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Current and Future Long Baseline Neutrino Experiments

Peter Shanahan

Neutrino Summer Student Lecture Series

20 July 2015

Neutrino Mixing

Phase δ changes sign for anti-neutrino

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

$c_{13} \equiv \cos\theta_{13}, etc.$

"Atmospheric" ν_μ disappearance - SK

θ_{13} measured in reactors – Daya Bay, Reno

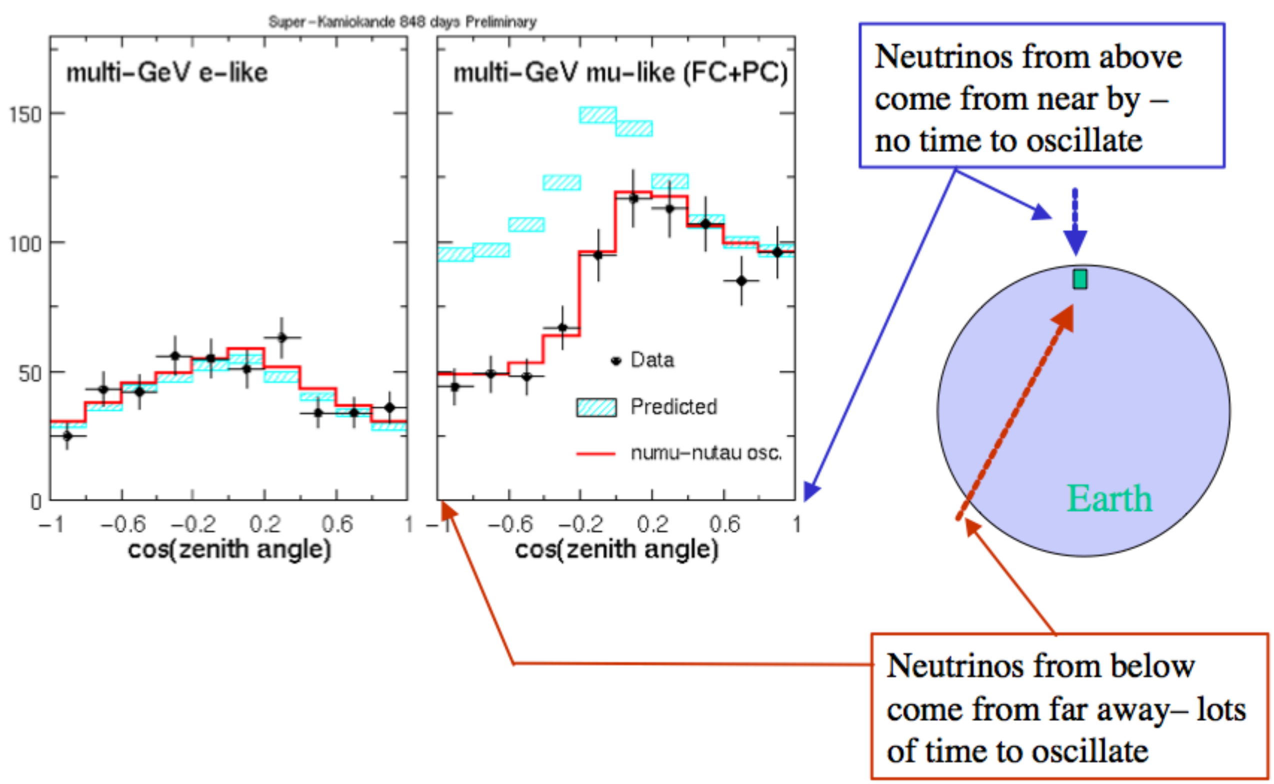
"Solar" ν_e disappearance - SNO

Oscillation probability, **in the limit of 2 flavors α and β**, mixed by angle θ, mass-squared difference Δm^2:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(\frac{\Delta M^2 L}{4E})$$

Neutrino energy E
Baseline L

SuperKamiokande told us ***early on***:
ν_μ must be oscillation mainly to ν_τ



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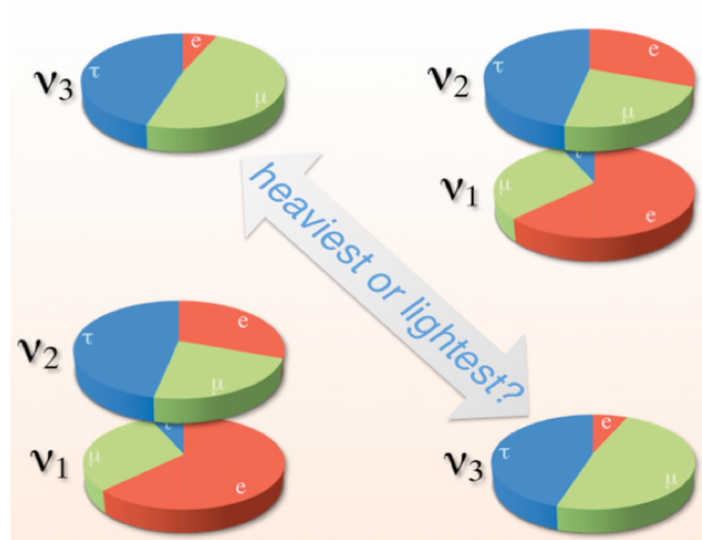
Neutrino Oscillations

- Important questions can be addressed with neutrino oscillations
  - What is the pattern of neutrino mass mixing, and what does it tell us when compared to that of quarks?
    - Large mixing, or small? Answered: Large!
    - What is the neutrino mass ordering?
    - $\theta_{23} > 45^o$ or $\theta_{23} < 45^o$?
  - Is there CP violation in the lepton sector? At what level?
    - Is this why matter >>> antimatter, and therefore why we exist?
- The rich phenomenology of long baseline/appearance has a critical role in answering these questions



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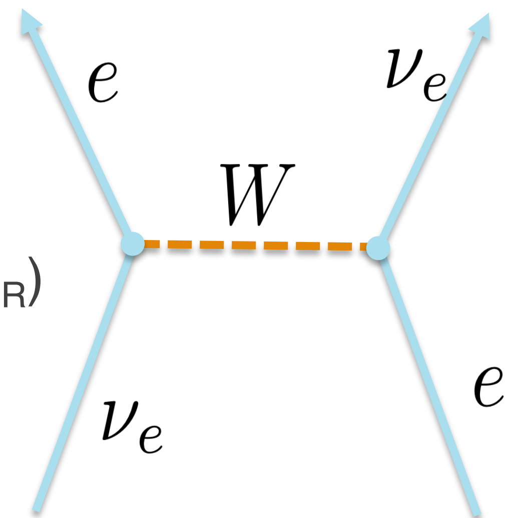
Why Long Baseline?

- Thresholds
  - 735m baseline would be a lot cheaper than 735 km
    - All other things equal, $\phi(m)/\phi(km)=10^6$
  - ***However***, for atmospheric $\Delta m^2 \sim 2.5\times10^{-3}$ eV^2, Oscillation max at L=735m is at E=1.47 MeV
    - Well below ν_μ CC quasi-elastic threshold ~100 MeV!
- Sensitivity to neutrino Mass Ordering
  - via MSW (Matter) effect
    - Effectively a modification of some oscillation terms of form $P \rightarrow P_1(1 \pm 2E/E_R)$

$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2}G_F\rho_e} \approx \text{11 GeV for Earth's Crust}$$

  - Longer baseline ➔ larger effect

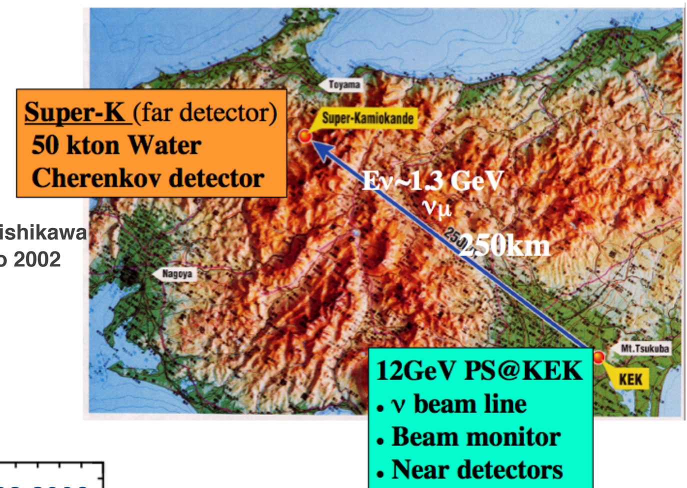


Challenges of Long Baseline Experiments

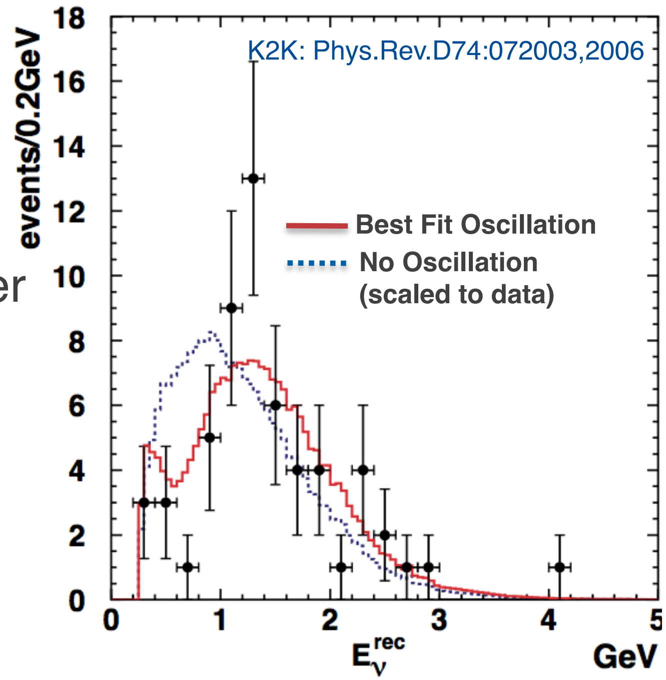
- Event Rate
  - $N \sim \phi M \sigma$
  - Flux → High Intensity Beams
  - Mass → Massive detectors
- Backgrounds
  - Looking for small effects → Detector technologies, etc
- Uncertainties in
  - Flux
  - Cross Sections → **Near Detector**
  - Detector effects

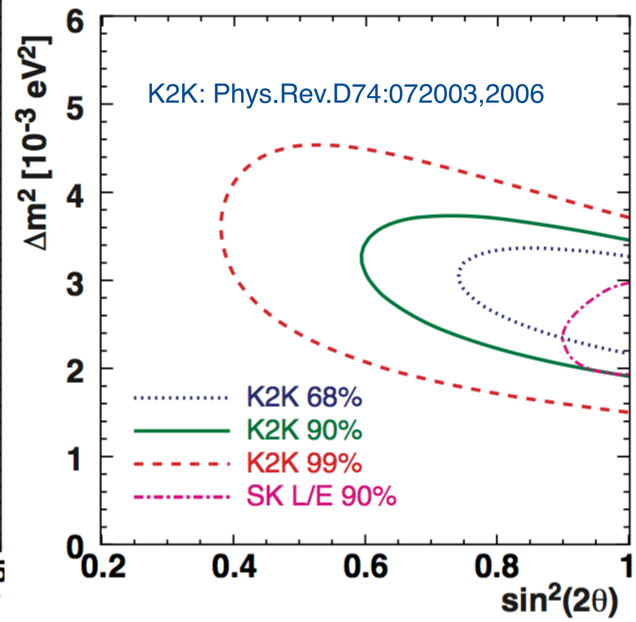
K2K – The First Long Baseline Experiment

- K2K – KEK (Tsukuba) to Kamioka
  - 250 km baseline, ~5 kW beam
- Extra challenges
  - SK PMT accident – 2001
  - Oscillation maximum close to threshold
- First evidence for ν_μ disappearance using an accelerator
  - Plots: from Measurement paper Several months after MINOS' first results



Koichiro Nishikawa
Neutrino 2002





Accelerator Long Baseline

- Soudan Lab website c. 1997

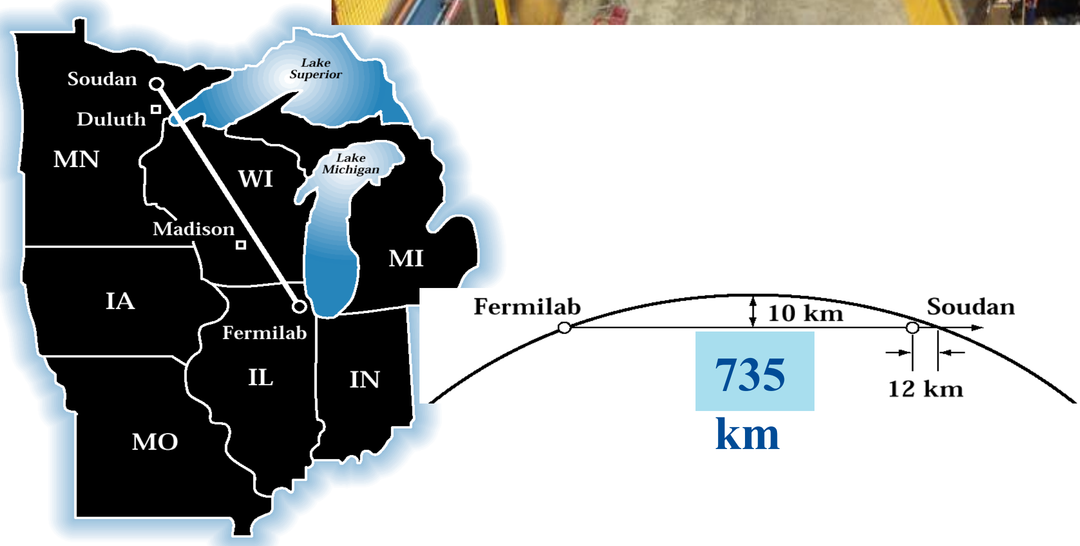
Preliminary data taken at Soudan confirm results from two other detectors indicating a shortage of muon-type neutrinos, supporting the idea that neutrinos do have mass.

This possibility is so important that further experiments on neutrino mass are planned at several laboratories worldwide. The proposed MINOS (Main Injector Neutrino Oscillation Search) experiment would generate neutrinos at Fermi National Accelerator Laboratory, about 70 km west of Chicago. These neutrinos would then be directed north northwest about 730 km through the earth to the laboratory at Soudan. A "near" detector located at Fermilab would be used to measure the relative numbers of the three types of neutrinos near the production point. Both a new 10,000 ton MINOS detector and the existing Soudan 2 detector would be used to measure the same ratios at the remote location. A change in the proportions of electron, muon and tau- type neutrinos between the near and far laboratories would indicate that neutrinos have mass. The magnitude of the neutrino mass and the strength of the overlap among neutrino types could then be measured using the same instrumentation. Since neutrinos almost never interact with matter, neutrino beams have no influence on people, animals and plants.

If the MINOS experiment is approved, the new detector would be built in a new laboratory located about 50 m east of the current Soudan laboratory. **The MINOS experiment would likely begin data collection about the year 2000, thus extending the usefulness of the Soudan laboratory for at least another decade.**

MINOS

- Focus on ν_μ disappearance
  - And $\nu_\mu \rightarrow \nu_e$
- Original user of NuMI beam
- Magnetized Fe-Plastic Scintillator tracking calorimeters
  - Near (1kt) and Far (5kt) detectors separated by 734 km



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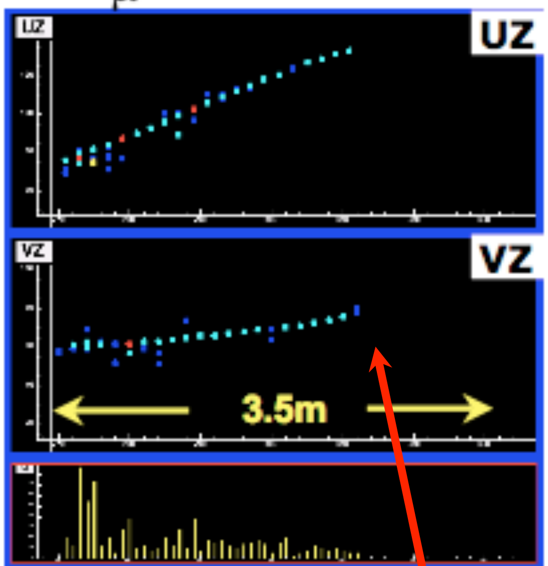
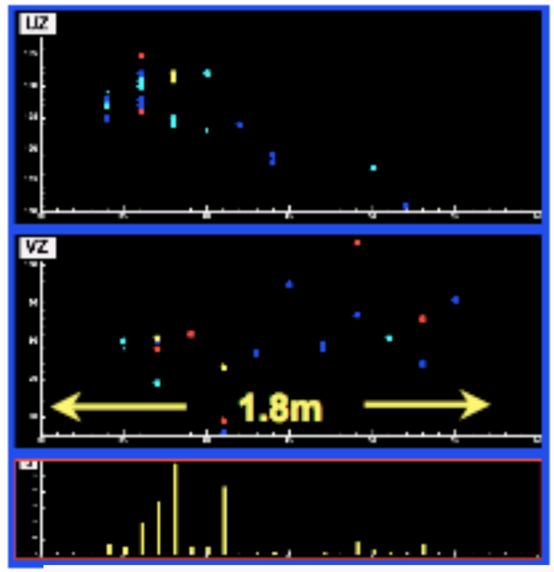
Neutrino Event Signatures in MINOS

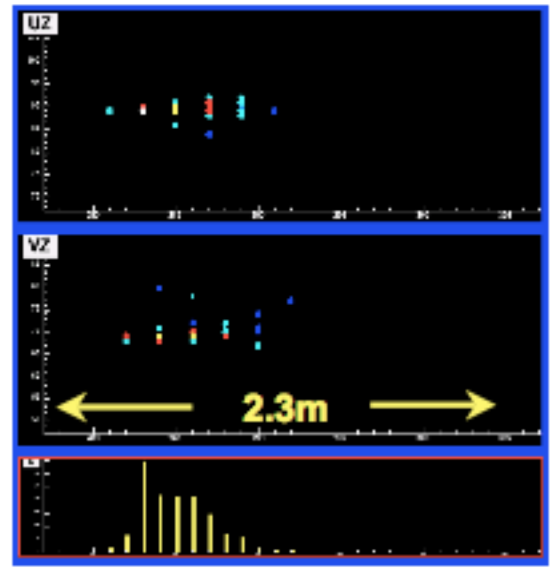
ν_μ CC Event



NC Event



ν_e CC Event



Hadronic recoil

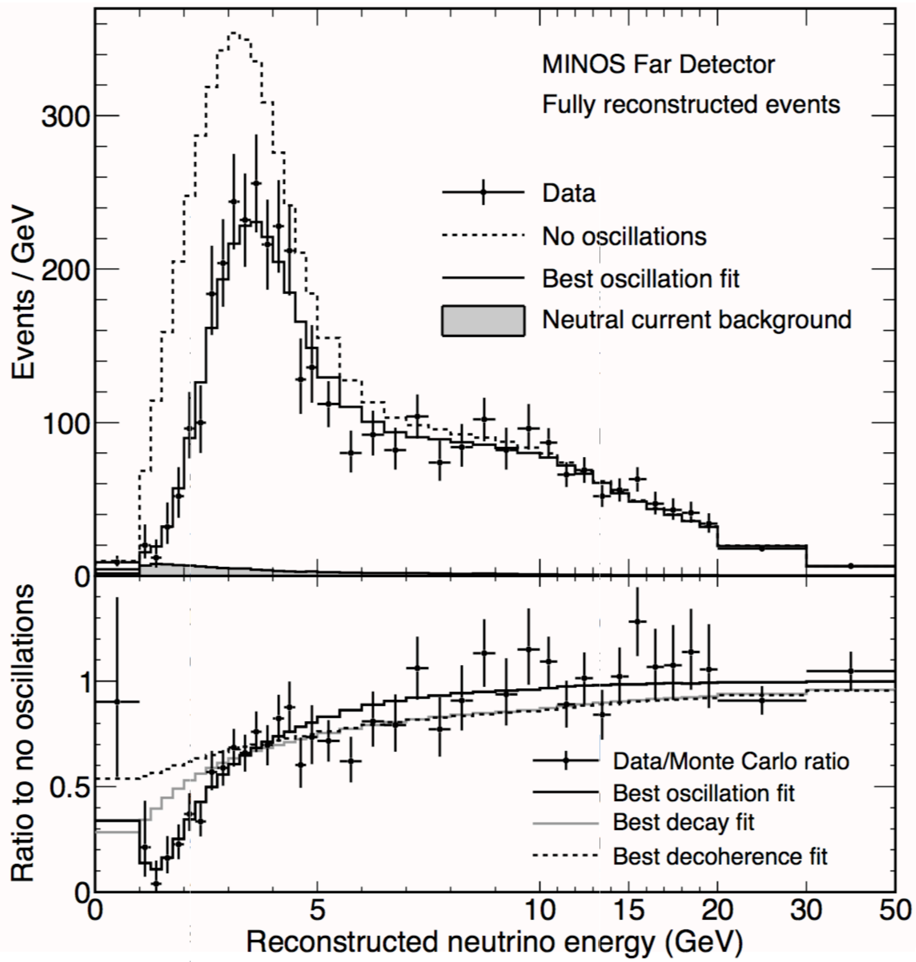
Long muon track

Momentum from range and/or curvature

Only a (diffuse) shower from hadronic recoil

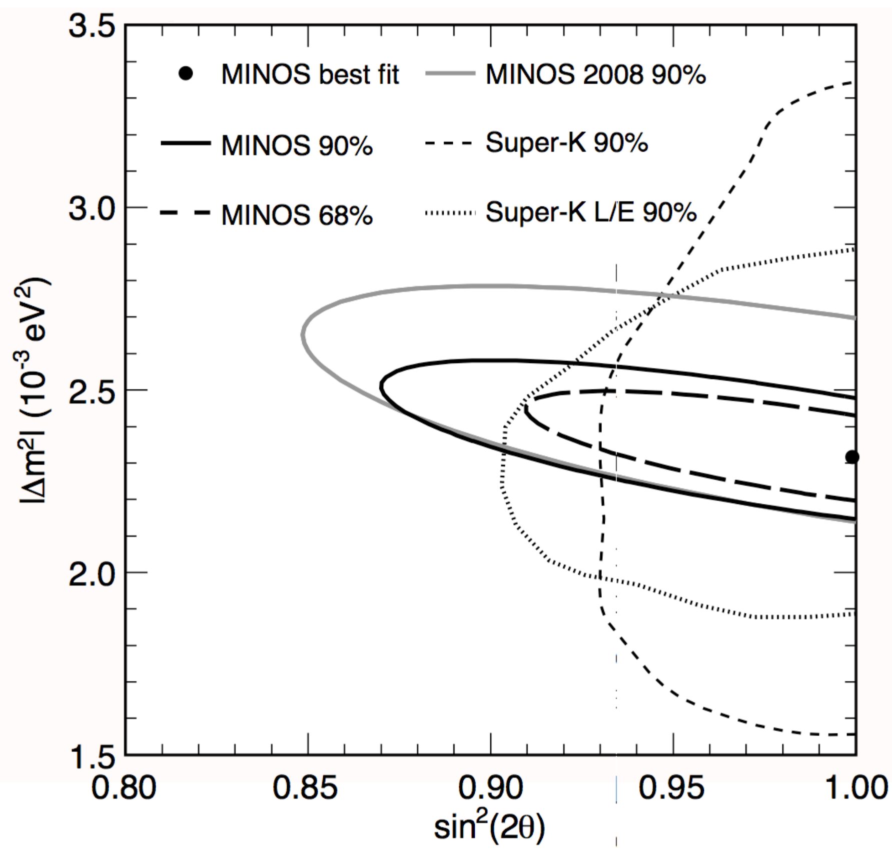
ν_e CC: Electromagnetic shower, shorter with higher pulse heights

MINOS



Last MINOS ν_μ disappearance results from NuMI only

Phys.Rev.Lett.106:181801,2011



Going beyond Δm^2 vs $\sin^2(2\theta_{23})$ in ν_μ Disappearance?

- Full 3-flavor survival probability in vacuum

$P(\nu_\mu \rightarrow \nu_\mu) =$

$$
\begin{aligned}
1 \quad & - 4(s^2_{12}c^2_{23}+s^2_{13}s^2_{23}c^2_{12} + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{31} \\
& - 4(c^2_{12}c^2_{23}+s^2_{13}s^2_{23}s^2_{12} - 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{32} \\
& - 4(s^2_{12}c^2_{23} + s^2_{13}s^2_{23}c^2_{12} + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta) \\
& \times (c^2_{12}c^2_{23} + s^2_{13}s^2_{23}s^2_{12} - 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)\sin^2\phi_{21}
\end{aligned}
$$

$$\phi_{ij}=\Delta m^2_{ij}L/4E$$

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$P(\nu_\mu \rightarrow \nu_\mu) \approx$

$$1 \quad - 4(s^2_{12}c^2_{23}+s^2_{13}s^2_{23}c^2_{12} + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{31}$$
$$- 4(c^2_{12}c^2_{23}+s^2_{13}s^2_{23}s^2_{12} - 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{32}$$

To within <1% near the atmospheric oscillation maximum, given the value of Δm^2_{21}

$P(\nu_\mu \rightarrow \nu_\mu) \approx$

$$1 \quad - 4(s^2_{12}c^2_{23}+s^2_{13}s^2_{23}c^2_{12} + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta$$
$$+ \quad c^2_{12}c^2_{23}+s^2_{13}s^2_{23}s^2_{12} - 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{Atm}$$

To within ~ %

$$P(\nu_\mu \rightarrow \nu_\mu) \approx$$

$$1 \quad - 4(s^2_{12}c^2_{23}+s^2_{13}s^2_{23}c^2_{12}$$

$$+ \quad c^2_{12}c^2_{23}+s^2_{13}s^2_{23}s^2_{12} \quad)s^2_{23}c^2_{13}\sin^2\phi_{Atm}$$

$P(\nu_\mu \rightarrow \nu_\mu) \approx$

$$1 - 4(\, c^2_{23} + s^2_{13}s^2_{23}\,)s^2_{23}c^2_{13}\sin^2\phi_{Atm}$$

For $\theta_{23}=45^o$ and $\theta_{13} \sim 9^o$

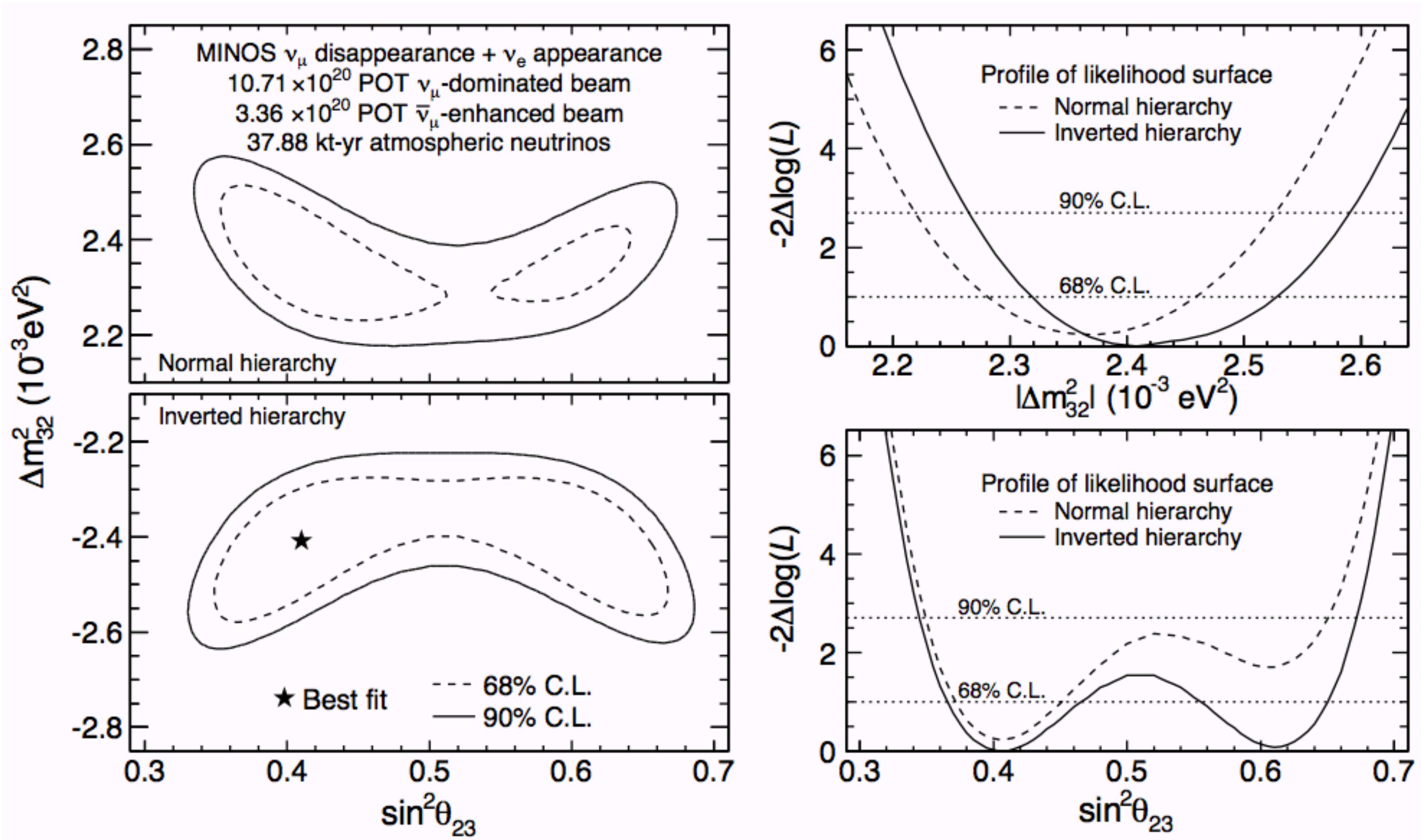
$$\approx 1-(1+ 0.025)\sin^2(2\theta_{23})\sin^2\phi_{Atm}$$

I.e., ν_μ survival probability has 2 flavor form to ~few %

% scale precision measurements needed for to see 3-flavor effects

MINOS Joint Fit: beam and atmospheric $\overset{(-)}{\nu}_\mu$, beam ν_e

- As MINOS uncertainty on Δm^2_{Atm} approached Δm^2_{21}, 3-flavor fit became possible/necessary

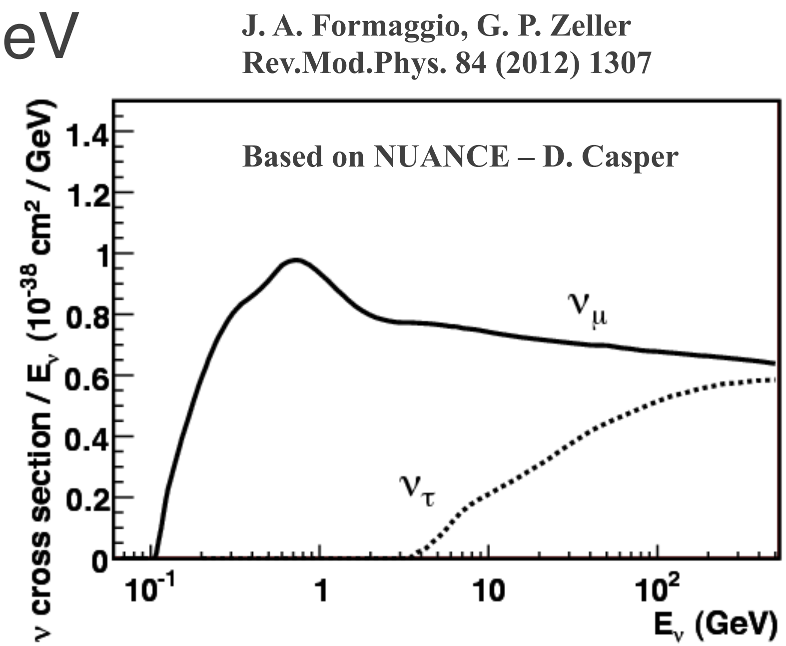


Phys. Rev. Lett. 112, 191801 (2014)

ν_τ Appearance – A BIG Challenge!

- CC τ production threshold = 3.45 GeV
  - **If** you want σ=1x10^{-38}cm^2, you **would need** E_ν=7 GeV
- Osc Max for Atmospheric Scale at 7 GeV occurs at 3600 km!

Example 3600 km: Fermilab to San Jose, Costa Rica



- Also, τ are very difficult to detect

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Opera – ν_τ Appearance

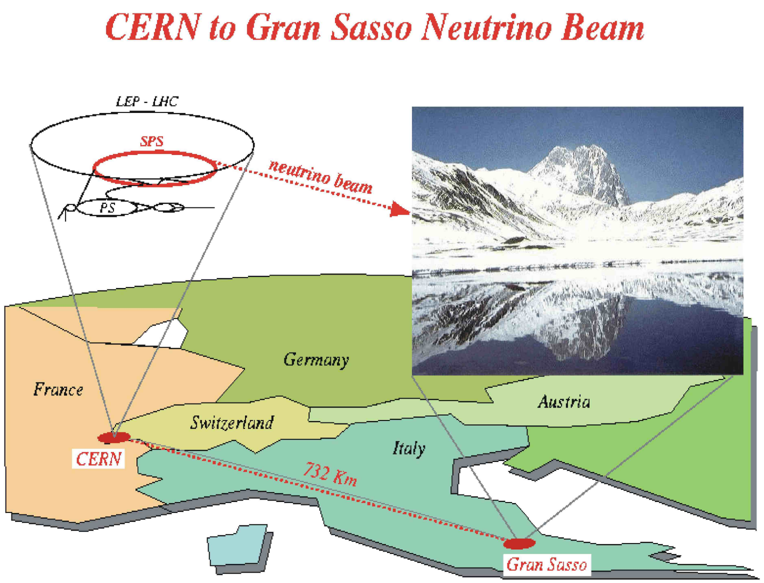
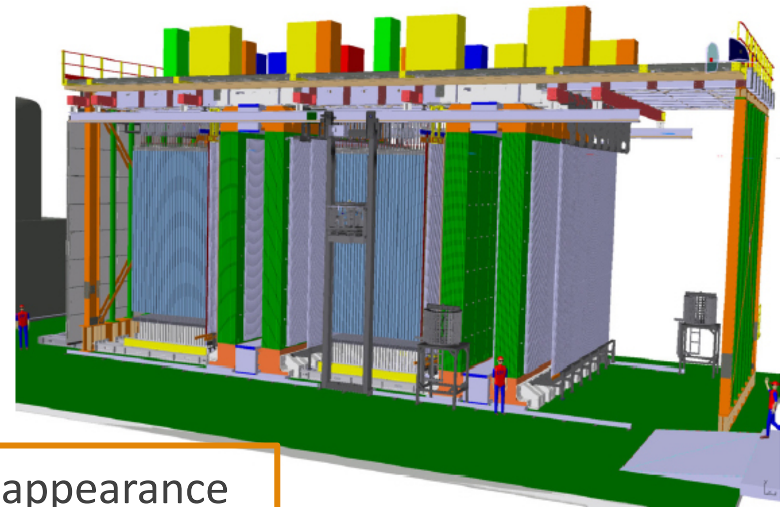
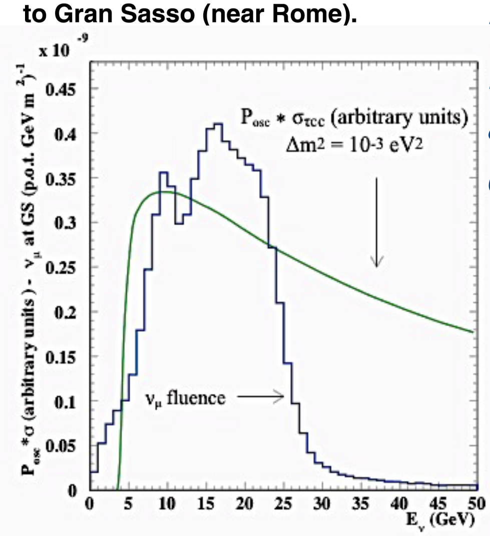


Fig. 2: Sketch of the 732 km distance from CERN in Geneva to Gran Sasso (near Rome).

Opera target: 15000 emulsion bricks

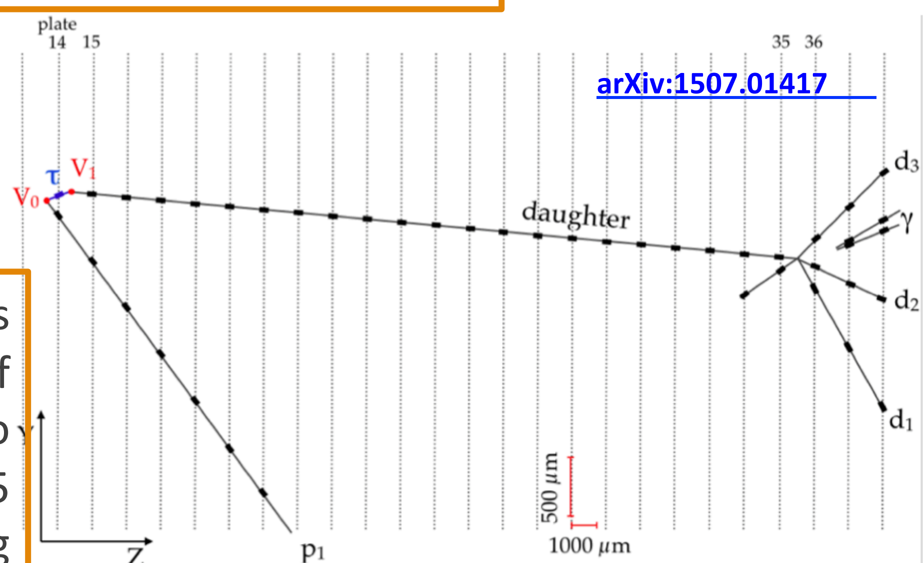


5 σ $\nu_\mu \rightarrow \nu_\tau$ appearance announced this month



ν_μ flux optimized for ν_τ appearance and detection

5 events observed out of 5400 neutrino interactions in 5 years of running



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Long Baseline ν_e Appearance

- What can ν_e appearance do for us?
  - $\sin^2(2\theta_{13})$ – we've known that since 2011 thanks to Daya Bay
  - Exploration of effects on the scale of $\sin^2(2\theta_{13})$
    - Not diluted by $\sin^2(2\theta_{23})$
  - Neutrino Mass Ordering via Matter Effect
  - CP Violation
    - "Disappearance = total time evolution operator = mass = CP invariant by CPT symmetry" ➔ Cannot detect CP violation in disappearance, even comparing ν and $\bar{\nu}$
  - θ_{23} Octant
    - If not maximal, is $\theta_{23} < 45^o$ or $> 45^o$?

Long Baseline ν_e Appearance Probability

- $P(\nu_\mu \rightarrow \nu_e) \cong P_{Atm} + P_{\sin\delta} + P_{\cos\delta} + P_{Sol}$

DUNE Science Report and References

$$P_{Atm}=\sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(A-1)\Delta]}{(A-1)^2}$$

$$P_{Sol}=\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(A\Delta)}{A^2}$$

$$P_{\sin\delta}=\alpha 8J_{CP}\sin\Delta\sin(A\Delta)\frac{\sin[(1-A)\Delta]N}{A(1-A)}$$

$$P_{\cos\delta}=\alpha 8J_{CP}\cot\delta_{CP}\cos\Delta\sin(A\Delta)\frac{\sin[(1-A)\Delta]}{A(1-A)}$$

δ_{CP} and A change sign for $\bar{\nu}$

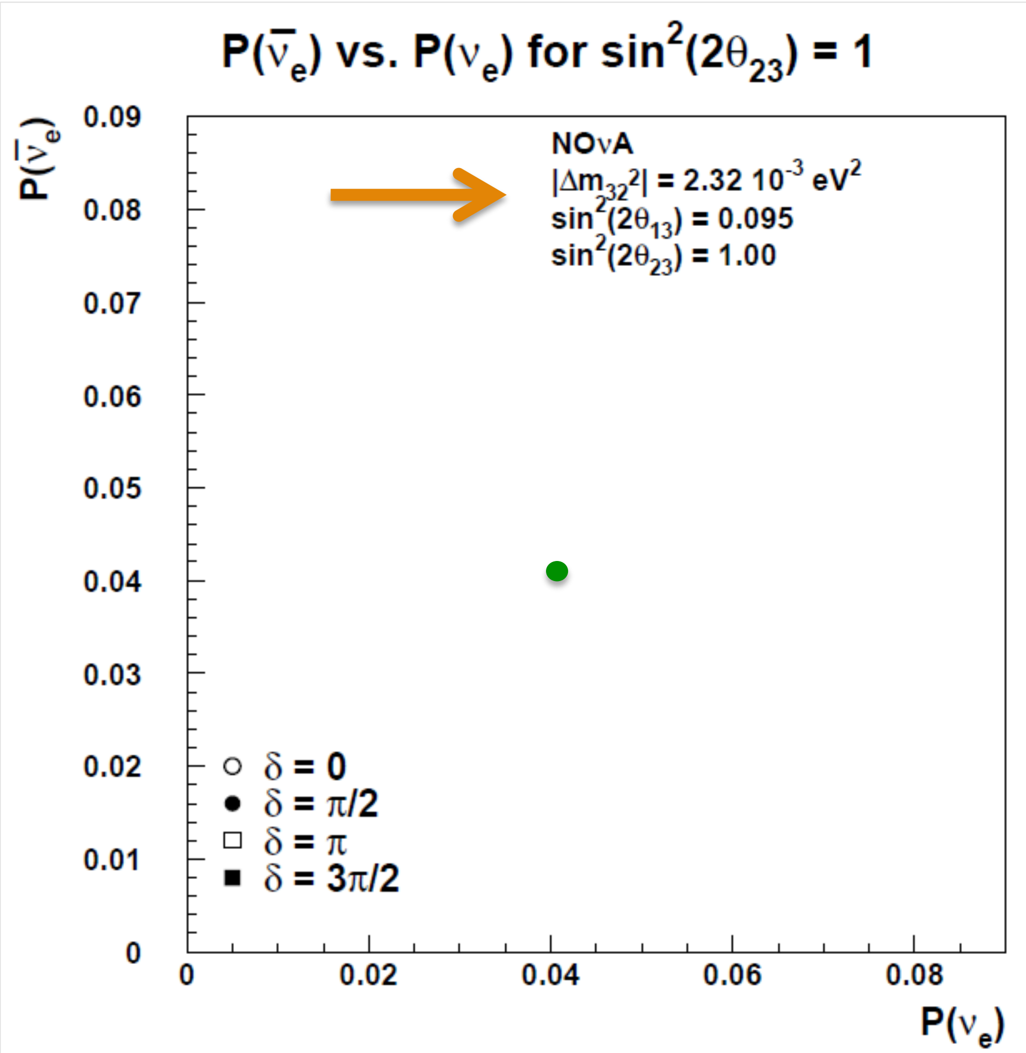
A depends explicitly on (sign of) Δm^2_{31}

$\Delta=\Delta m^2_{31}L/4E$ $\quad$ $A=\sqrt{2}G_F N_e 2E/\Delta m^2_{31}$ $\quad$ $\alpha=|\Delta m^2_{21}|/|\Delta m^2_{31}|$

$J_{CP}=\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\delta_{CP}/8 \approx 0.03\,\delta_{CP}$

Jarlskog Invariant

Principle of Measurement



Comparison of neutrino and anti-neutrino appearance for case of

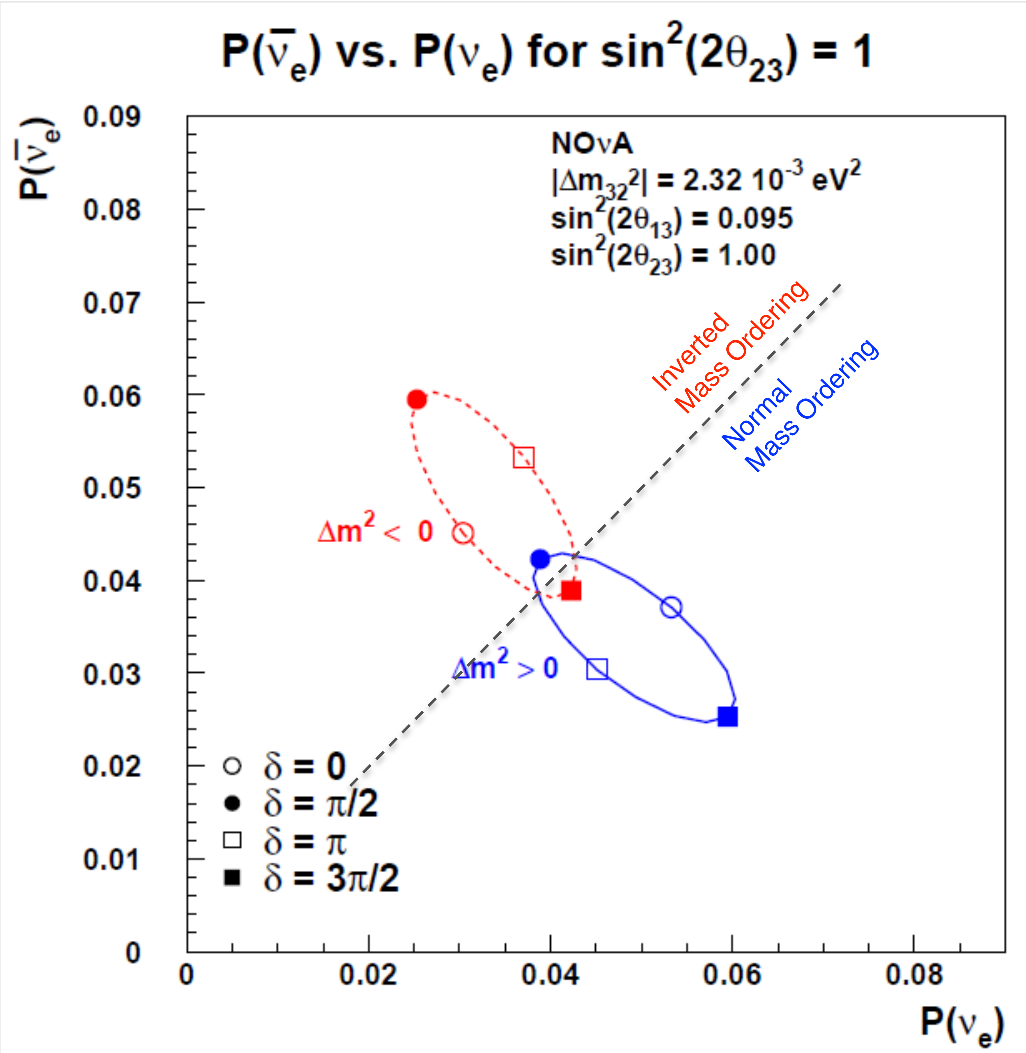
-No matter effect

-No CP Violation

-Maximal θ_{23}

-Not terribly exciting…

Principle of Measurement



CP Violation

-Probabilities vary on an ellipse with δ_{CP}

Mass Ordering

-Matter effect shifts ellipse

Shown for Maximal θ_{23}

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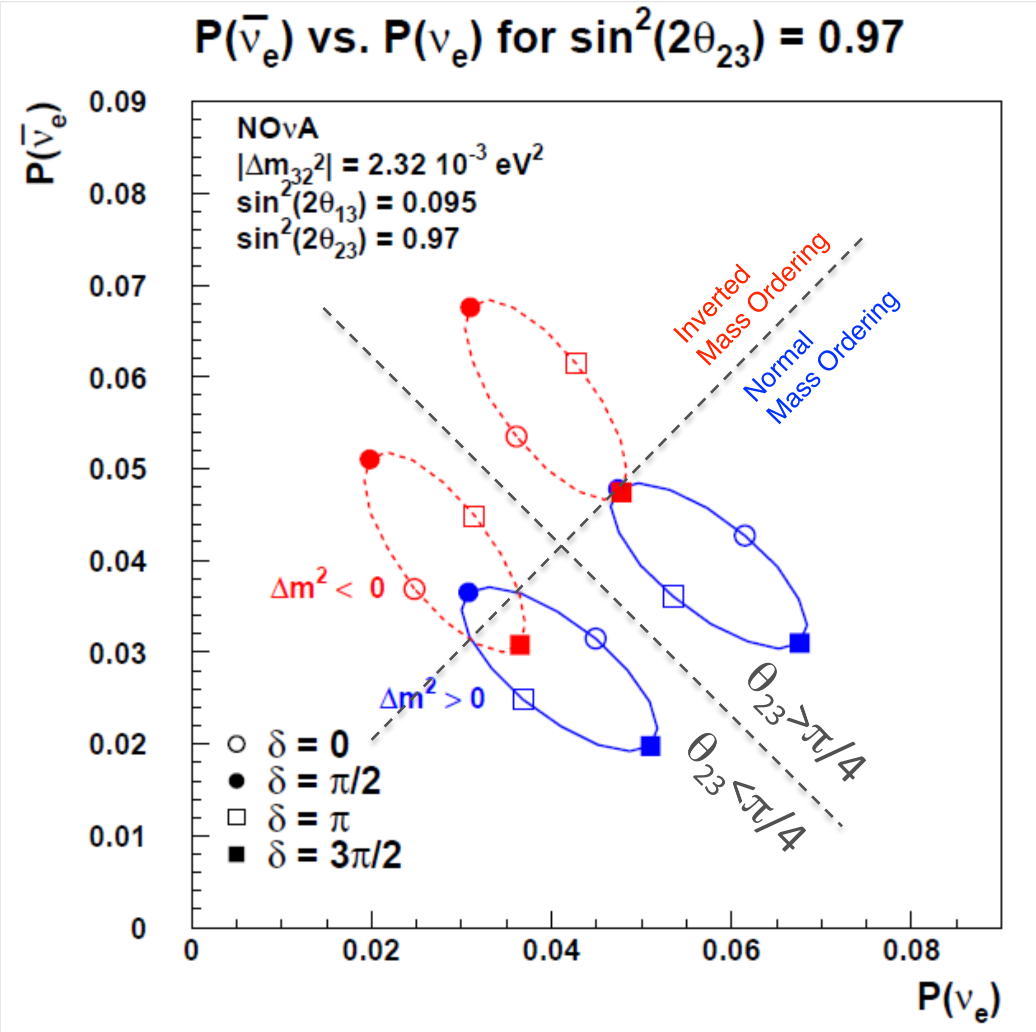
Principle of Measurement



θ_{23} Octant
From $P_{atm} \sim \sin^2(\theta_{23})$

Design Requirements for ν_e Appearance

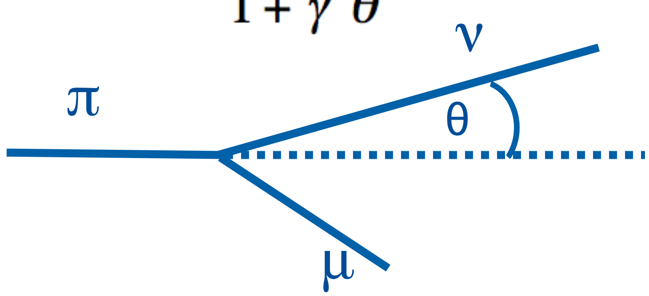
- High(er) Beam Power & Large(r) Detectors
  - 10+ kt scale
- Good Electron Identification
  - Technology for detecting electromagnetic showers
- Background Suppression
  - Detector Technology, possibly Off-Axis Beam
- ν and $\bar{\nu}$ bar modes
  - Reverse horn current to focus p^- ,k^- for $\bar{\nu}$
- Baseline for Matter Effect
  - Really a matter of energy/resonance energy: $E_R \approx 11$ GeV
- Measurement of backgrounds and unoscillated rate
  - Near Detector

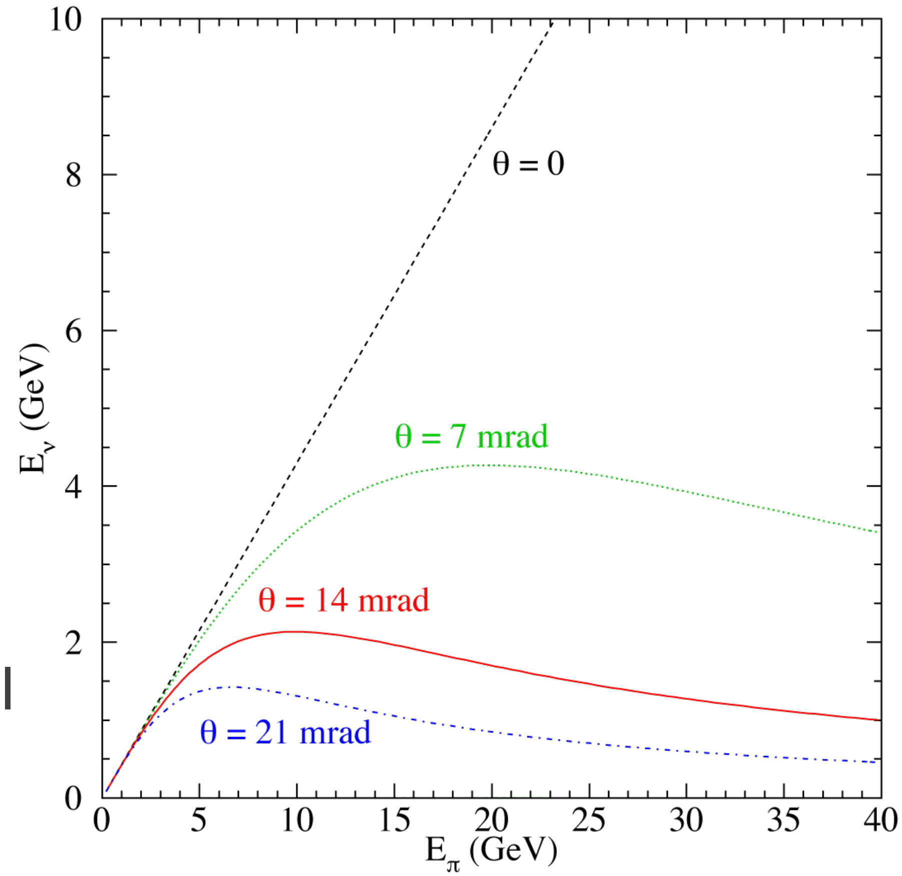
Such an experiment will also do ν_μ disappearance very well!

Off-Axis

- Place Detector Off-axis for narrow-band beam
  - Pion 2-body decay kinematics

$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$





  - Off-axis: Large variation in parent pion energy gives small variation in neutrino energy

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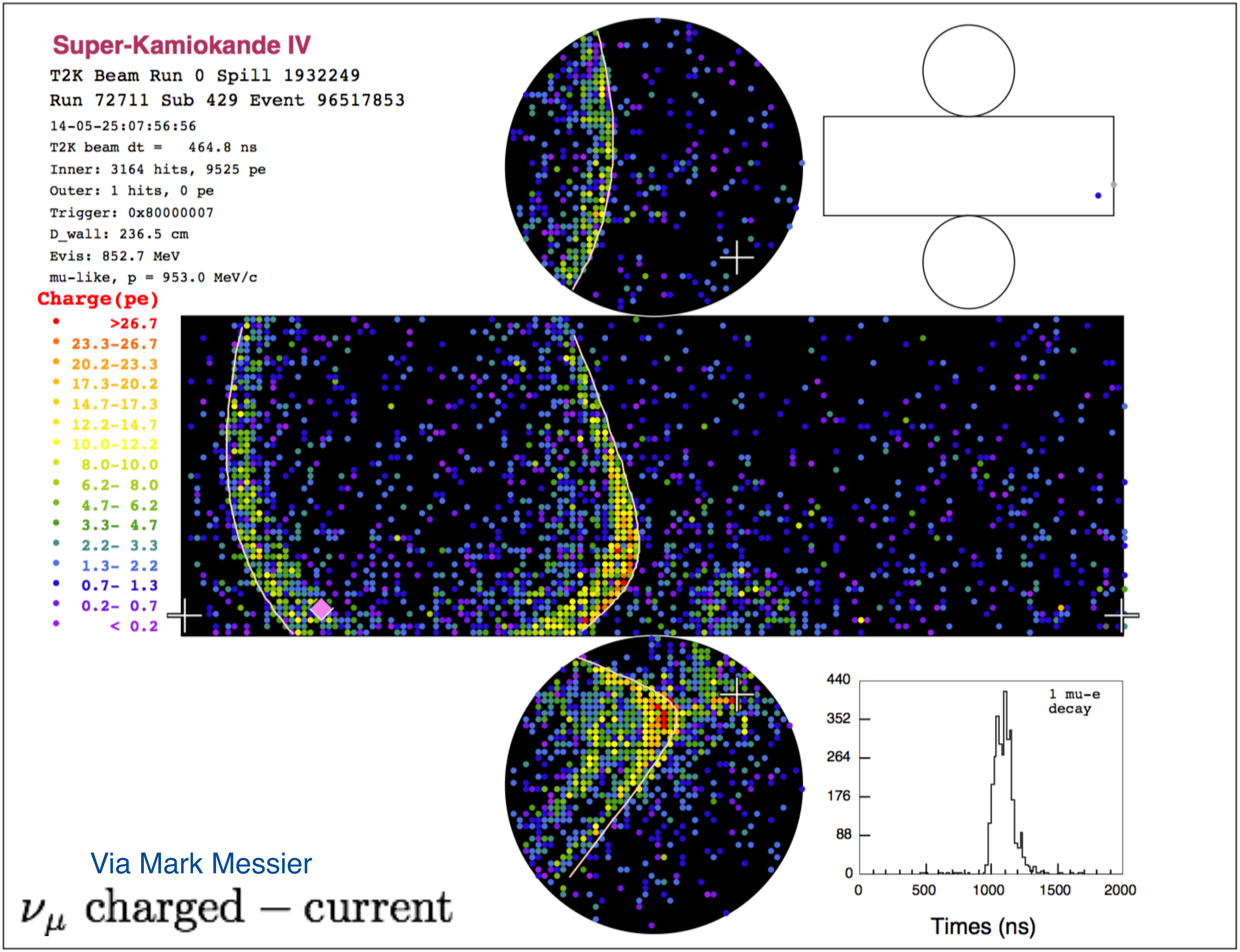
T2K

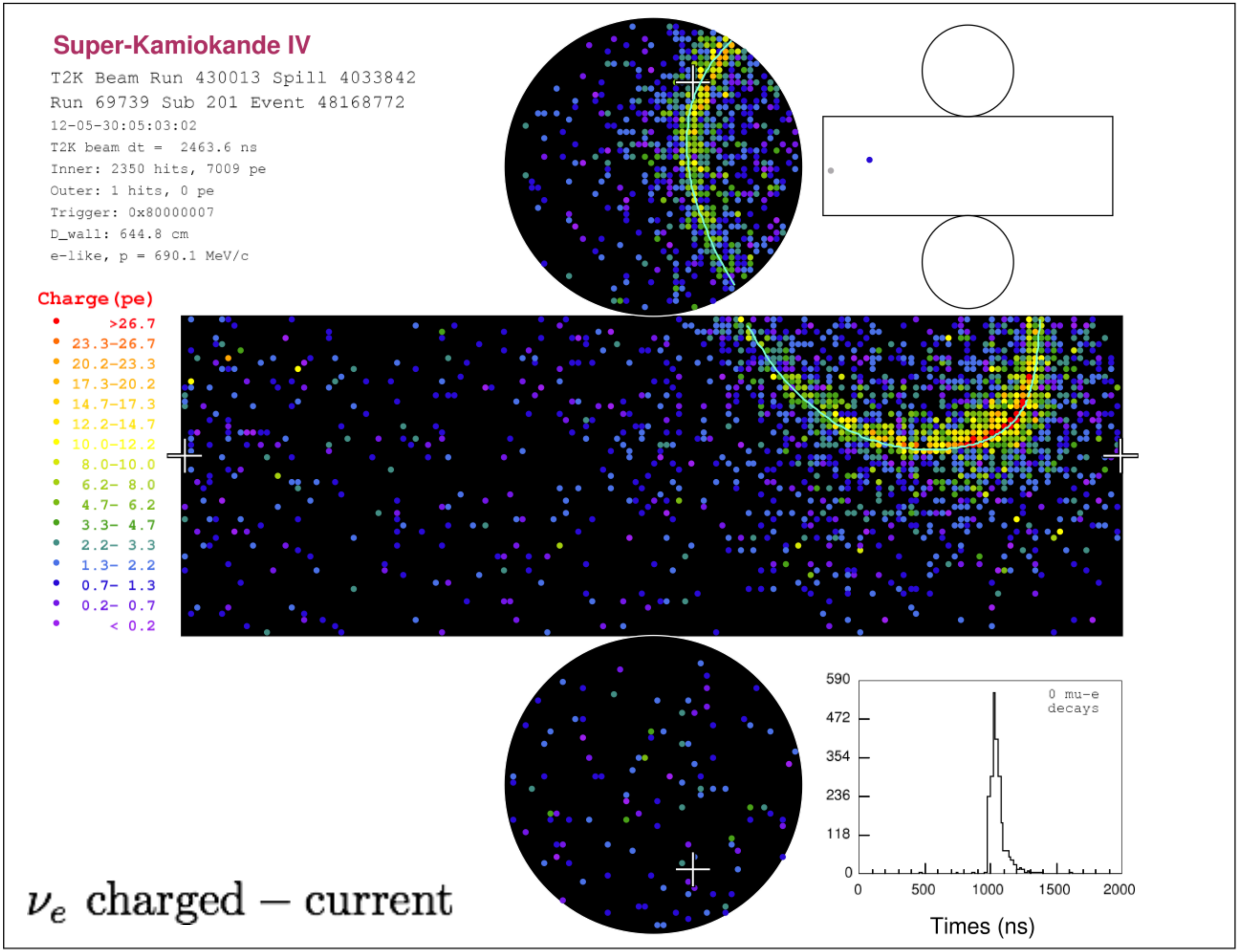
50 kt Far Detector

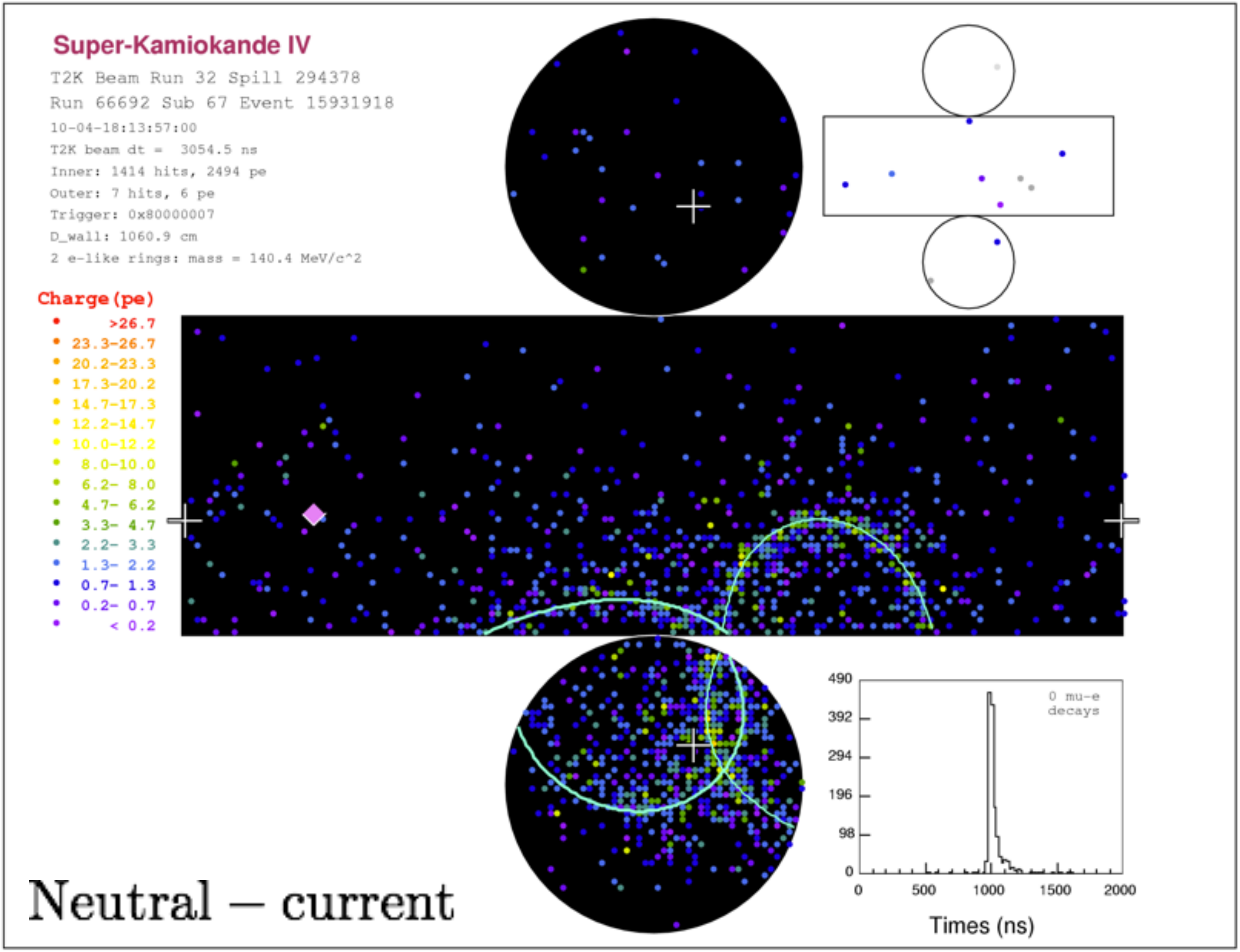
750 kW design beam power
2.5^{o} off-axis angle



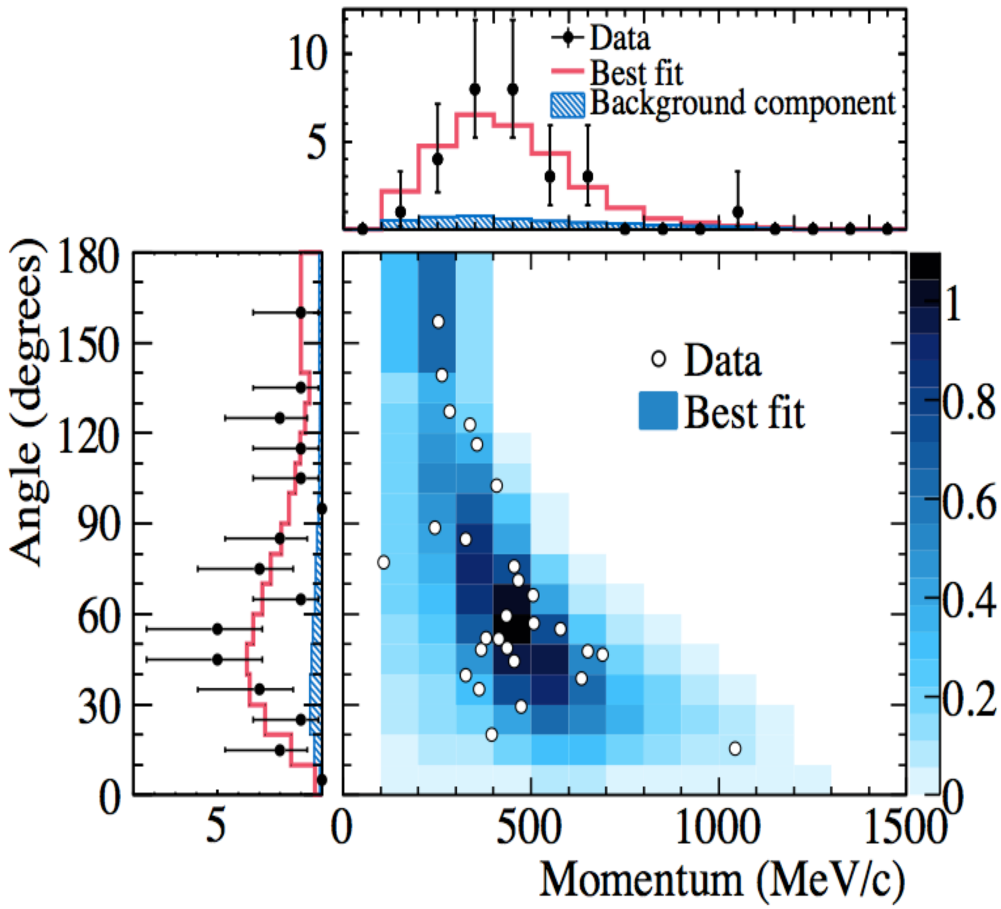
Via Mark Messier

ν_μ charged − current


Super-Kamiokande IV
T2K Beam Run 430013 Spill 4033842
Run 69739 Sub 201 Event 48168772
12-05-30:05:03:02
T2K beam dt = 2463.6 ns
Inner: 2350 hits, 7009 pe
Outer: 1 hits, 0 pe
Trigger: 0x80000007
D_wall: 644.8 cm
e-like, p = 690.1 MeV/c
Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
590
472
354
236
118
0
0
500
1000
1500
2000
0 mu-e decays
Times (ns)
ν_e charged − current


Super-Kamiokande IV
T2K Beam Run 32 Spill 294378
Run 66692 Sub 67 Event 15931918
10-04-18:13:57:00
T2K beam dt = 3054.5 ns
Inner: 1414 hits, 2494 pe
Outer: 7 hits, 6 pe
Trigger: 0x80000007
D_wall: 1060.9 cm
2 e-like rings: mass = 140.4 MeV/c^2
Charge(pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
0 mu-e decays
490
392
294
196
98
0
0
500
1000
1500
2000
Times (ns)
Neutral – current

T2K ν_e Appearance



4.92 ± 0.55 background

28 events observed

7.3σ observation of oscillations

21.6 events expected

$\sin^2 2\theta_{13}=0.1$

$\delta_{CP} = 0$

$\sin^2\theta_{23} = 0.5$

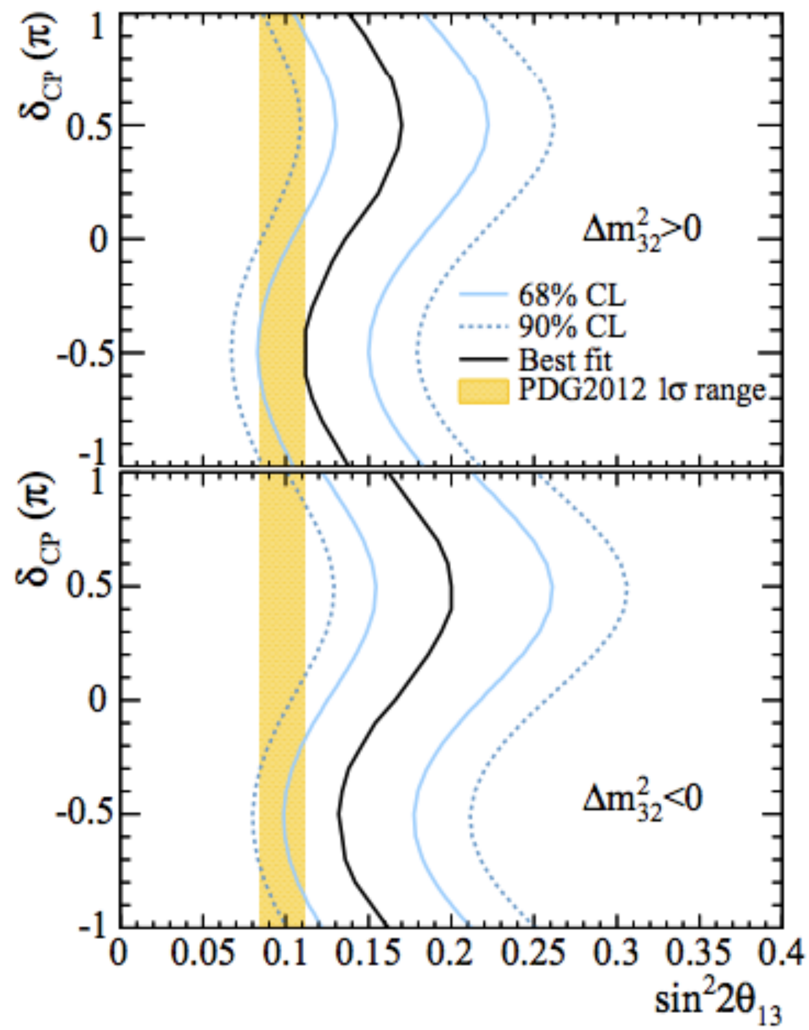
T2K Compared to Reactor θ_{13}

T2K $\sin^2\theta_{13}$ result vs δ_{CP}

$\sin^2\theta_{23}$ and Δm^2_{23} varied as allowed by T2K disappearance results

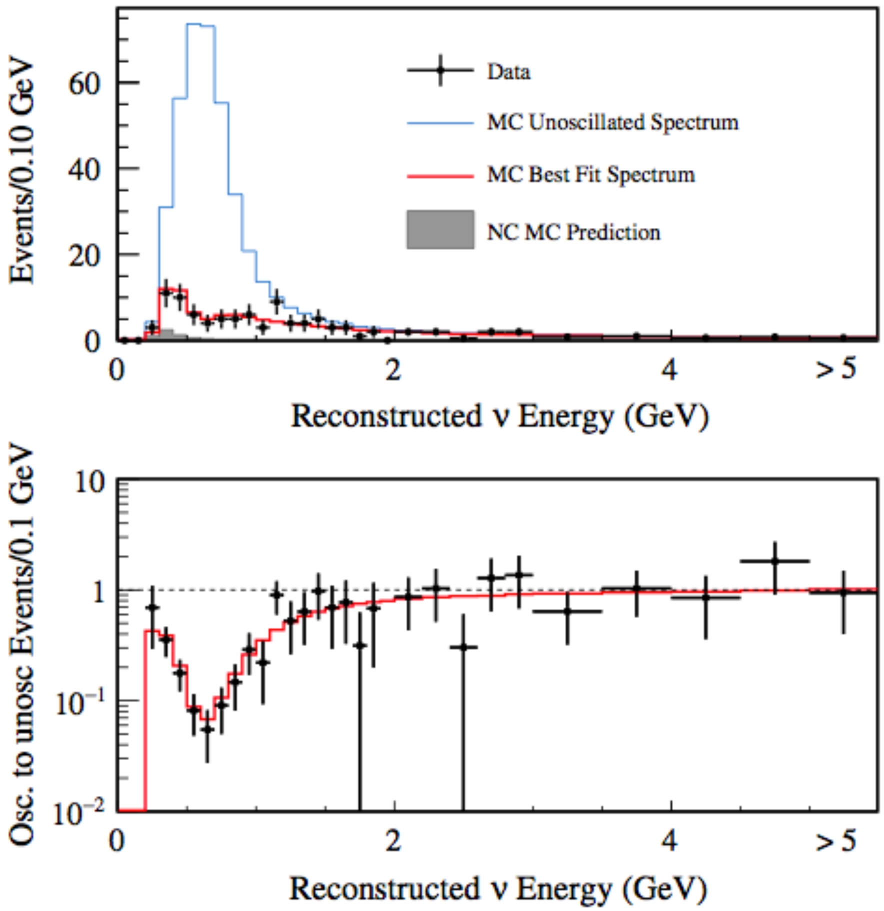
Slight favoring of Normal Ordering, $\delta_{CP}=-\pi/2$

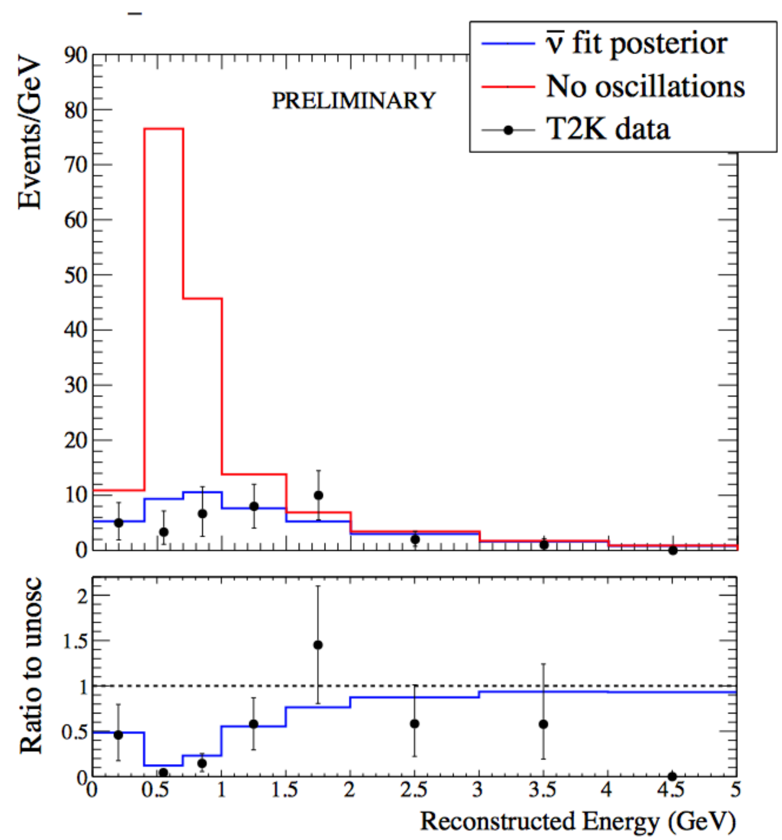
Note! $\delta_{CP}=3\pi/2$ in NOvA convention



T2K Disappearance

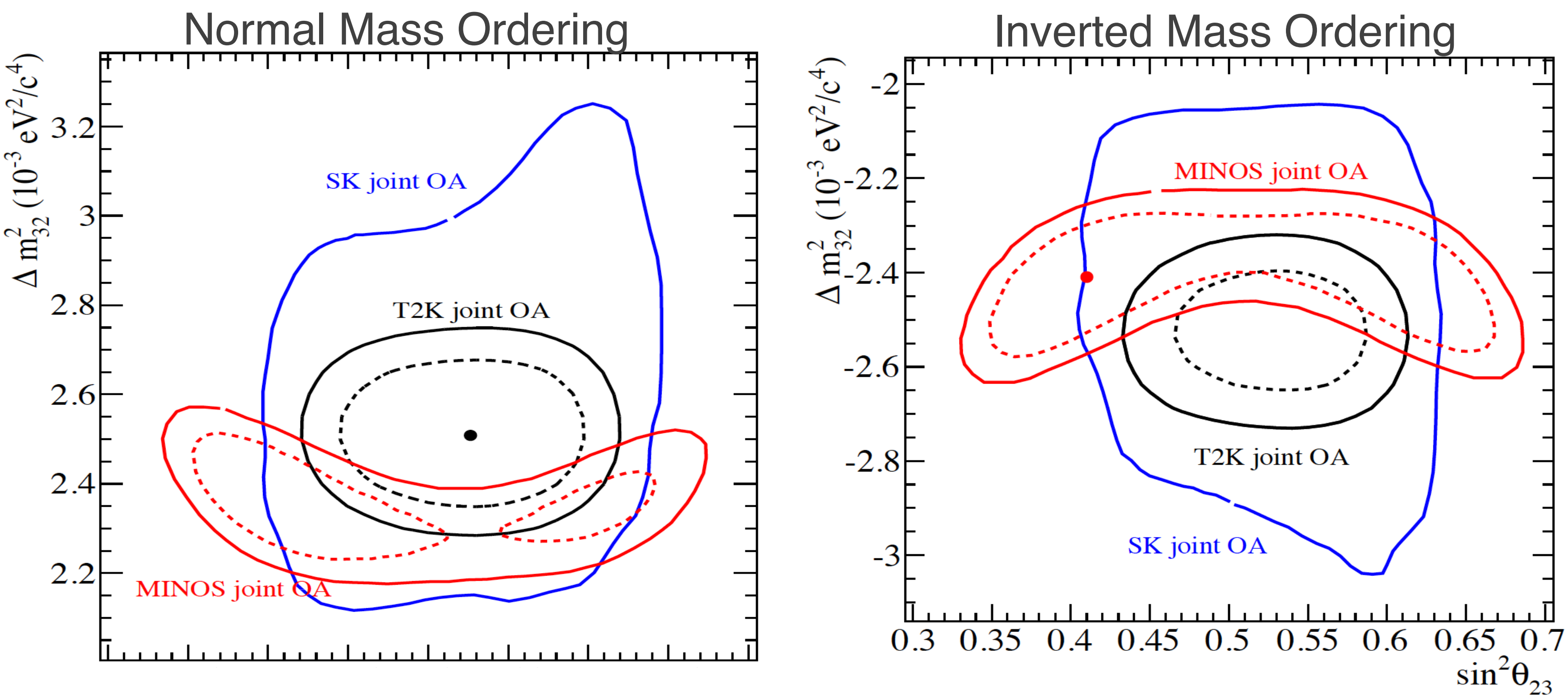
Neutrino Mode
Phys. Rev. D 91, 072010





Anti-neutrino mode
KEK Seminar
May 18, 2015
A. Kobath

T2K Joint ν_μ Disappearance / ν_e Appearance results



T2K best fits: (negligible) preference for Normal Ordering

$\sin^2\theta_{23}=0.524^{+0.057}_{-0.059}$ (NO) $\sin^2\theta_{23}=0.523^{+0.055}_{-0.065}$ (IO)

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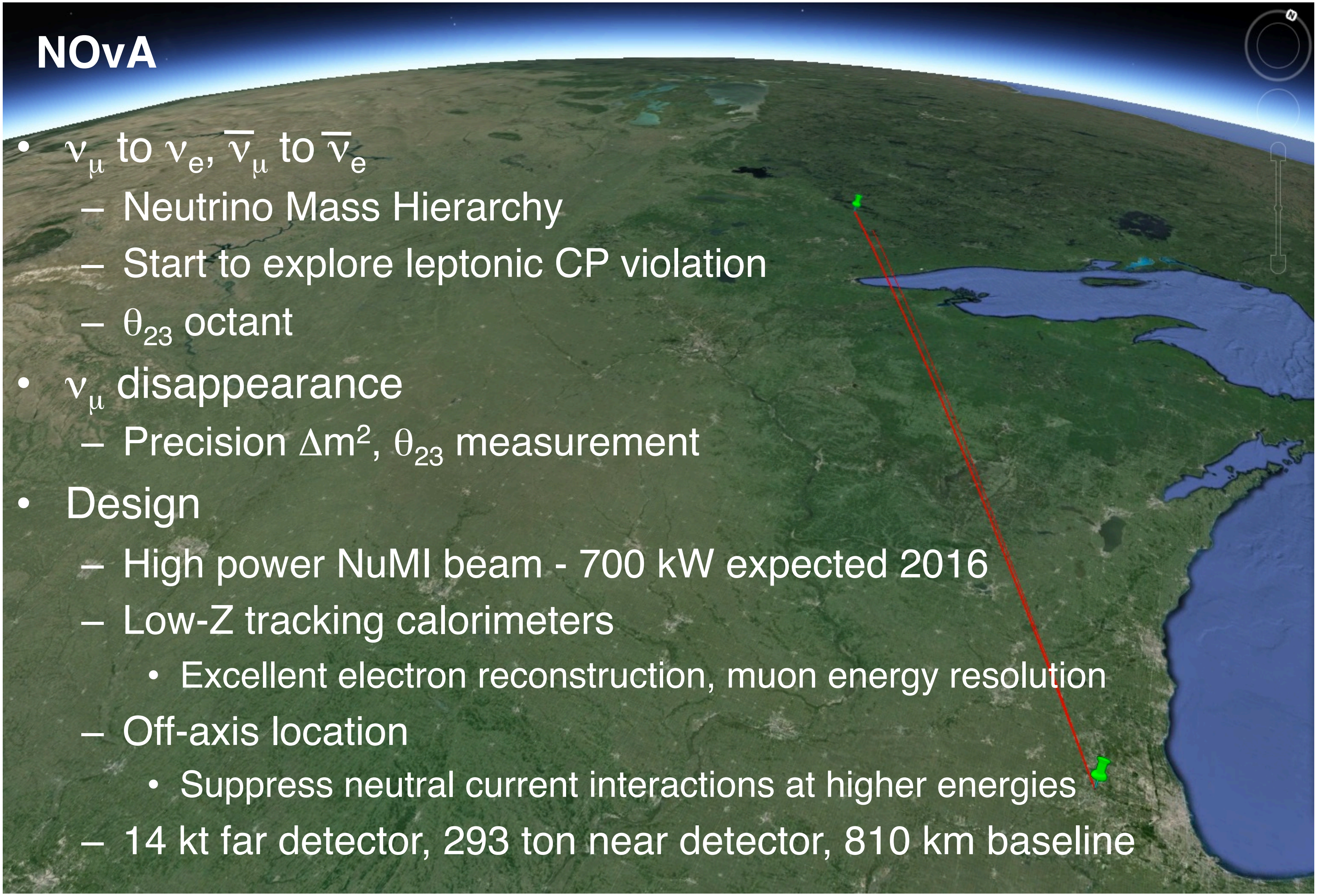
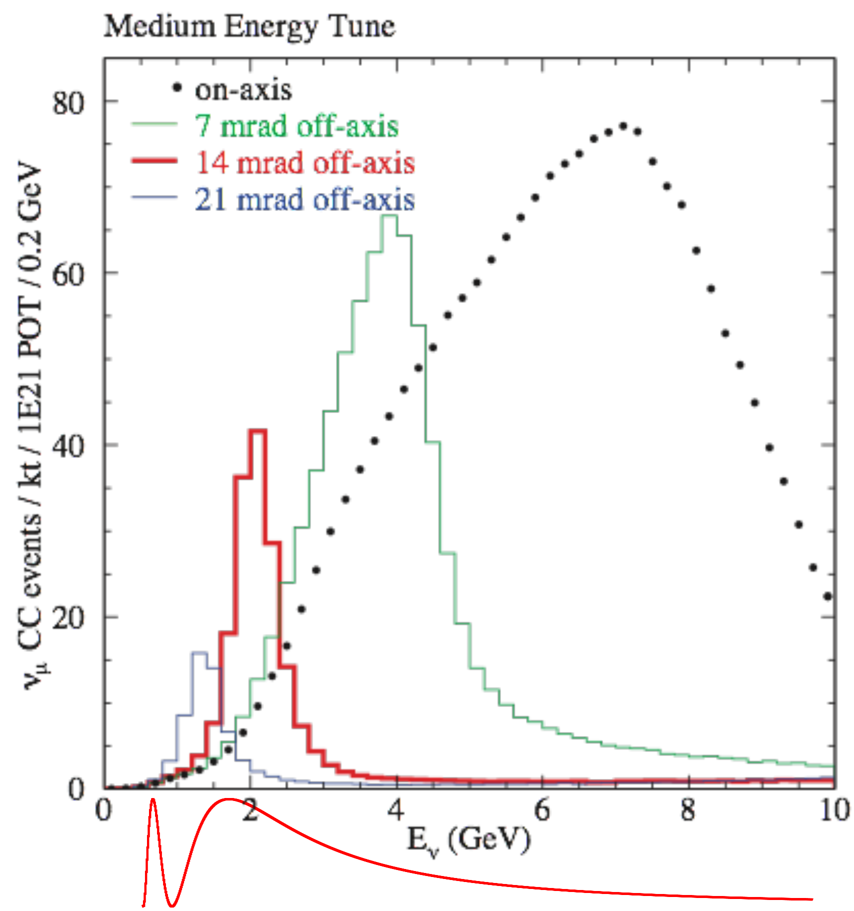
NOvA



- ν_μ to ν_e, $\bar{\nu}_\mu$ to $\bar{\nu}_e$
  - Neutrino Mass Hierarchy
  - Start to explore leptonic CP violation
  - θ_{23} octant
- ν_μ disappearance
  - Precision Δm^2, θ_{23} measurement
- Design
  - High power NuMI beam - 700 kW expected 2016
  - Low-Z tracking calorimeters
    - Excellent electron reconstruction, muon energy resolution
  - Off-axis location
    - Suppress neutral current interactions at higher energies
  - 14 kt far detector, 293 ton near detector, 810 km baseline

Location

- 14 mrad (11km) off NuMI Beam Axis
  - Neutrino spectrum peaks around 1st oscillation max
  - High energy tail suppressed: reduces Neutral Current π^0 background
    - NC "feed down" in energy due to energy of outgoing neutrino
- As far as possible from Fermilab for maximum matter effect – Mass Ordering
  - 810 km



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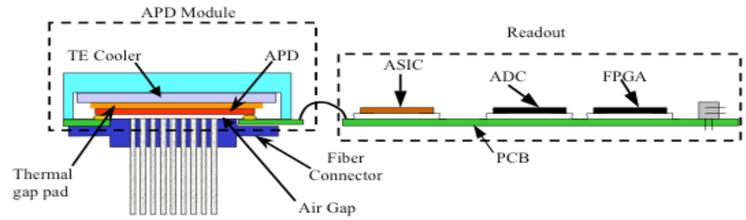
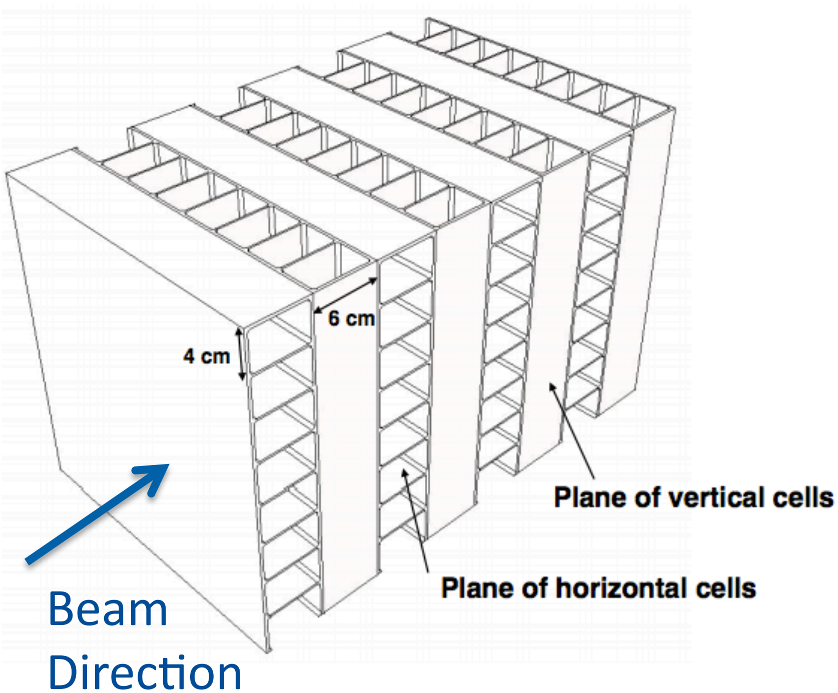
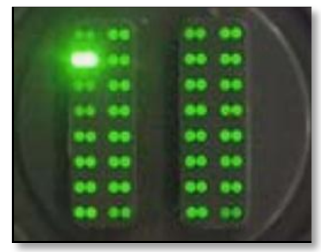
NOvA Detector Technology

- Low-Z tracking Calorimeter
  - PVC Cell Structure
  - Mineral oil + 5% pseudocumene

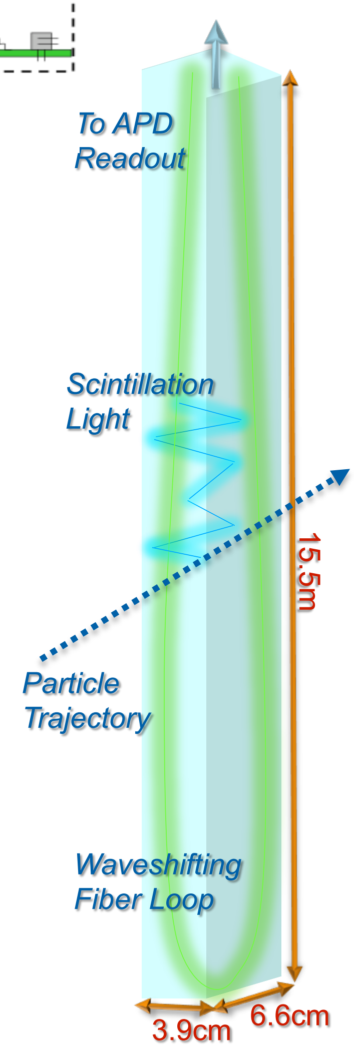




32 cells per APD

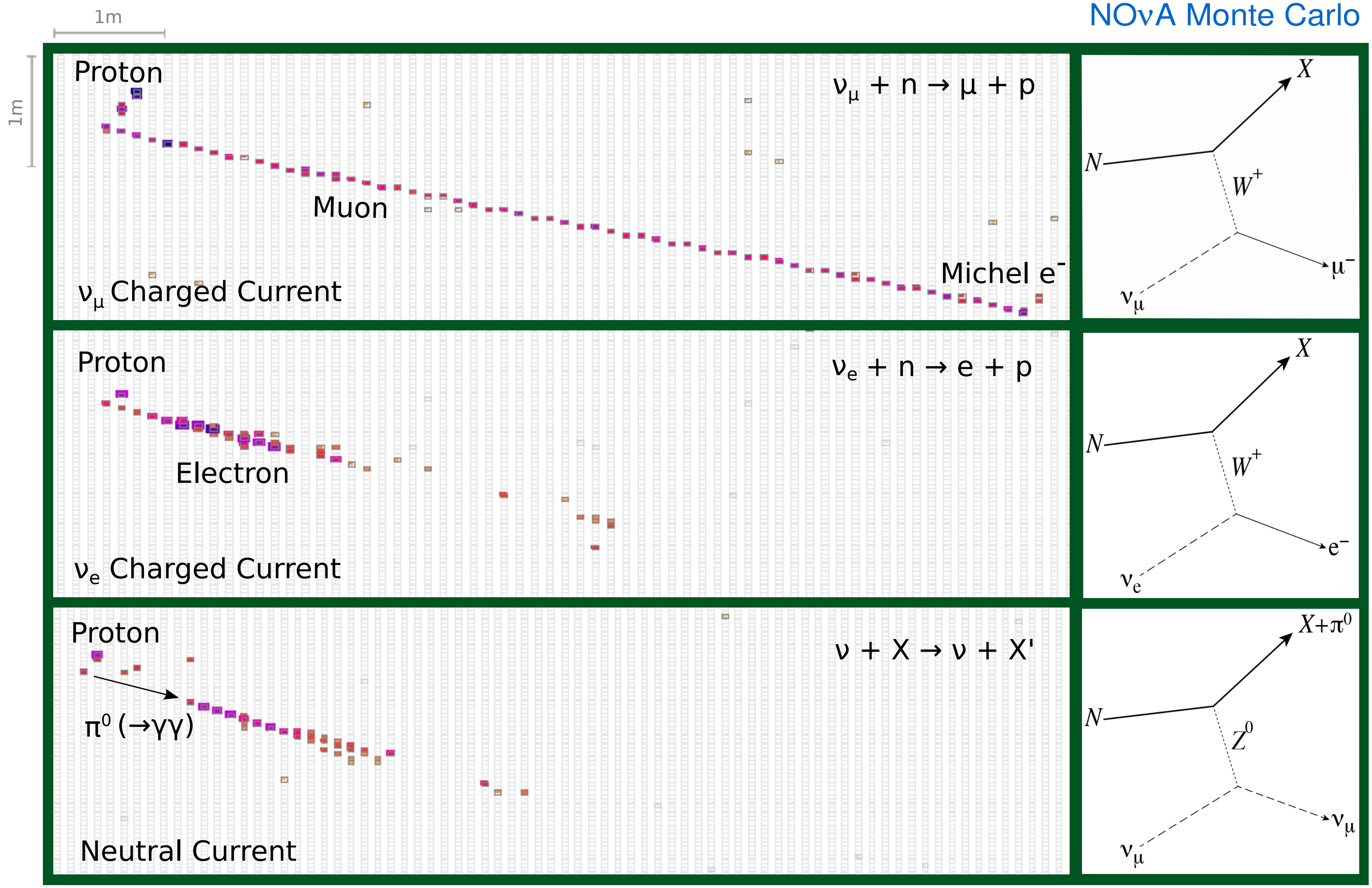


- ~6 planes per radiation length
  - Excellent Electro-magnetic shower characterization

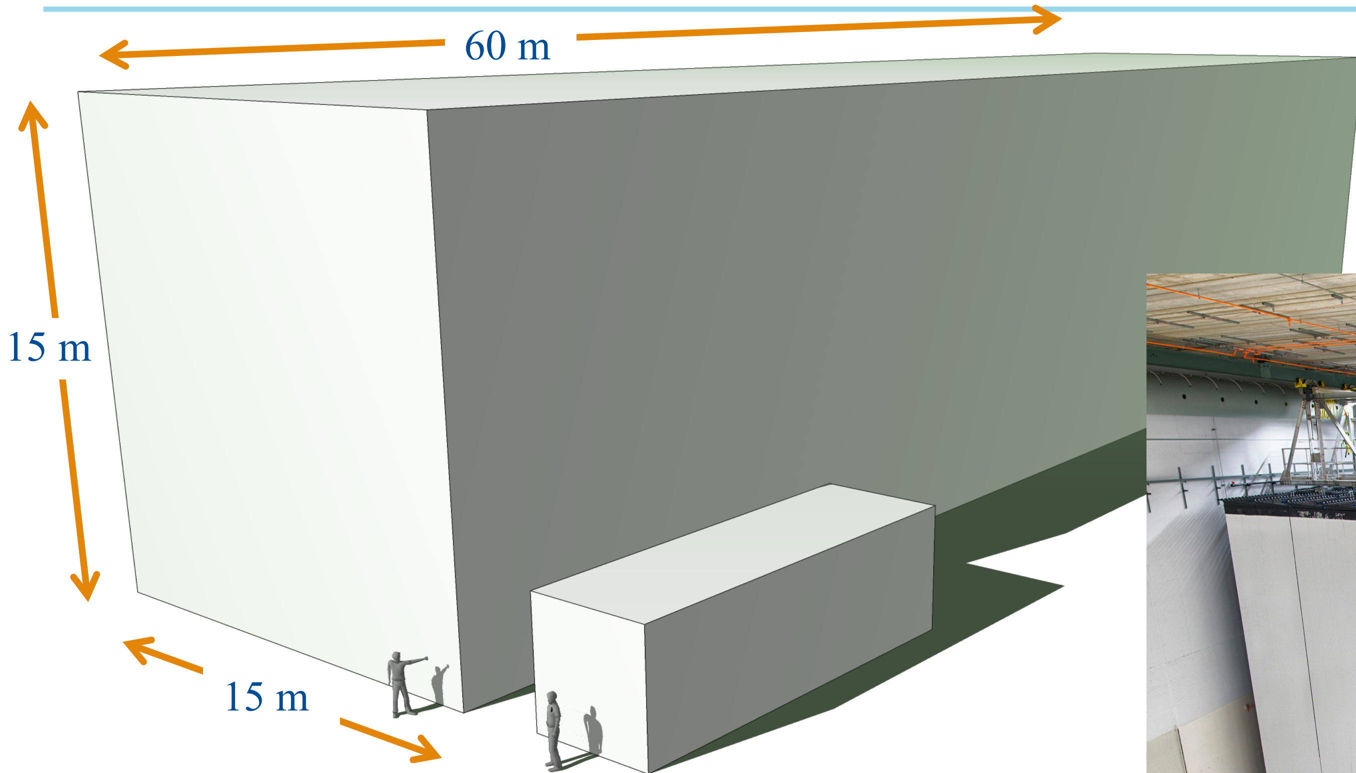


Event Topologies

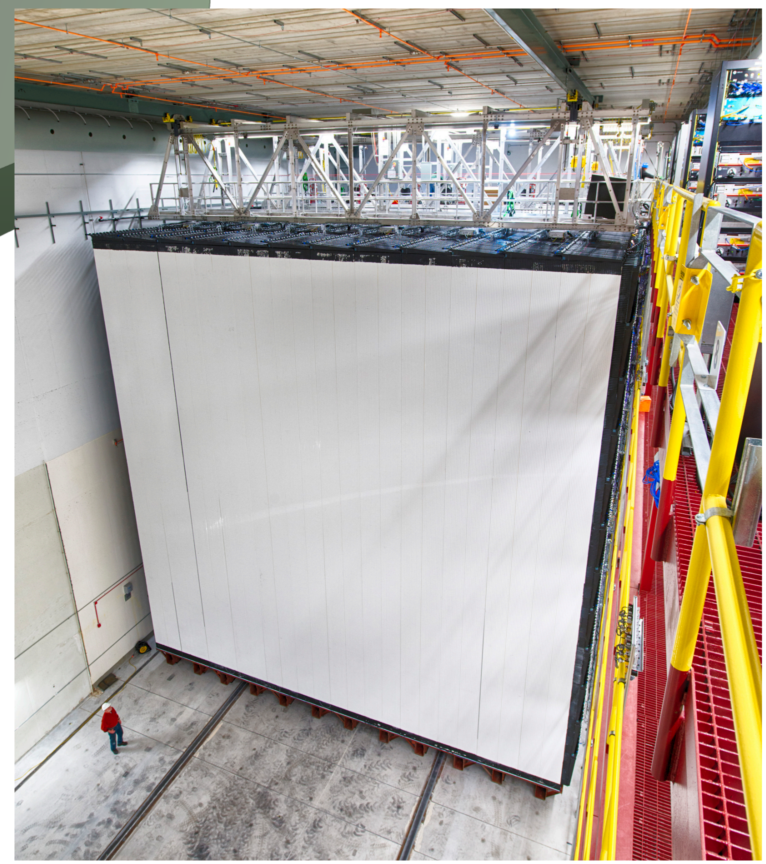
NOνA Monte Carlo



NOvA Detectors

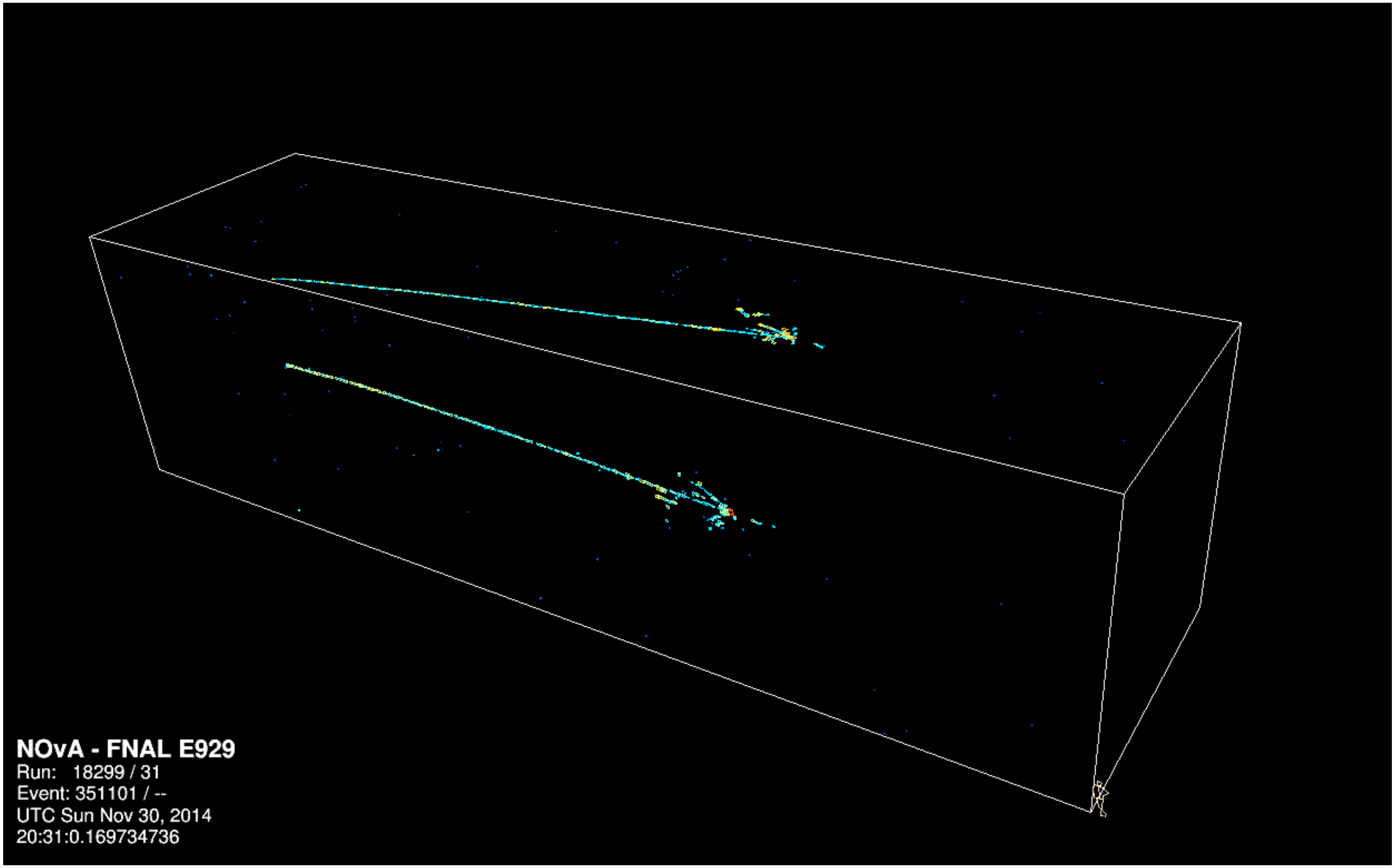


- Far Detector
  - 14 kT
  - 896 planes

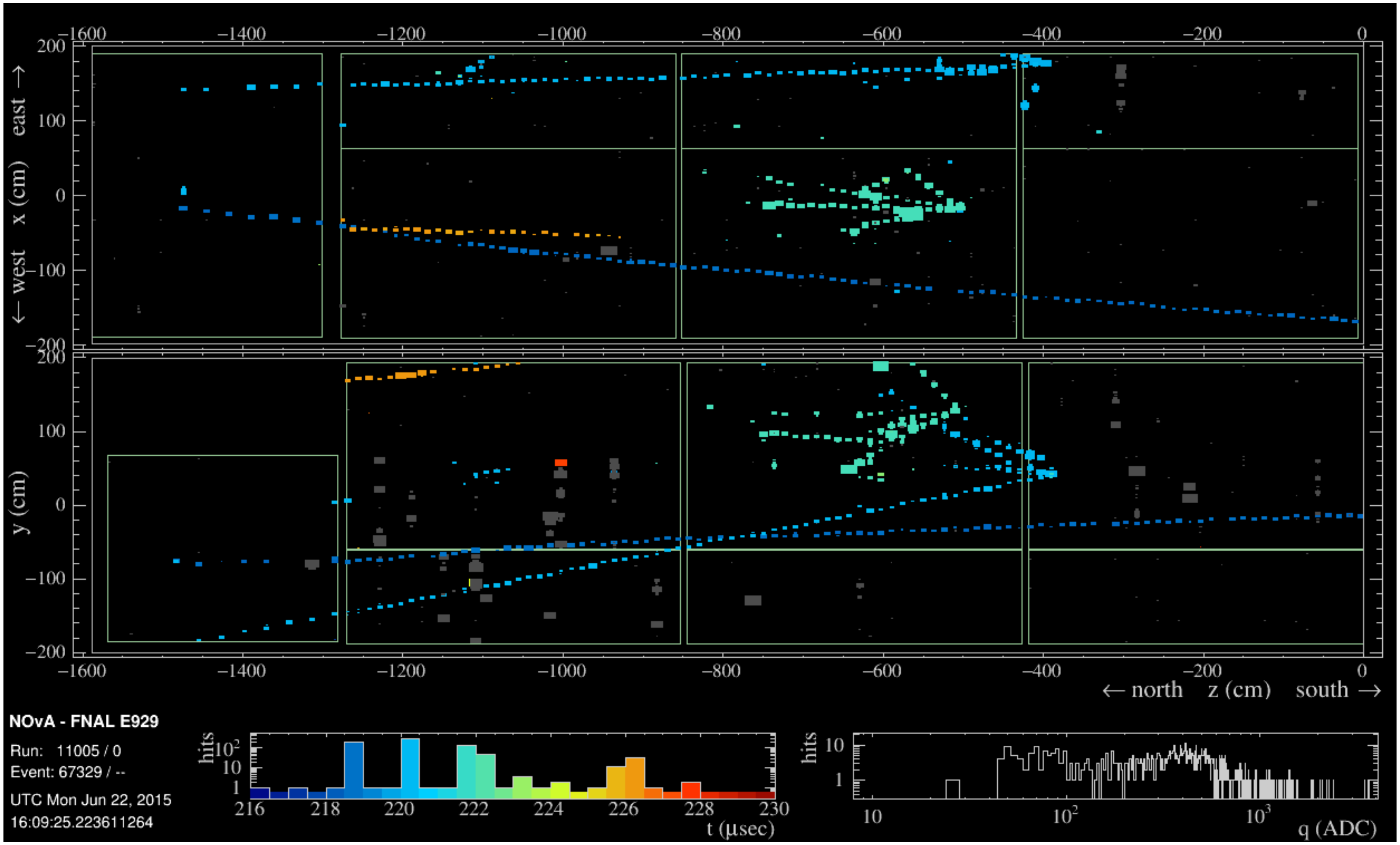


- Near Detector
  - 293 tons
  - 192 planes, plus a muon catcher with 10 planes of iron

NOvA Far Detector ν_μ Candidate



NOvA Near Detector – Typical NuMI Spill



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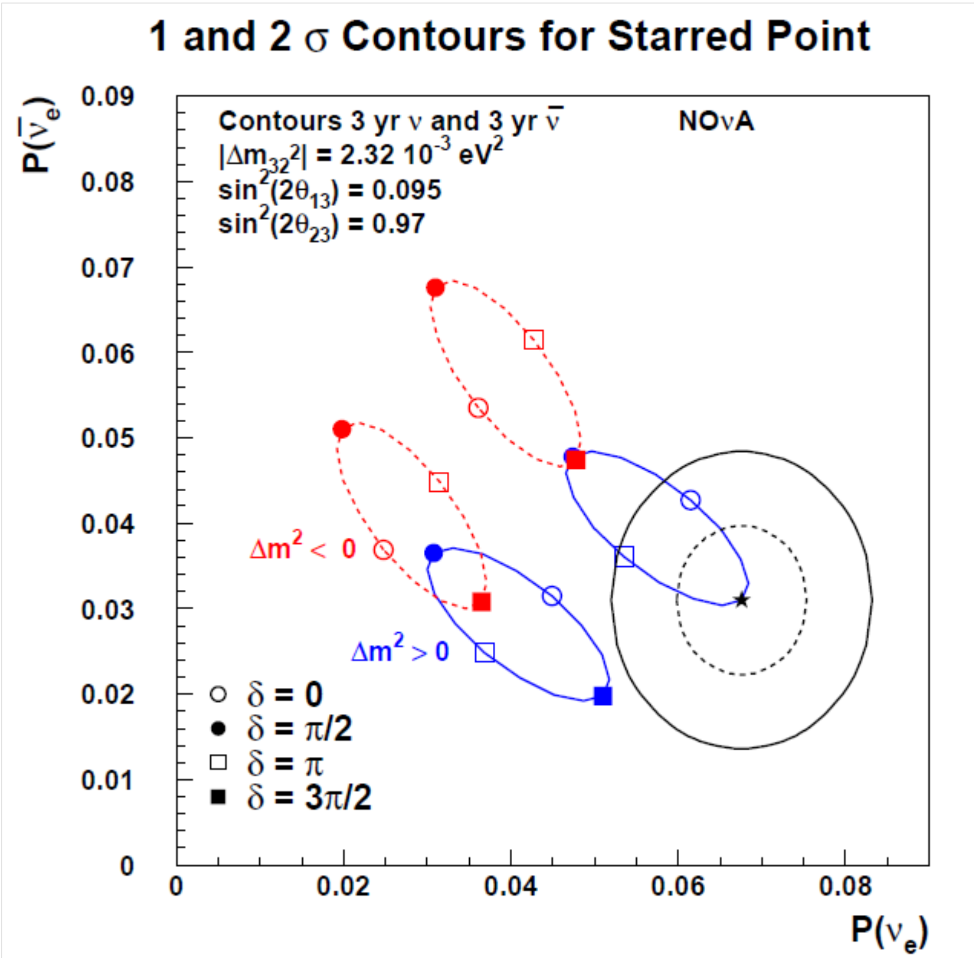
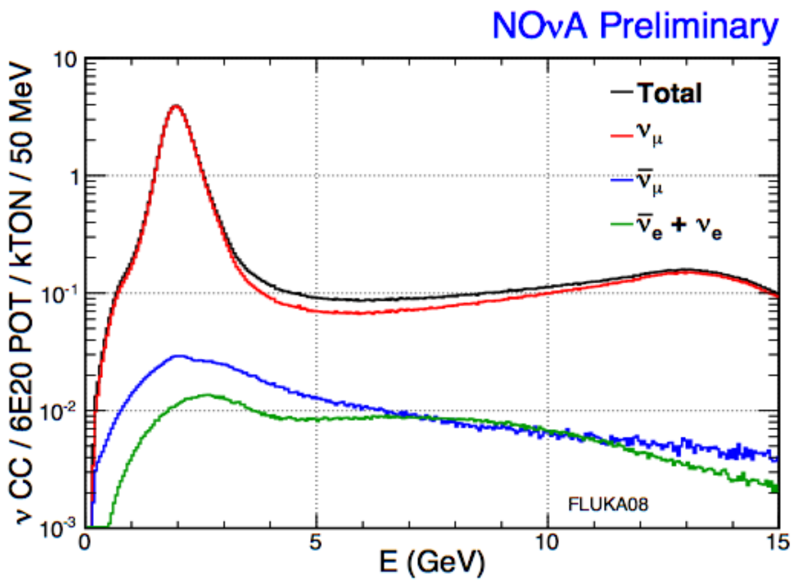
NOvA Measurement



Nominal Design Year
6x10^{20} protons on target

Example of a favorable measurement for NOvA

NOvA Wrong Sign Contamination

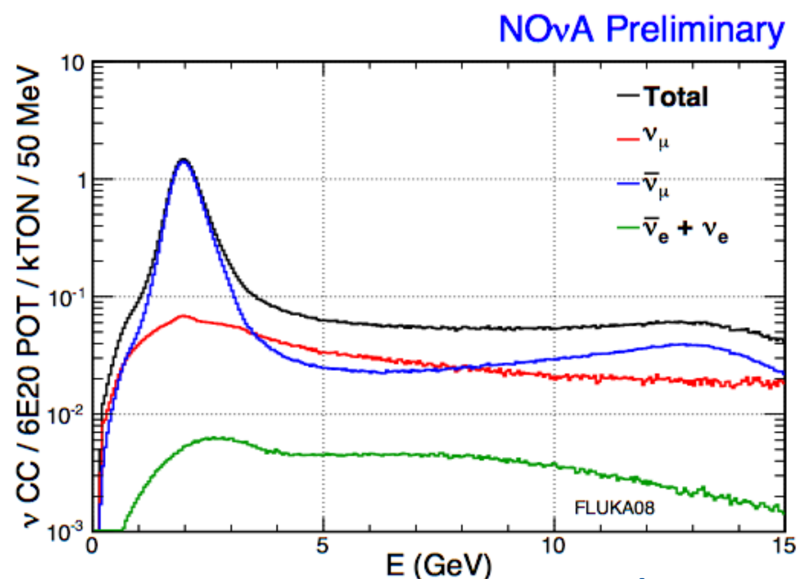


Neutrino mode

Small Wrong-sign contamination

~% in ν

10% in $\overline{\nu}$



Anti-neutrino mode

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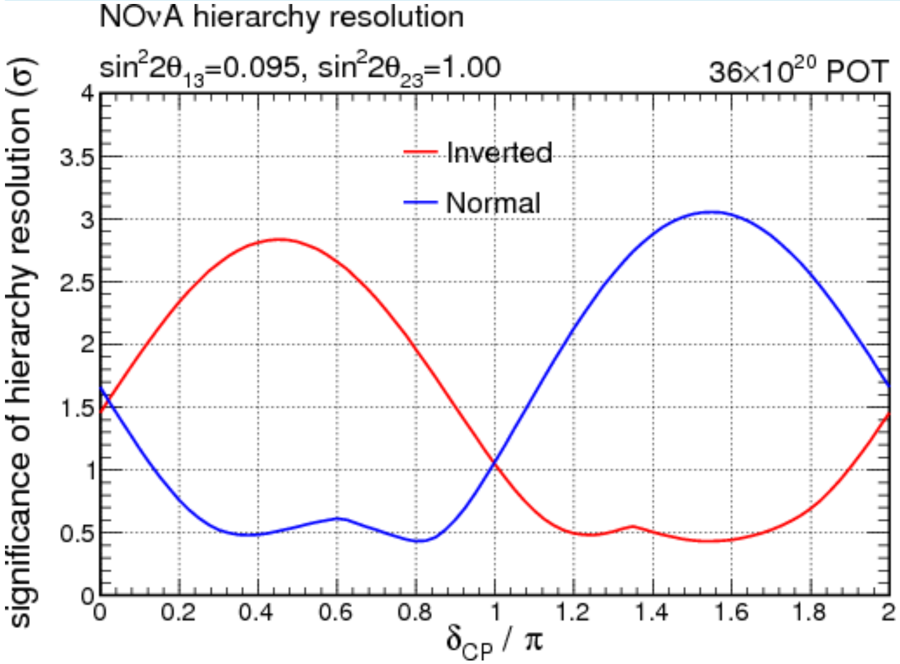
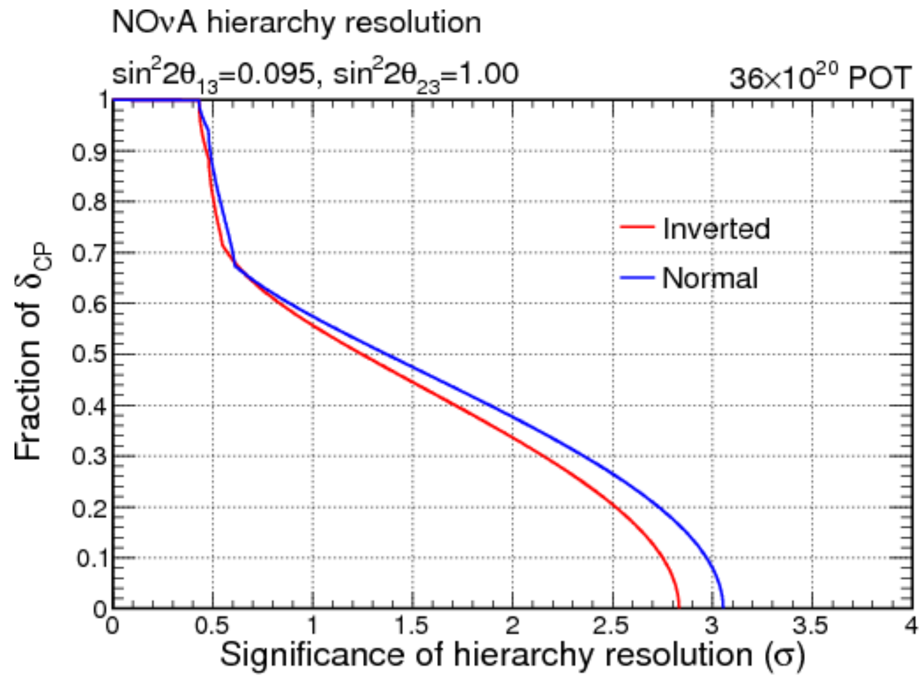
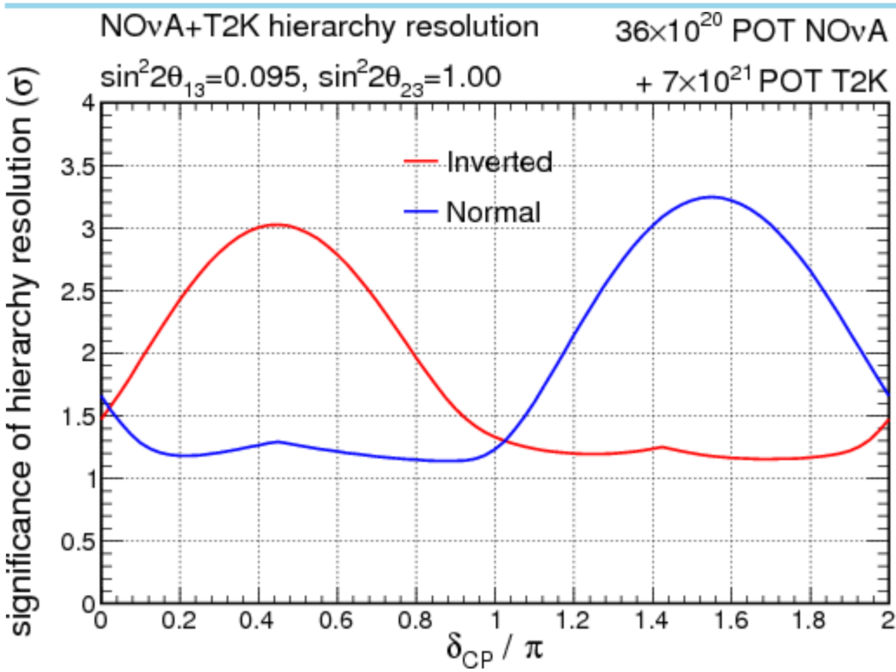
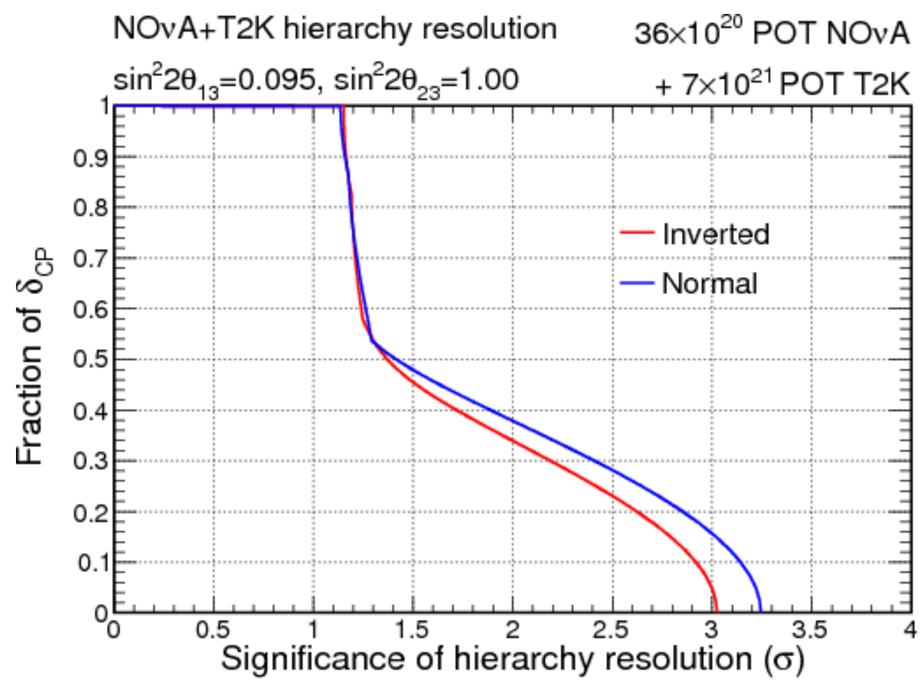
Mass Hierarchy – NOvA



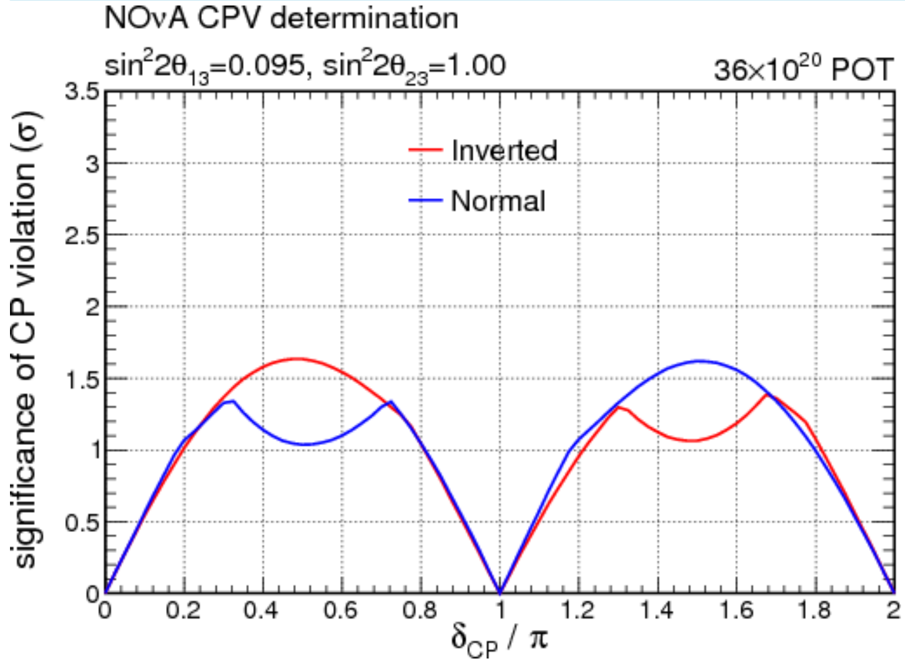


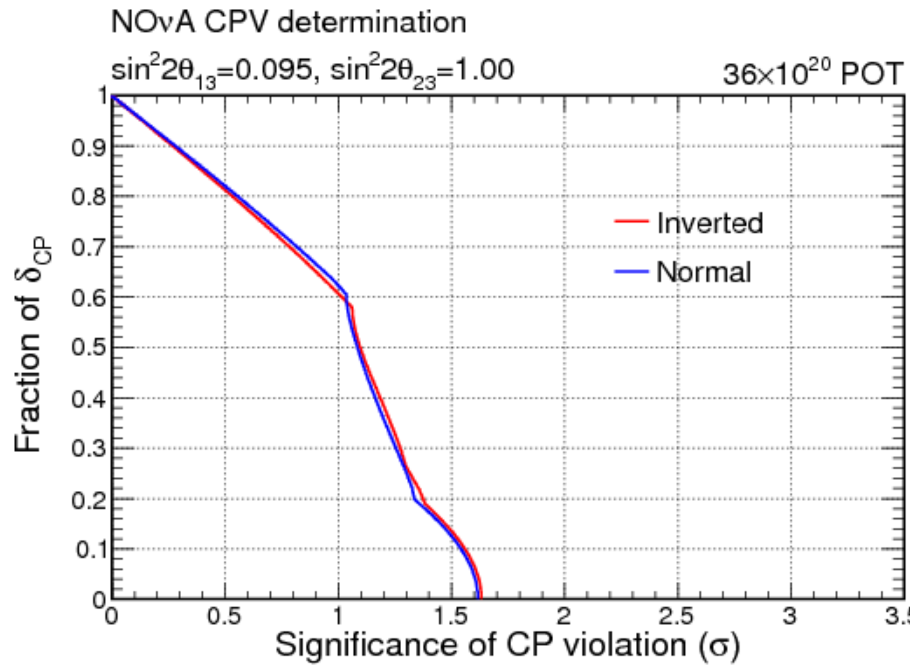
Mass Hierarchy – NOvA+T2K





CP Violation – NOvA





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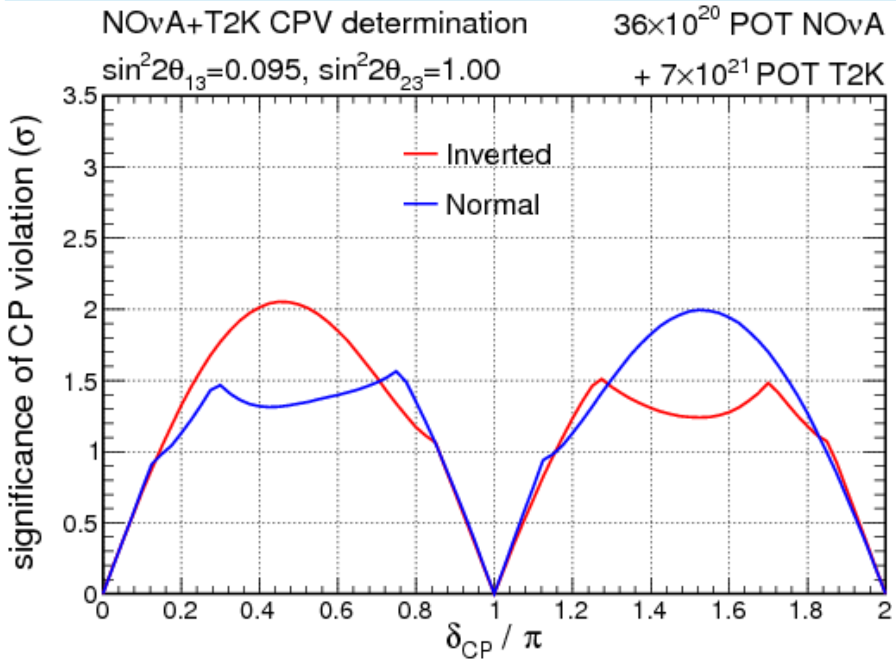
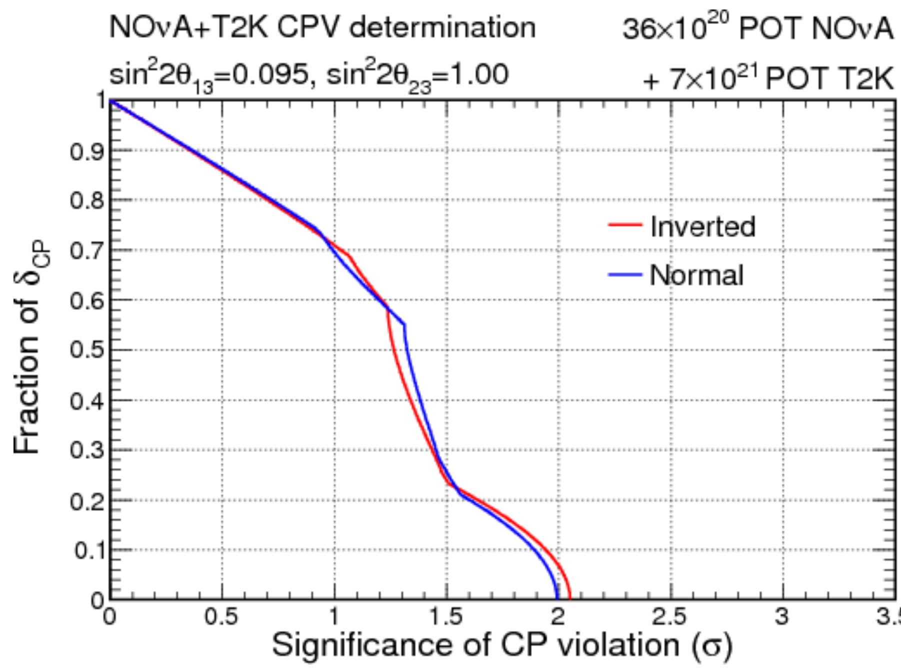
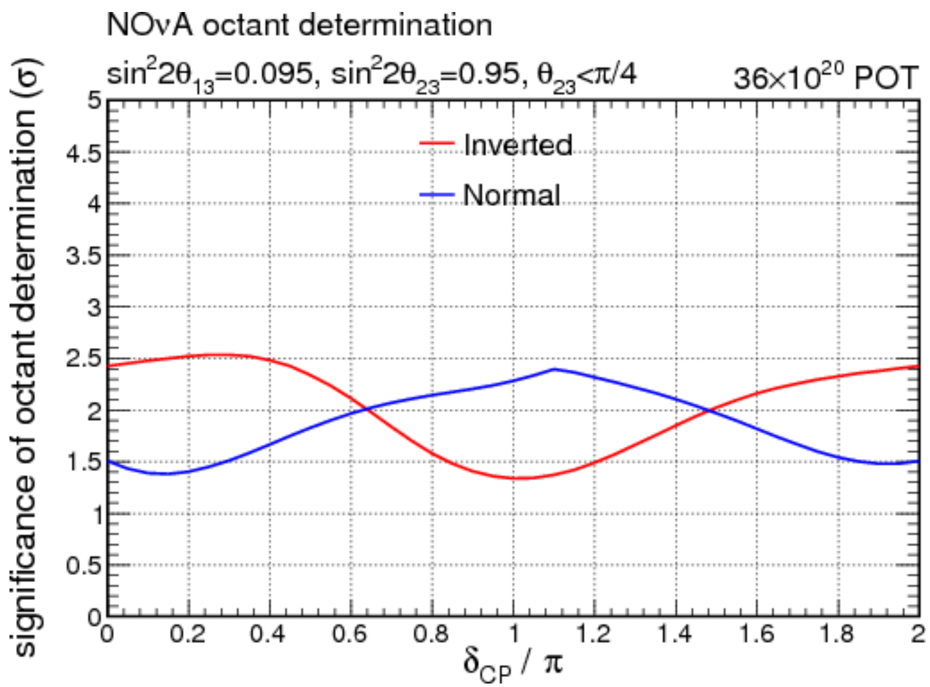
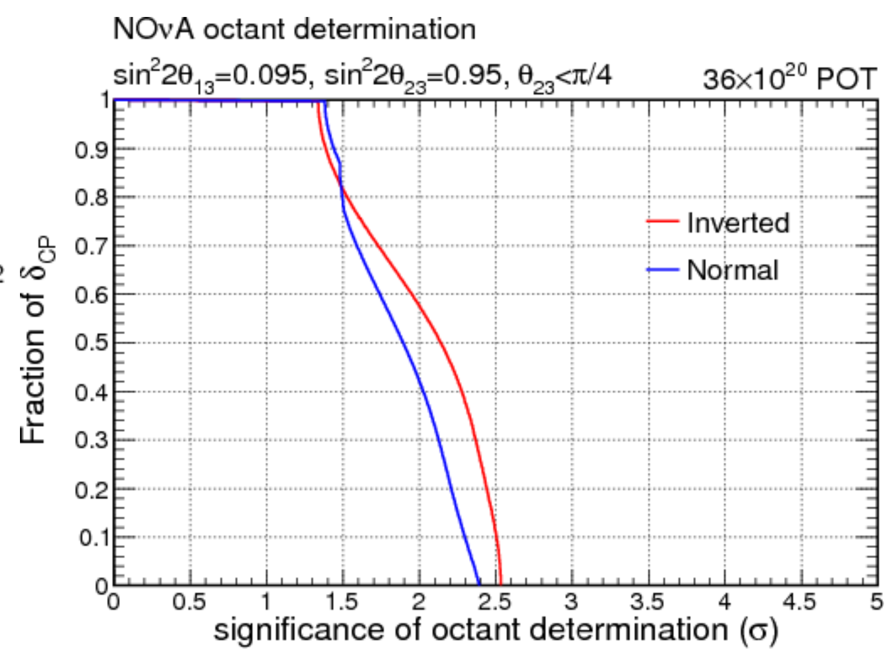
CP Violation – NOvA+T2K





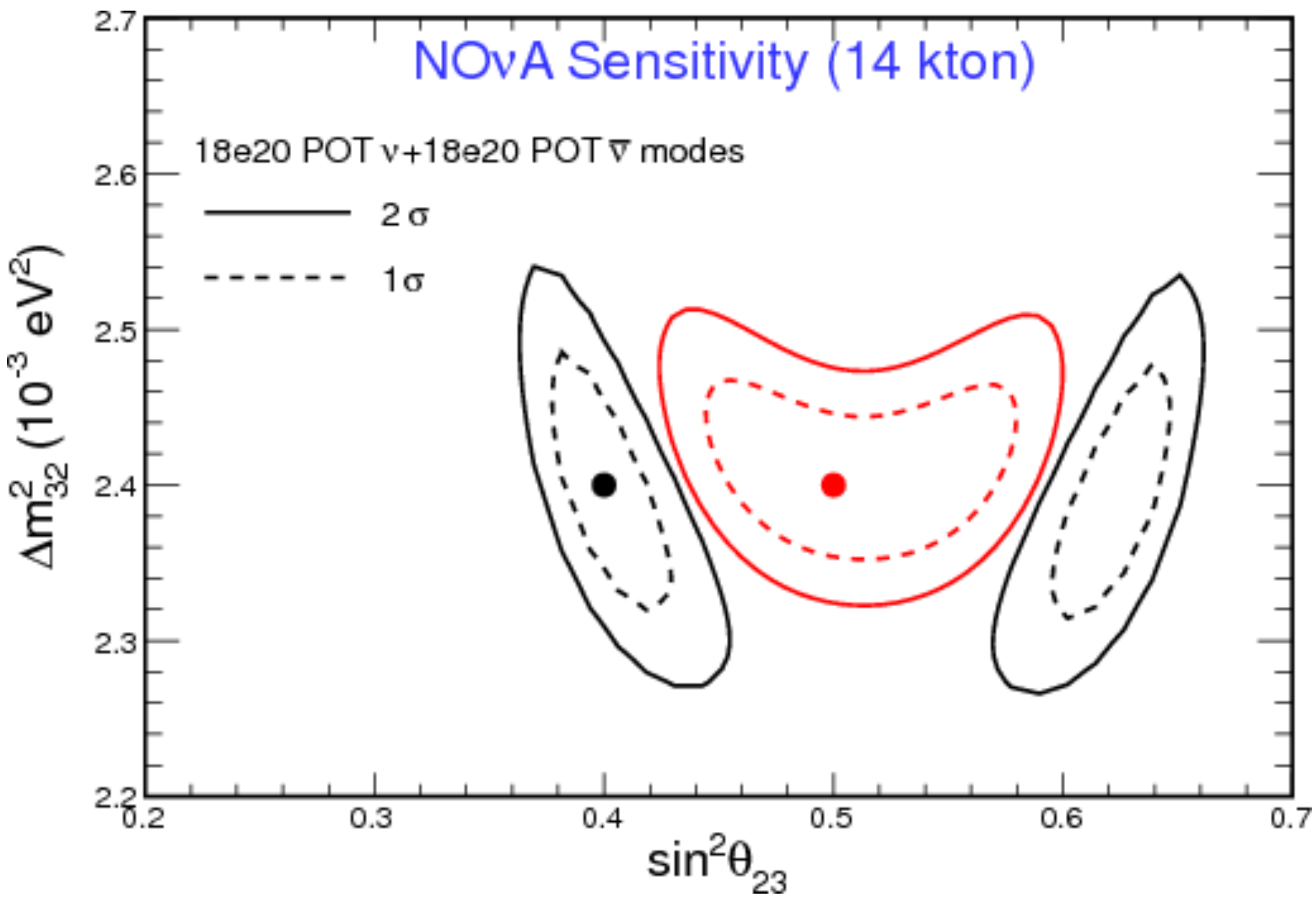
θ_{23} Octant - NOvA





NOvA Disappearance

6 Nominal Design Years



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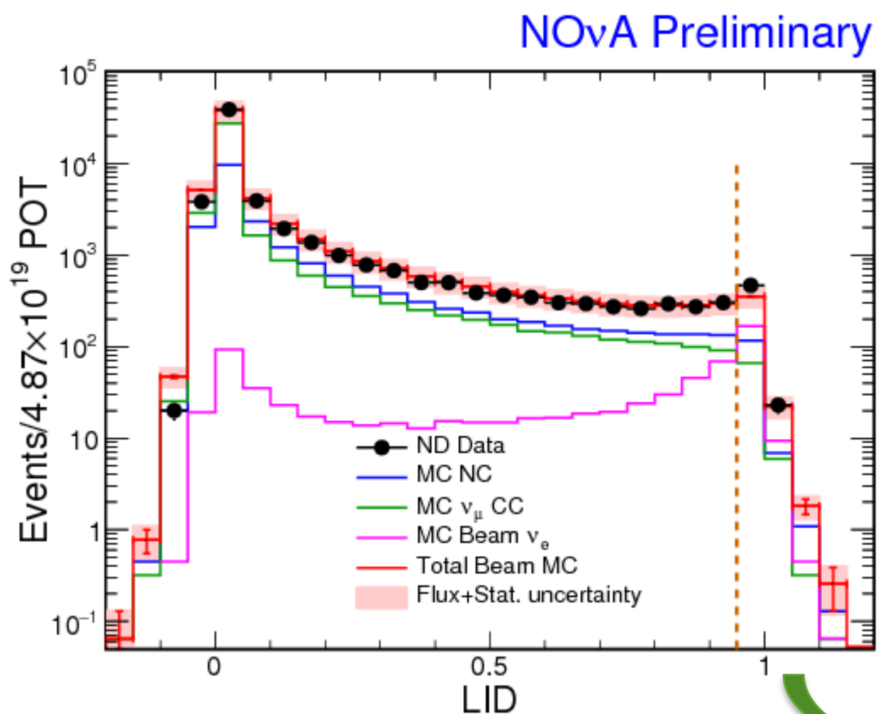
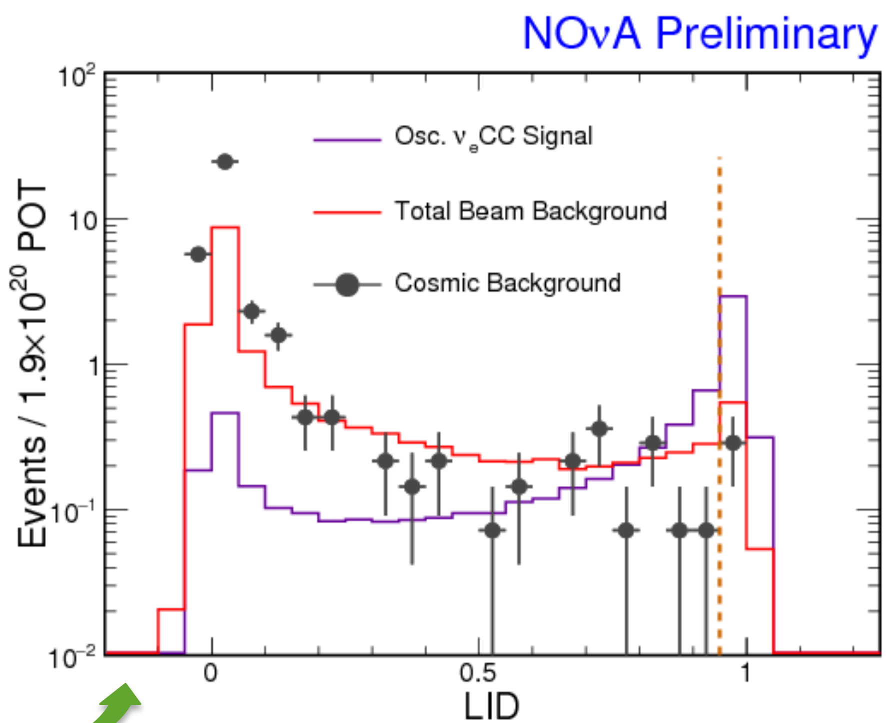
NOvA Appearance Analysis

LID: Shower-shape likelihood-based classifier



Data-MC comparison in **Near Detector**



Far Detector Prediction:
Extrapolation of beam background and signal, measurement of cosmic background

NOvA Status

- NOvA is aiming for first results this summer
- First data set: early days of Far Detector construction through spring 2015
  - Rates shown for ~1/3 nominal design year. Actual expected ~1/2 nominal design year (Nominal year=6×10^{20} POT x 14 kt)
  - ν_e appearance

	Osc. ν_e CC Signal	Total BG	ν_μ CC	NC	Beam ν_e	Cosmic Background
LID	3.25	1.02	0.05	0.32	0.33	0.29
LEM	3.48	1.14	0.05	0.41	0.36	0.29

Assuming δ_{CP}=0, no matter effect, $\sin^2(2\theta_{13})$=0.095 Maximal 23 mixing, Unknowns can change signal by +/- 60%

  - ν_μ disappearance

	ν_μ CC Signal	Total BG	Cosmic Background	NC Background
Final Selection	23.7	1.6	0.3	1.3

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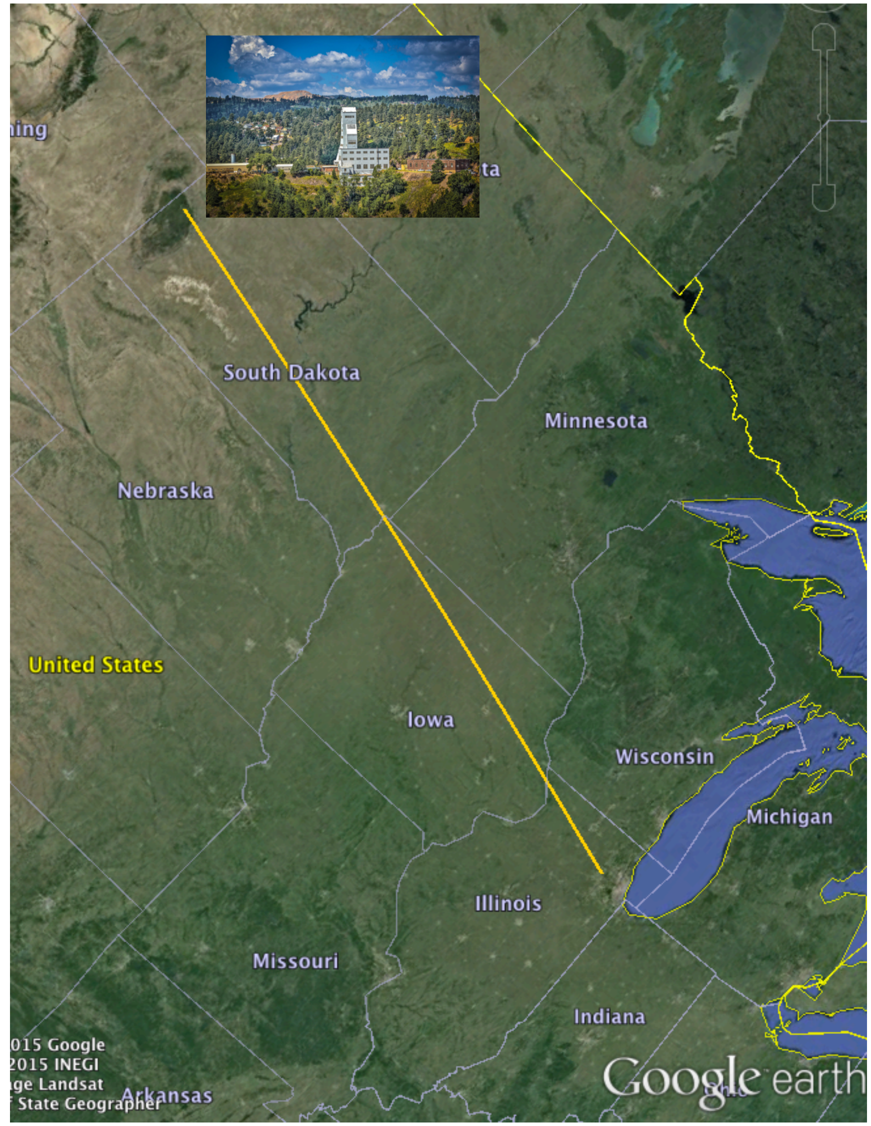
Next Generation – DUNE/LBNF

- Goals
  - Precision study of $\nu_\mu \rightarrow \nu_e$, $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
    - Measure δ_{CP}
    - Determine the ν Mass Ordering
  - Precision test of 3-flavor mixing in appearance and disappearance with ν, $\overline{\nu}$
    - Measure θ_{23}, including the octant
- 1300 km baseline
  - Fermilab to Sanford Underground Lab
- Liquid Argon TPC Detector
- Wide-band, megawatt beam
  - Similar to NuMI design



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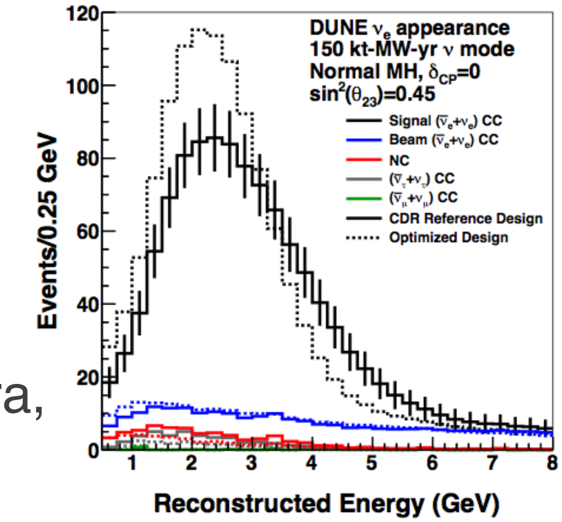
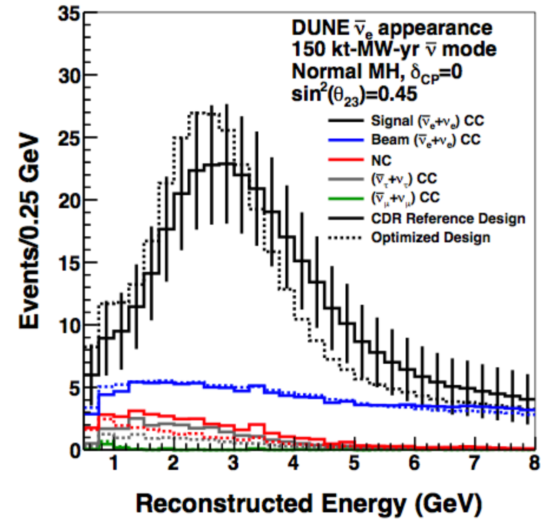
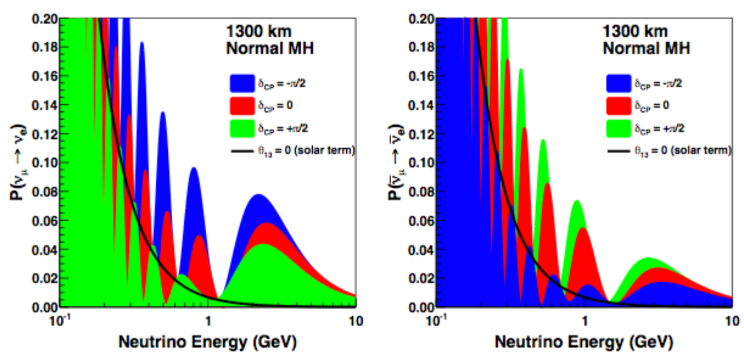
DUNE

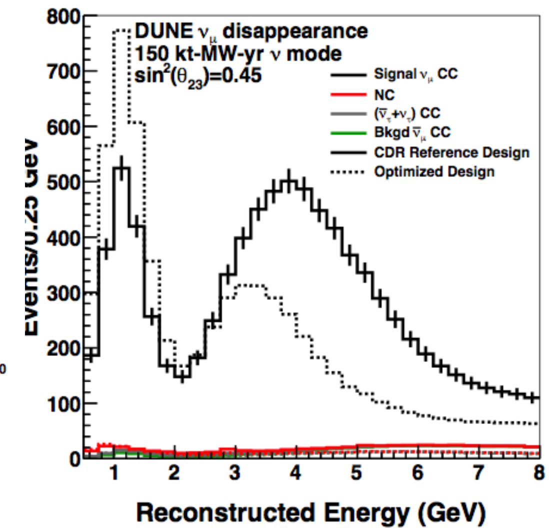
- Broad-band beam
  - Disentangle MO and δ_{CP} effects
    - Longer baseline
    - Use shape of spectra, not just rates

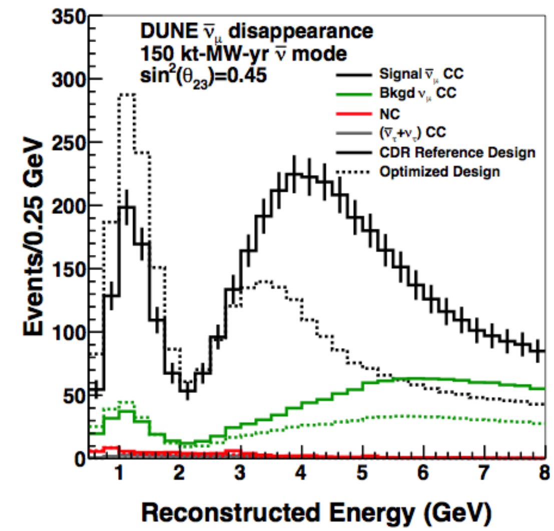






Appearance Probabilities





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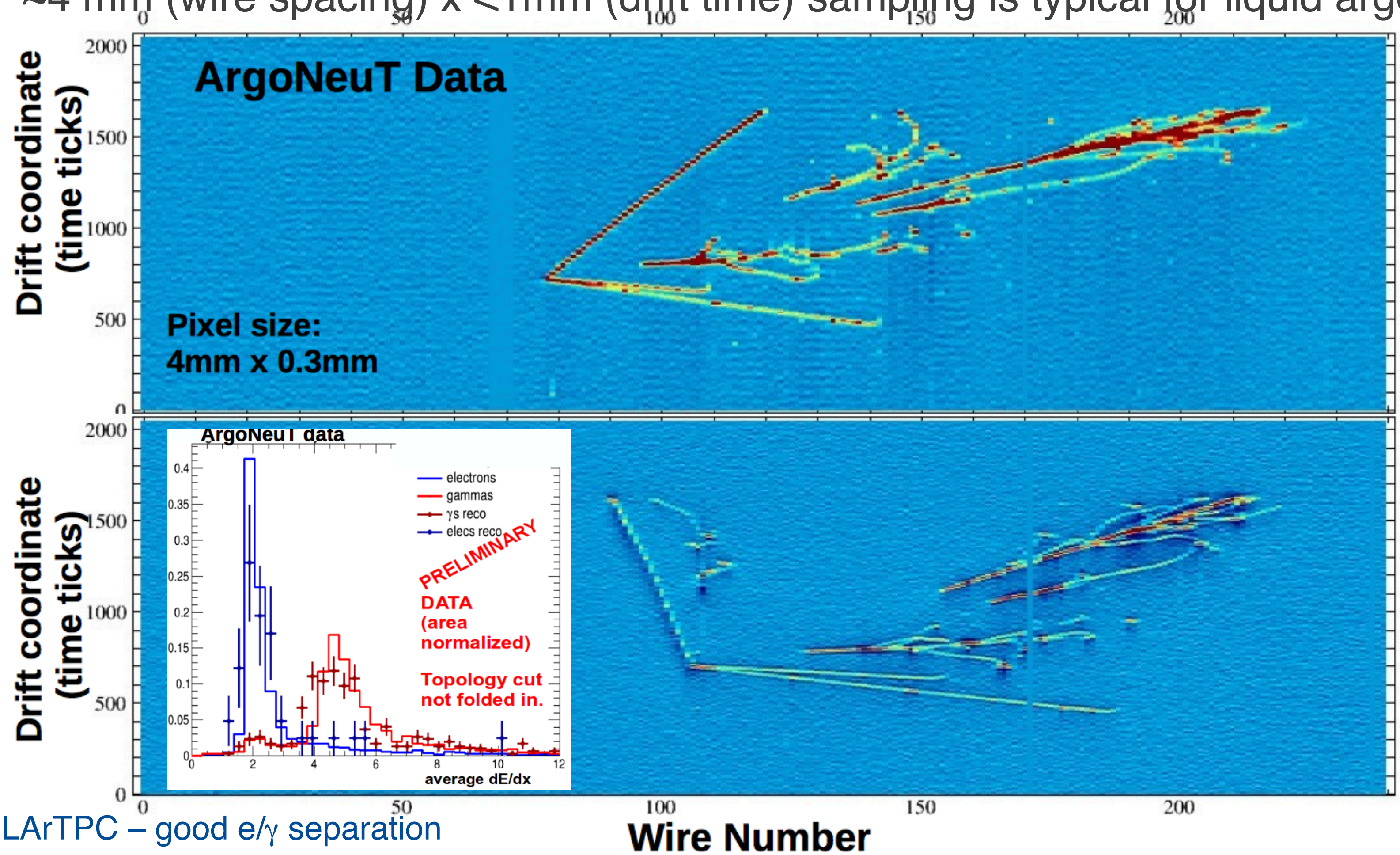
Liquid Argon Time Projection Chambers

Argoneut event display from Jonathan Asaadi's talk in this series

Ionization charge drifts over meters with speed O(mm/μs)

~4 mm (wire spacing) x <1mm (drift time) sampling is typical for liquid argon TPCs



LArTPC – good e/γ separation through initial dE/dx

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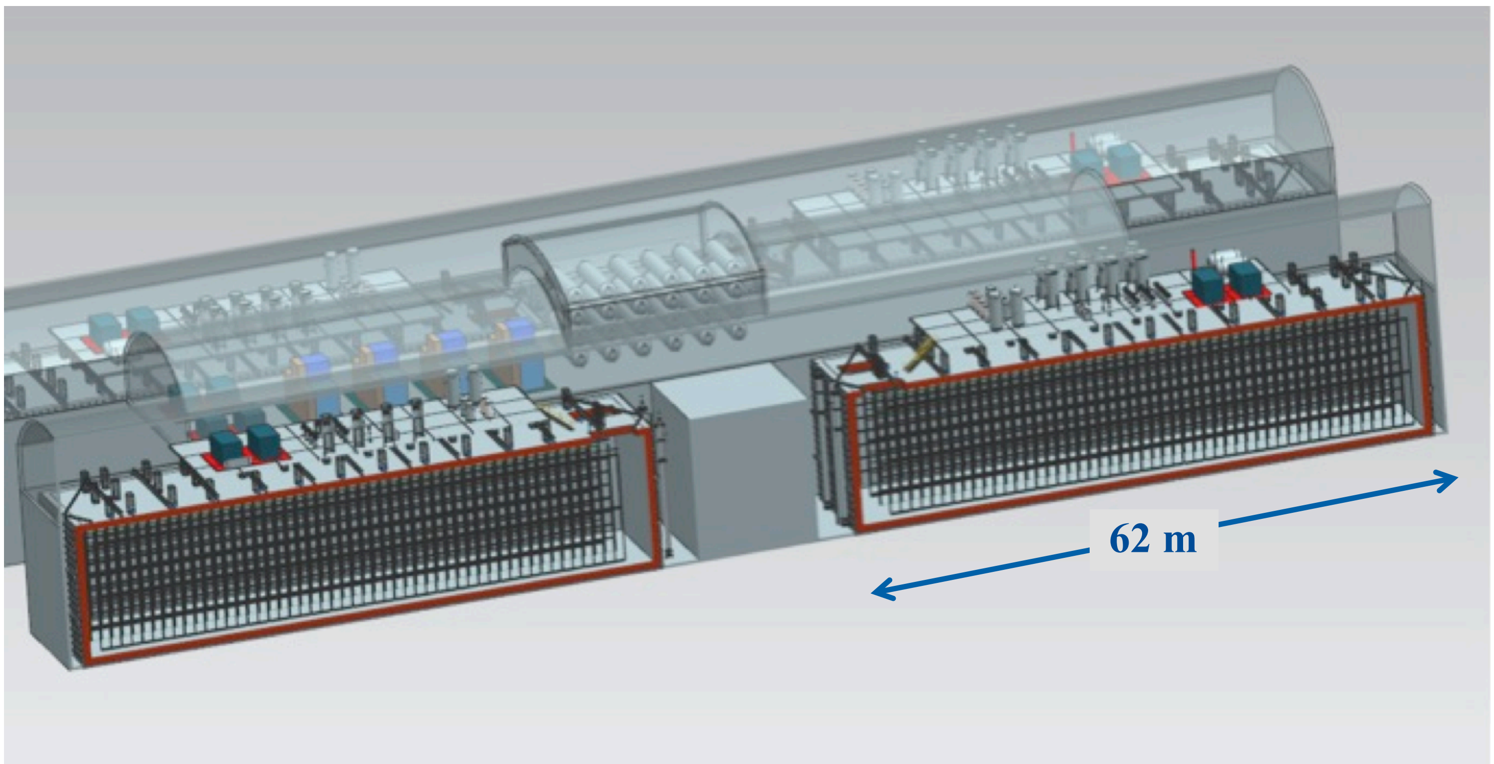
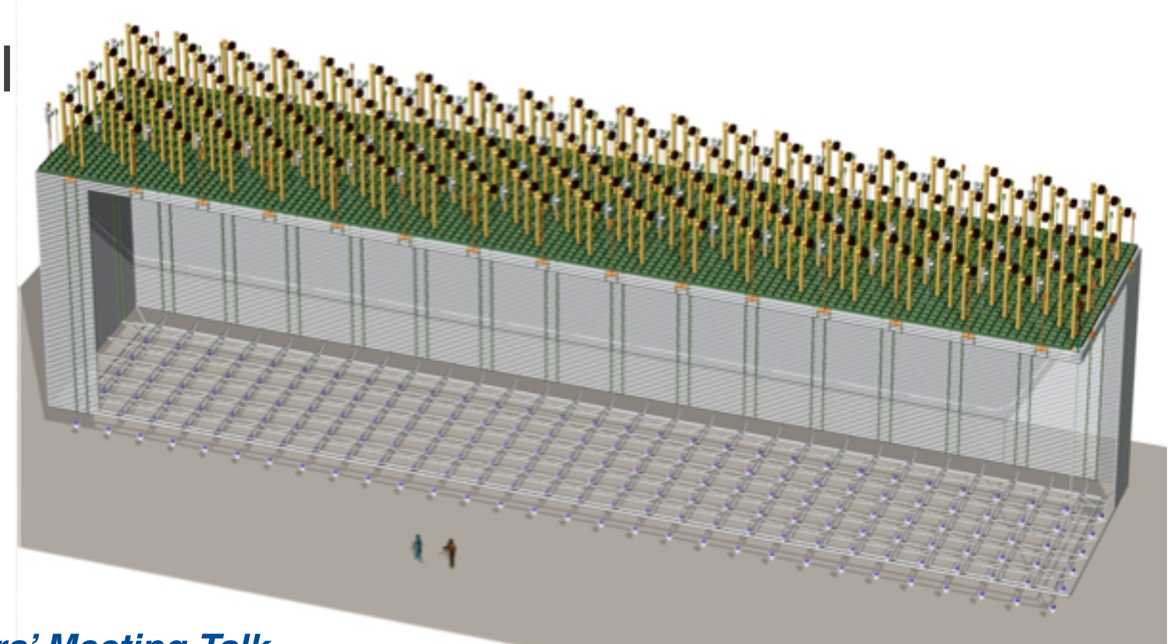
Dune Far Detector

- Liquid Argon TPCs 4850' (1470 m) underground at Sanford
  - 4 independent modules of 10 kt each
    - Take advantage of possible technology improvements without having to wait to start detector construction



Possible Alternative Design – Dual Phase

- Amplify & detect signal charge in gaseous Ar above liquid surface
- Allows finer readout wire pitch, lower energy thresholds, better pattern recognition

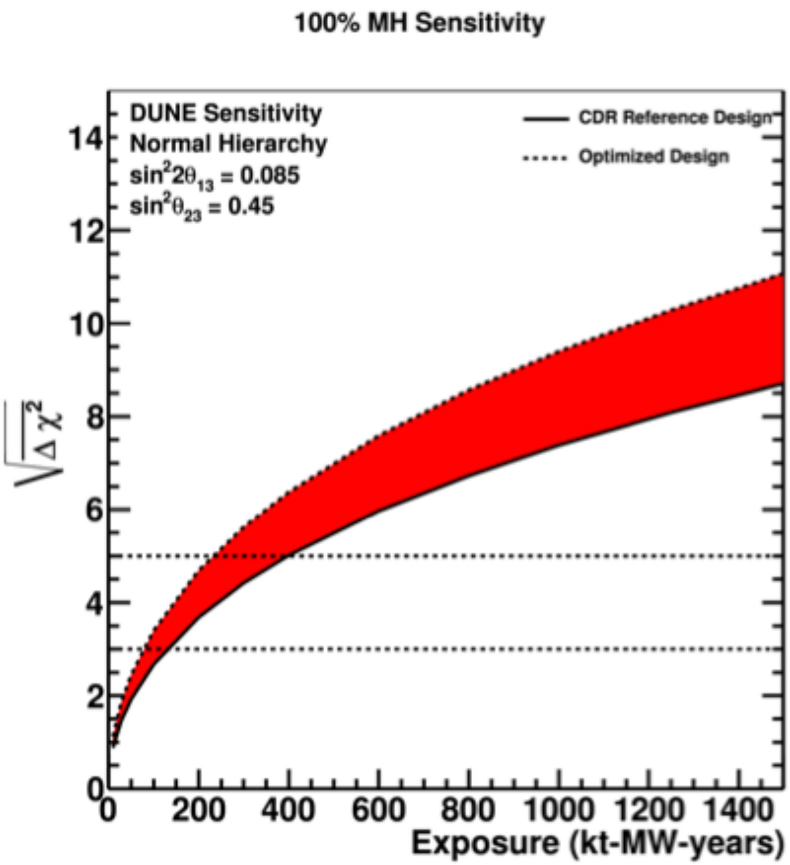


L. Fields, Users' Meeting Talk

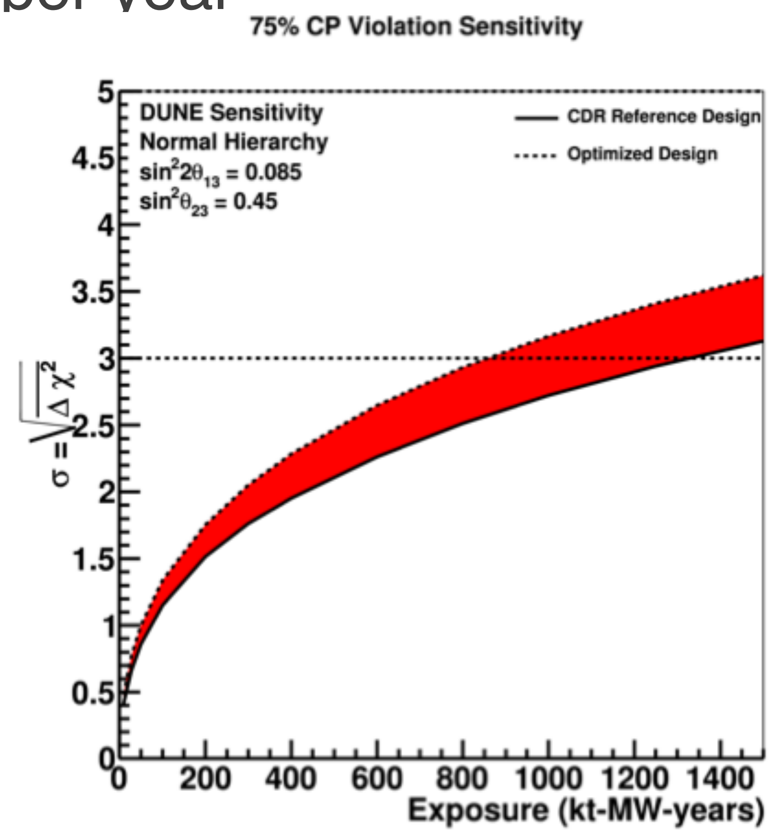
- Possible choice beyond 1st 10 kt module
  - Development and evaluation at CERN WA105

Dune Sensitivities

- 40 kt x 1.2 MW – 48 kt-MW-yr per year



3 σ determination of MH in ~3-4 years



3 σ detection of CP violation:
either a very long run, or
beam & detector upgrades required

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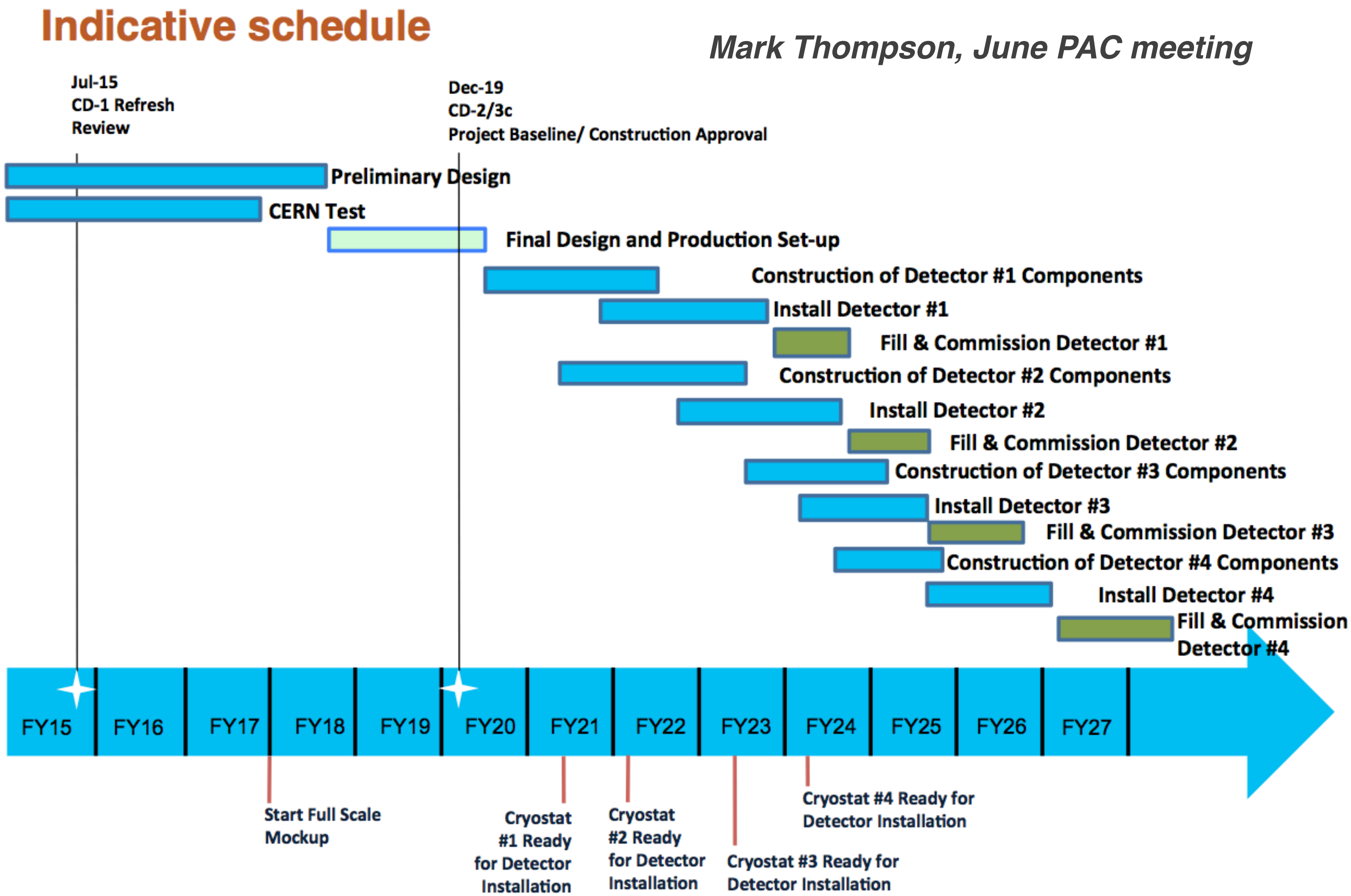
Dune Schedule



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Conclusions

- We are ~15 years into the era of Long Baseline Experiments
- These are challenging measurements
  - A long-term, programmatic view has served is well
- A huge amount has been learned
  - Often by making experiments reach well beyond their design

- The current and next generation experiments stand to answer some of the most important questions in physics will