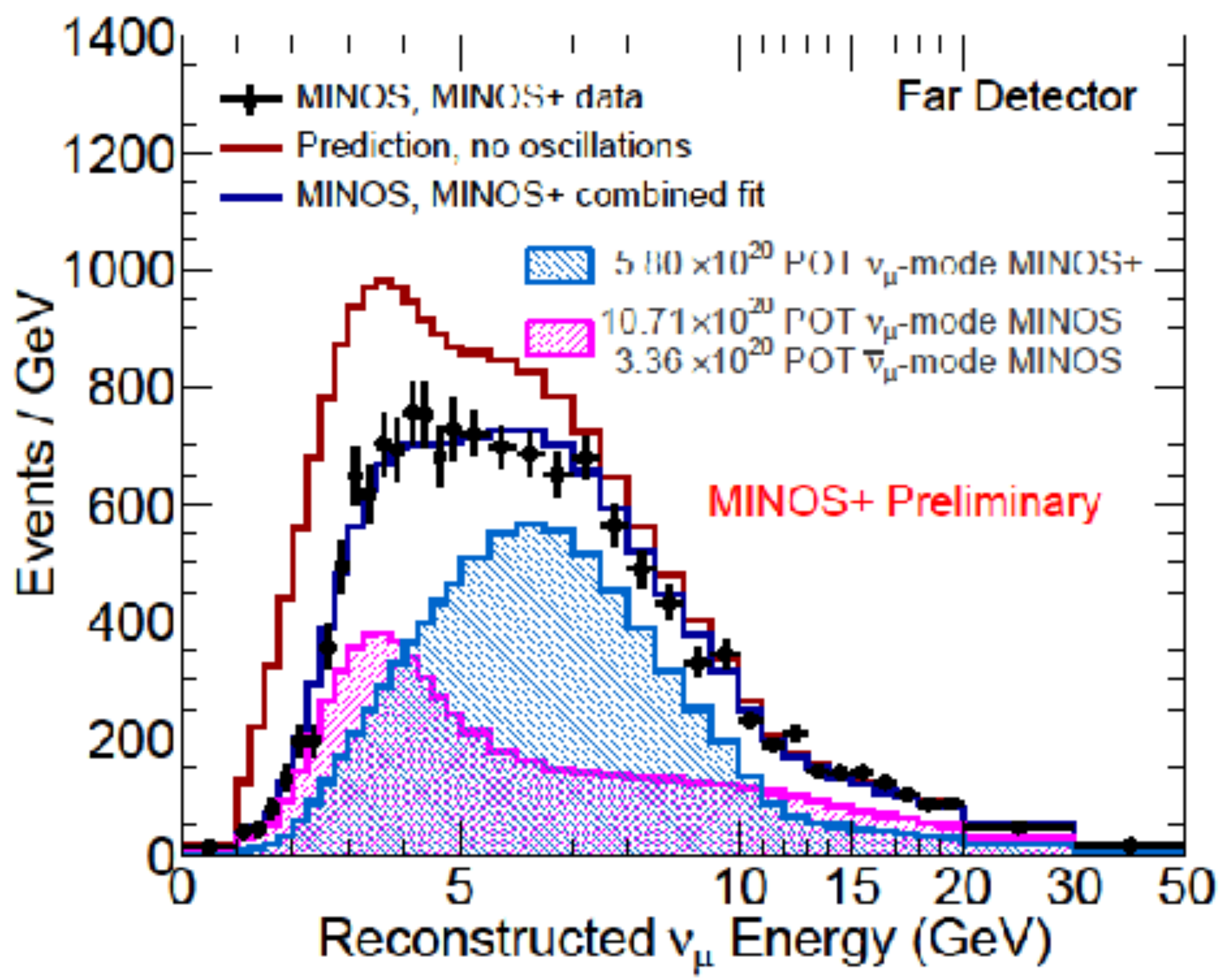
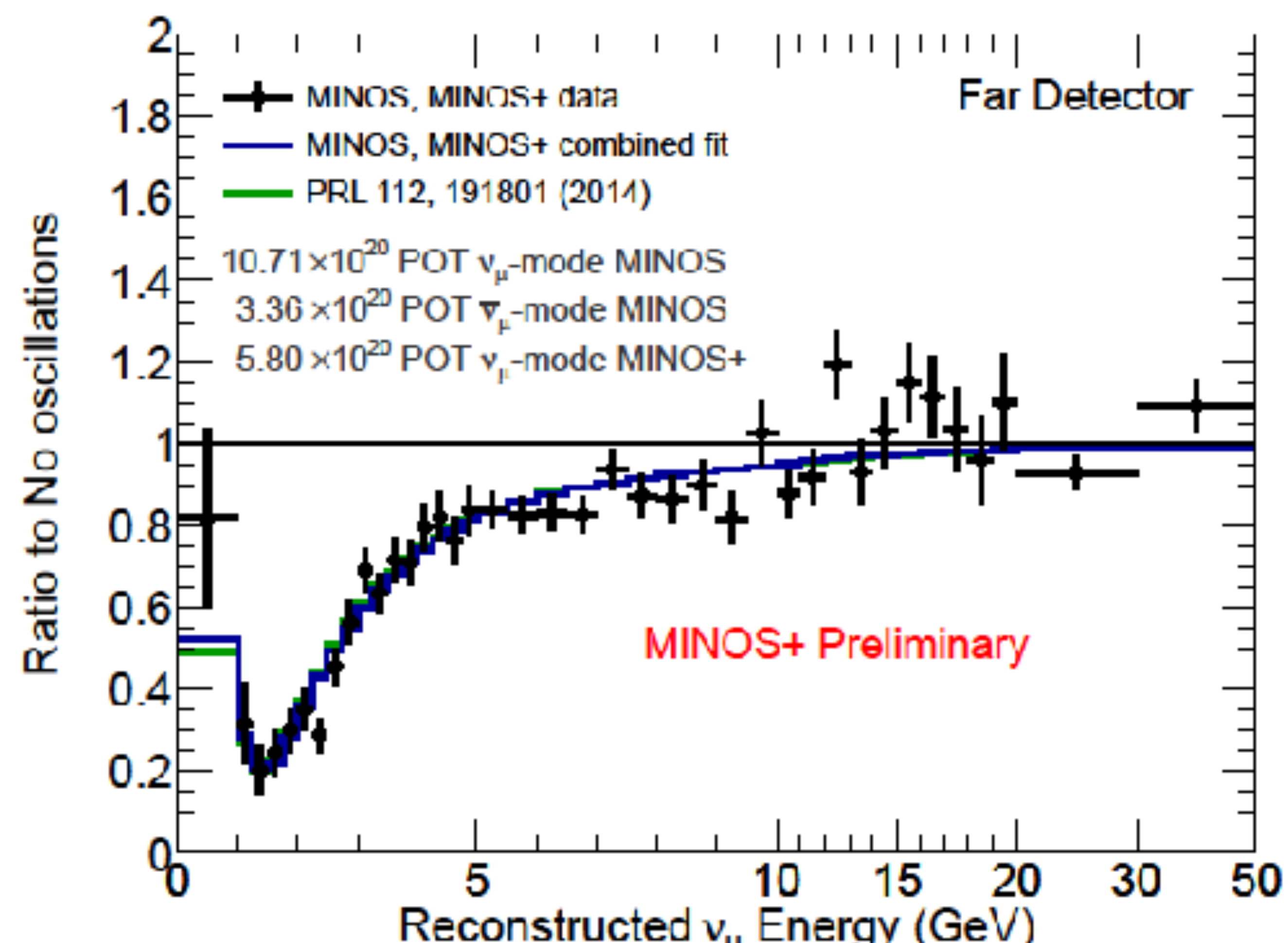
Three Flavour Oscillations

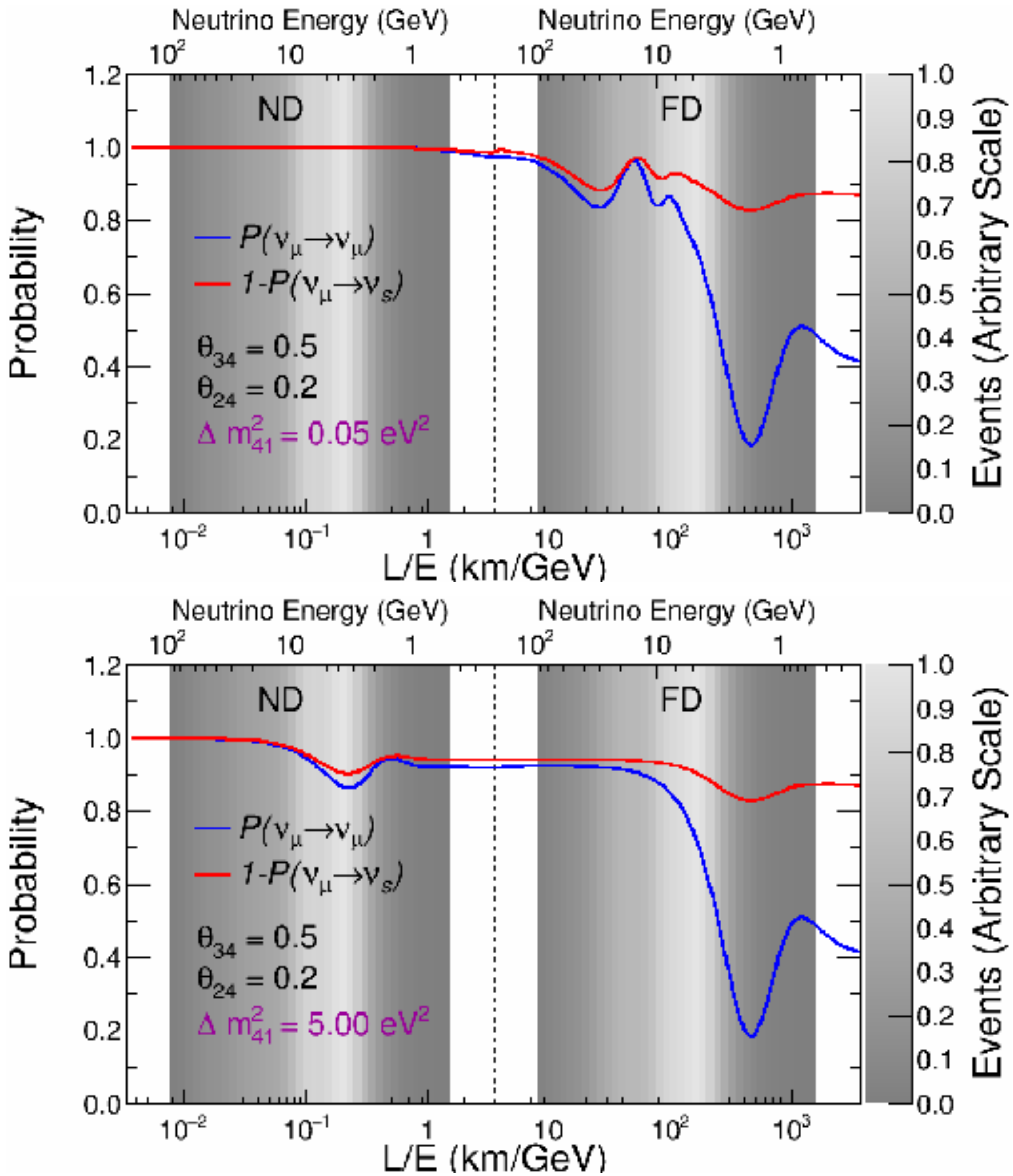
- MINOS was designed to measure the atmospheric scale oscillation parameters Δm^2_{32} and $\sin^2 2\theta_{23}$
  - Look for disappearance of CC ν_μ interactions in the FD relative to ND.
  - Continue the search with MINOS+





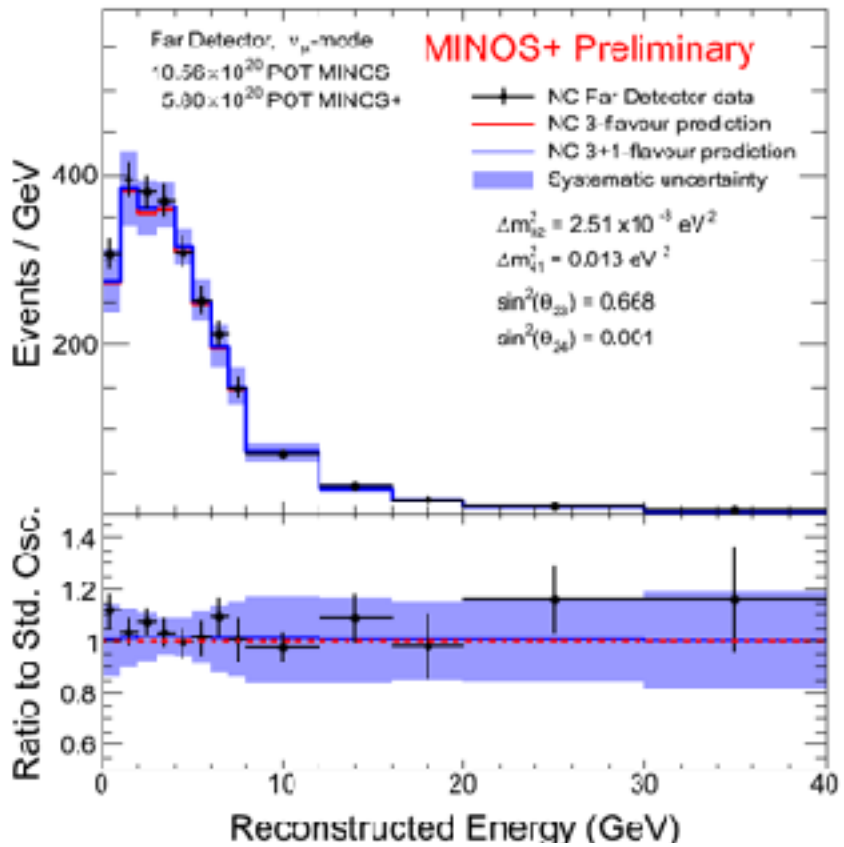
Sterile Oscillations in MINOS/MINOS+

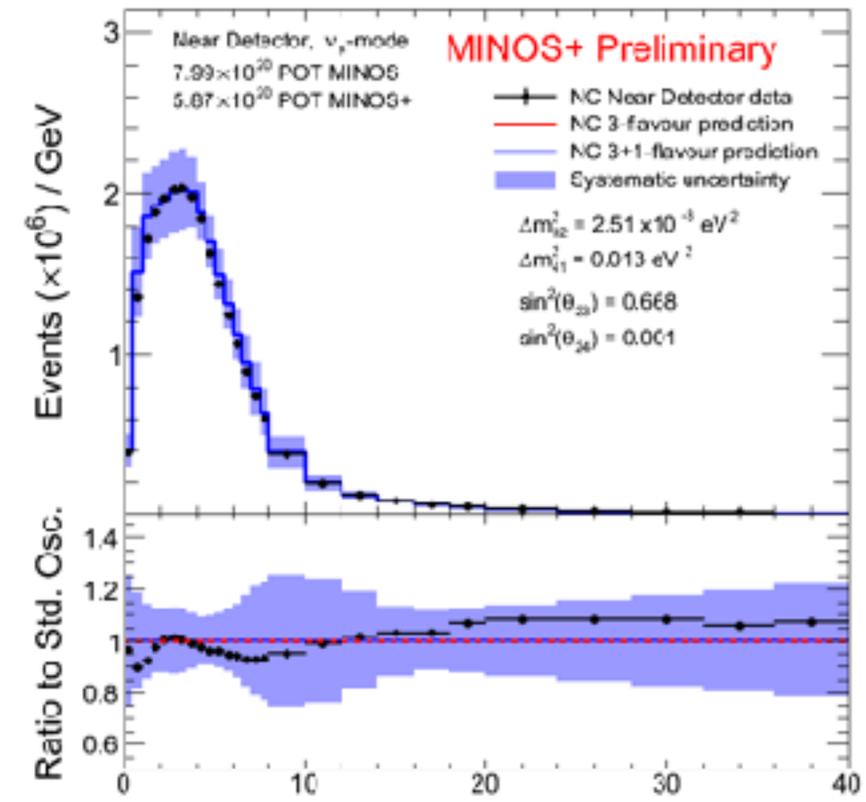
- MINOS is sensitive to three sterile neutrino parameters
  - θ_{24} , θ_{34} and Δm^2_{41}
- Oscillations can cause effects in both detectors
  - Low Δm^2_{41} only affects FD
  - High Δm^2_{41} causes oscillations in the ND. Rapid oscillations cause a constant deficit in FD
- Can't use ND as a flux measurement in this analysis



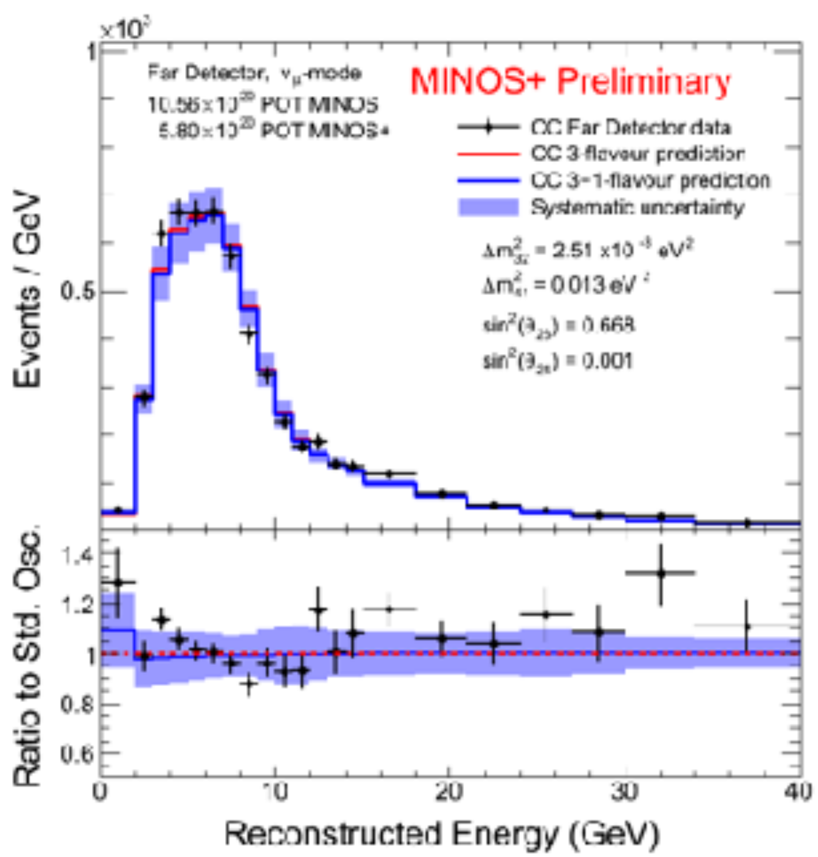
MINOS NC and CC spectra

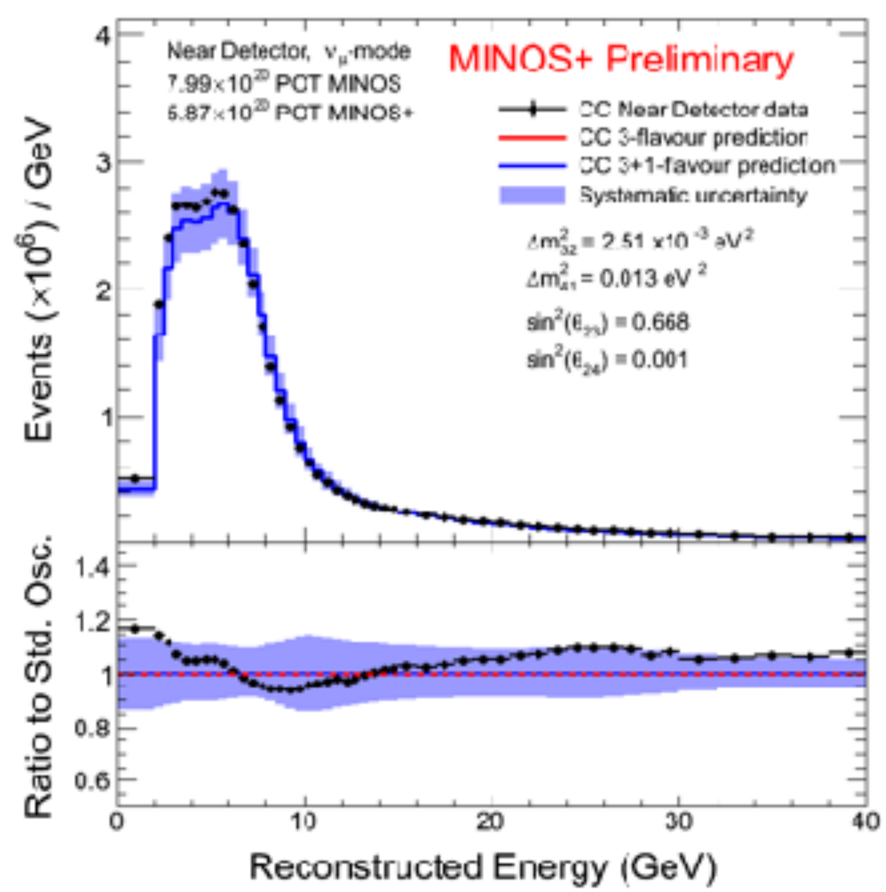
external NA61 hadron production information for systematics from Minerva+focussing+normalisation





NC

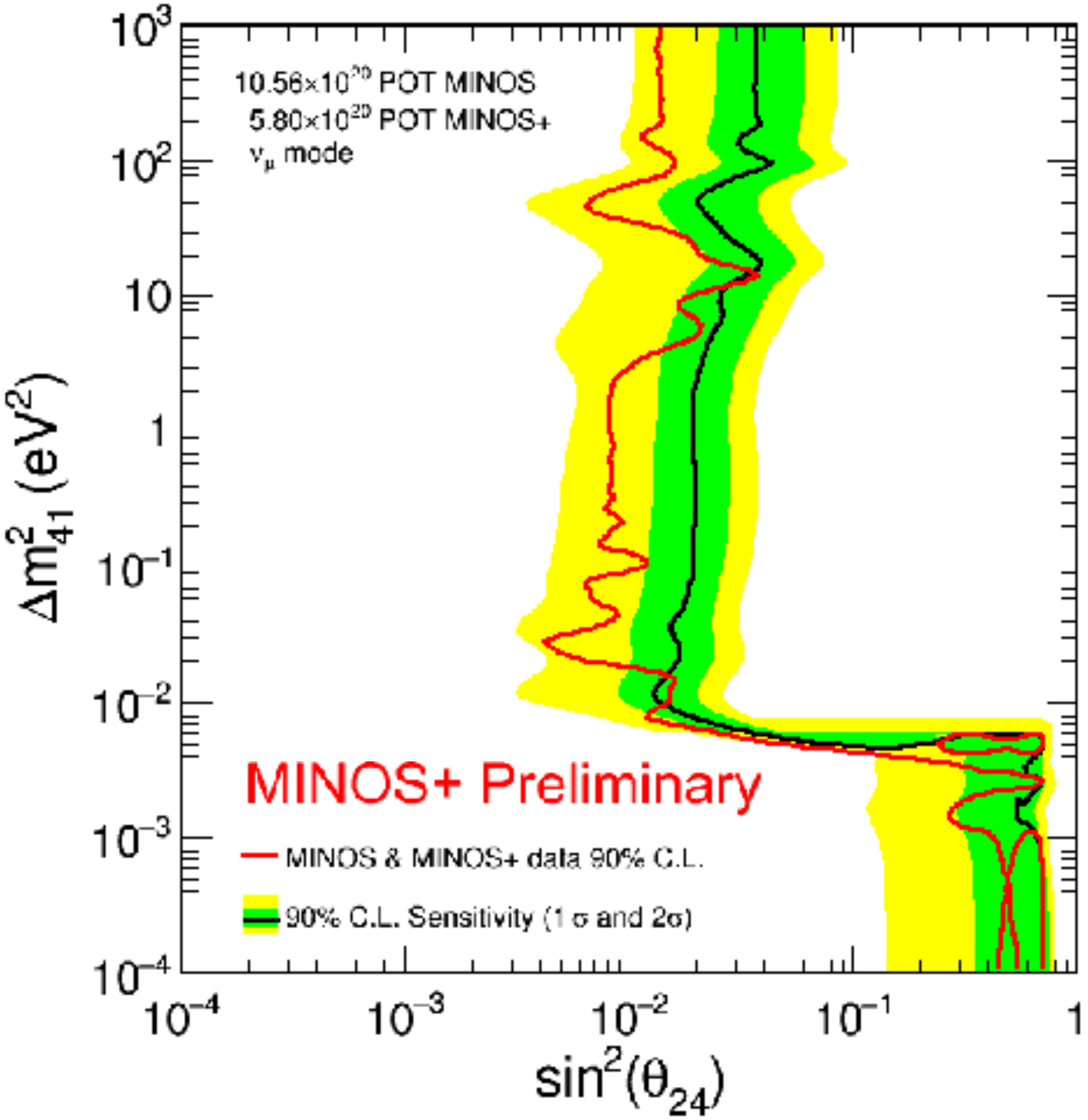




CC,
&.NOT. NC

Exclusion Contour

- For each bin in (Δm^2_{41}, θ_{24}) space, minimise with respect to Δm^2_{32}, θ_{23}, and θ_{34}
- Limit constructed using the Feldman-Cousins approach
- Strong limit on θ_{24} set over seven orders of magnitude in Δm^2_{41}
- Limit falls within expected 2σ sensitivity band



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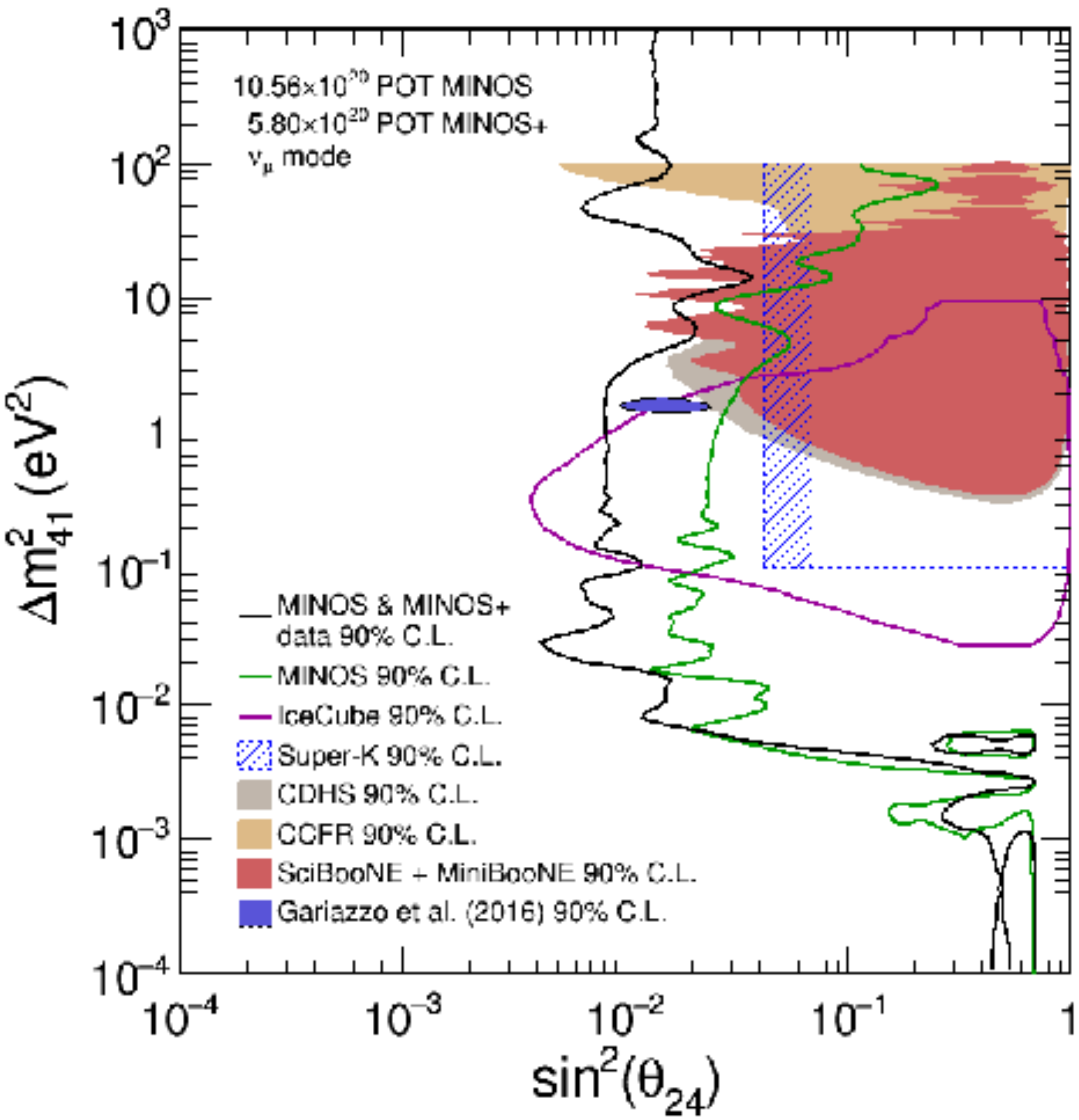
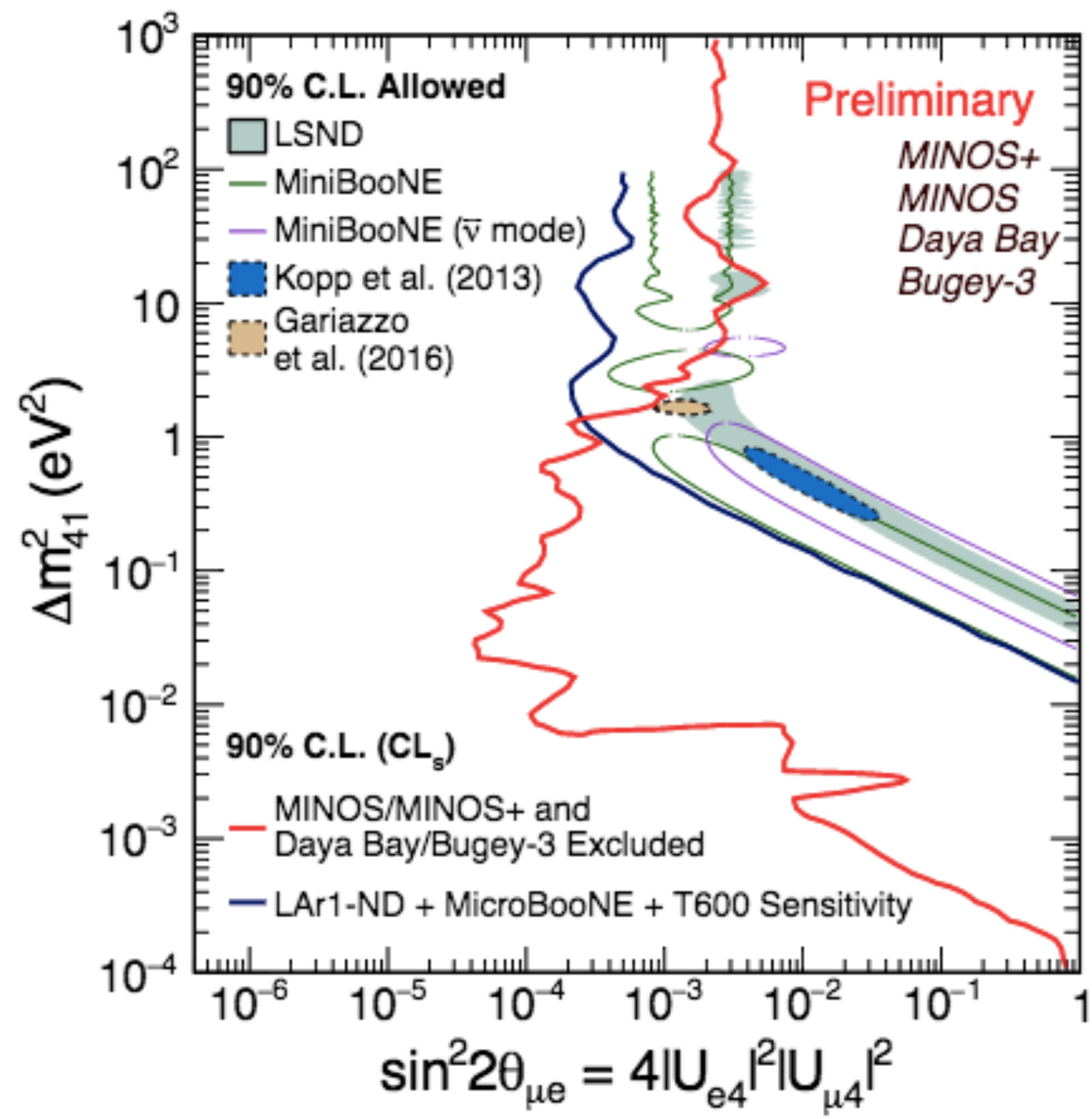
- Gariazzo region is from a global fit (not including MINOS or IceCube).



Combination with Daya Bay

- Need a measurement of θ_{14} to compare with results in the LSND phase-space
- Preliminary result of the ongoing collaborative effort between MINOS+/MINOS and Daya Bay (with inclusion of Bugey-3 data)
- Significant increase in the constraint at $\Delta m^2_{41} > 10$ eV^2 due to two-detector fit method, as expected
- Final combination with a larger Daya Bay and MINOS+ data set is planned



Three Flavour Oscillations

- Updated measurement of Δm^2_{32} using new PDG value of θ_{13}
  - Also includes 48.67 kt-yrs of atmospheric neutrinos and the ν_e appearance sample

Normal Hierarchy

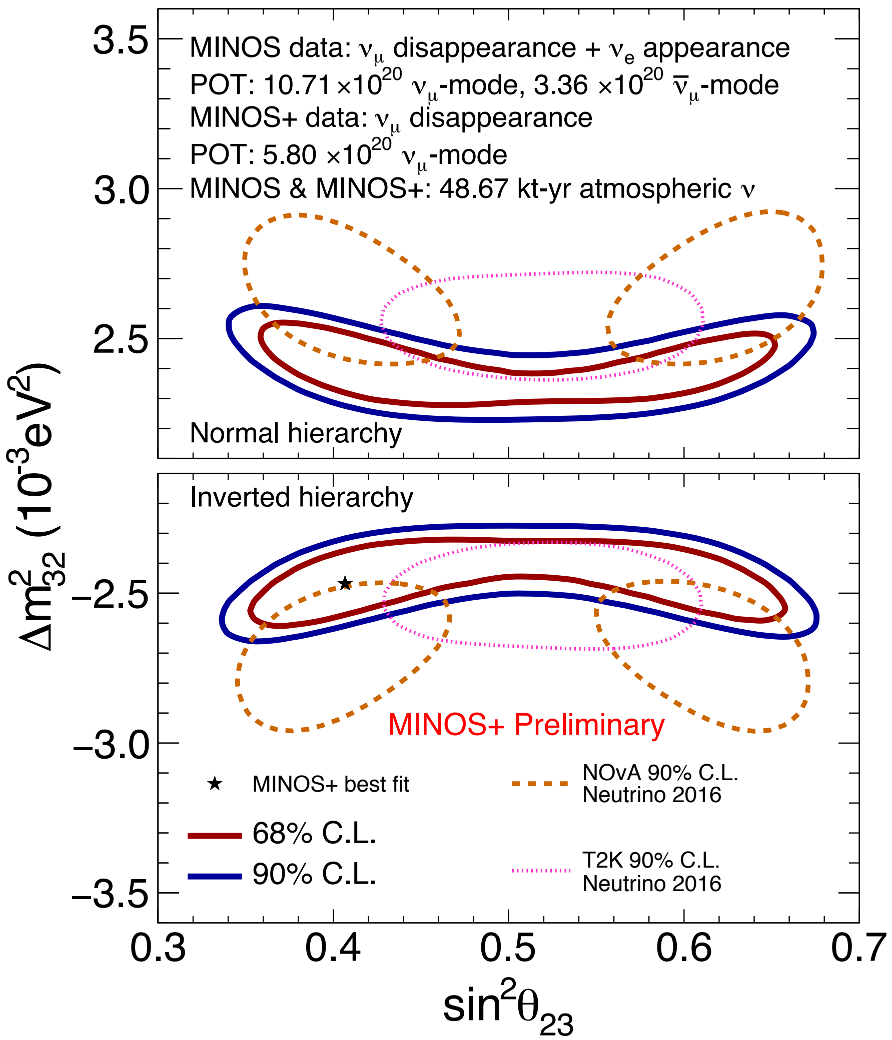
$$\Delta m^2_{32} = 2.42 \pm 0.09 \times 10^{-3}\ \mathrm{eV}^2\ (68\%\ \mathrm{C.L.})$$

$$\sin^2\theta_{23} = 0.35 - 0.65\ (90\%\ \mathrm{C.L.})$$

Inverted Hierarchy

$$\Delta m^2_{32} = -2.48^{+0.09}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2\ (68\%\ \mathrm{C.L.})$$

$$\sin^2\theta_{23} = 0.35 - 0.66\ (90\%\ \mathrm{C.L.})$$



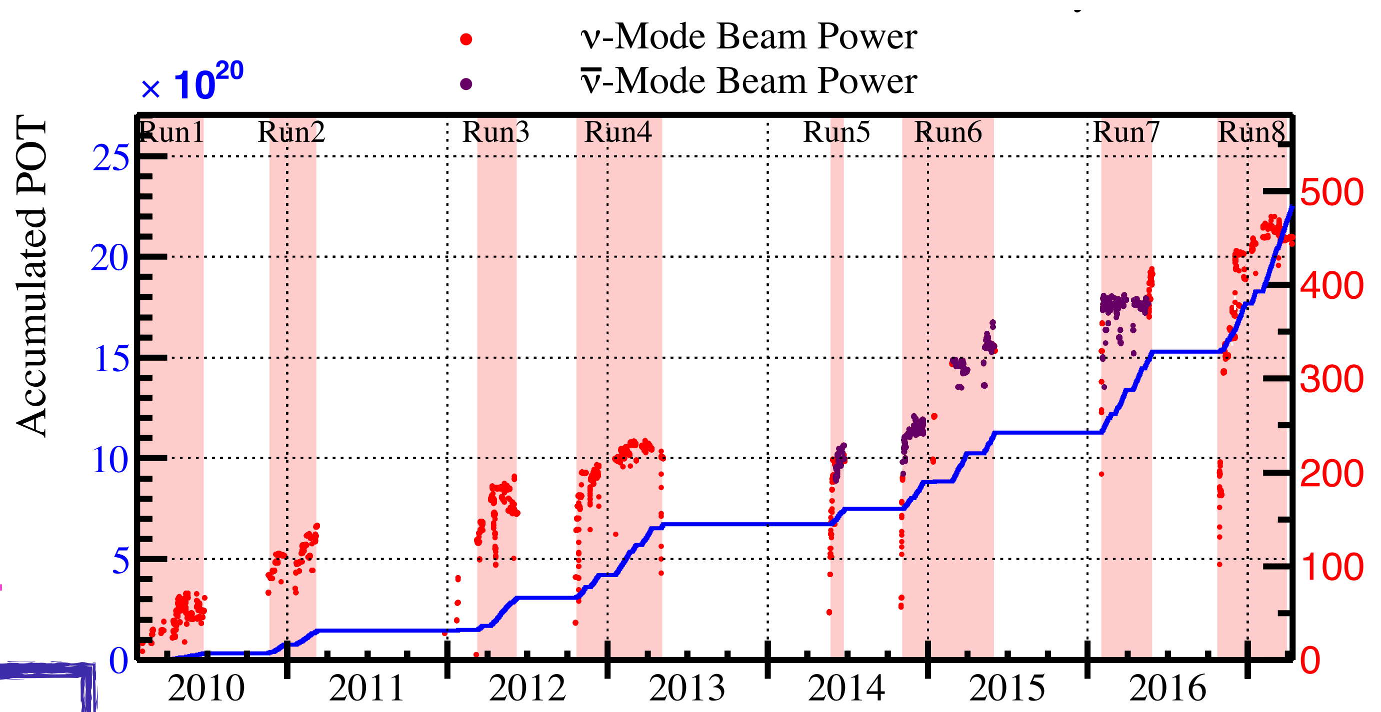
- Still to come: 50% MINOS+ beam data, 3 years of atmospherics

The T2K Experiment

- ~500 researchers, 63 institutes, 11 countries
- Muon (anti) neutrino beam generated at J-PARC and detected at Super-Kamiokande
- In 2013 T2K makes first discover of appearance: νμ→νe (Phys. Rev. Lett. 112, 061802 (2014))

JPARC Beam delivery & stability

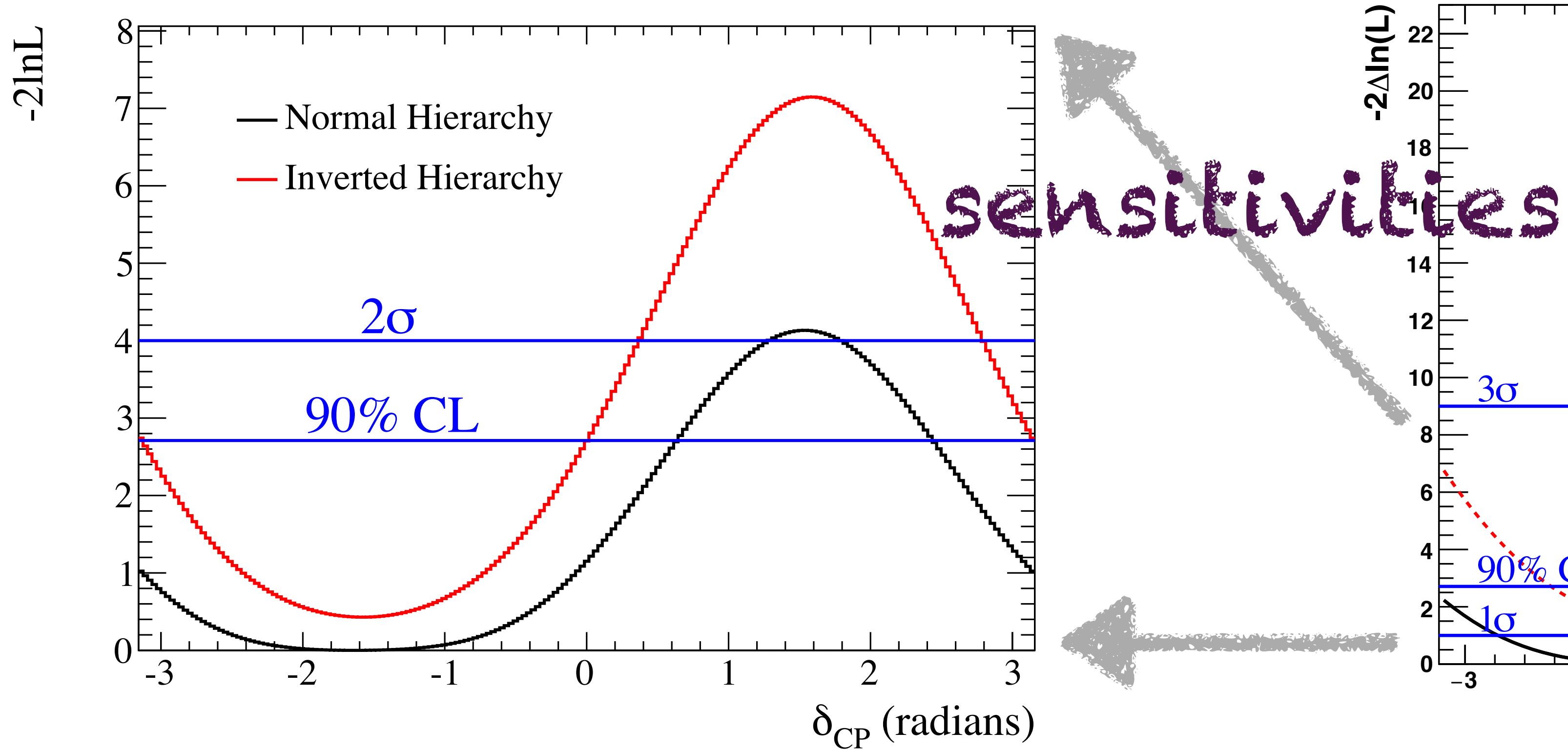
- Beam delivery until Apr 2017
  - 2.5×10^{21} POT TOTAL
  - 1.49×10^{21} POT in ν-mode
  - 0.76×10^{21} POT in $\bar{\nu}$-mode
- Beam operated stably at 470 kW
- Expect 0.8×10^{21} POT in 2017-18 data run
- Main Ring power supply upgrade approved by MEXT
- Will allow operation up to and beyond 750 kW in 2019

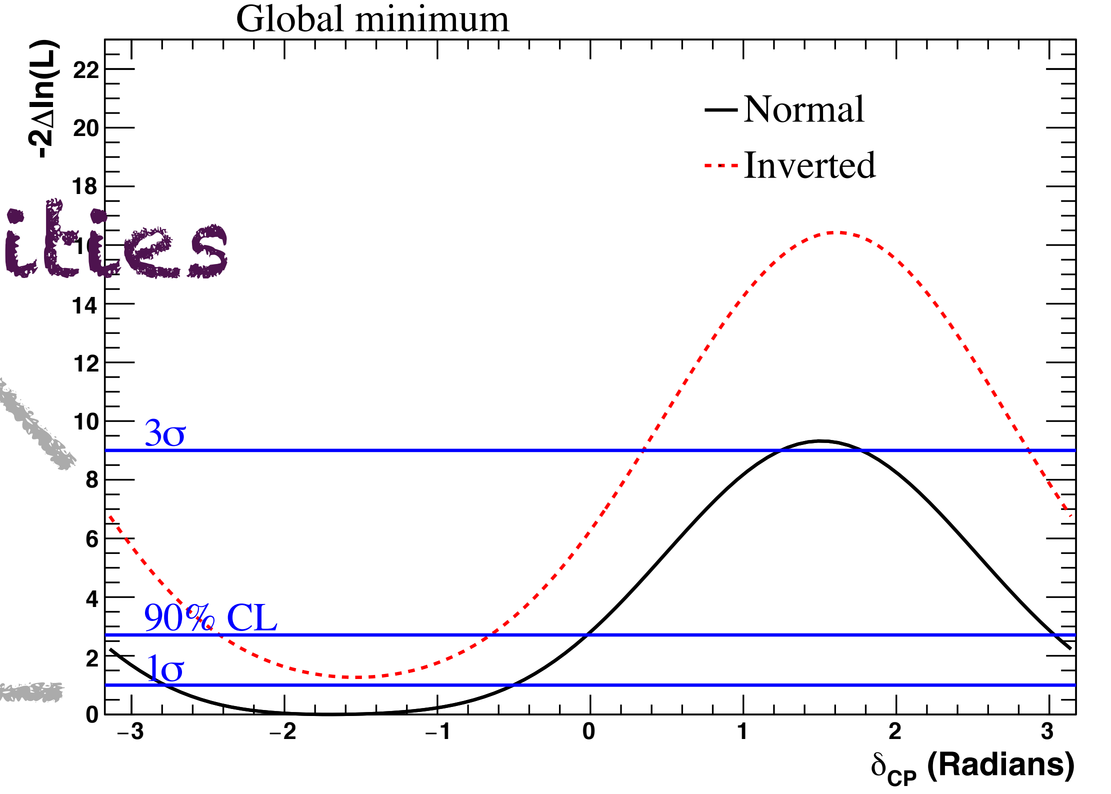


IMPORTANT!!

SK reconstruction improvements

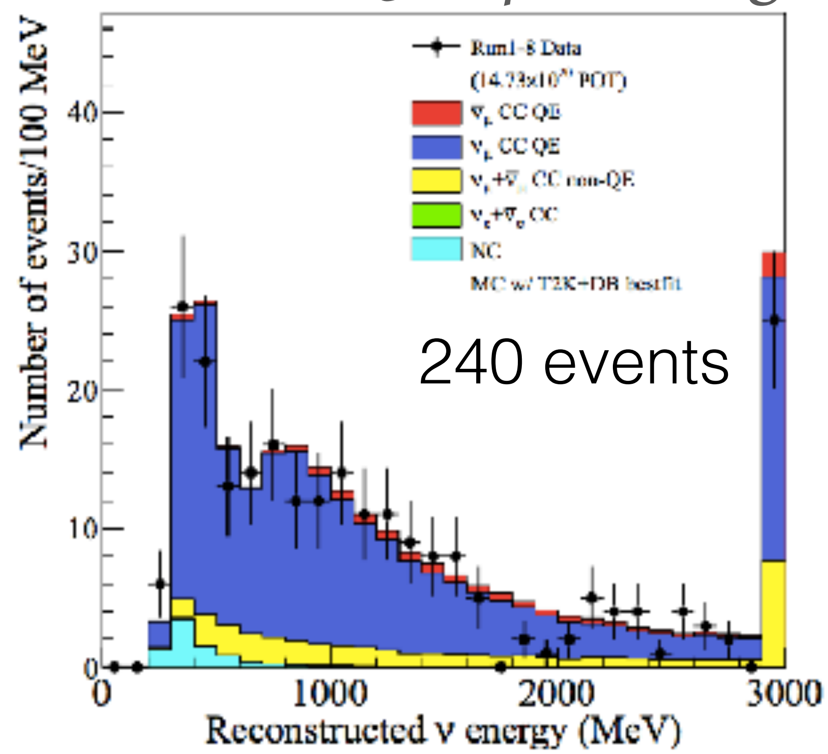
- Super-K event reconstruction updated to use charge and time likelihood
  - fiTQun previously used in T2K analyses for the rejection of π^0 from electron neutrino candidates
- Nearly twice the neutrino mode statistics
  - More running in neutrino mode in 2016/17
  - Expansion of SK fiducial volume increases SK statistics by ~20%
- CC1π data sample added to oscillation analysis
  - increases neutrino mode statistics by another ~10%



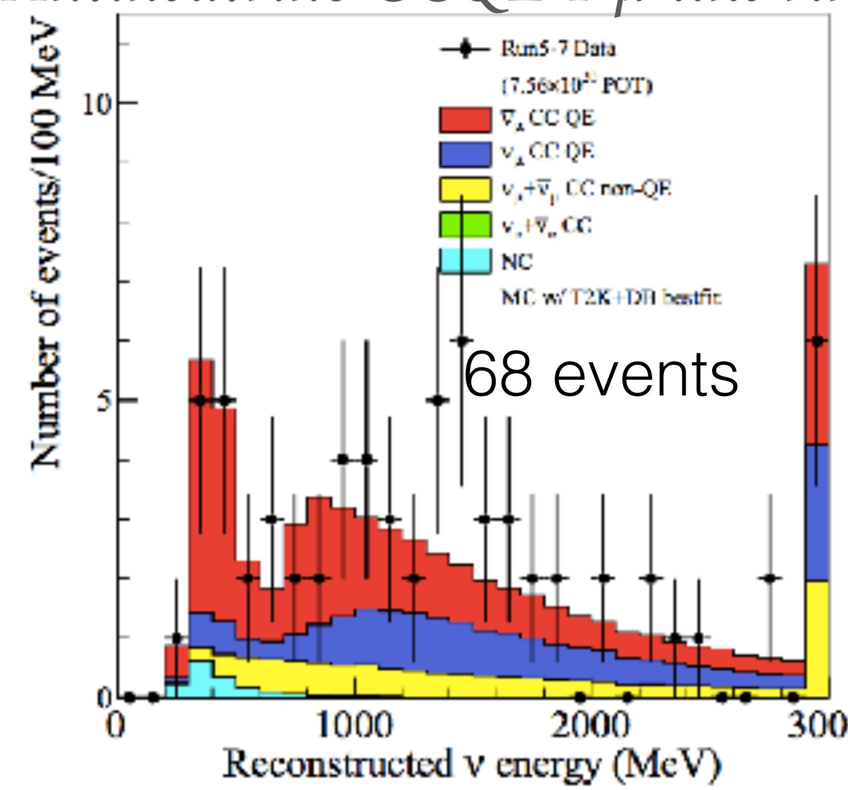


Observed SK Spectra

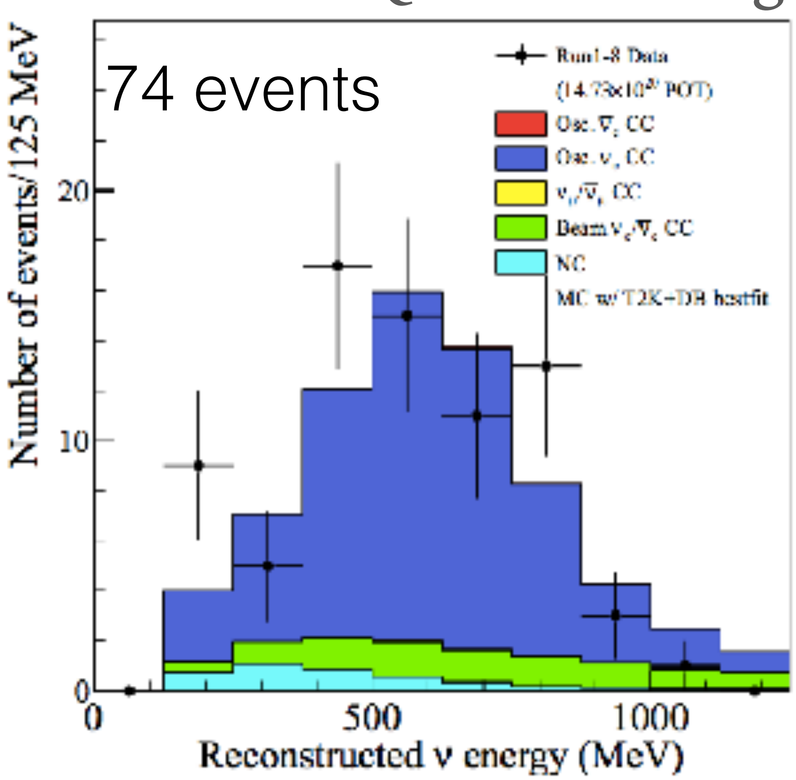
Neutrino CCQE 1 μ-like ring



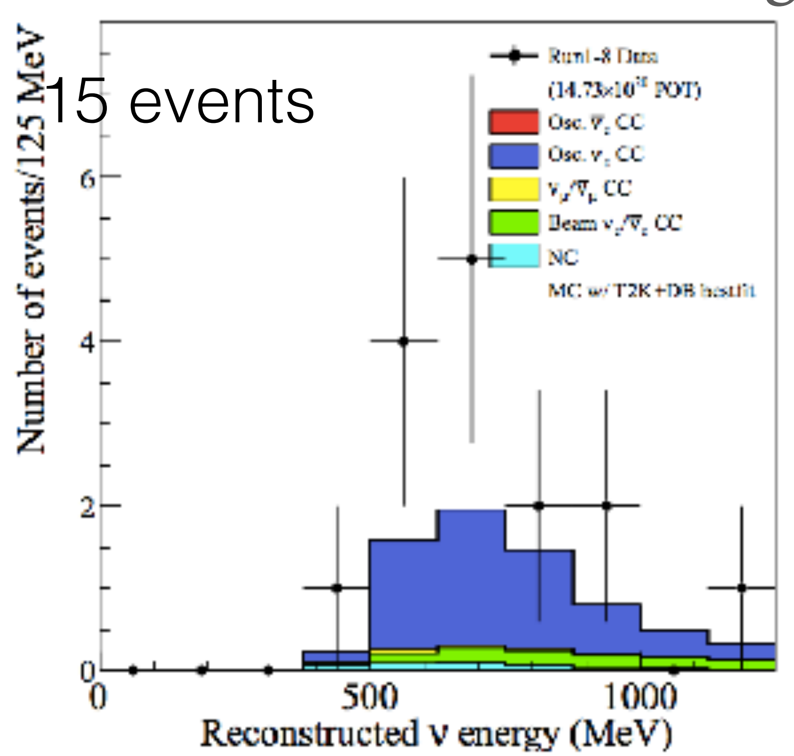
Antineutrino CCQE 1 μ-like ring



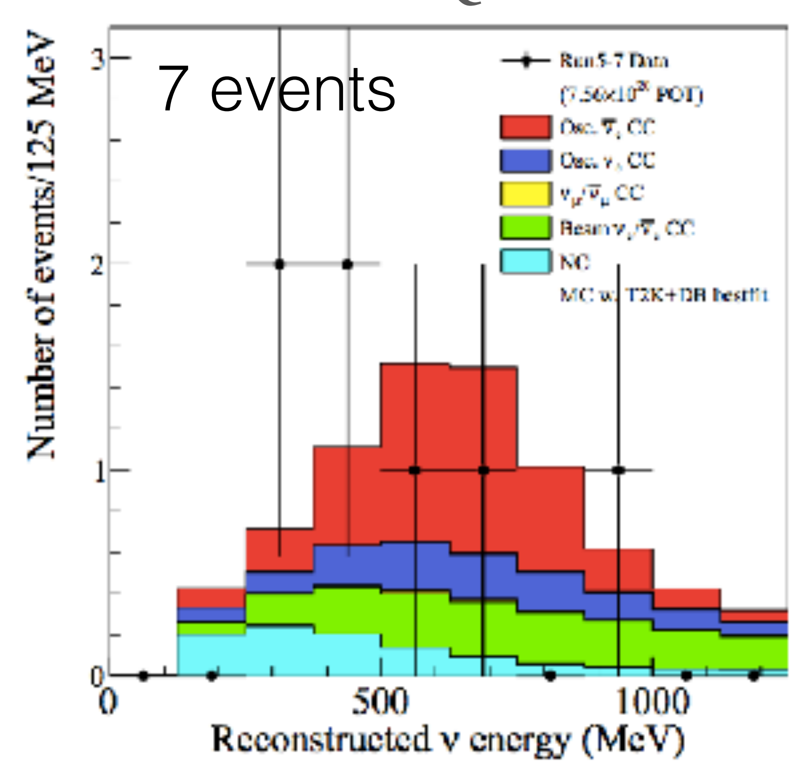
Neutrino CCQE 1 e-like ring



Neutrino CC1π 1e-like ring



Antineutrino CCQE 1e-like ring



T2K new results

- Fit without the reactor constraint has closed contours in δ_{cp} at 90% CL for both hierarchies

- The T2K value for $\sin^2\theta_{13}$ is consistent with the PDG 2016 average:

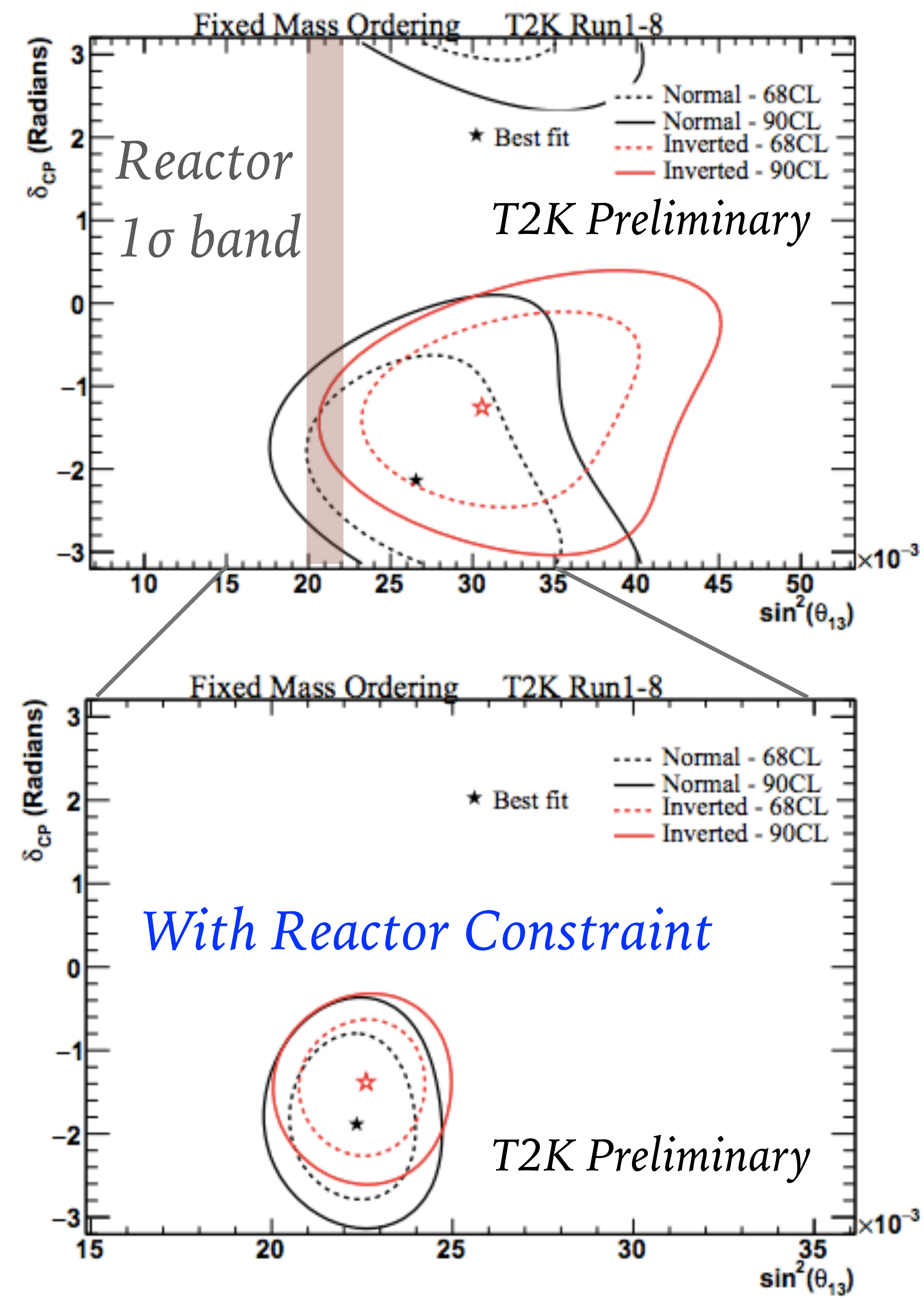
T2K Best Fit:

$$\sin^2\theta_{13}=0.0277^{+0.0054}_{-0.0047}\ \text{(NH)}$$

PDG 2016:

$$\sin^2\theta_{13}=0.0210\pm0.0011$$

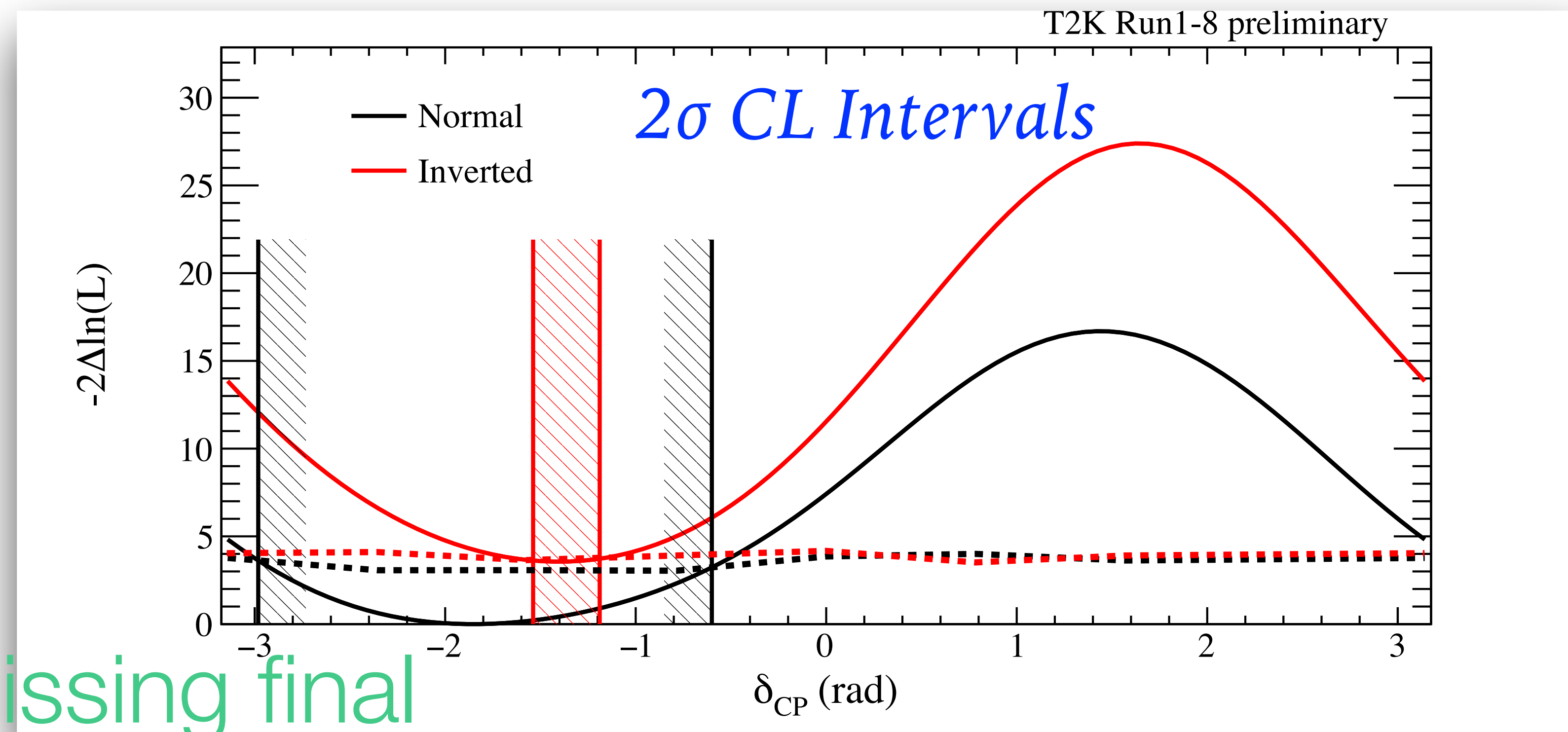
- Adding the reactor constraint improves the constraint on δ_{cp}



T2K CONSTRAINT ON δ_{cp}

- To determine δ_{cp} intervals, produce the 1-D **Δ[-2ln(L_{marg})]** curves relative to the global minimum in the two hierarchies

- Critical **Δ[-2ln(L_{marg})]** values using the Feldman-Cousins prescription



missing final systematic

- The 2σ confidence interval is:

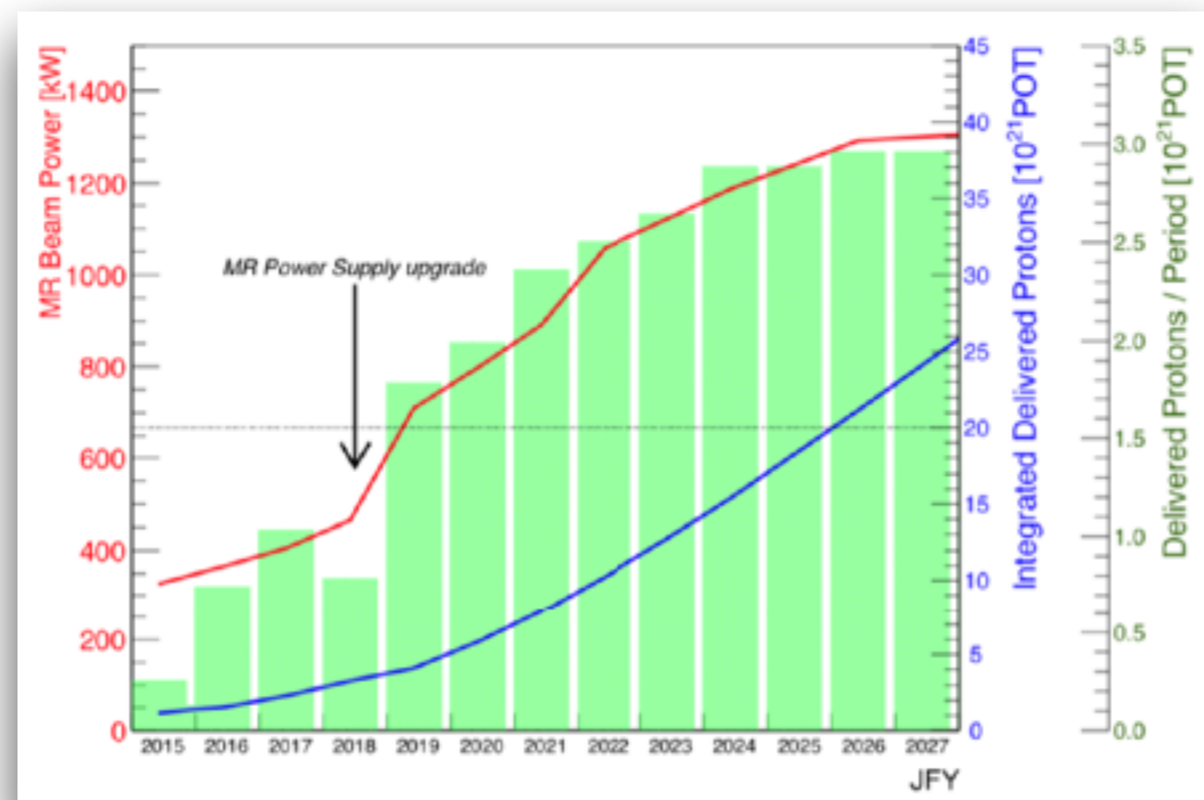
Normal hierarchy: [-2.98, -0.60] radians

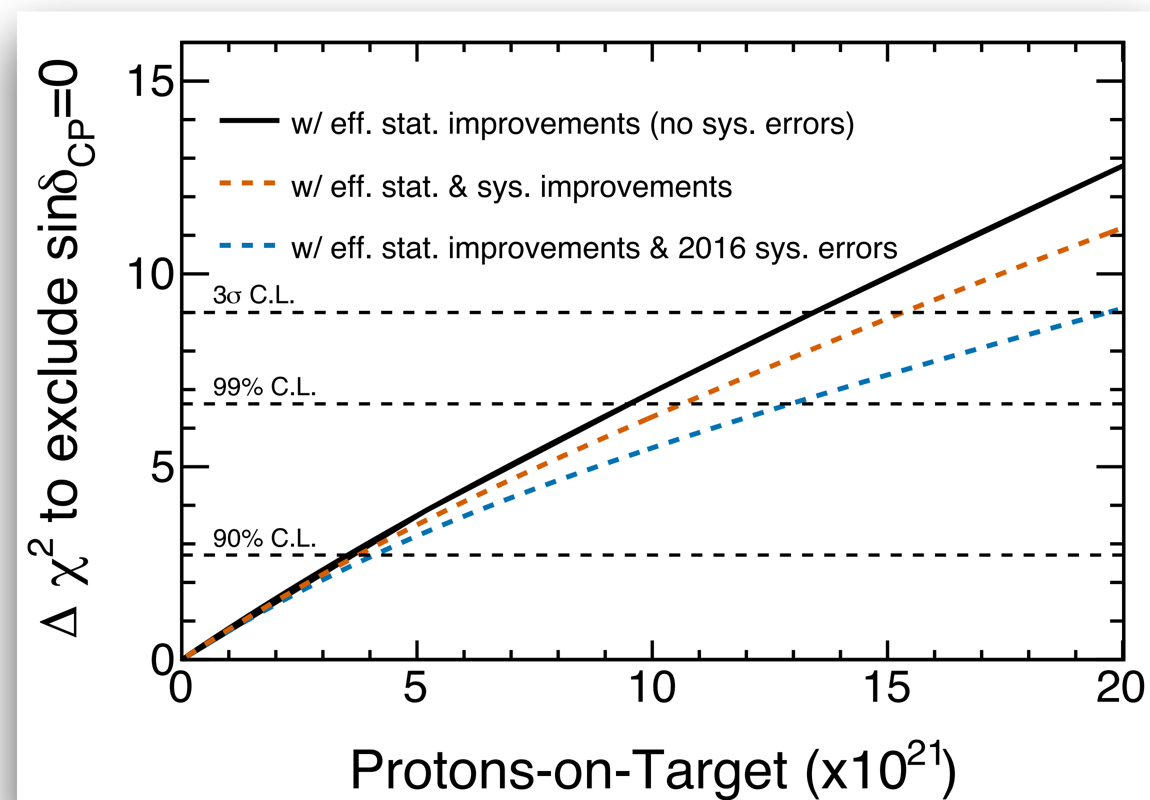
Inverted hierarchy: [-1.54, -1.19] radians

CP conserving values (0,π) fall outside of the 2σ intervals!

T2K run extension

- T2K's long term goal is the pursuit CP Violation in the neutrino sector.
- In 2016, T2K run extension given Stage-1 status by KEK/J-PARC.
- Proposal to collect 20×10^{21} POT by ~**2025** (arXiv:1609.04111 [hep-ex]).
- With 20×10^{21} POT, T2K has up to 3σ CPV sensitivity:
  - ➡ Sensitivity improves beyond 3σ with reduced systematic errors;
  - ➡ Beam, ND upgrades motivated by systematic error goals.



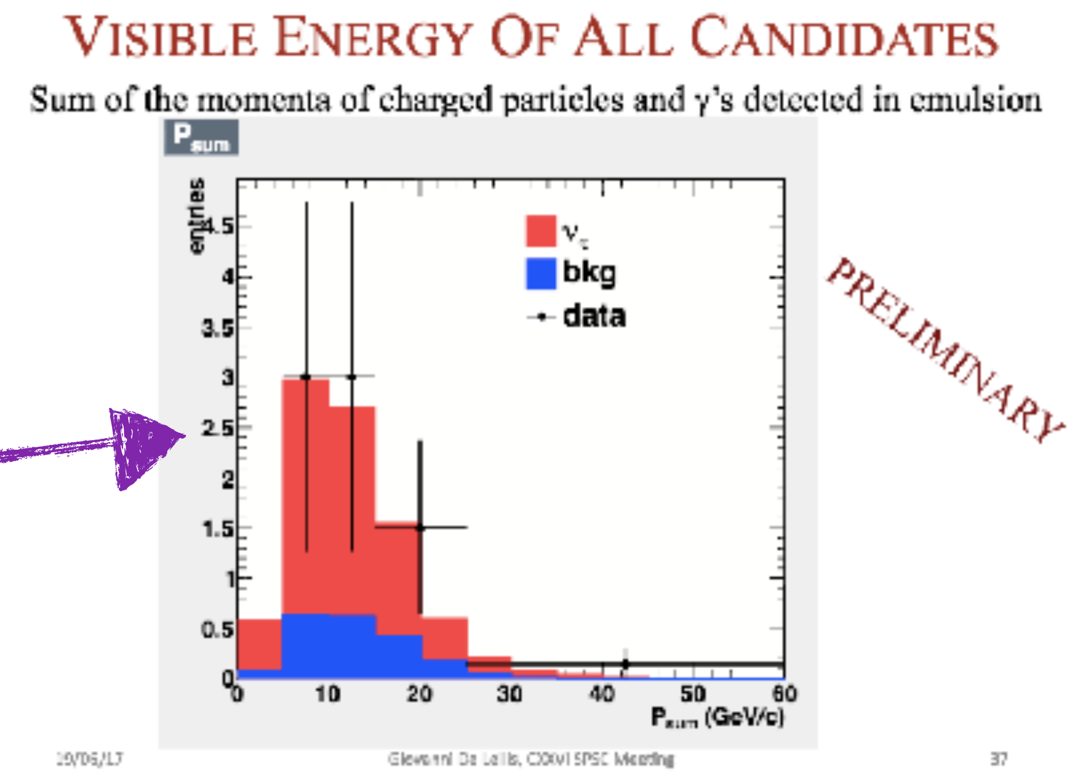


Pause

- ✦ Its exciting.
- ✦ A moment to summarise the excitement
  - ➡ δ_{cp} not zero at 90% C.L.
  - ➡ NOVA rule out maximal mixing at 2.6σ
  - ➡ no sign of sterile neutrinos

OPERA (Cern to Gran Sasso)

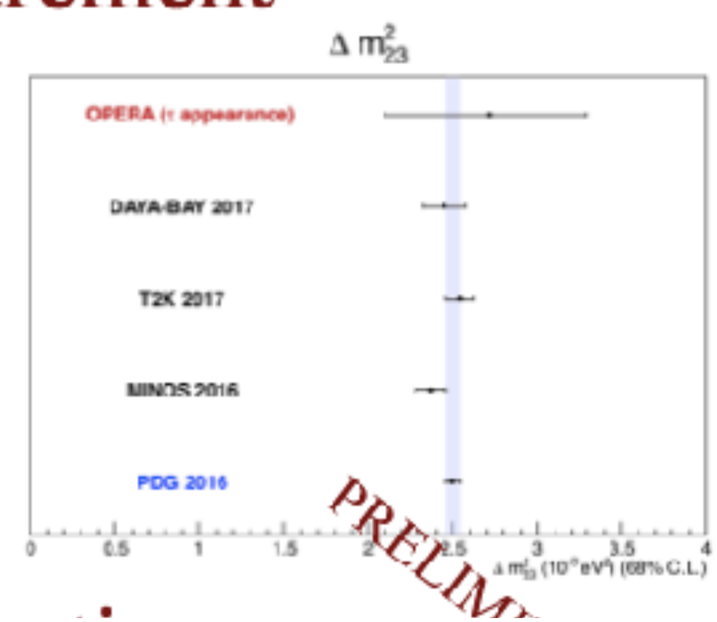
- Opera have been continuing to mine their data since shutdown in 2012
  - loosened cuts increase tau data sample from 5 to 10 events
  - 5.2σ significance of appearance
  - first measurement of Δm^2_{23} using appeared taus!



Δm² measurement

$$N_{\nu_\tau} \propto P(\nu_\mu \to \nu_\tau)\sigma_{\nu_\tau}$$

Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} (10^{-3} eV^2)
6.8	2.0	10	2.7 ± 0.6 68% C.L



Something New and Risky

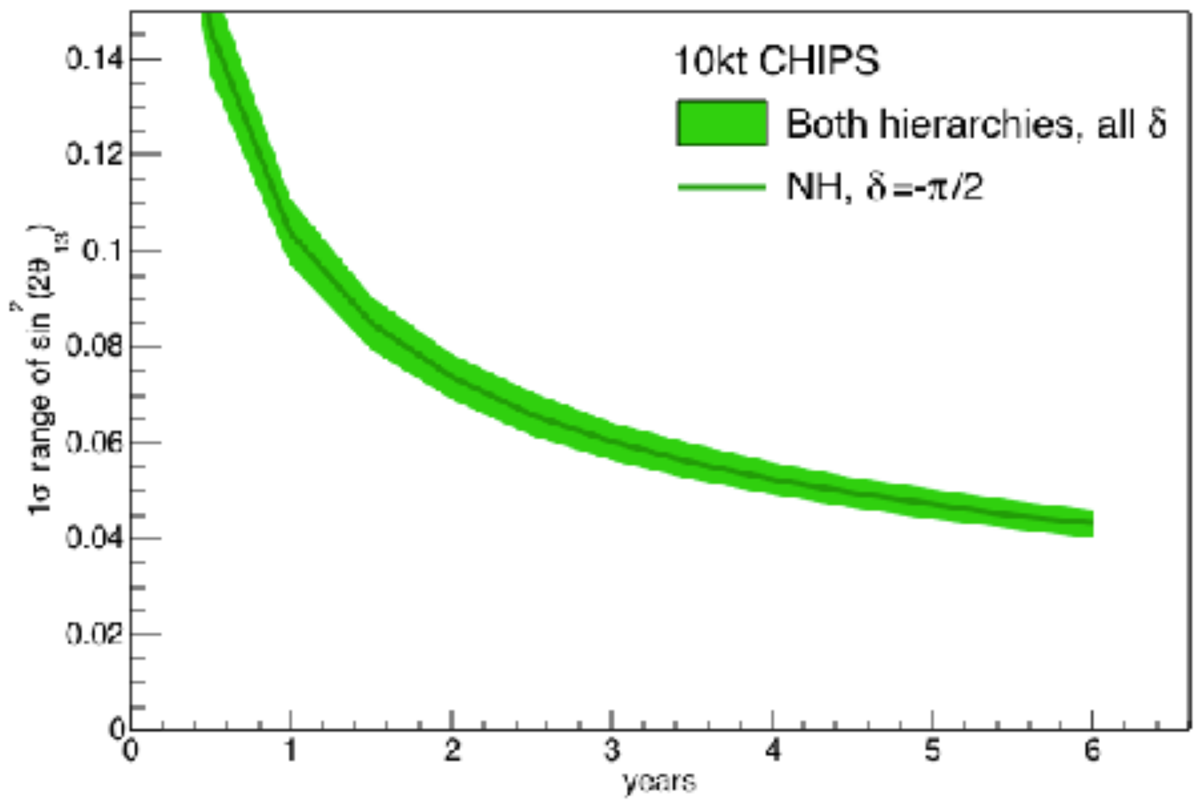
CHIPS

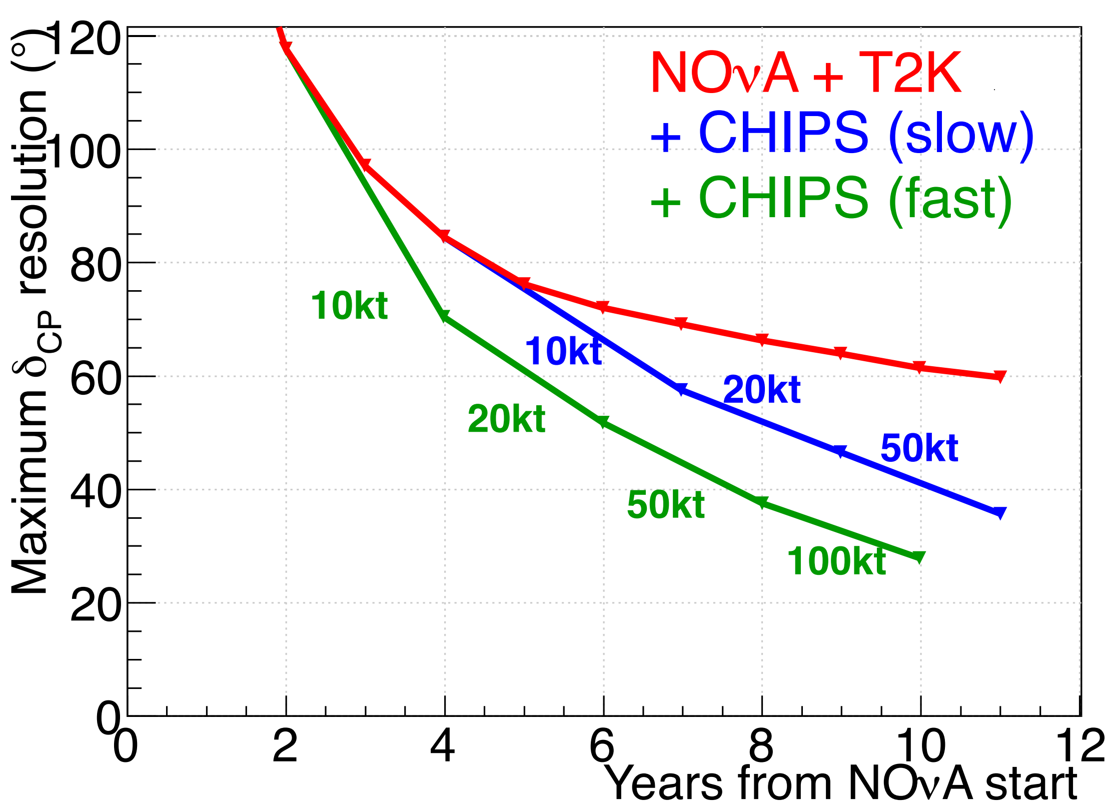
CHIPS : Cherenkov Detectors in Mine PitS

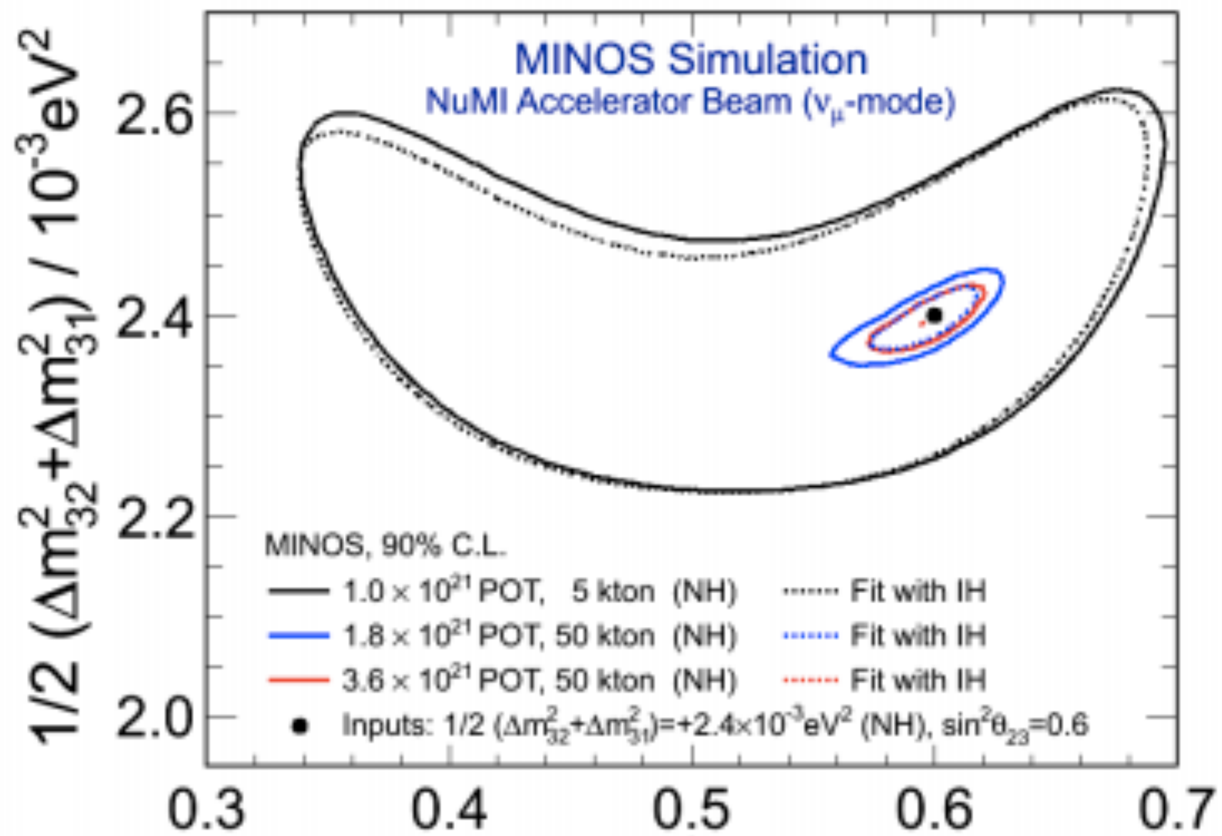
- The CHIPS goal is to prove that a water Cherenkov detector can do oscillation physics for a fraction of the cost of present neutrino detectors, and also to contribute to constraining δ_{CP} using NuMI neutrinos in the short term
  - to \$200k/kt (presently \$2-10M/kt water, \$10-20M/kt Liquid Ar
  - These prices include location/infrastructure etc
- CHIPS will be submerged in a flooded mine pit in the path of the NuMI beam

CHIPS Physics Goals

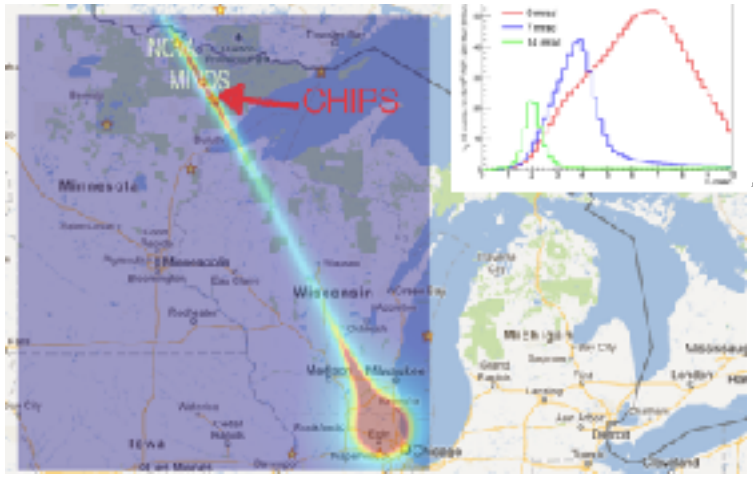
- Improve global knowledge
  - Measurement of θ_{13}
  - Measurement of θ_{23}
  - Contribution to δ_{cp} knowledge
- These plots assume old SK like reconstruction ability..
  - Key will be to grow beyond 5kt!
  - If proof-of-principle succeeds, this may be possible

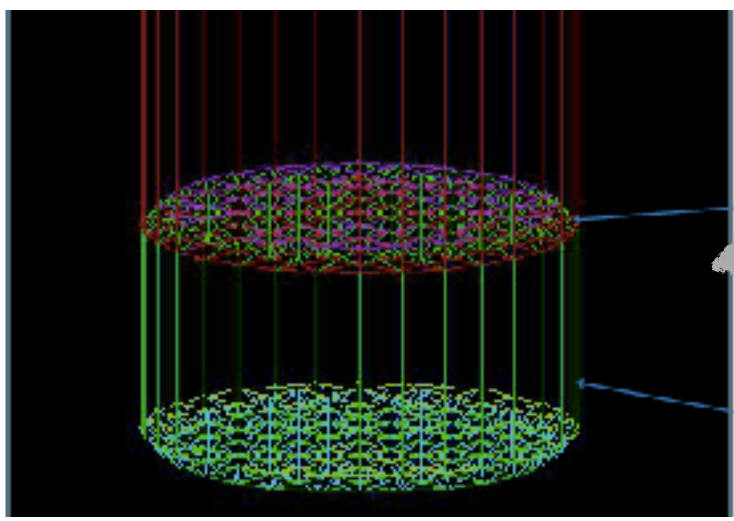


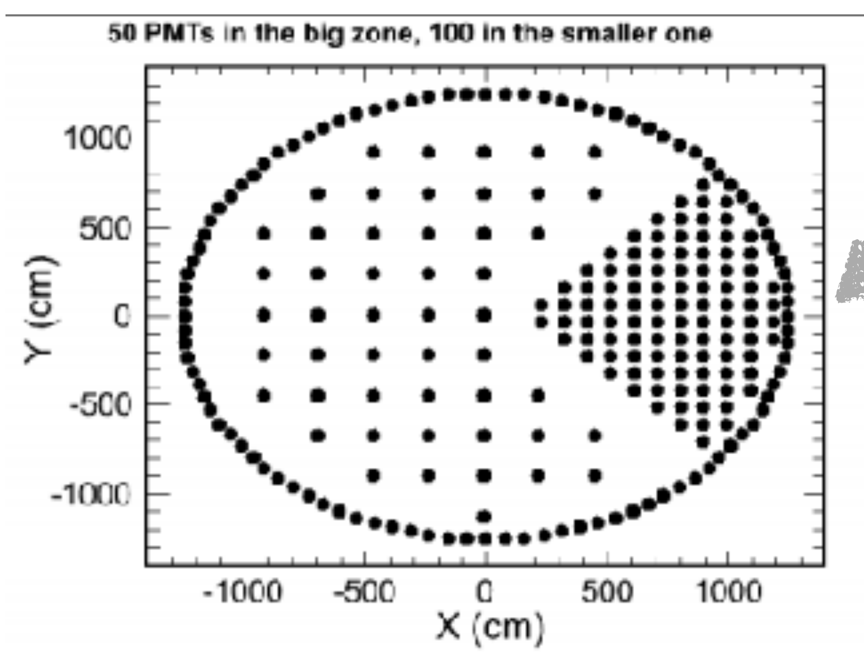




5 Steps to (cheap as) CHIPS

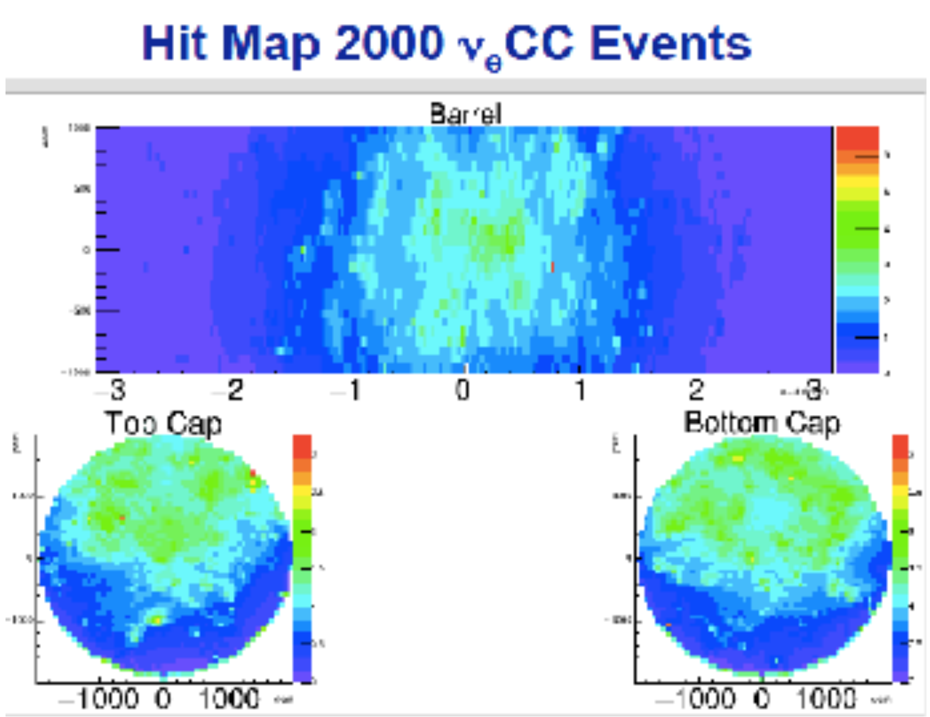




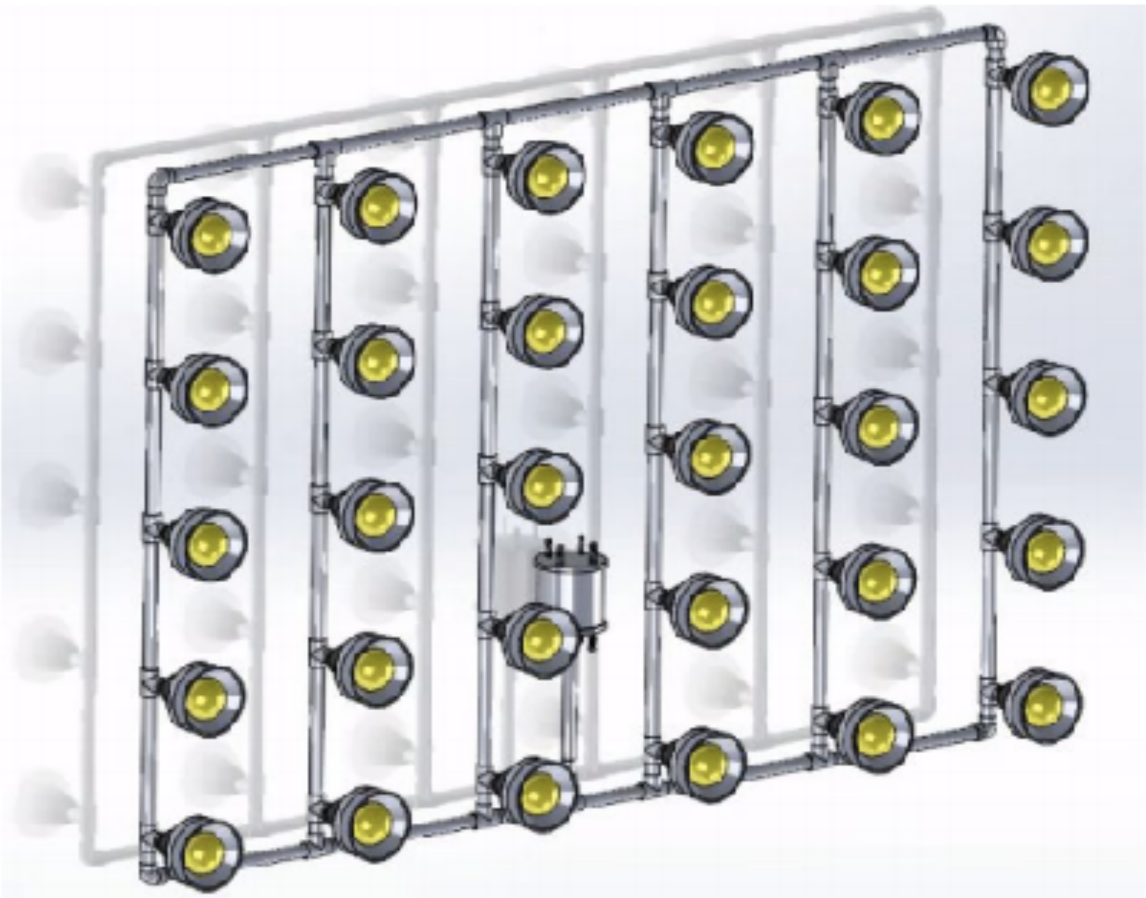


1) **Location**
   sunk in a flooded mine pit in the path of the NuMI neutrino beam, will make use of the water for cosmic overburden and mechanical support;
2) **Structure design**
   will allow it to grow in size with time but with no financial penalty beyond the instrumentation costs
3) **PMT choice and layout**
   3" PMT's good position and time resolution and beam optimized layout
4) **Electronics**
   will make use of ubiquitous mobile phone and communications technology and already developed KM3Net Solutions
5) **Simple water purification plant**
   will use straightforward filtering to maintain water clarity.

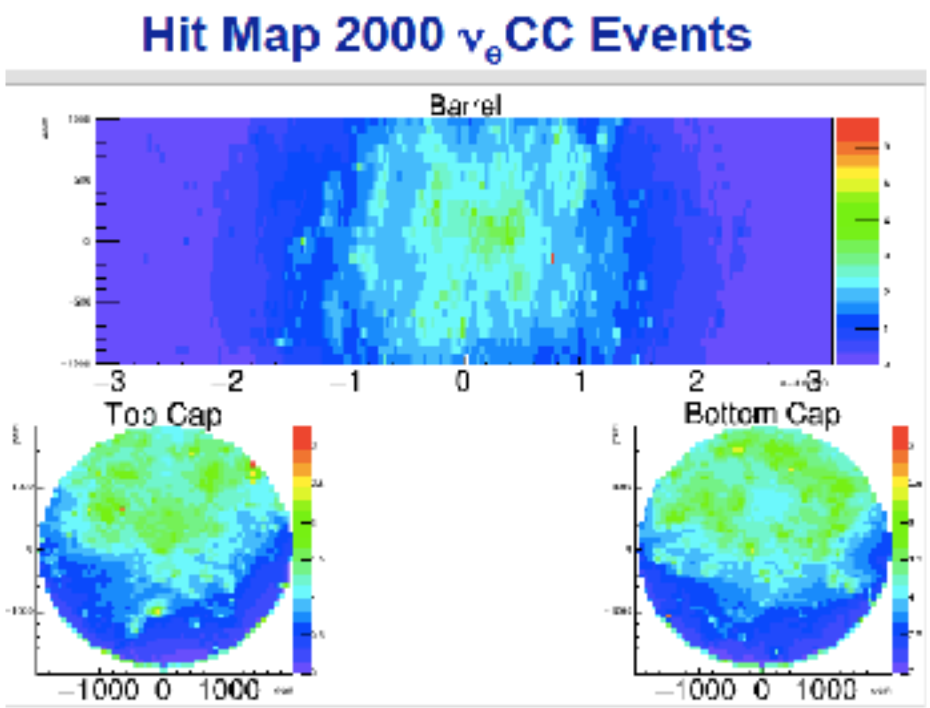
CHIPS detector planes



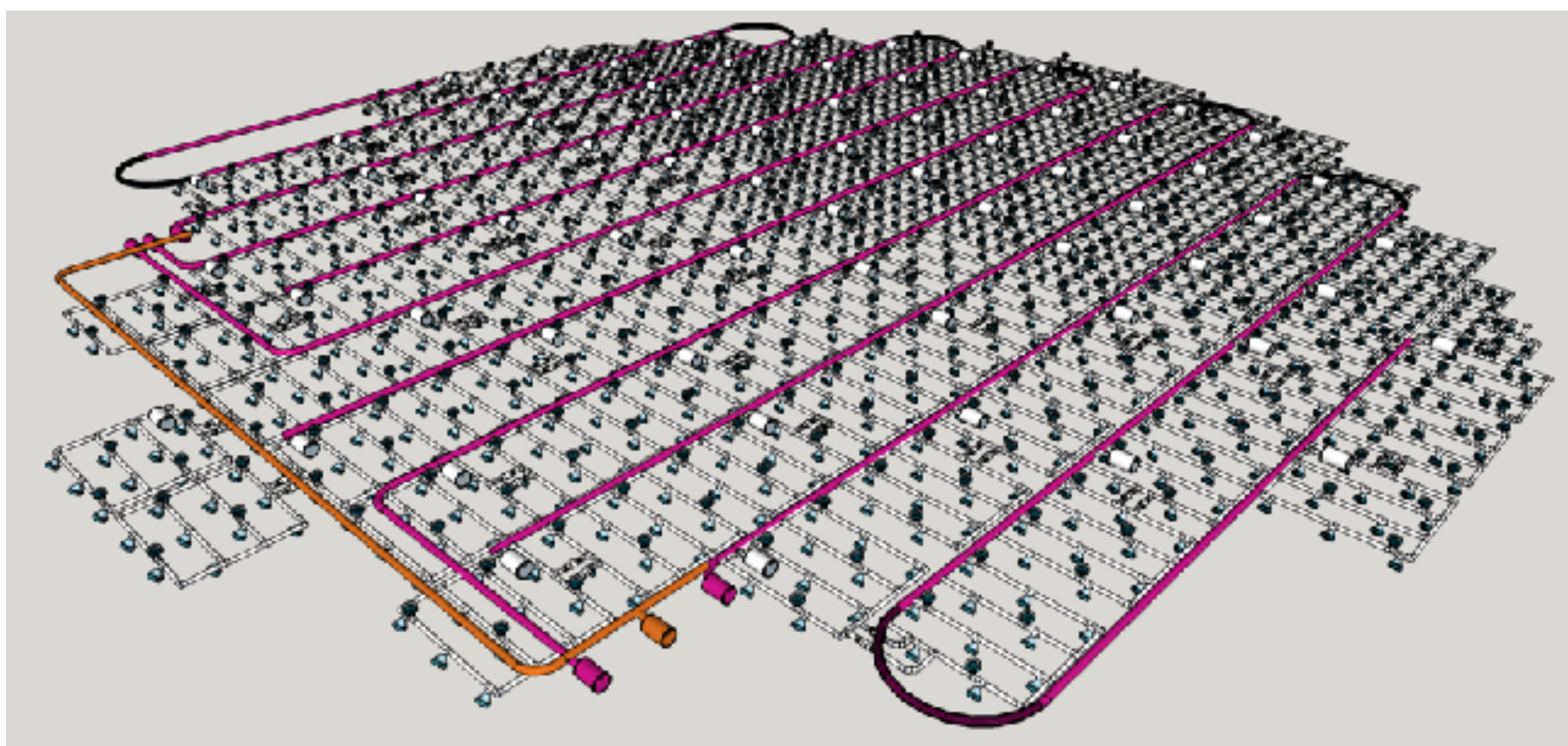
- CHIPS-M design will be carried forward
- Layout will involve high and low density planes
- A big part of the instrumentation will just implement KM3Net technology
  - New 3″ PMTs at 6% coverage in front and end caps, and 4% coverage back end cap region
- Low density wall planes will be made with NEMO-III 3″ PMTs and Madison electronics.
  - Old 3″ PMTs at 4% coverage in back



CHIPS detector planes

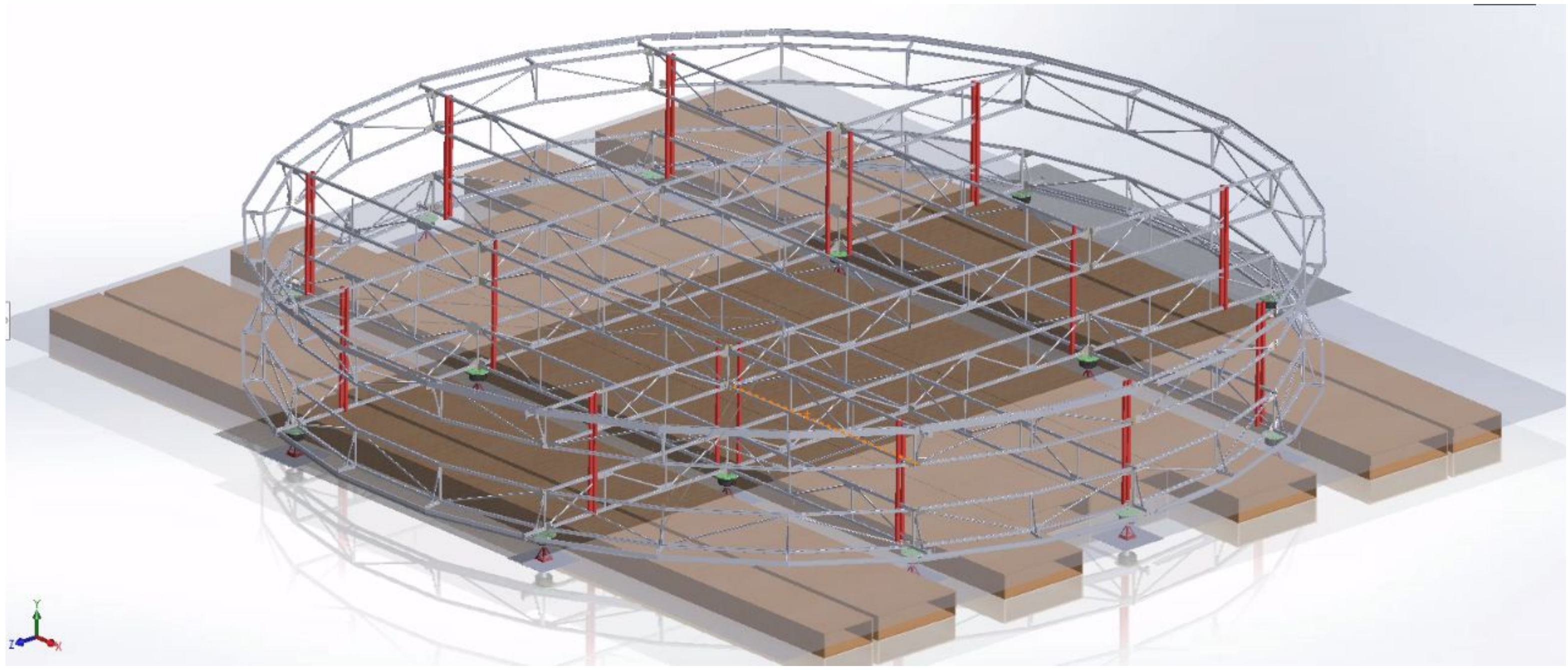


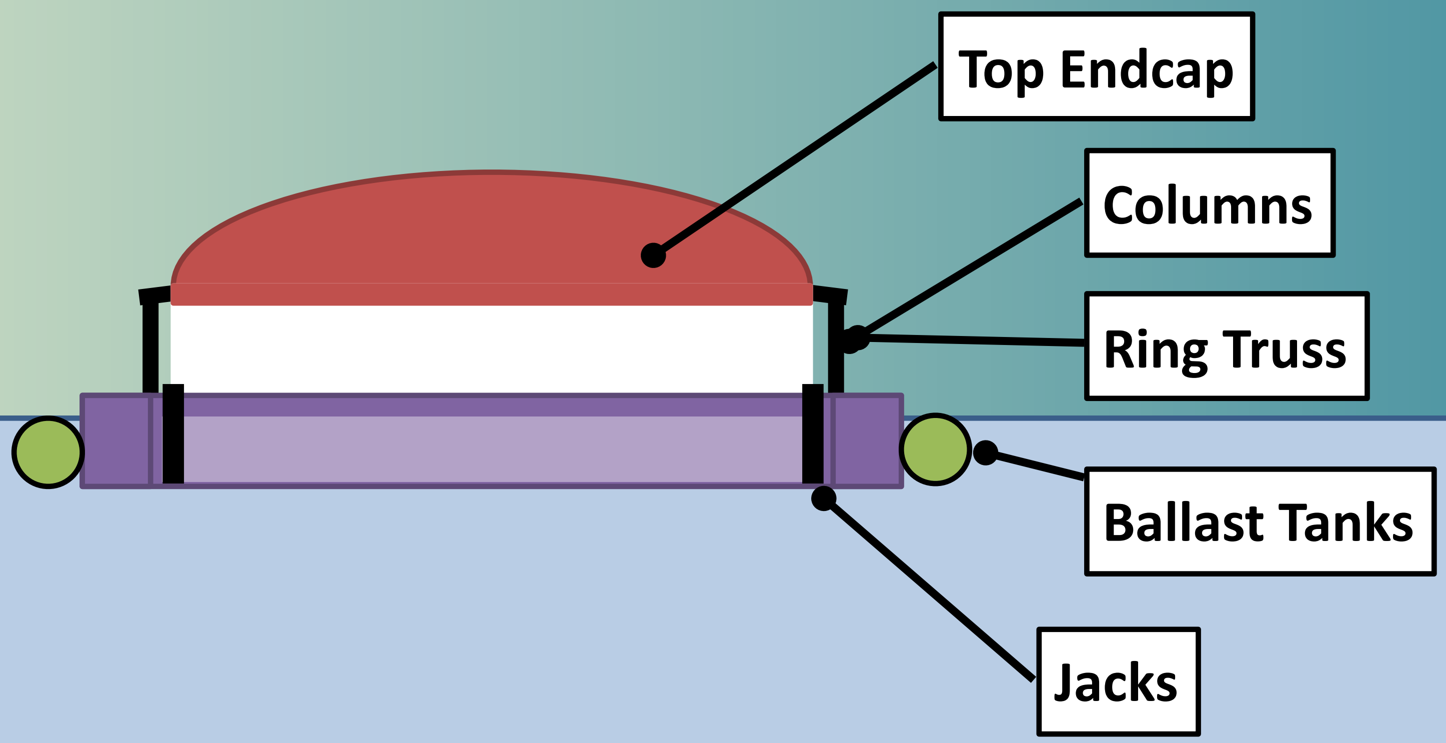
- CHIPS-M design will be carried forward
- Layout will involve high and low density planes
- A big part of the instrumentation will just implement KM3Net technology
  - New 3" PMTs at 4% coverage in front and end caps, and 3% coverage back end cap region
- Low density wall planes will be made with NEMO-III 3" PMTs and Madison electronics.
  - Old 3" PMTs at 2% coverage in back



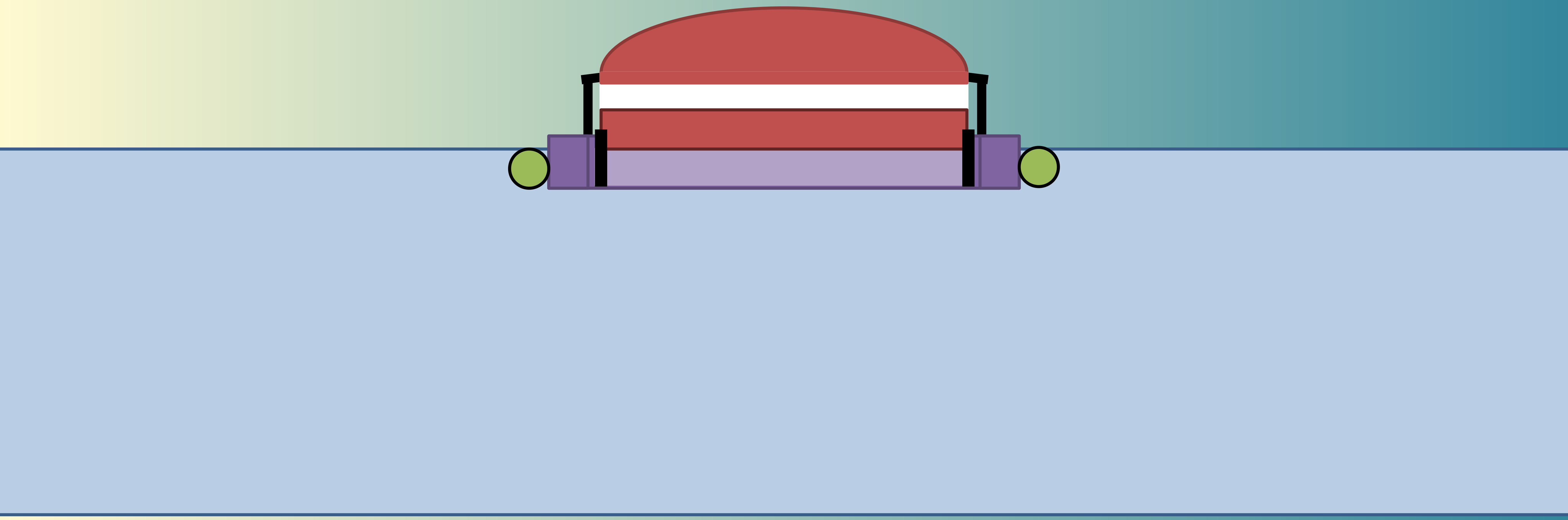
CHIPS Deployment

Coffer Dam technology can prepare area for building



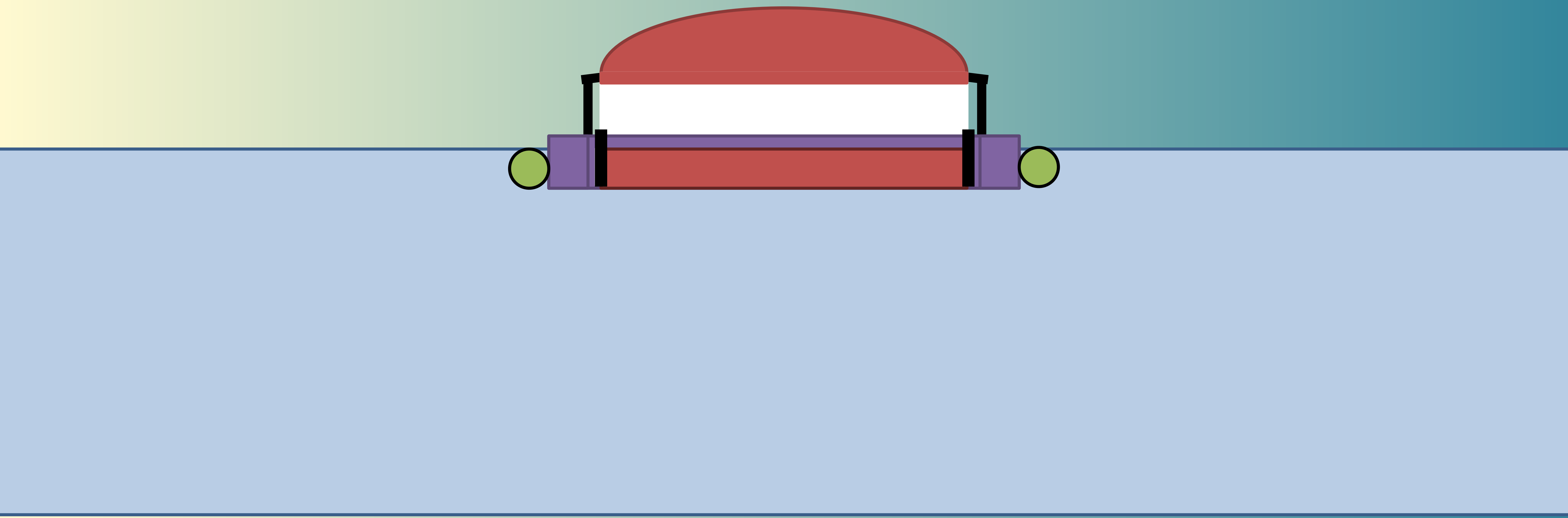


- Domed roof self-supporting in air
- Supported by circumferential columns
- Columns supported by floating ring truss equipped with ballast tanks
- Entire assembly built next to shore with crane support
- Floating ring truss provides work surface
- Temporary curtain around circumference to keep inside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



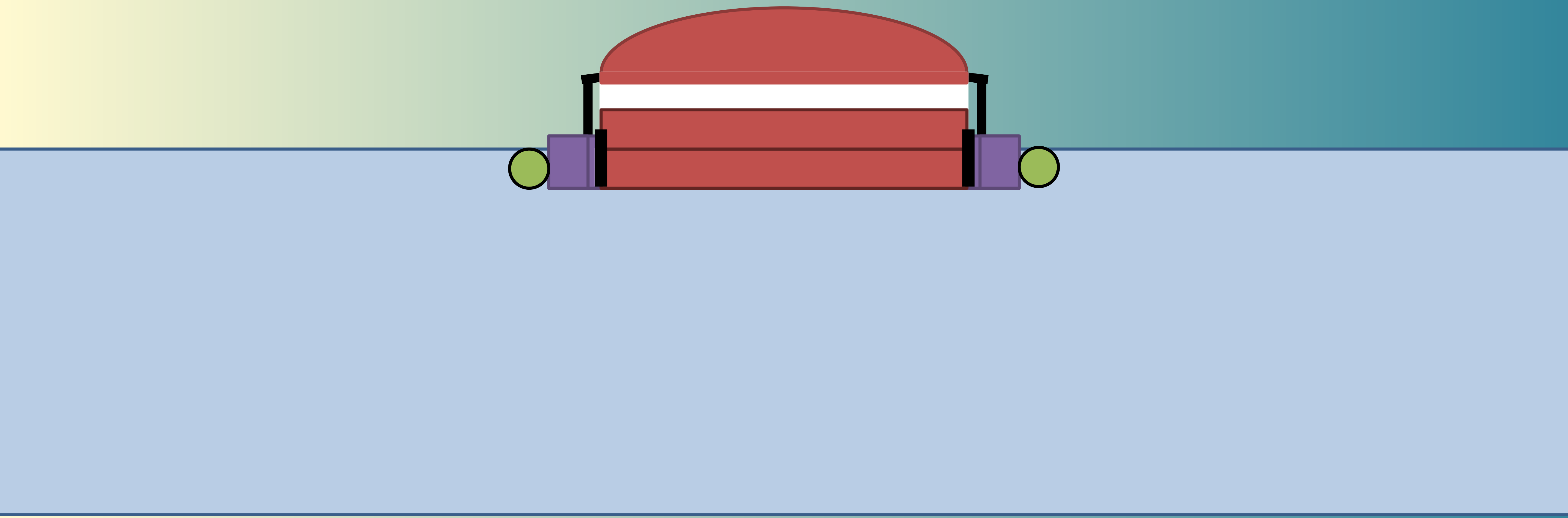
Assembly sequence on water

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



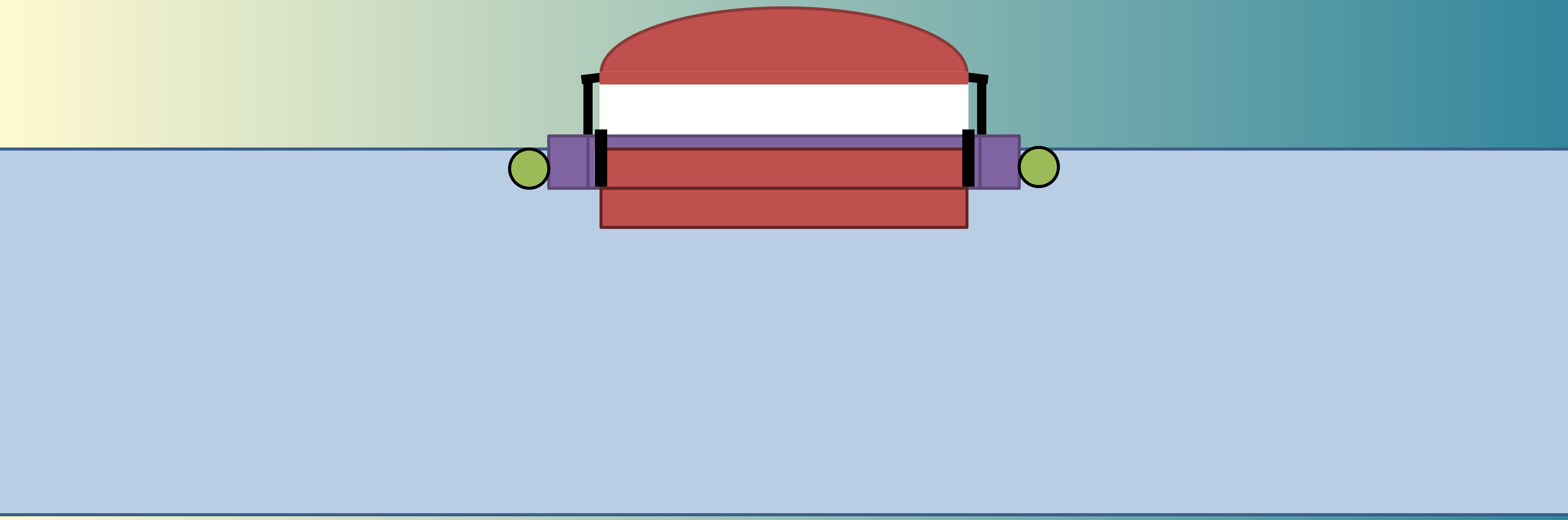
Assembly sequence on water

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.



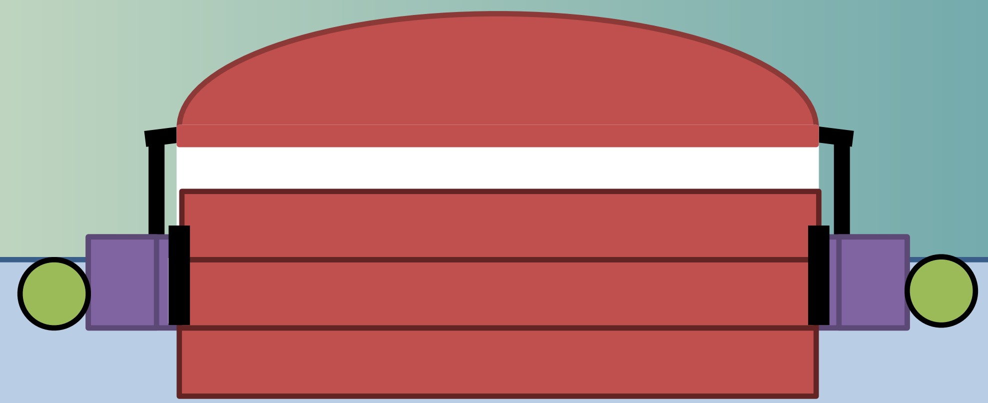
Assembly sequence on water

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.



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.



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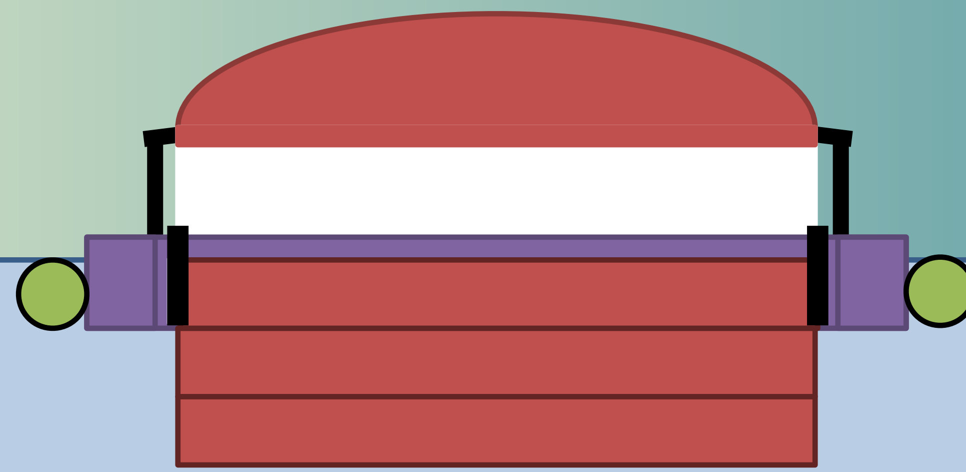

Similar to how a tower crane assembles itself

Assembly sequence on water

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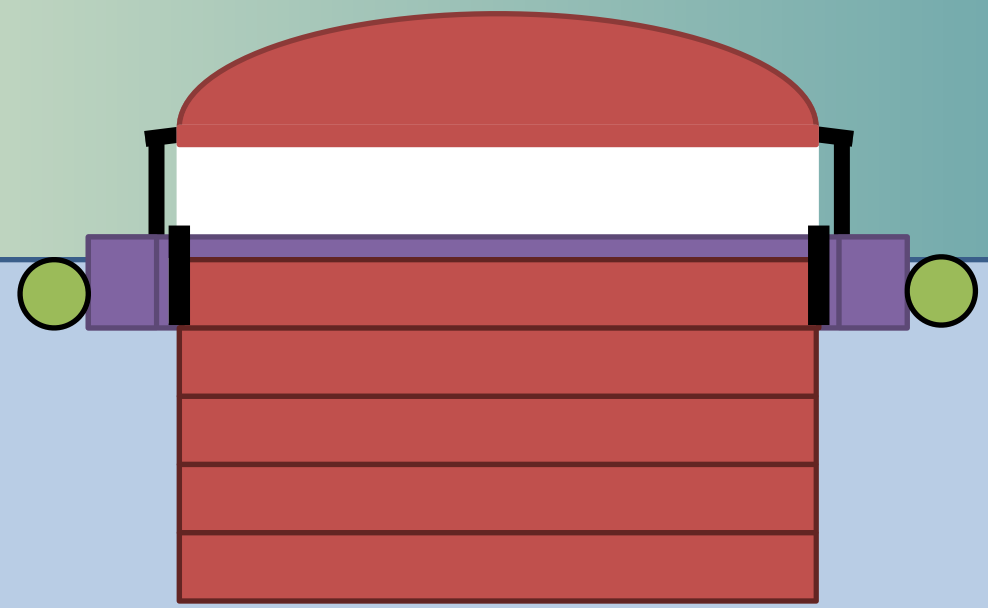

Assembly sequence on water

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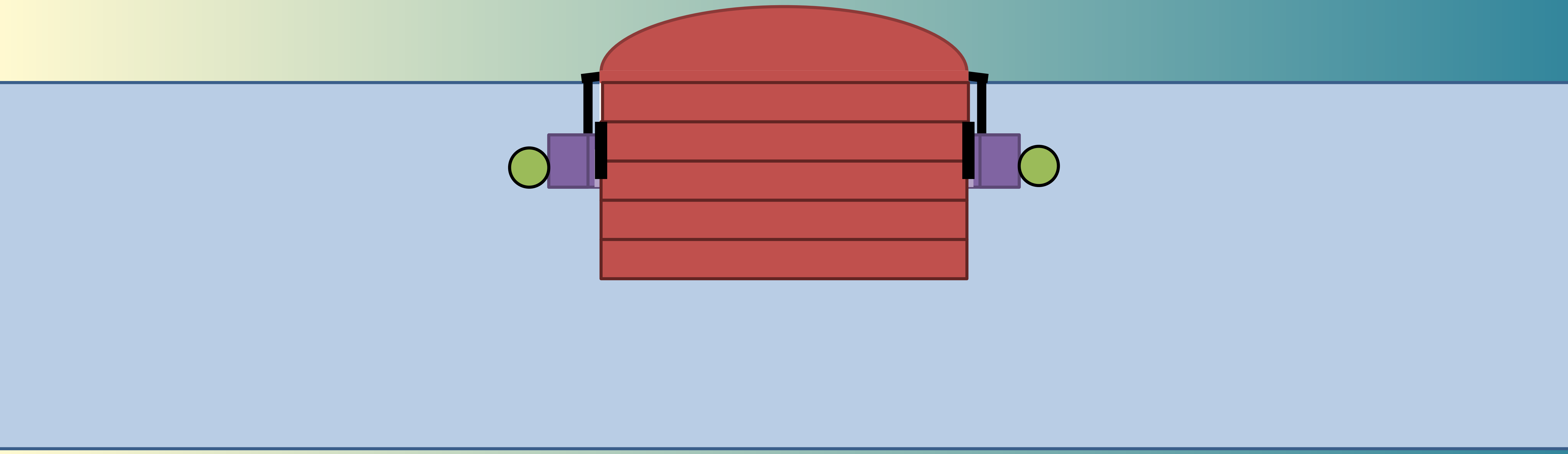
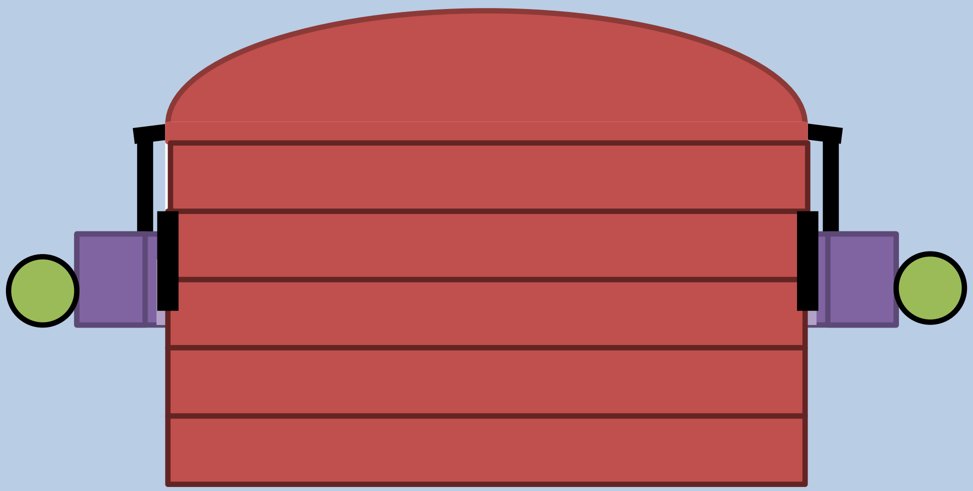


Assembly sequence on water

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.



(Lowering)

Additional comments

- The ring truss may also be used for rigging and mooring.

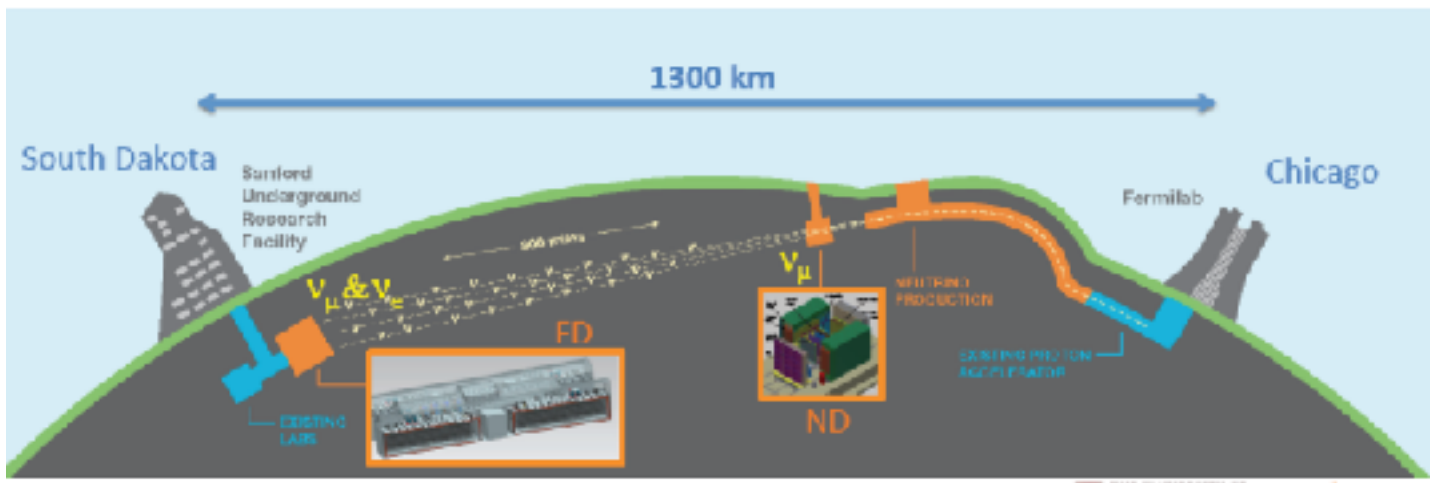
CHIPS schedule

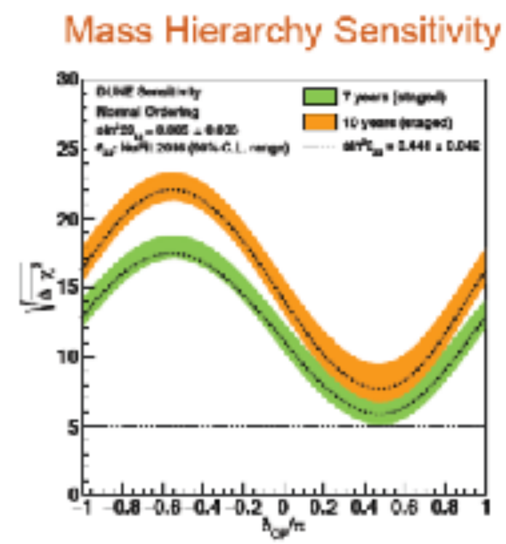
- Detector plane factories being set up now in Madison and Minneapolis
- 5 kilotons will be deployed next summer (2018)
- Hopefully data taking will start before end of 2018
- If successful,
  - we could expand the detector for $200k/kiloton in NuMI
  - we could propose a new larger detector for deployment in LBNE
    - If the PMTs don't get flooded :-)…

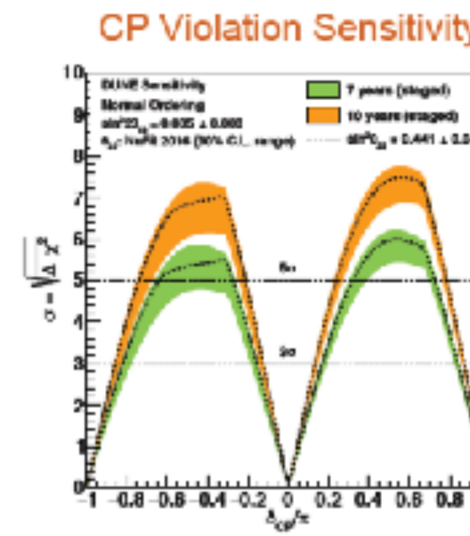
Plans for further future : advert for Saturday

✦DUNE in the US

- ➡ 1.2MW from day 1
- ➡ 4x17kton LAr detectors, fiducial pass > 40kt







✦Hyper-K in Japan

✓ Gigantic neutrino and nucleon decay detector

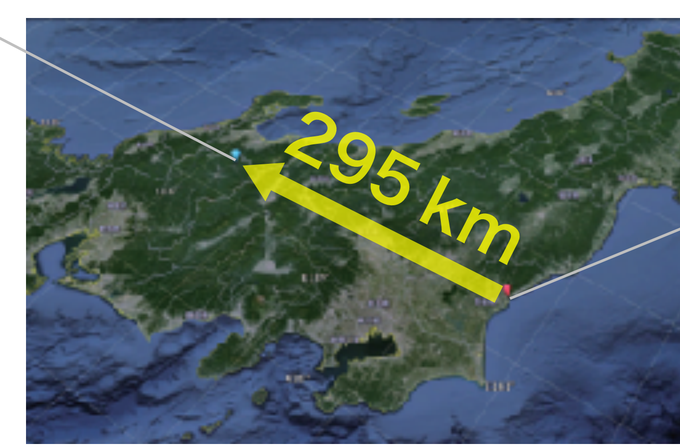
- ✓ 186 kton fiducial mass : ~10 × Super-K
- ✓ × 2 higher photon sensitivity than Super-K

✓ MW-class world-leading ν-beam by upgraded J-PARC

✓ Project now in the MEXT Large Projects Roadmap

- ✓ Aiming to start construction in FY2018, operation in FY2026

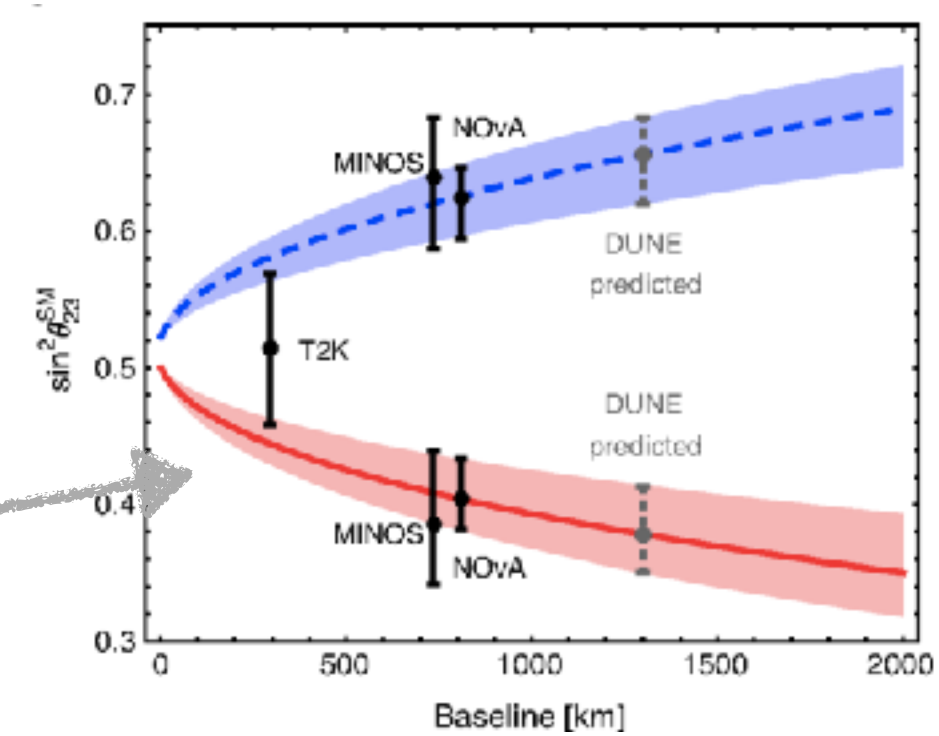
Hyper-K

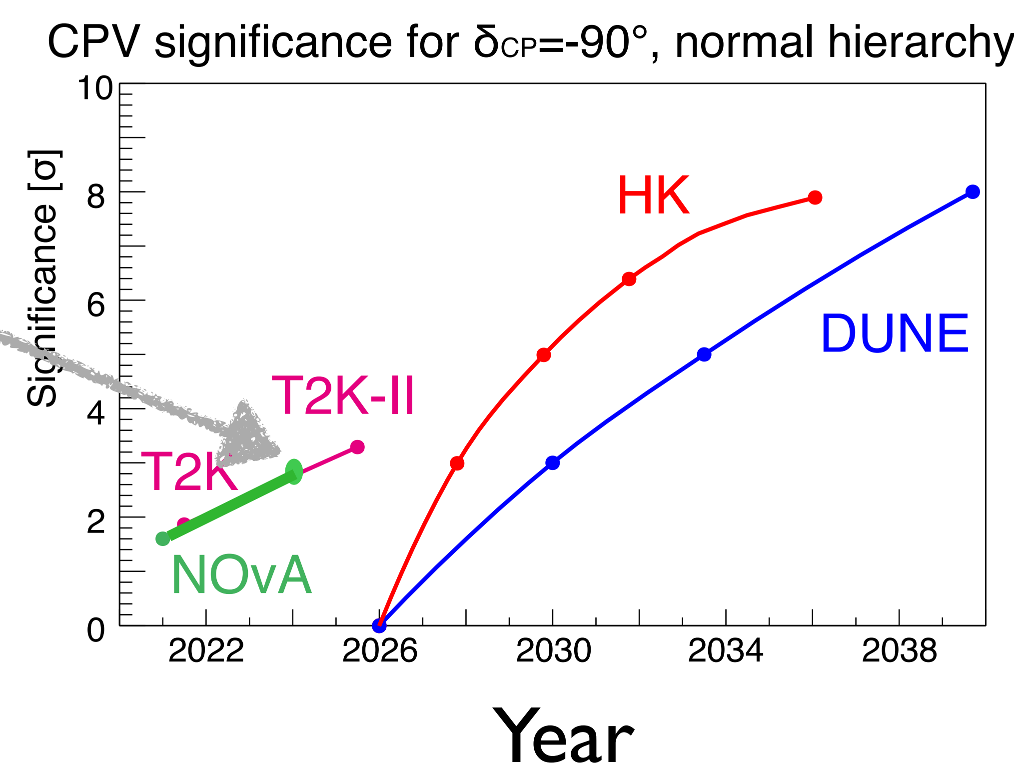


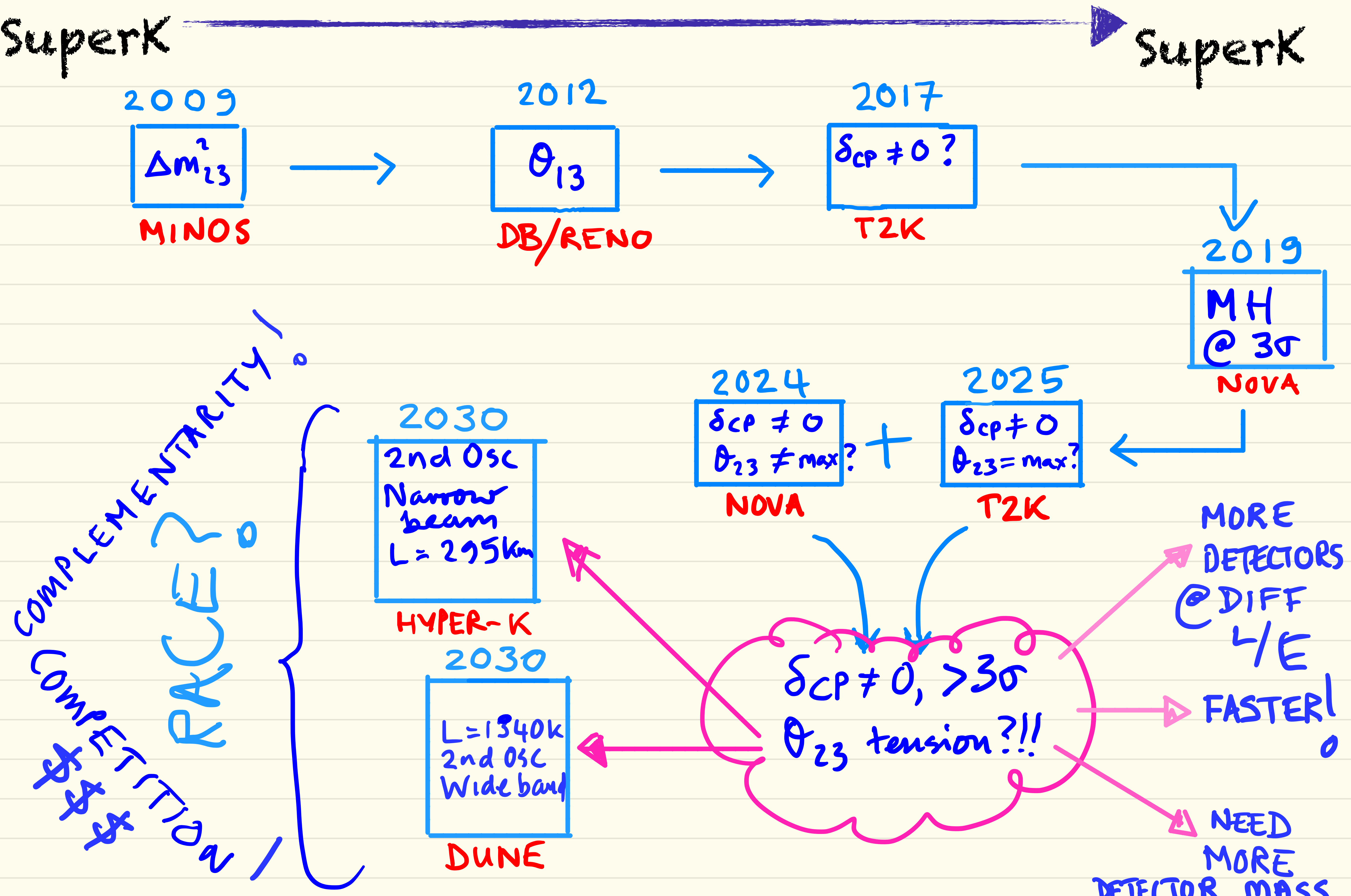
J-PARC Accelerator Complex

Messages for the future

- Neutrinos = beam power **X** detector mass **X** t
  - ➡ beam power will increase by a maximum of factor of 2 before 2030
  - ➡ time is what we don't have an infinite amount of!
  - ➡ detector mass is the ONLY thing we really have a handle on
- What if T2K/NuMI θ_{23} tension is real?
  - ➡ J.Coehlo et al.(Phys. Rev. Lett. 118, 221801 (2017))suggest decoherence as an explanation
  - ➡ This is an example, but maybe there is a hidden L dependence to be discovered, or something else?
- We have to chart the right path forward
  - ➡ Have the goalposts have changed?
    - δ_{cp} already non-zero (at 95%), and MH in the next few years
  - ➡ Experiments will take a long time to build and then collect enough data to add significantly to present knowledge
  - ➡ more detectors, different L, but maximal L/E (DUNE,LBNE)
  - ➡ detectors with broader physics remit
  - ➡ cheaper detectors! (different off-axis angles)



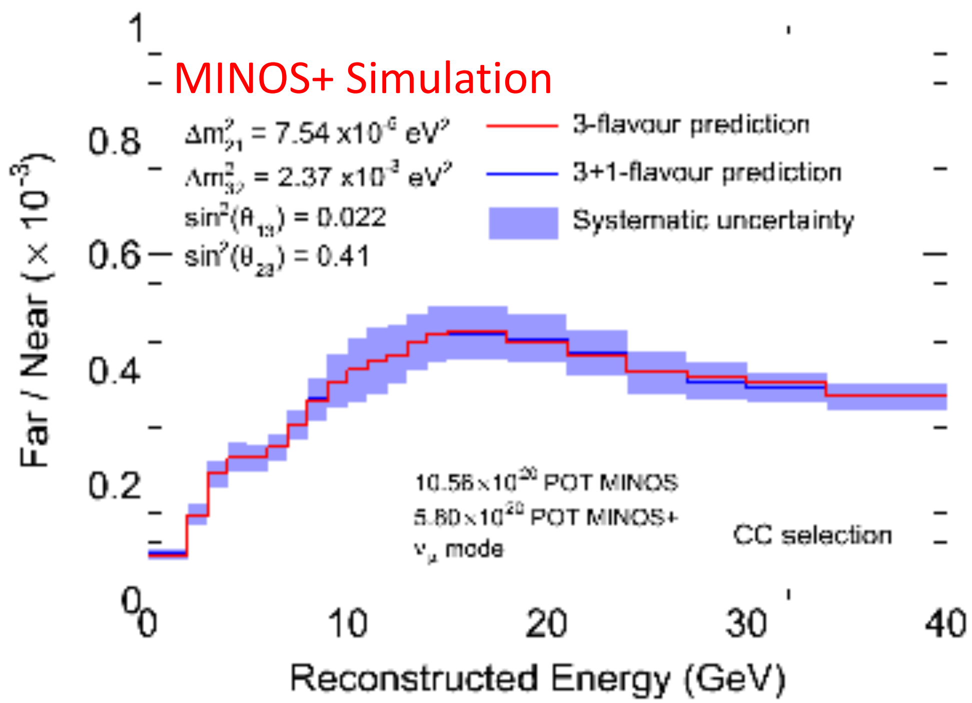


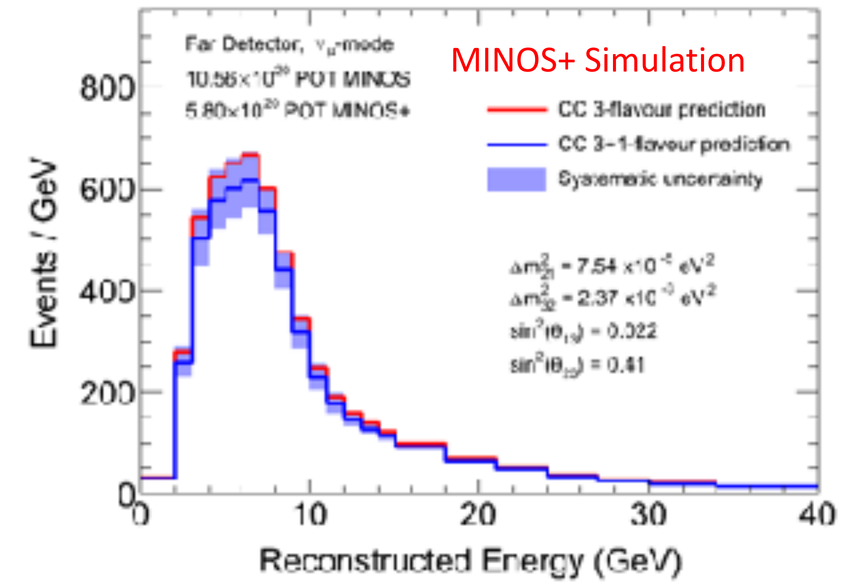


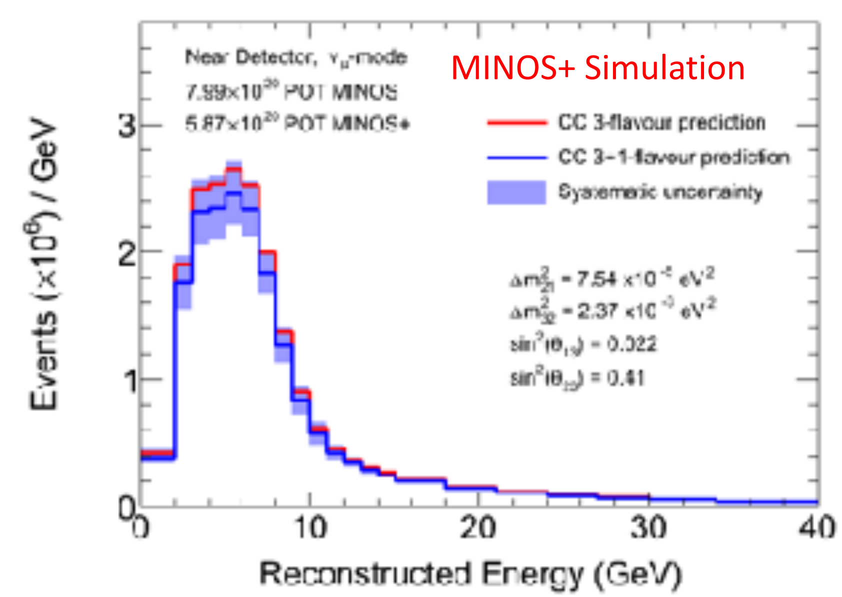
Don't turn off great neutrino detectors!

Analysis Method

- MINOS sterile neutrino analysis used the ratio of FD & ND spectra [1]
  - Use both CC and NC channels
  - Many systematics cancel in the ratio



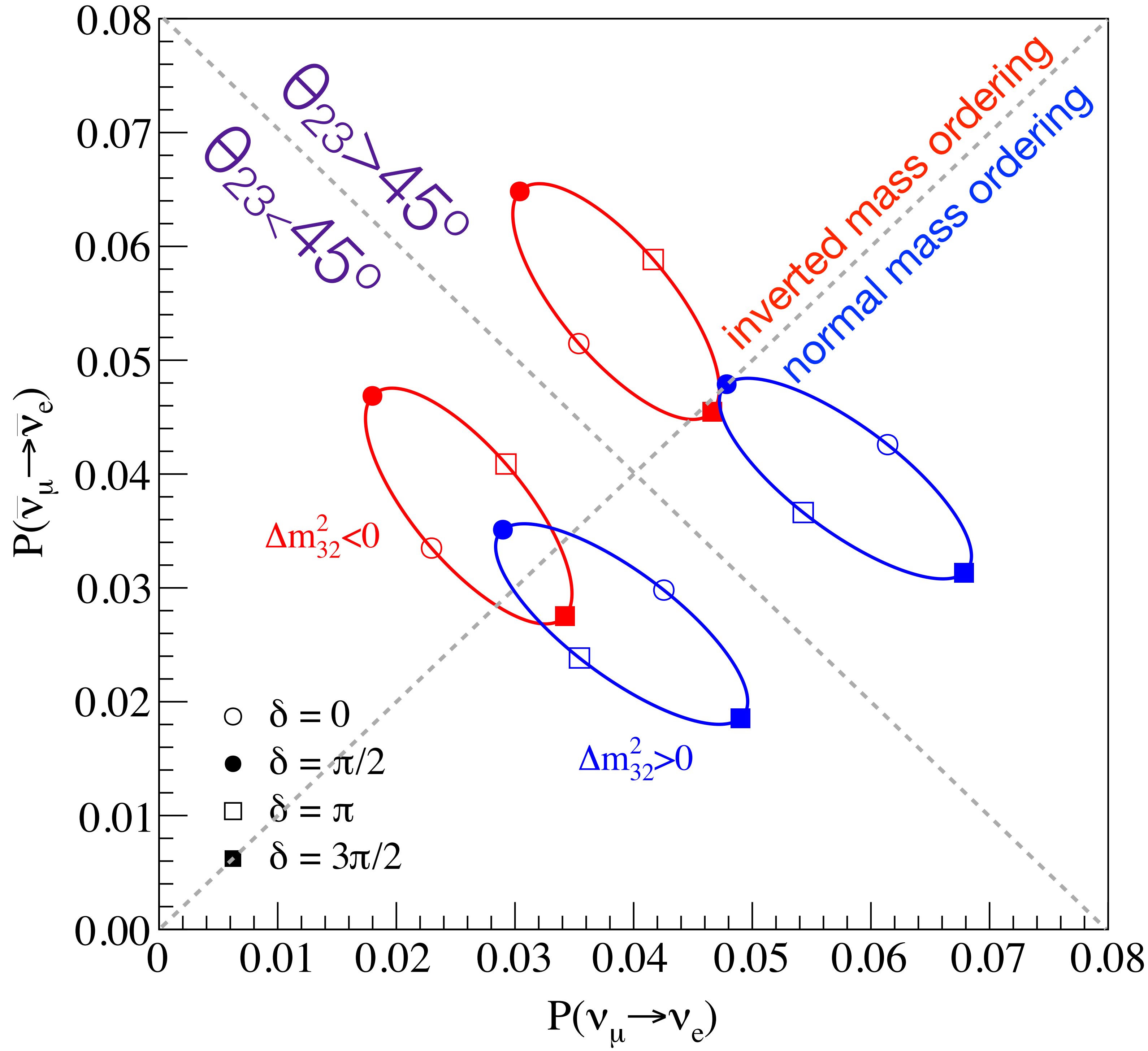




Sample Parameters: $\theta_{24} = 0.2$, $\Delta m^2_{41} = 80.0\ eV^2$

- However:
  - Ratio uncertainty dominated by FD statistics
  - Effect of high-mass sterile neutrino cancels

[1] P. Adamson *et al.*, Phys. Rev. Lett. 117, 151803 (2016)

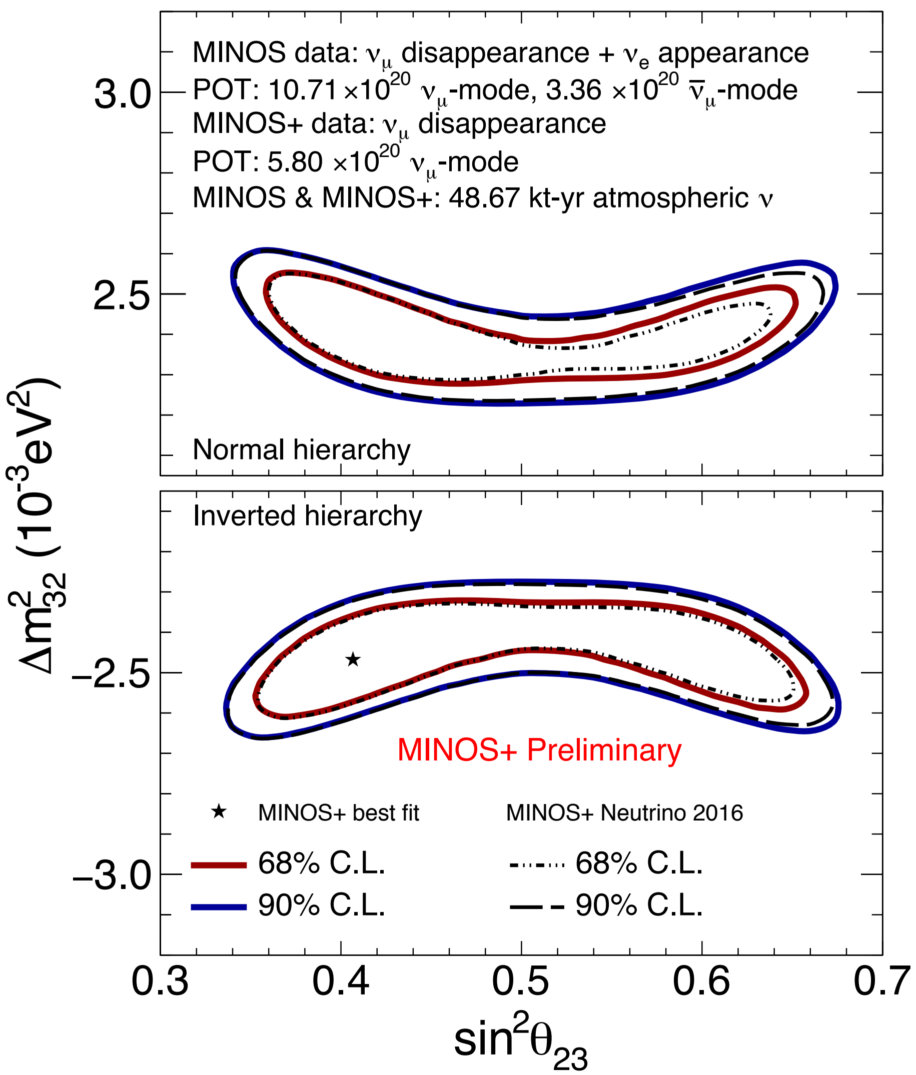


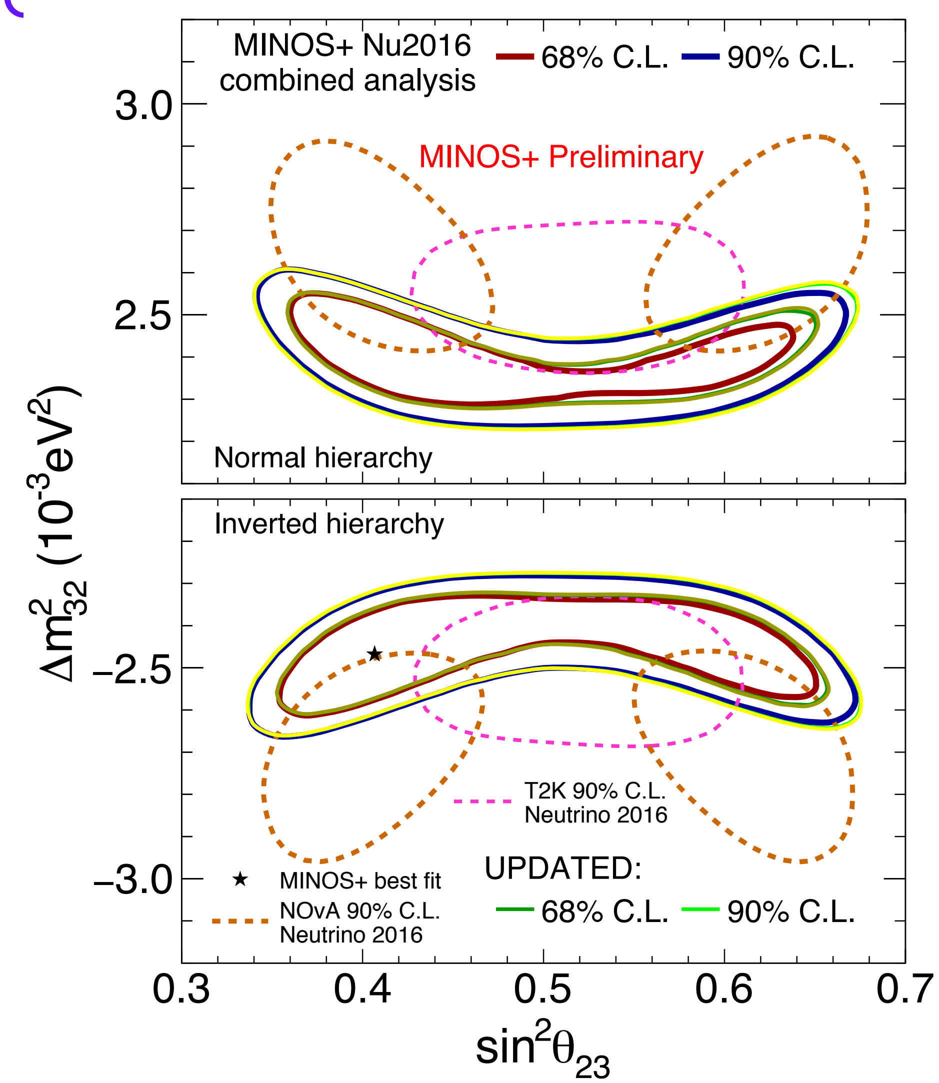
Neutrino Oscillations

Measurements at NOvA using neutrinos and antineutrinos can answer remaining questions

MINOS/MINOS+

- ✦ MINOS+ data focusses on the search for sterile neutrinos
  - ➡ Combination with MINOS has updated "standard oscillation" contours
  - ➡ (LED, high



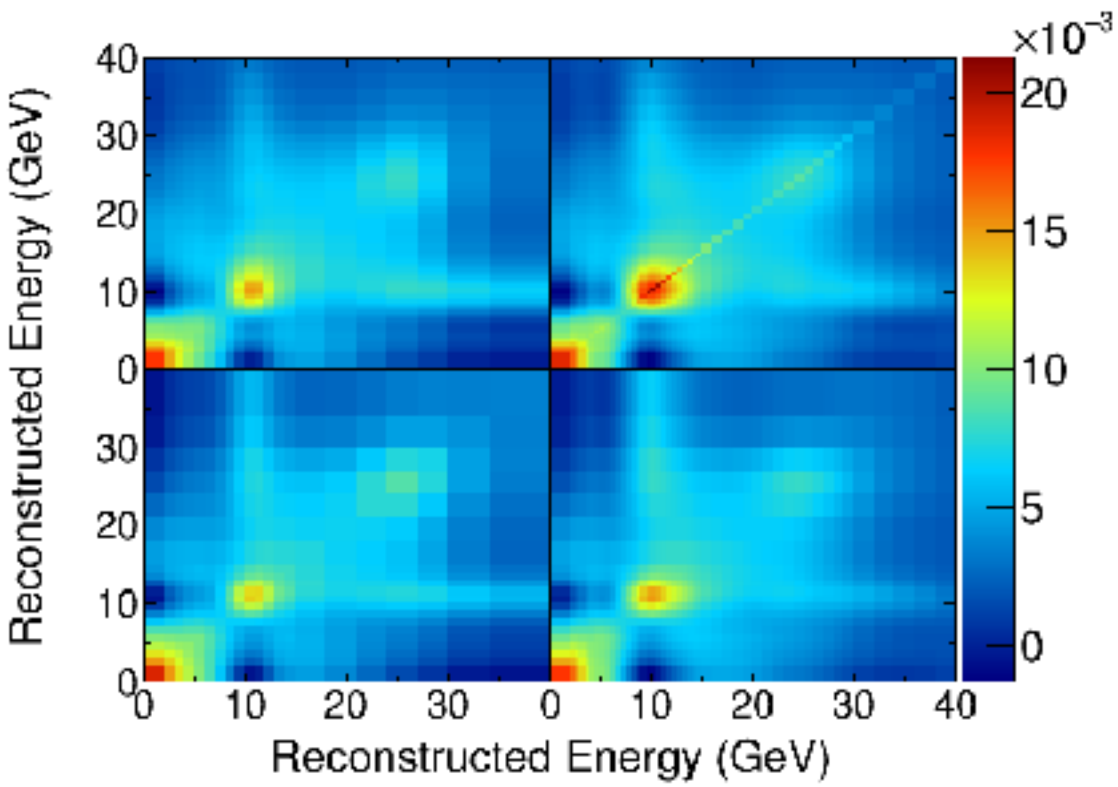


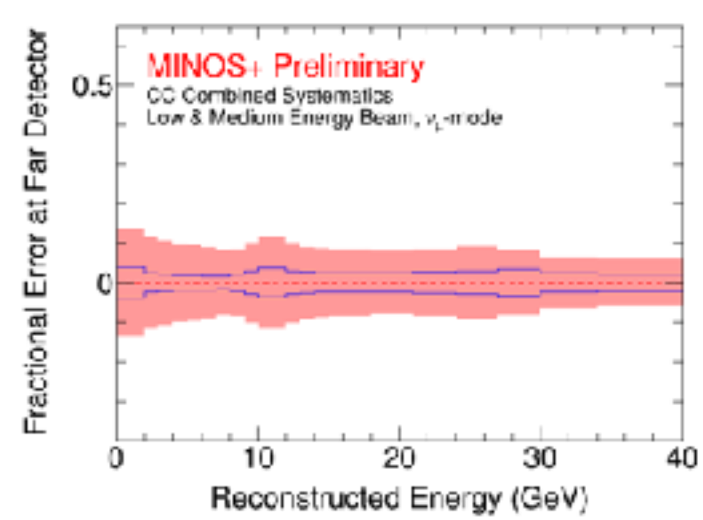
The Two Detector Fit

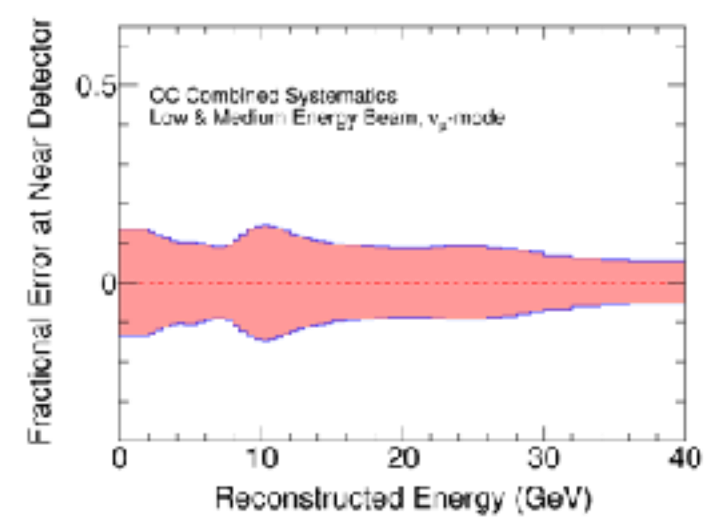
- We have now moved to a simultaneous two detector fit.
  - Use the a-priori flux prediction from MINERvA [1]

[1] L. Aliaga, et al, Phys. Rev. D 94, 092005, 2016

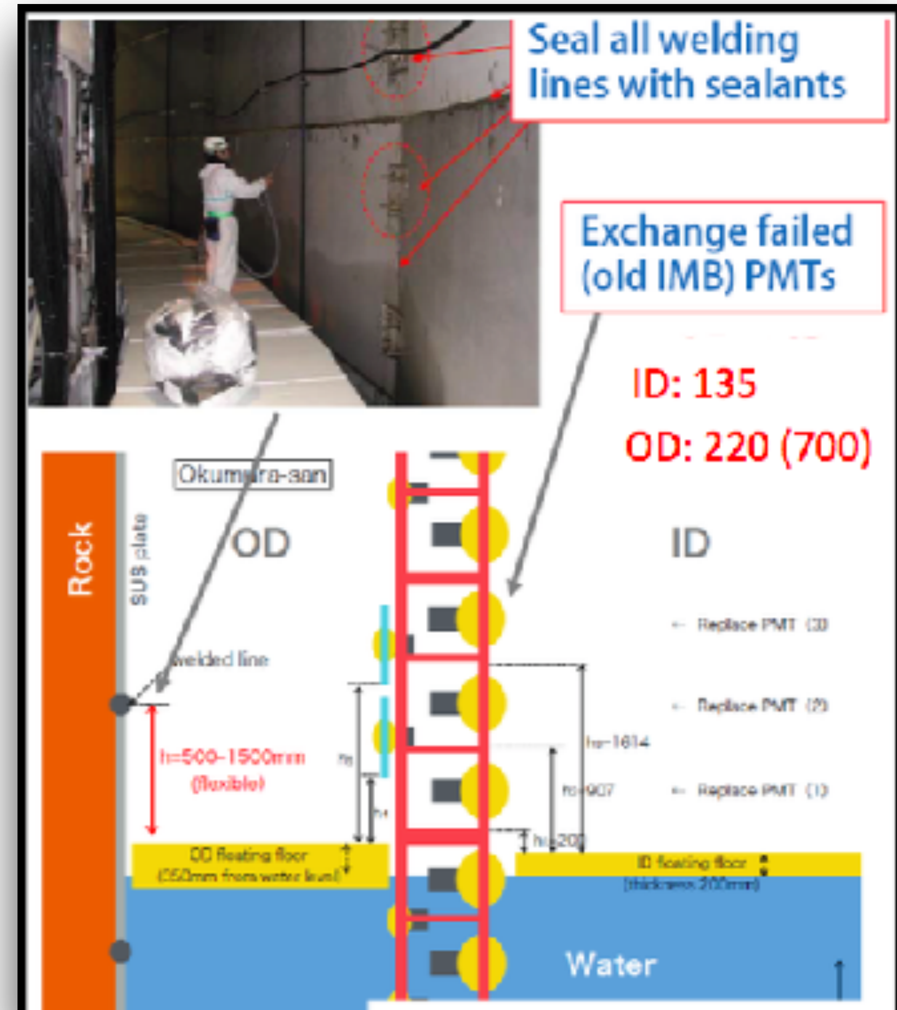
- We use a systematic uncertainty covariance matrix that encapsulates the correlations between detectors
  - Systematic uncertainty cancellation via the detector correlations.

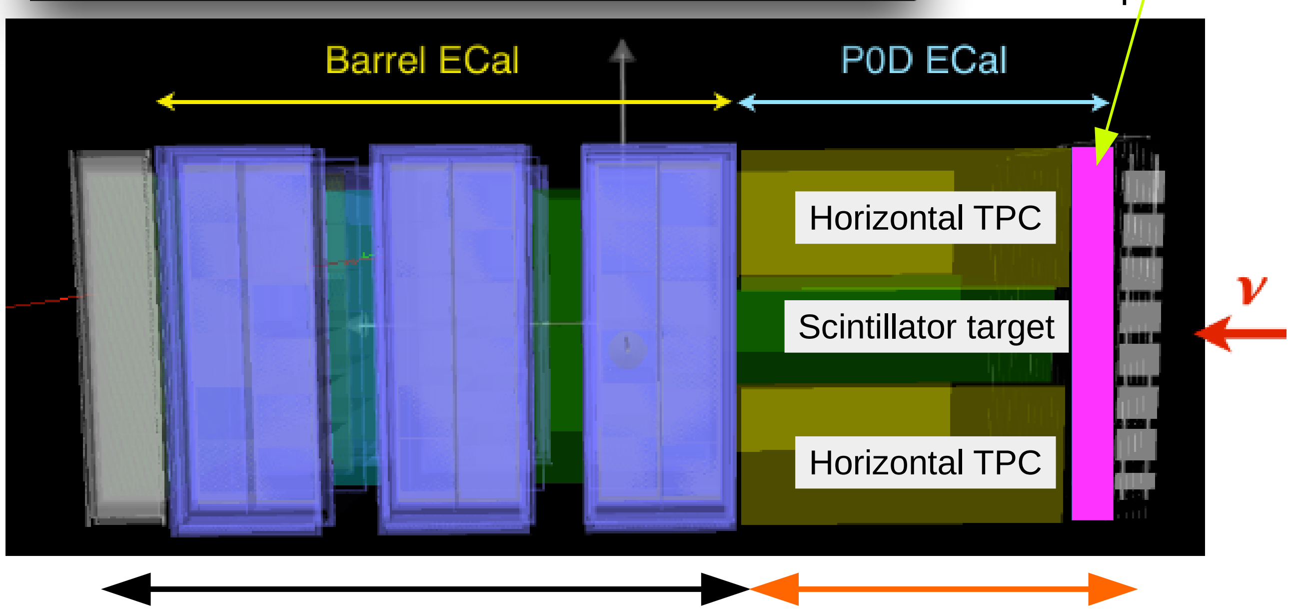






SK & ND280 outlook

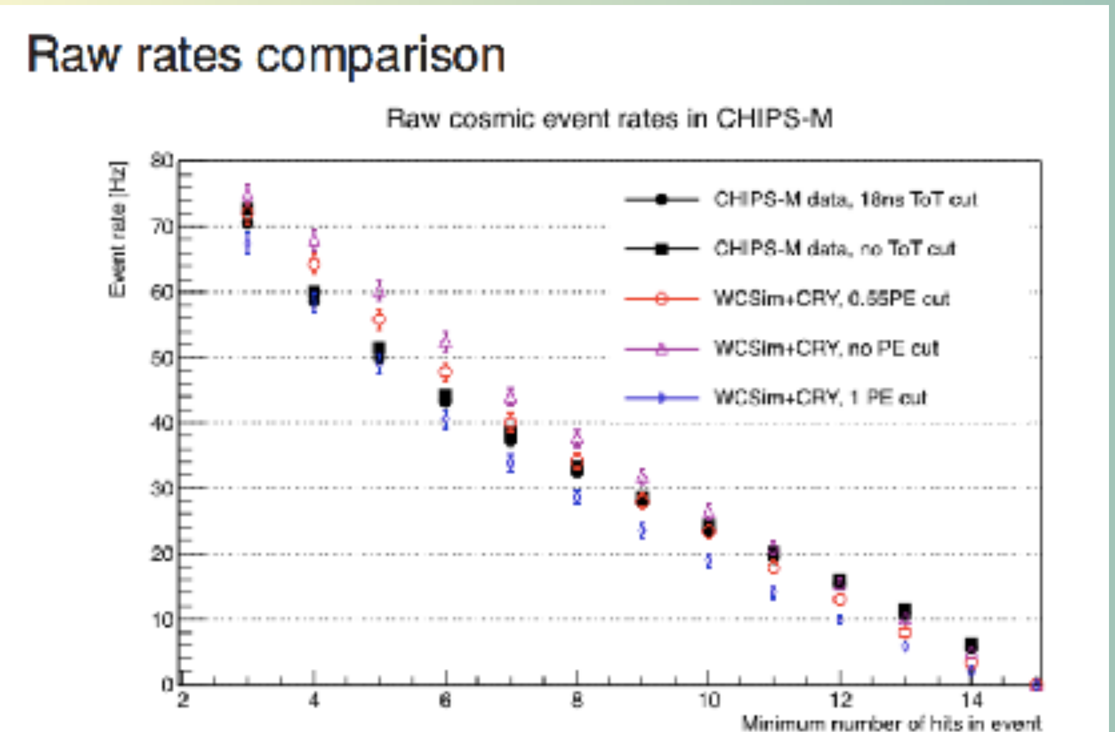


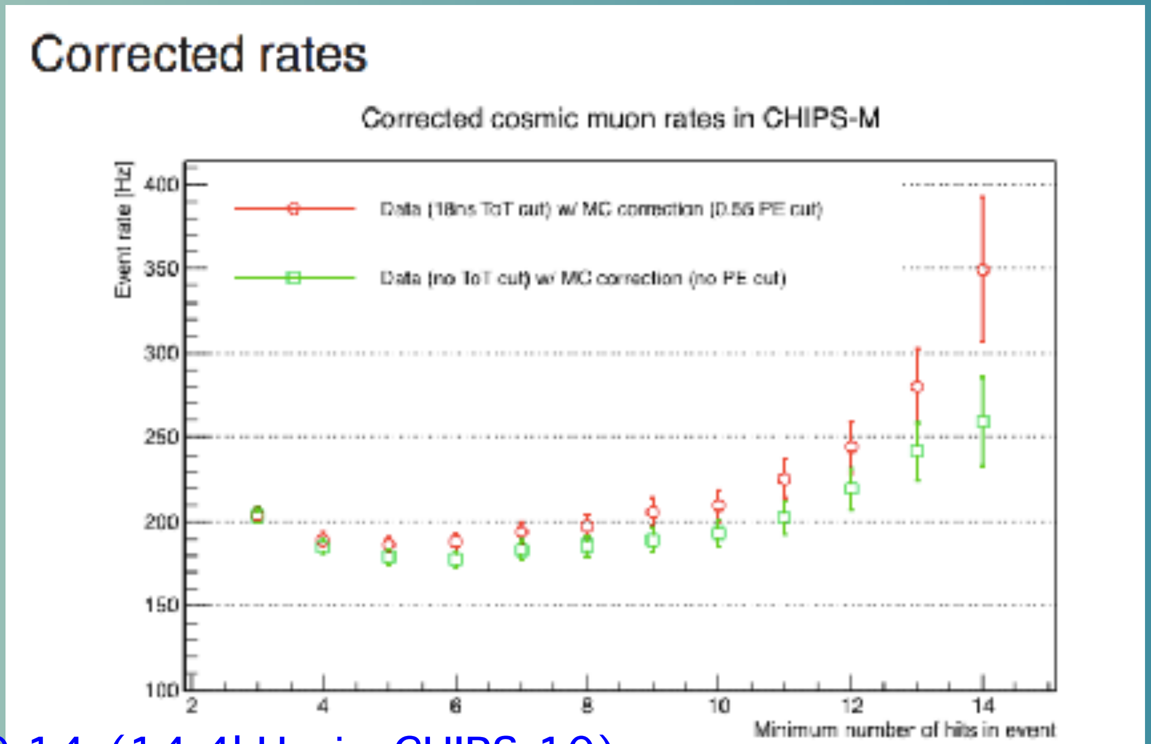


- ✦ SK-Gd project aims to enhance neutron detection capability with addition of Gd to water
  - Requires SK tank repair work in summer 2018
- ✦ ND280 upgrade:
  - replace most of volume occupied by P0D with horizontally oriented detectors
    - Active scintillator target
    - Horizontal gas TPCs
    - TOF detectors surrounding new modules
    - Improves high angle efficiency
  - Aim for installation ~2021

CHIPS-M 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)

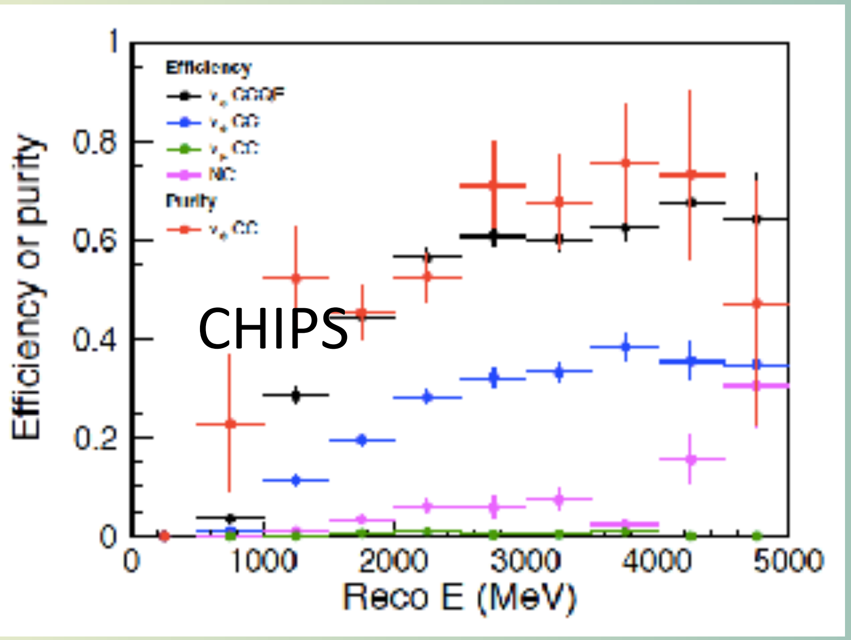
- PMT dark rate 200-800 Hz so cosmic rate dominates
- Cosmic rate for 10kton (25mx20m) is 14 kHz
- 14kHz used to calculate dead time/electronics speed etc

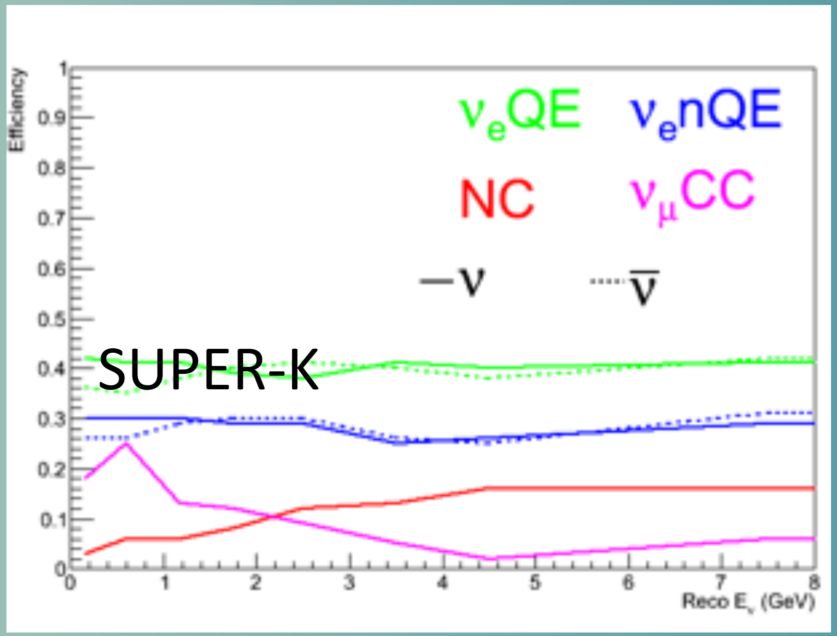
Less than 1% dead-time in 10kt detector during spill

Reconstruction

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

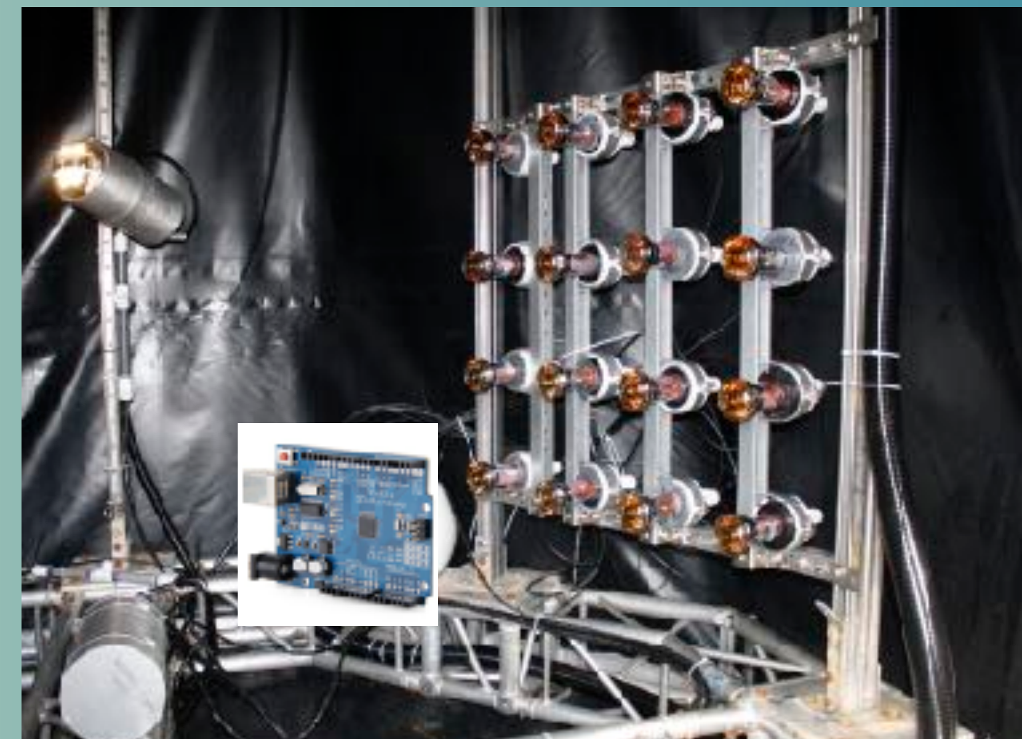


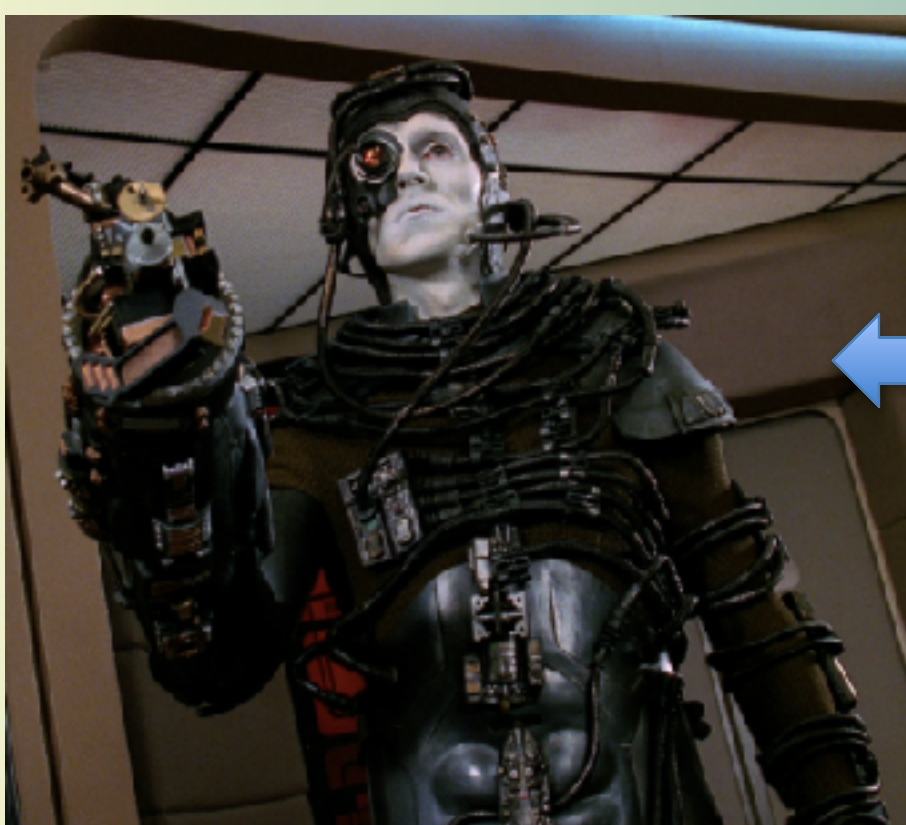


- Originally based on MiniBOONE approach, several innovations from that point (time)
- Neural Nets, Fourier transform analysis and even deep learning all being studied
- Pretty good basic bottom line so far, more improvements on the way

4. Electronics: 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
- Microprocessors on each PMT provide ToT and receive clock from WR system

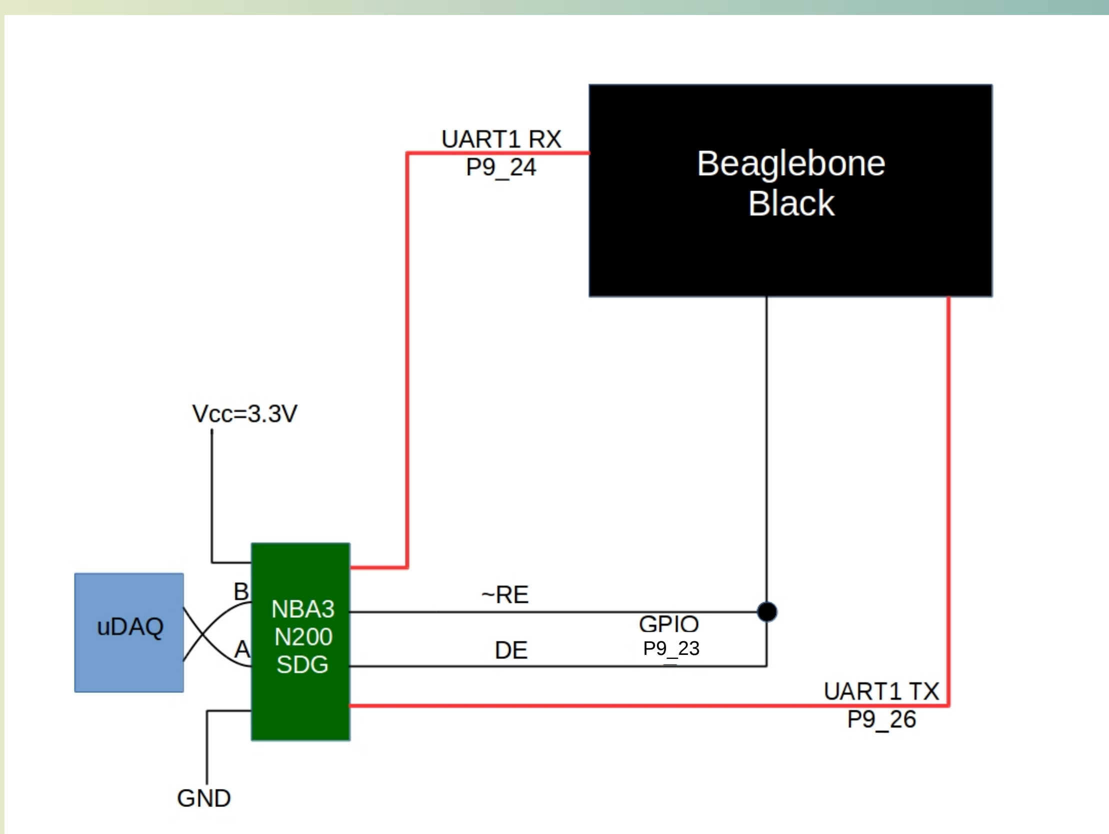


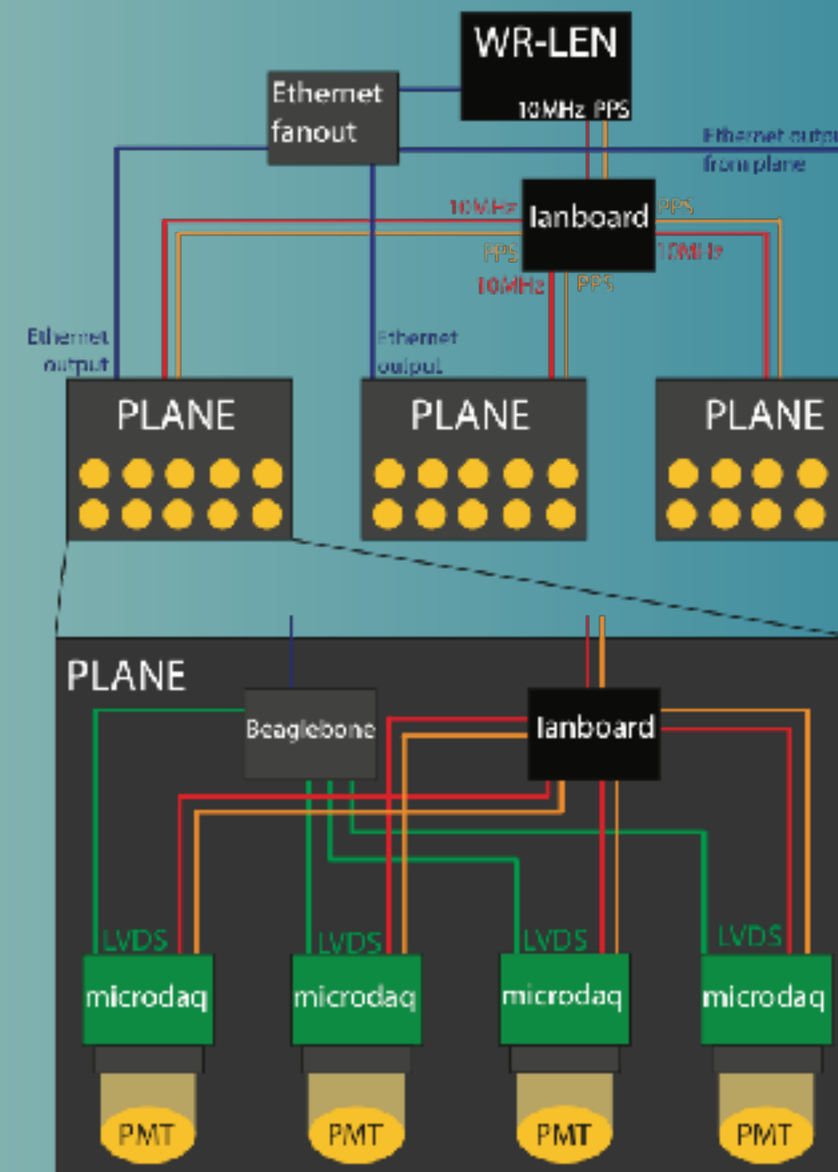


- Side comment: Industrially available ASICs in version 100 (ish): home grown electronics is typically in version 2-5the combination of cheap processors such as Raspberry Pi, BeagleBone and Arduino combined with the WWW means progress goes incredibly fast as solutions are known instantaneously
- Developers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

Status of Design

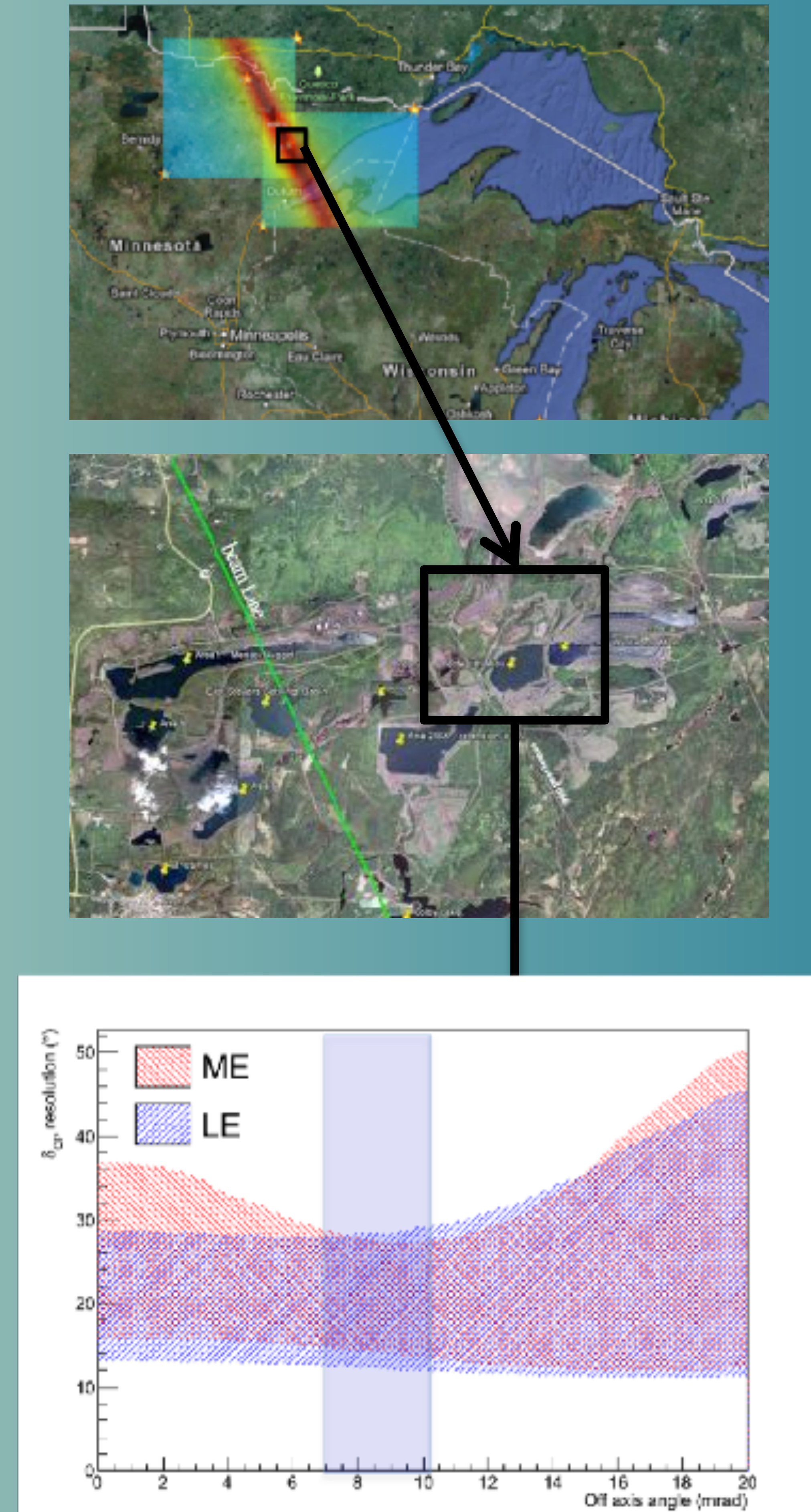
- Communication software between BBB and micro-daq demonstrates 1Mbps on RS485
- Rate of 1-10kHz per tube means scope for local filtering (maybe) or at least buffering during spills





CHIPS : Location

- Deep lake or body of water on mining site: Wentworth 2W
  - 60m depth, cosmic overburden (later)
- High energy neutrino beam
- At 7mrad off axis
  - Between signal and background extremes
- CHIPS-M (mini) prototyped in 2014 and 2015



CHIPS-M prototype 2014/15

- Being submerged in ←←←←2014
- After one year under the water in 2015 →→→

- Liner is robust, light-tight and mostly pristine after a year under the water
- Sealing method is robust
- Winter defence worked well, water continued to circulate, nothing broke!

International Hyper-K organization

Project Leaders

Chair of steering

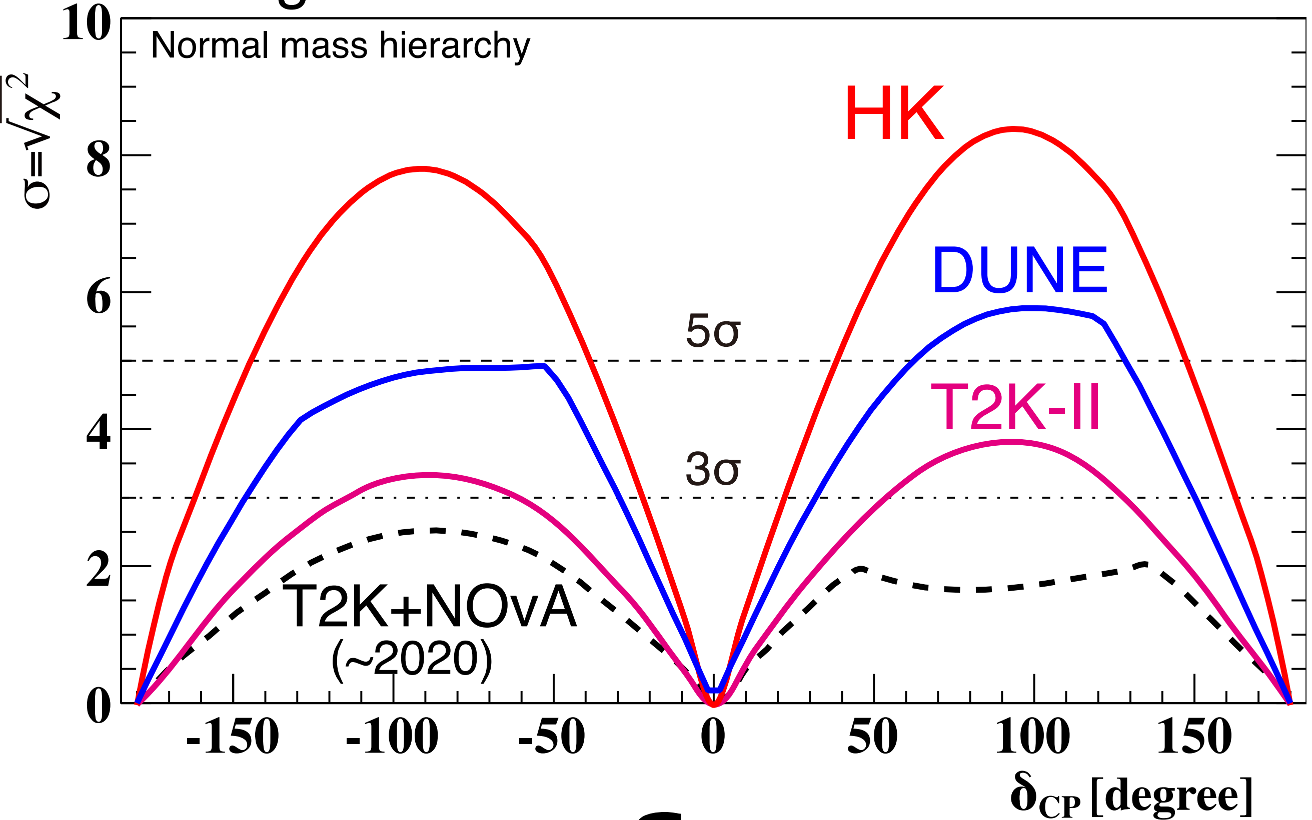
Chair of country rep.

Proto-collaboration meeting (July 2016)

- Host institutes: ICRR/UTokyo and KEK
  - UTokyo will launch new institute for Hyper-K in October 2017
  - ICRR future project committee concluded that Hyper-K should be the laboratory’s next main project
  - KEK project implementation plan put first priority to the J-PARC upgrade for Hyper-K
- Hyper-K proto-collaboration
  - 300 members, 75 institutes, 15 countries (as of April 2017)
  - International project leader, steering members, WG conveners
- External review by the advisory committee
  - International high-energy physicists and Japanese engineering specialists

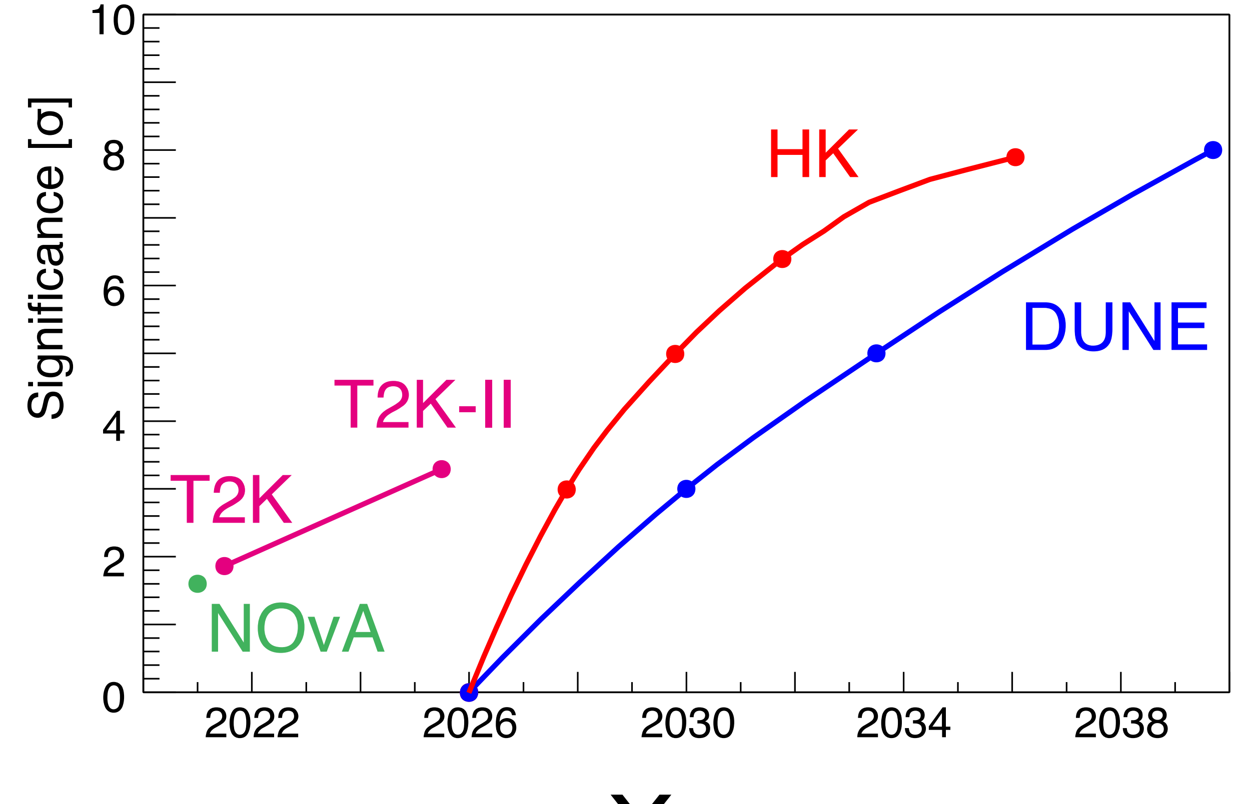
World-leading neutrino program

Significance for sinδCP=0 exclusion



δ(°)

CPV significance for δCP=-90°, normal hierarchy



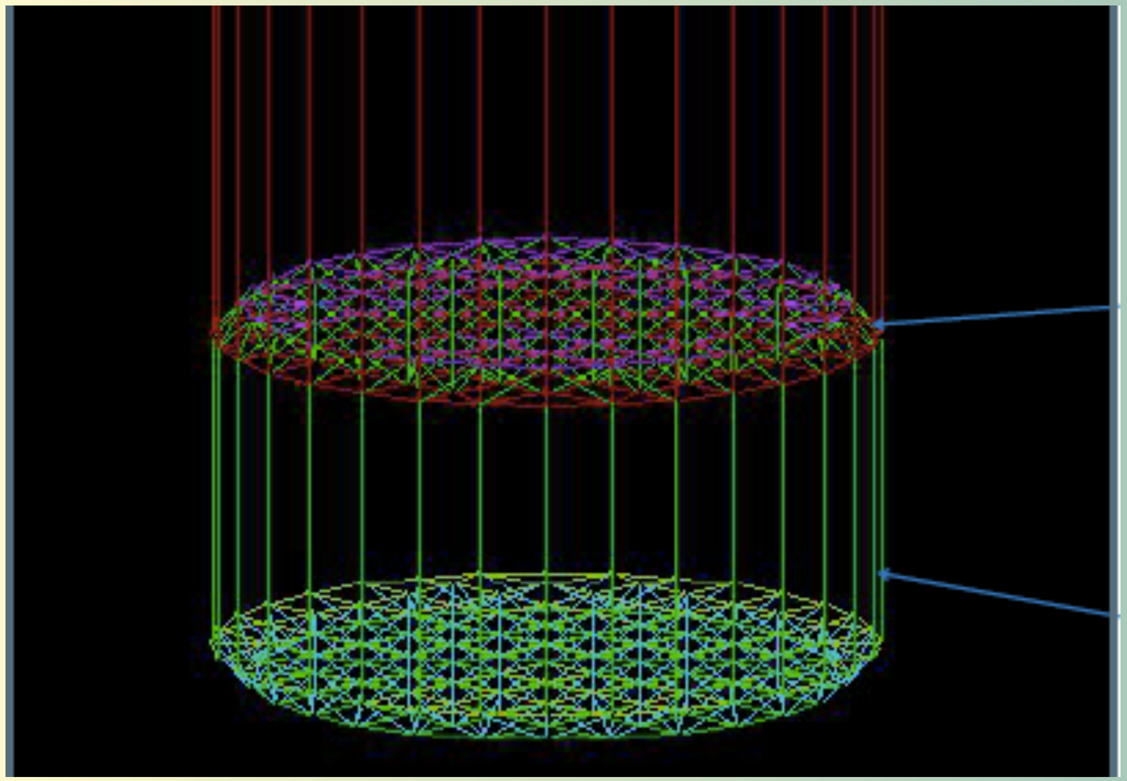
Year

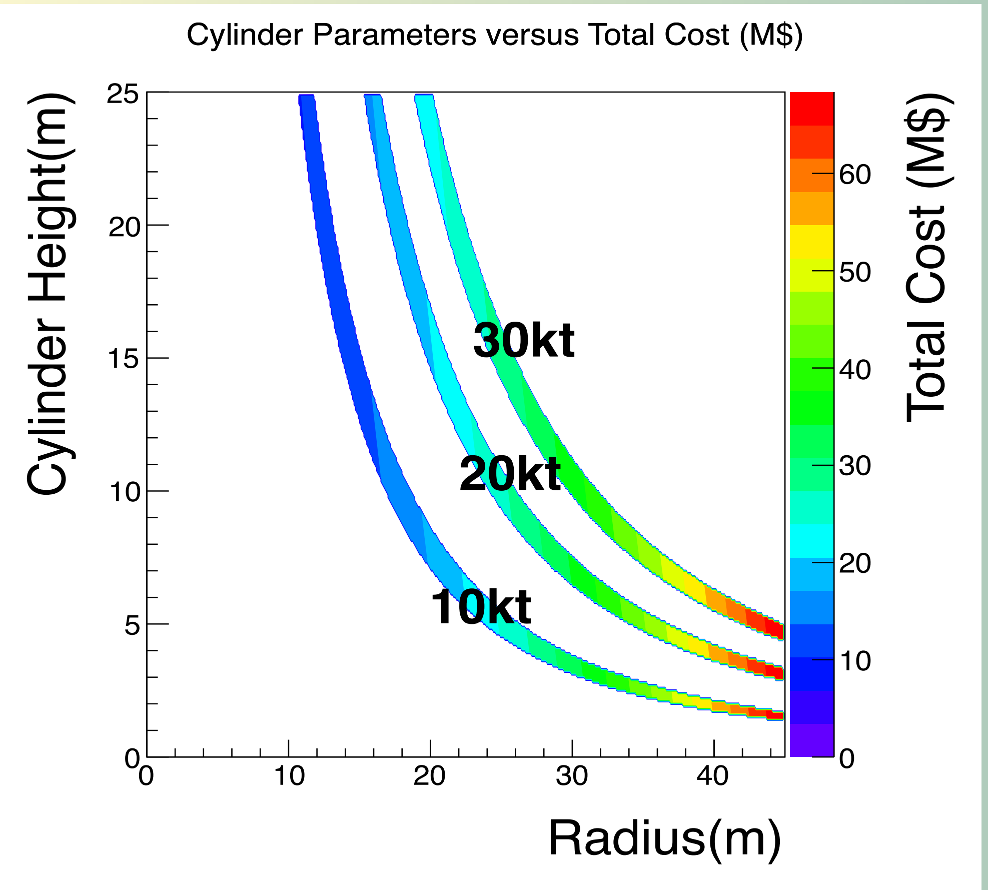
- T2K suggests $|\sin\delta_{CP}|=1$ and aims to discover CPV w/ 3σ
- Hyper-K expects to explore origin of CPV w/ >5σ
  - δ_{CP} precision of 22°(7°) for $\delta_{CP}=\pm 90°(0°/180°)$
- Mass hierarchy determination possible by combining high-statistics atmospheric neutrinos

5. 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 used a 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

2. CHIPS Structure Design

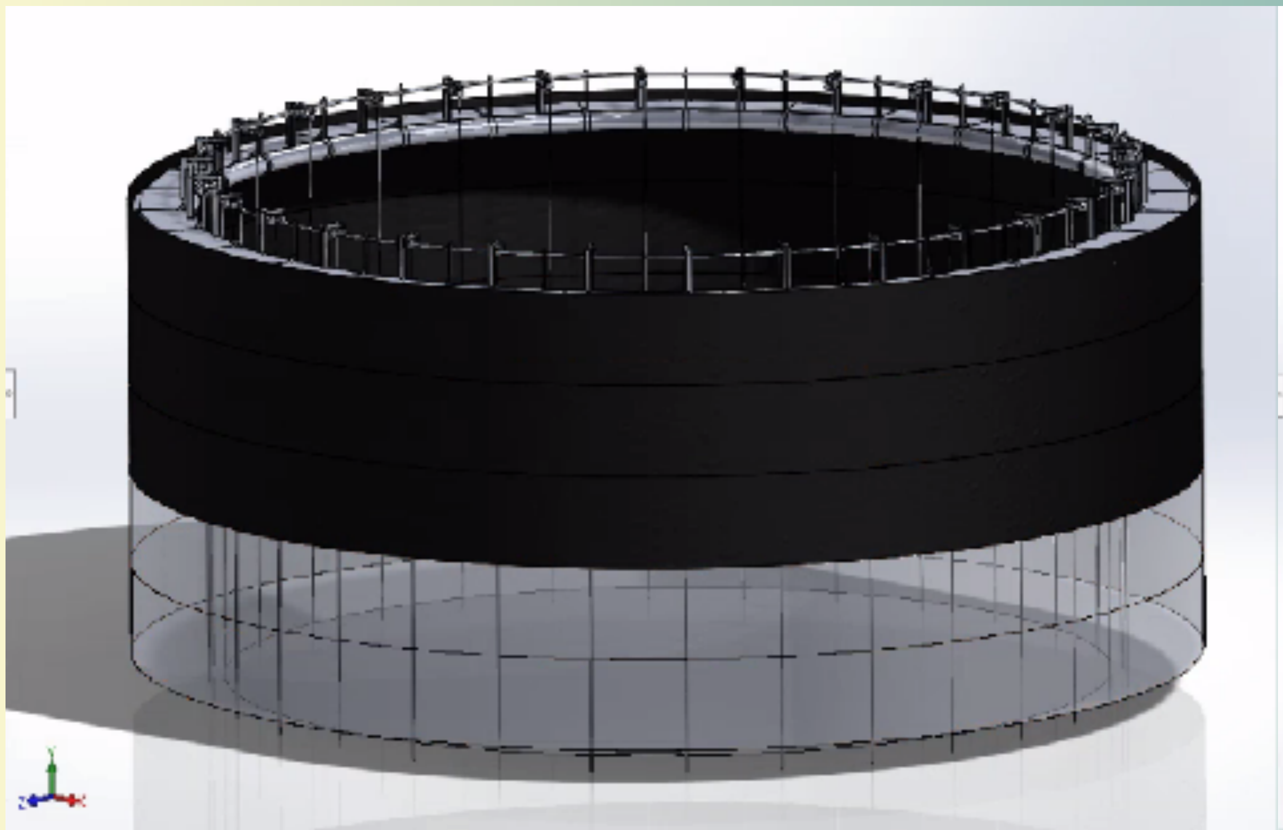
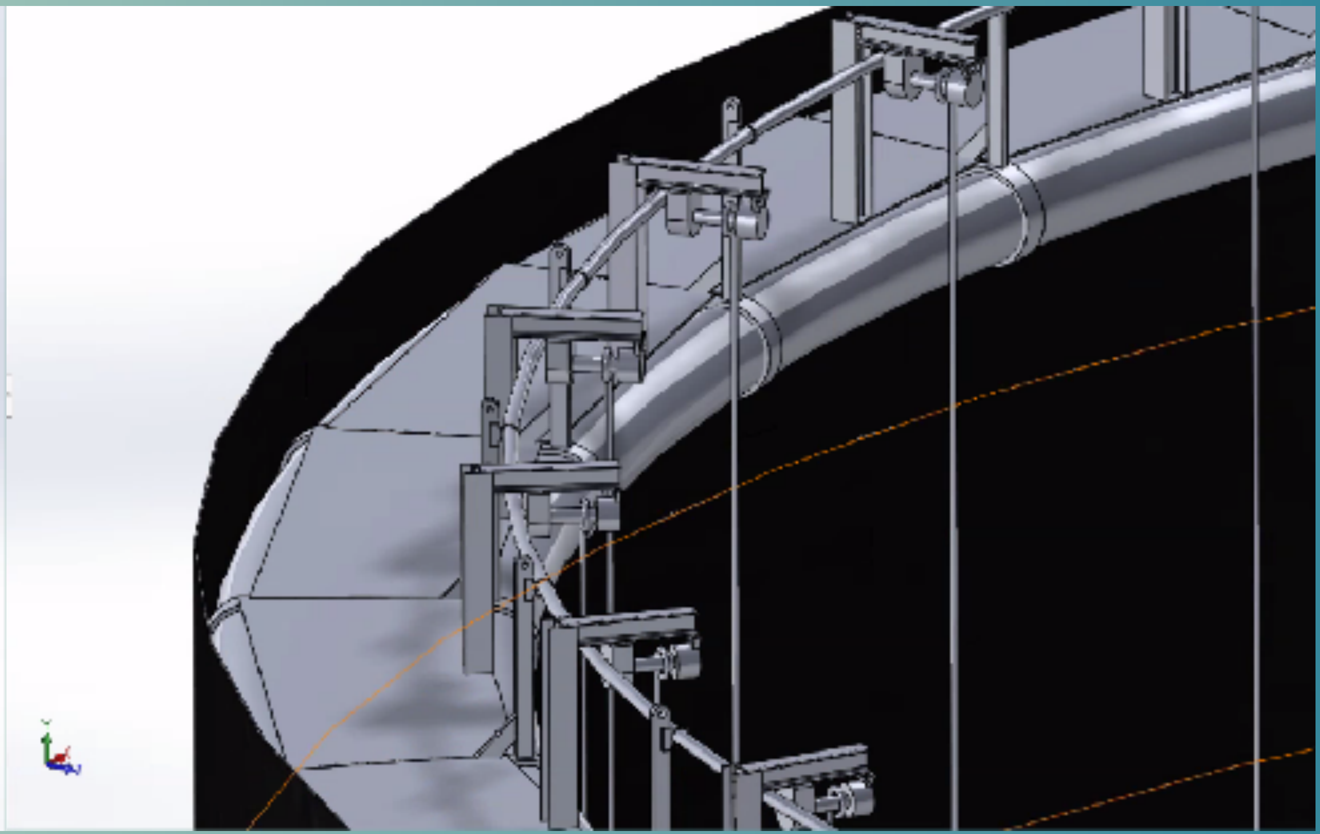


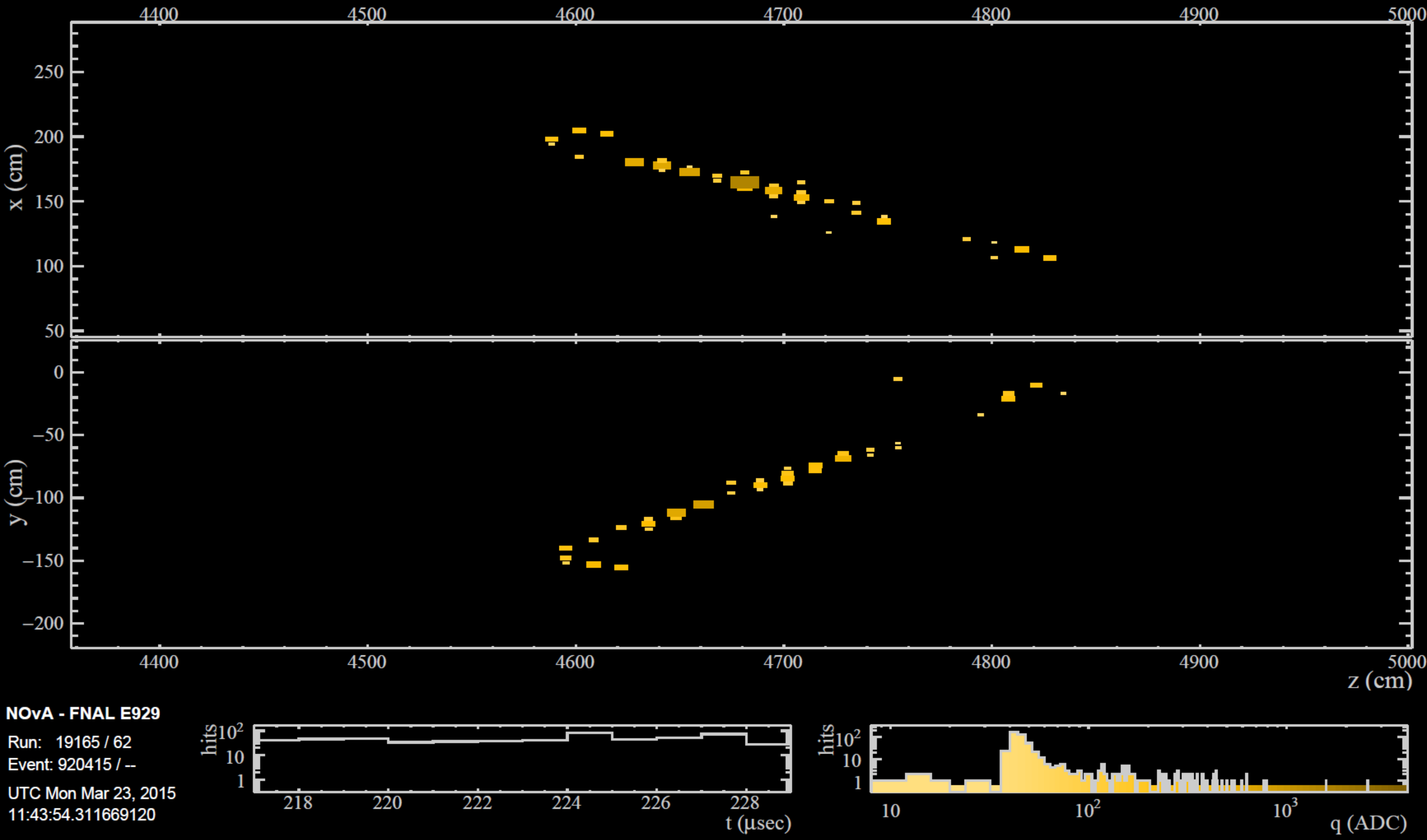


- Hang bottom truss end cap from top one with Dyneema ropes (used in KM3Net)
- Allows volume to grow if more PMTs are available
  – Recovery and ability to further instrument is designed in
- Saves 50% cost of the space frame sides
  – Pushing on 25% of original estimate
- PMT planes attached to ropes
- Make footprint large enough: bang for buck is impressive for walls
  – ~100k/kt for additional volume

CHIPS Deployment

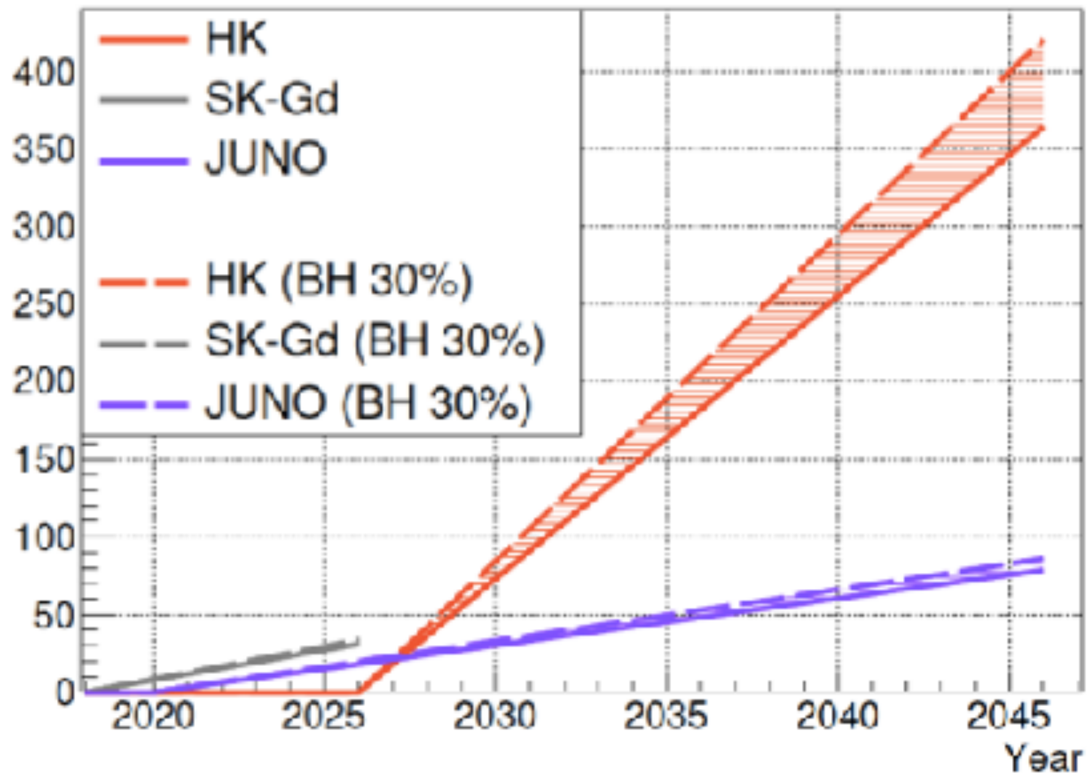
- Intense work on-going, not all issues are resolved
- Liner wrapped on a bobbin placed on a float to be attached to the floating dock
- Winches lower dyneema ropes as planes are attached to them
- Not all ropes are bottom-endcap weight bearing

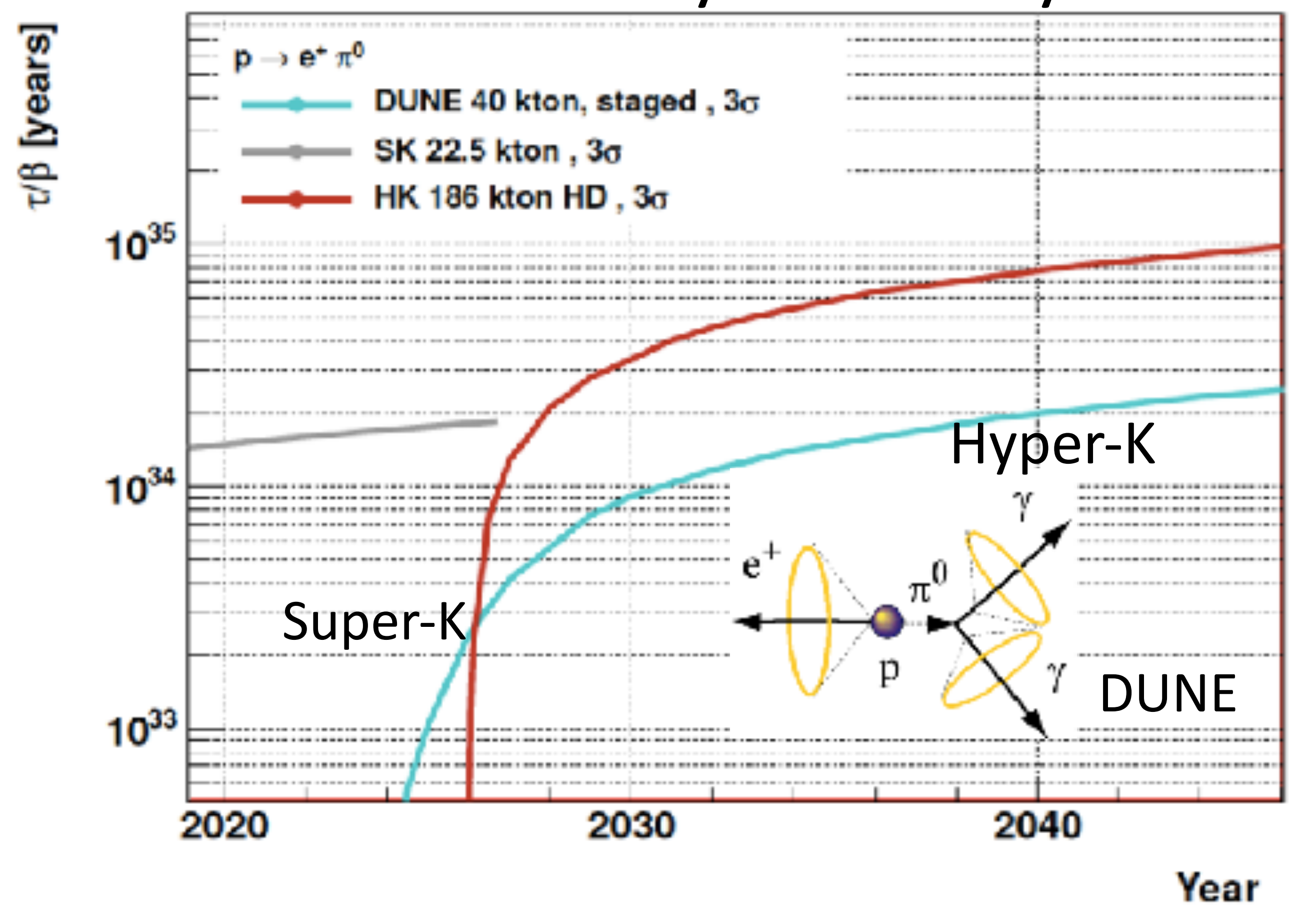


NOvA ν_e Candidate

Hyper-K : other physics!



3σ discovery sensitivity



Supernova Relic ν

- Expect SK-Gd to discover first
- Hyper-K will measure the spectrum

→ History of star/BH formation

Great potential for discovery

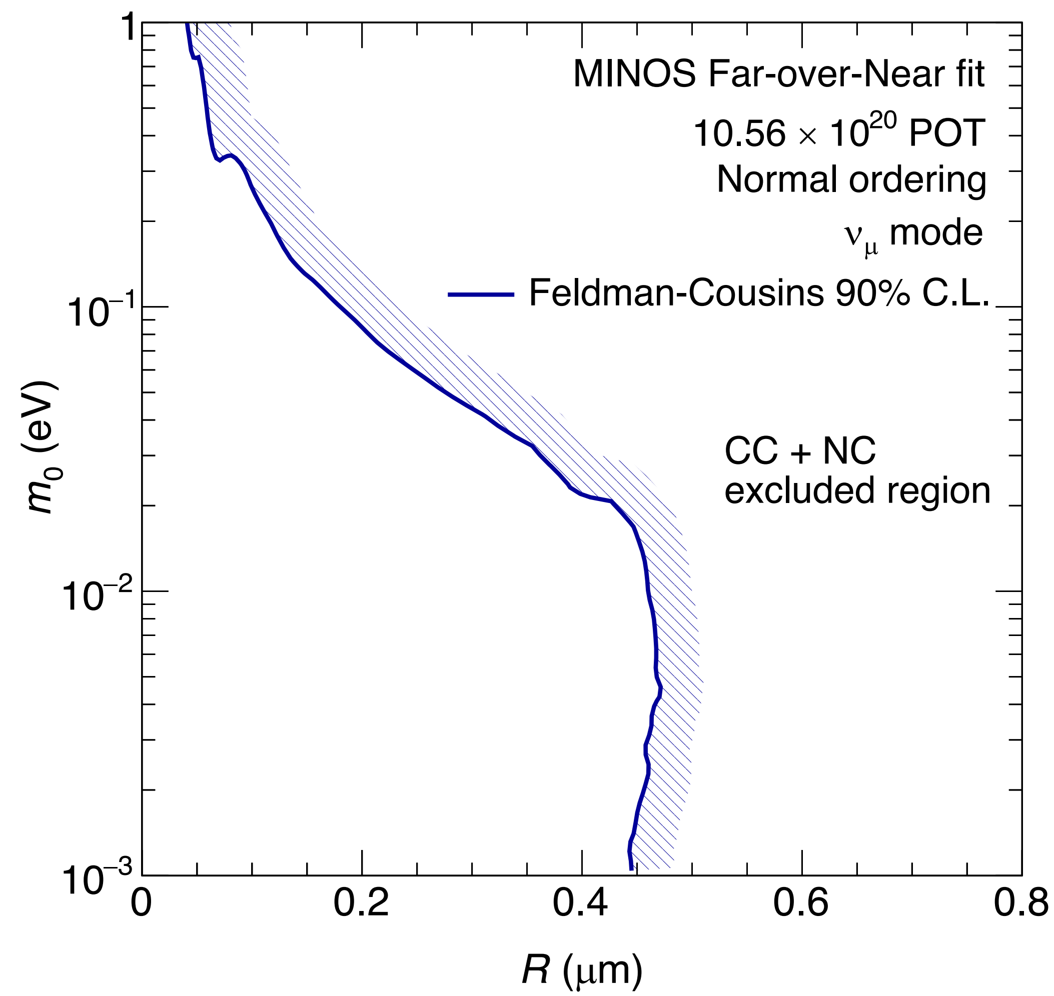
3σ discovery sensitivity reaching

$\tau_p/Br = 10^{35}$ years! ($p \rightarrow e^+\pi^0$)

$\tau_p/Br = 3 \times 10^{34}$ years for $p \rightarrow \nu K^+$

and on to exotics....

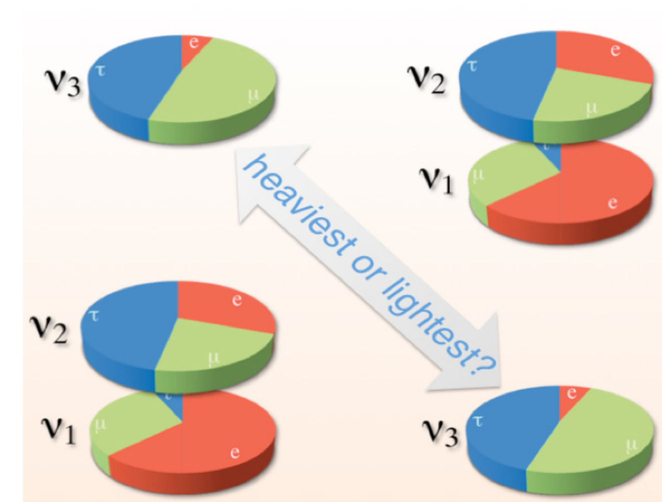
- the same analysis can be interpreted as evidence (or not) of large extra dimensions....
  - ➡ no evidence is found for that...
  - ➡ R<0.45m for m_0 0



Current Questions from Neutrino Oscillations

✦Neutrino Oscillations provide a fortuitous tool to study the nature of the neutrino

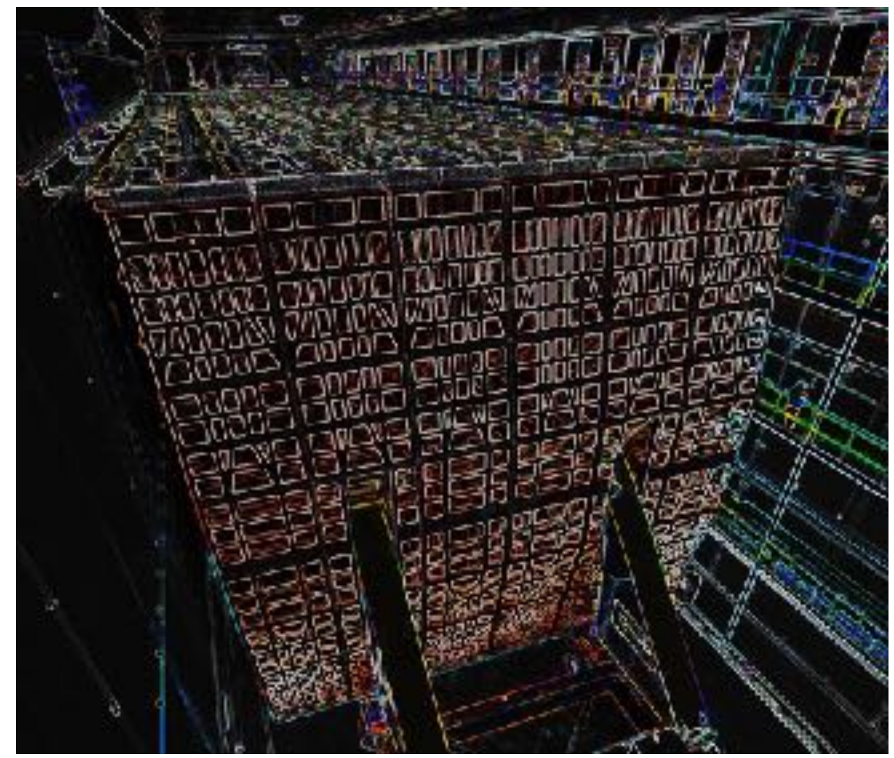
- ➡ CP Violation
  - $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ differ depending on value of CP violating phase of PMNS matrix, δCP
- ➡ Mass Hierarchy
  - Is ν_3 heaviest (normal) or lightest (inverted)?
    - increases $P(\nu_\mu \rightarrow \nu_e)$, decreases $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ for NH
    - vice versa for IH

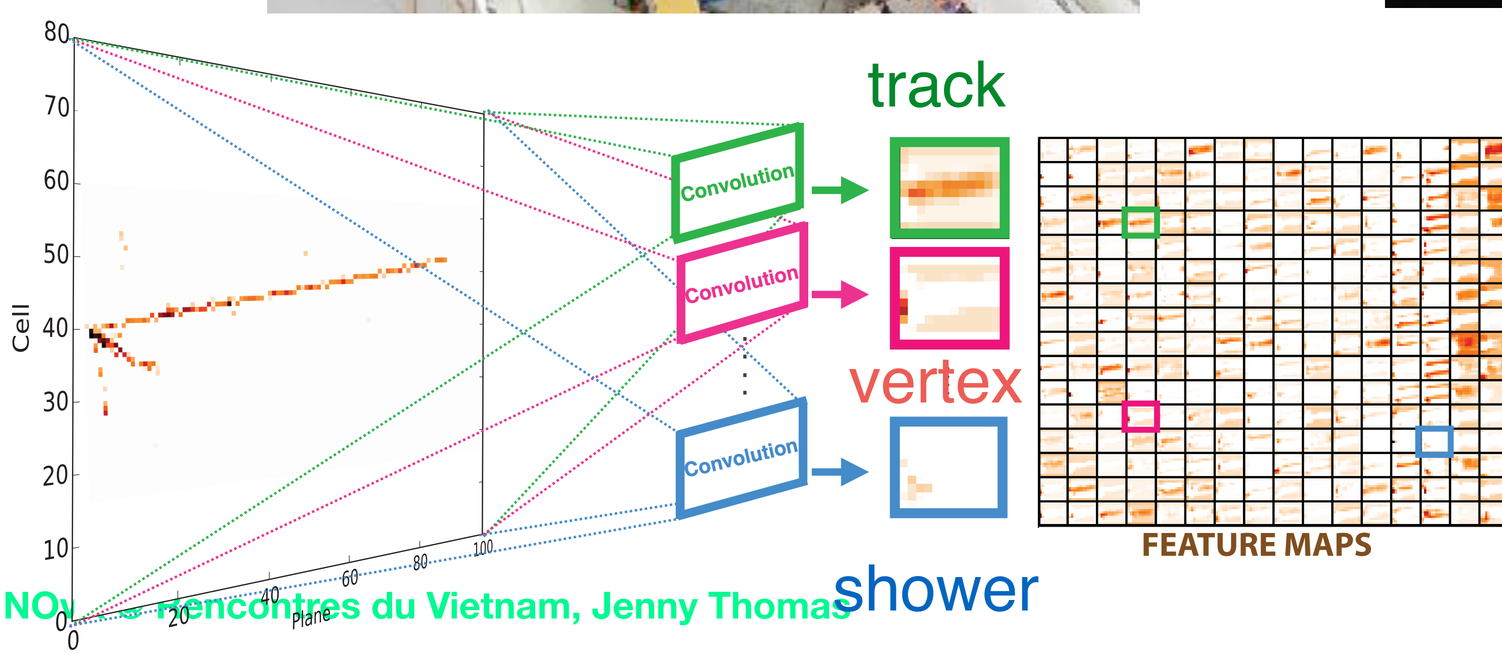


- ➡ Structure of mixing
  - Is there a new symmetry driving equal ν_μ - ν_τ contributions to ν_3?
    - Maximal mixing, $\theta_{23}=45^{\circ}$, $\sin^2(\theta_{23})=0.5$
  - If not, does ν_3 have more ν_τ, or more ν_μ
    - Lower octant vs upper octant of θ_{23}
  - $P(\nu_\mu \rightarrow \nu_\mu)$ depends on $\sin^2(2\theta_{23})$, $P(\nu_\mu \rightarrow \nu_e)$ depends on $\sin^2(\theta_{23})$
- ➡ Is there more to the picture?
  - Test for consistency among 6+ oscillation channels within 3-flavor framework
  - Is there evidence of oscillations to flavors not participating in Weak Interaction?
    - Sterile Neutrinos
  - Is there even something more?

Convolutional Visual Network (CVN) Selection

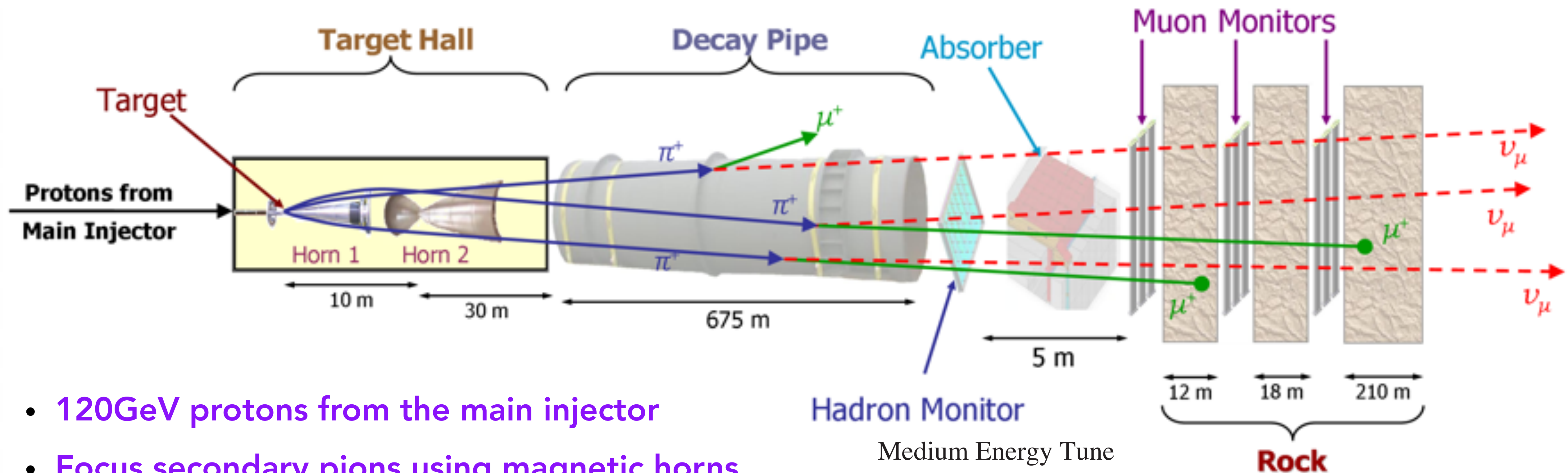
- Take advantage of recent advances in machine learning/computer vision
- Deep networks extract complex features from input data, GPUs greatly improve training time
- Inputs to the network are pixels in image
- Apply convolutional kernels to pull out event features
  - Image on right has gone through a convolutional kernel looking for edges





- Showing a muon neutrino interaction and the first layer of feature maps extracted from the convolutional kernels
- 73% ν_e CC selection efficiency, 76% purity with CVN classifier
- This has big implications for LAr detectors, presently struggling with full reconstruction

The NuMI neutrino beam



- **120GeV protons from the main injector**
- **Focus secondary pions using magnetic horns**
  - Focus positive hadrons for neutrino beam, negative for antineutrino
- **Pions decay to produce muon neutrinos**
  - Decay kinematics mean a detector at 14.6mrad sees a narrowly peaked energy spectrum
- **97.5% muon-neutrino, only 0.7% beam electron-neutrino (remainder wrong-sign) at NOvA**