Long Baseline Neutrino Experiments

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$$\begin{aligned} P(\nu_\mu \to \nu_e) \quad \approx \quad & \sin^2(2\theta_{13})\sin^2(\theta_{23})\frac{\sin^2(A-1)\Delta}{(A-1)^2} \\ & +2\alpha \sin\theta_{13}\cos\delta\sin 2\theta_{12}\sin 2\theta_{23}\frac{\sin A\Delta}{A}\frac{\sin(A-1)\Delta}{(A-1)}\cos\Delta \\ & -2\alpha \sin\theta_{13}\sin\delta\sin 2\theta_{12}\sin 2\theta_{23}\frac{\sin A\Delta}{A}\frac{\sin(A-1)\Delta}{(A-1)}\sin\Delta \end{aligned}$$

$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$A = \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\mathrm{GeV}}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$

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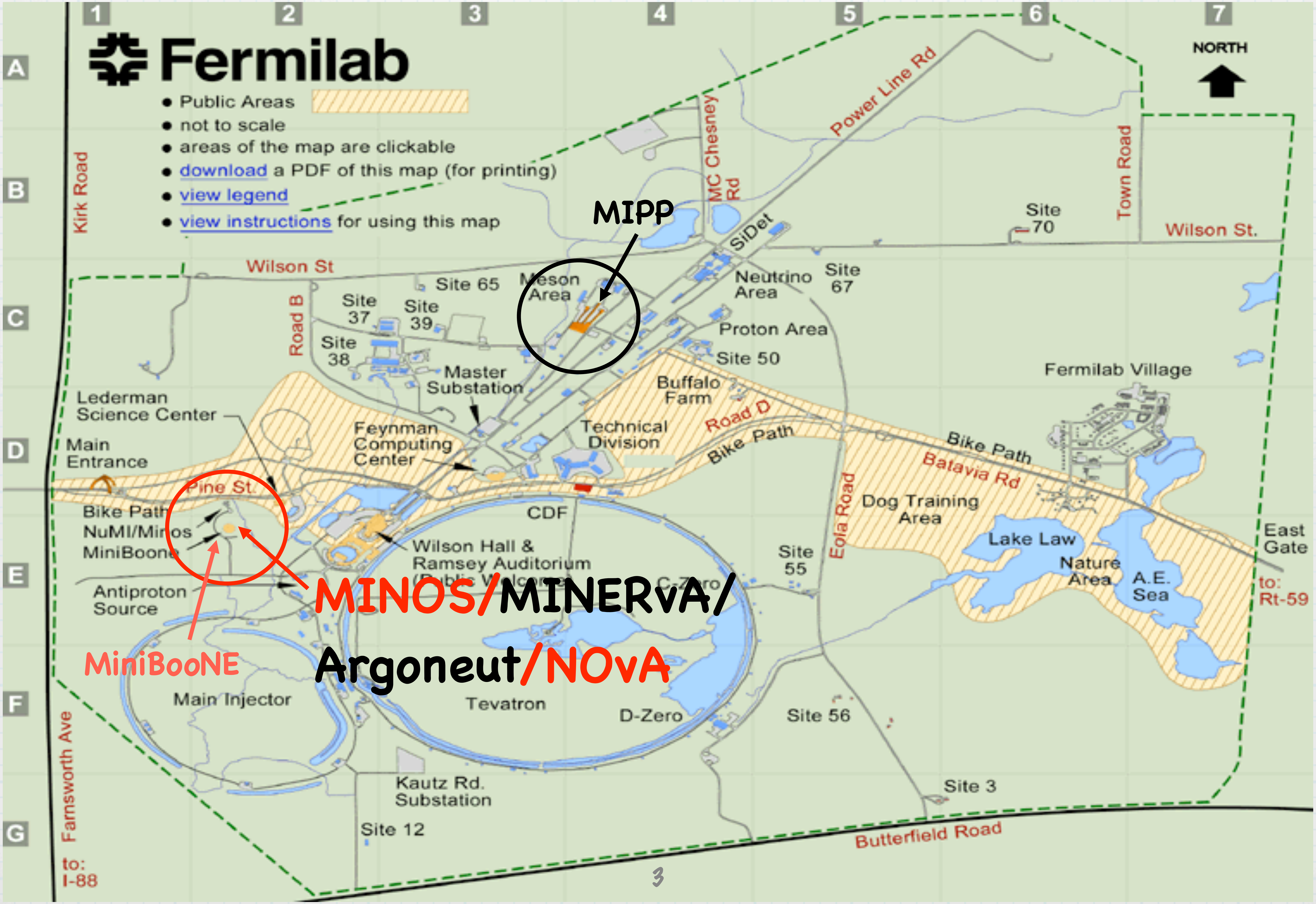
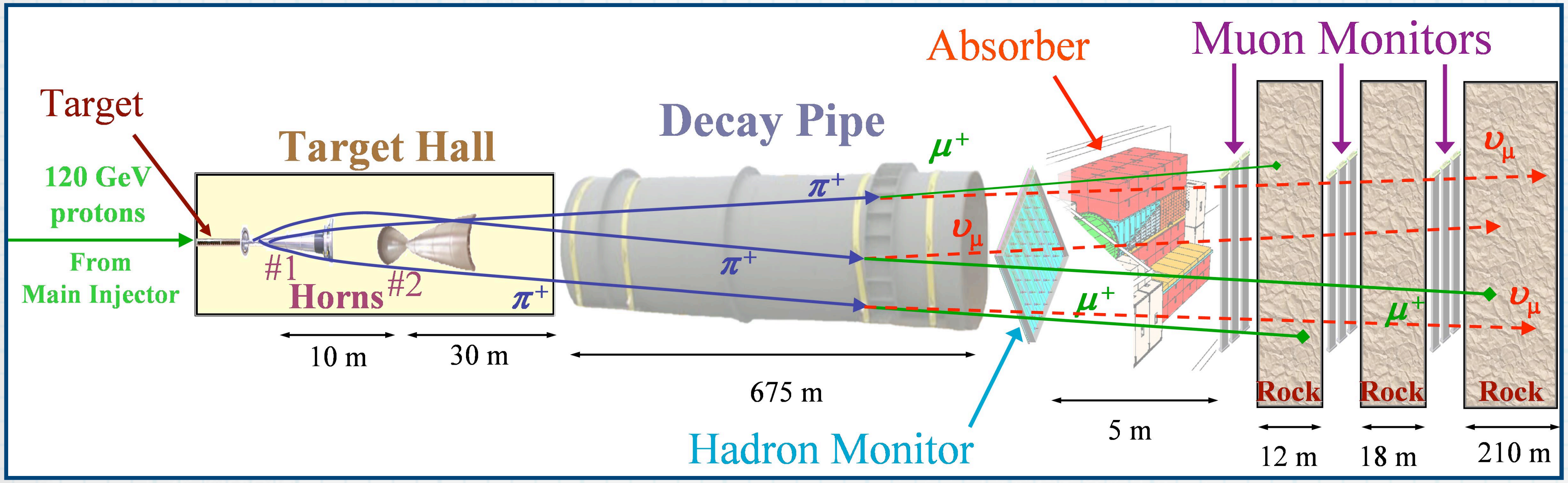
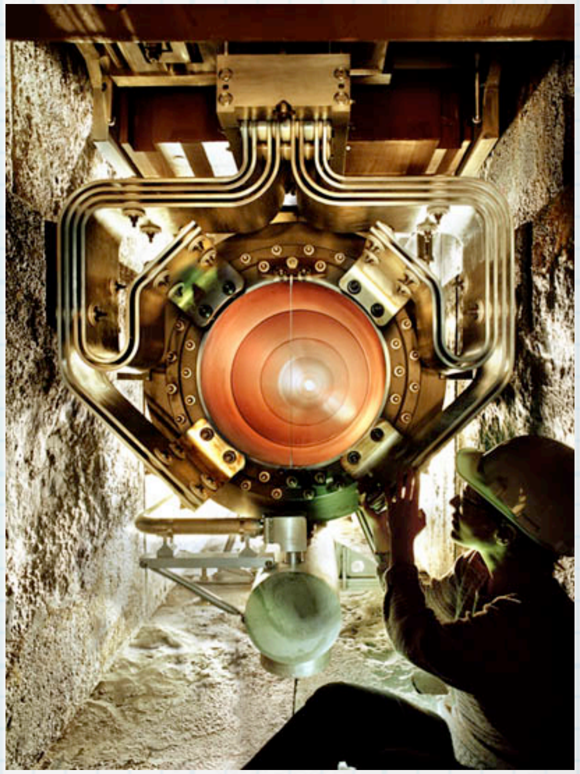
* CERN, J-PARC and FNAL all have active LB neutrino programs; today I will focus on MINOS, T2K and NOvA.

The Neutrino Program at Fermilab

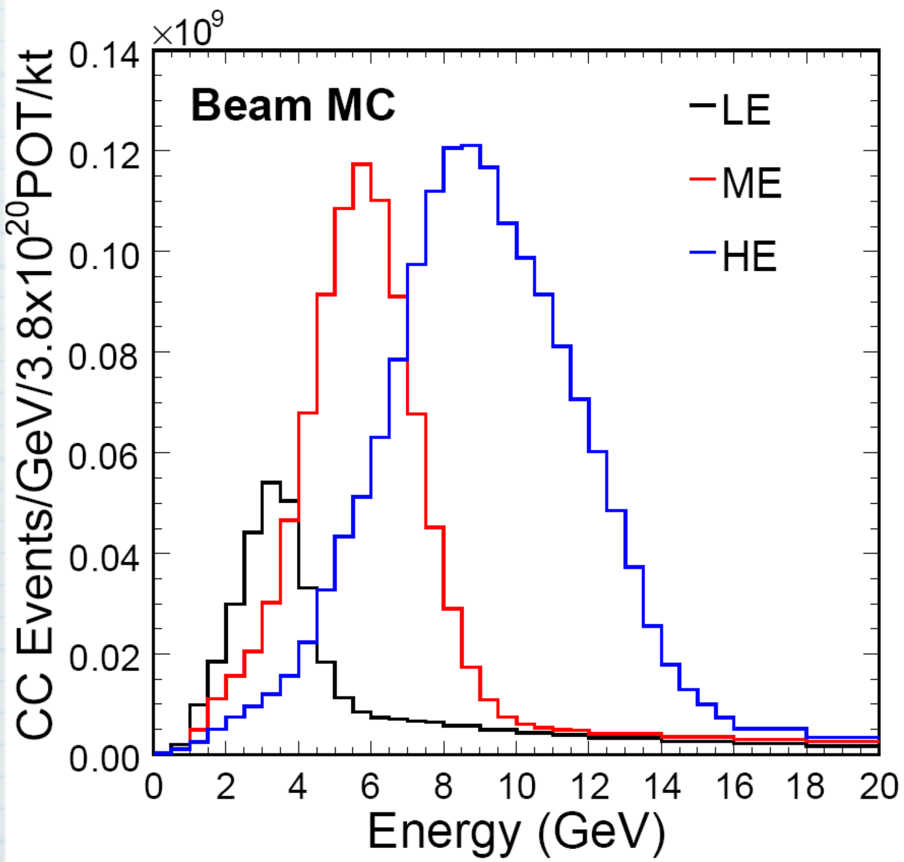


Neutrinos at the Main Injector (NuMI)





* Neutrinos are produced from secondary mesons created in 120 GeV/c p + graphite target interactions.
* Secondary mesons are focused by two magnetic horns; ν beam energy is tunable by moving target position longitudinally w.r.t. the horn positions.
* Intense source of neutrinos:
  * ~3 x 10^{13} POT ever 2.2 s
  * ~15 ν/POT



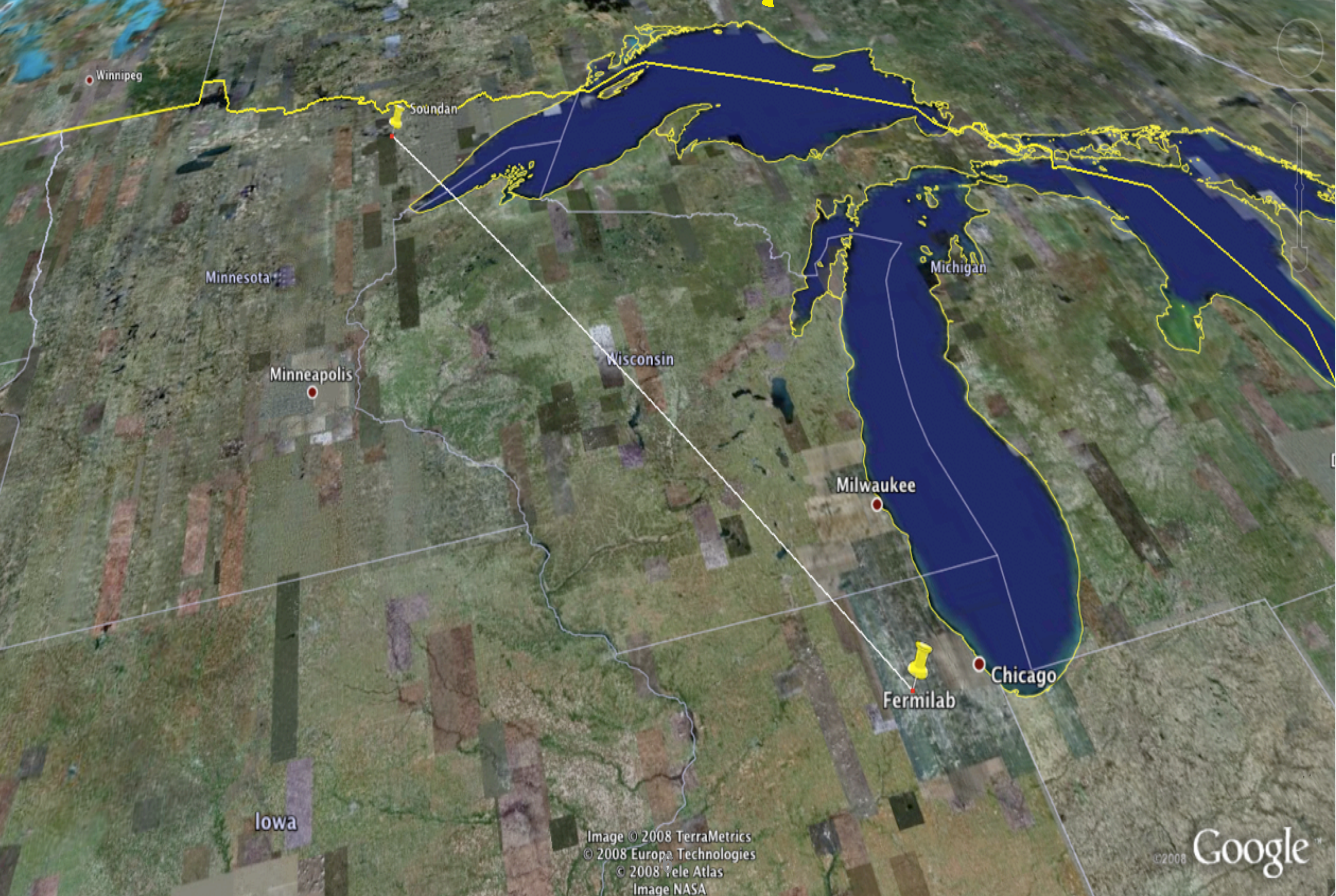
MINOS - Main Injector Neutrino Oscillation Search

* Primary goals:
  * Precise measurements of Δm_{32}^2 and $\sin^2(2\theta_{23})$

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27\Delta m_{32}^2 \frac{L}{E}\right)$$

  * Confirm oscillations vs. other explanations (decay, decoherence)
* Secondary goals:
  * Search for $\nu_\mu \rightarrow \nu_e$ oscillations (θ_{13})
  * Measurement of Δm_{32}^2 and $\sin^2(2\theta_{23})$ for antineutrinos and other CPT tests
  * Search for sterile neutrinos (NC events)
  * Neutrino cross-sections

MINOS - The Experiment

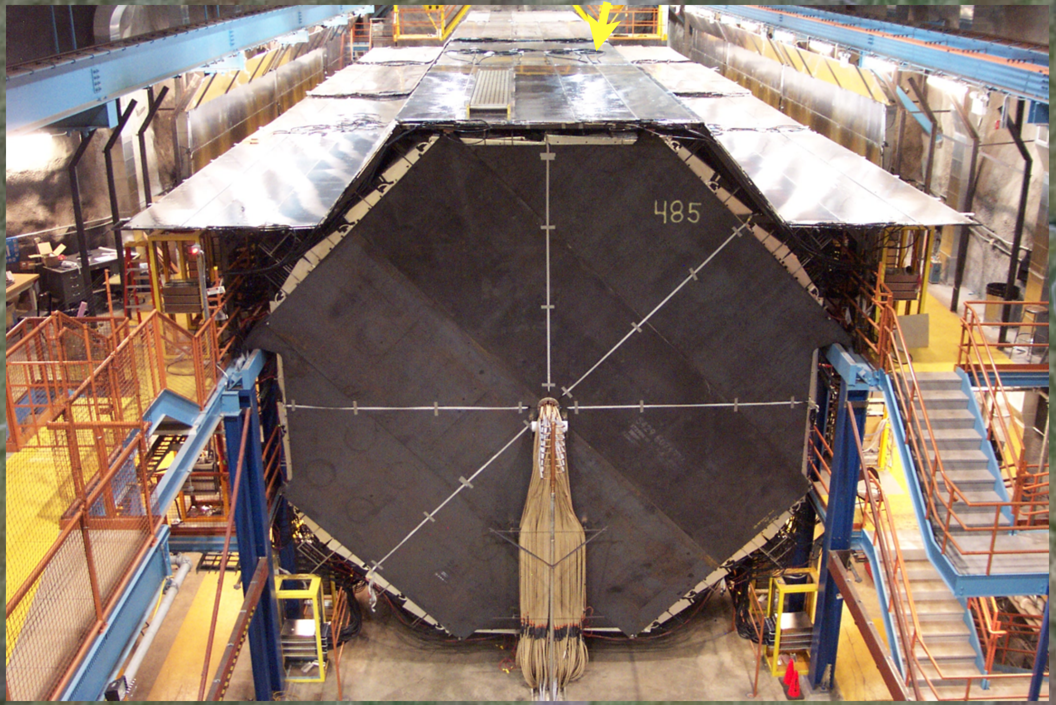


MINOS - The Experiment

- Near Detector:
- 0.98 kton
- 1 km from target

MINOS - The Experiment

* Far Detector:
  * 5.4 kton
  * 735 km from target



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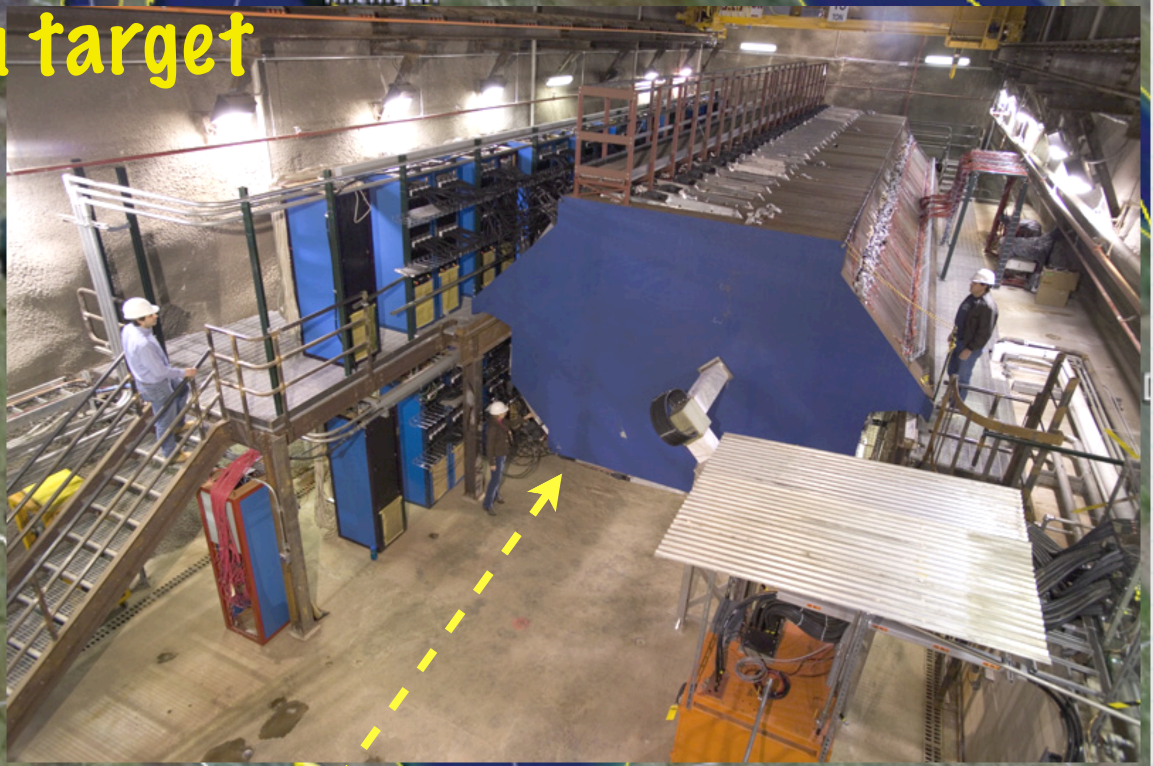

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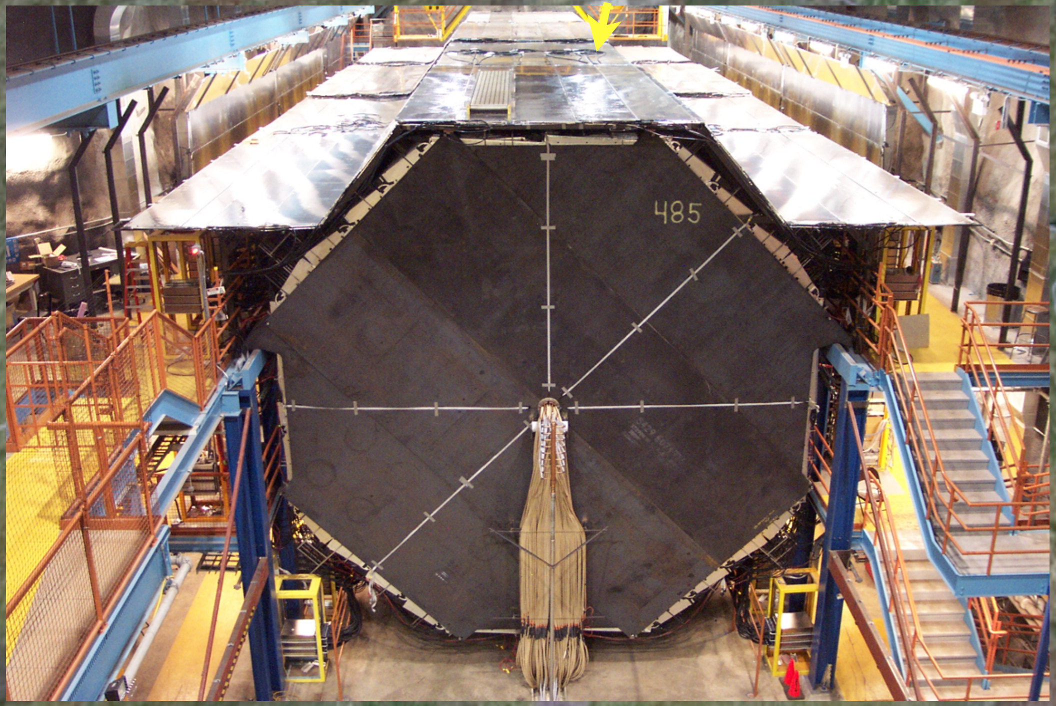

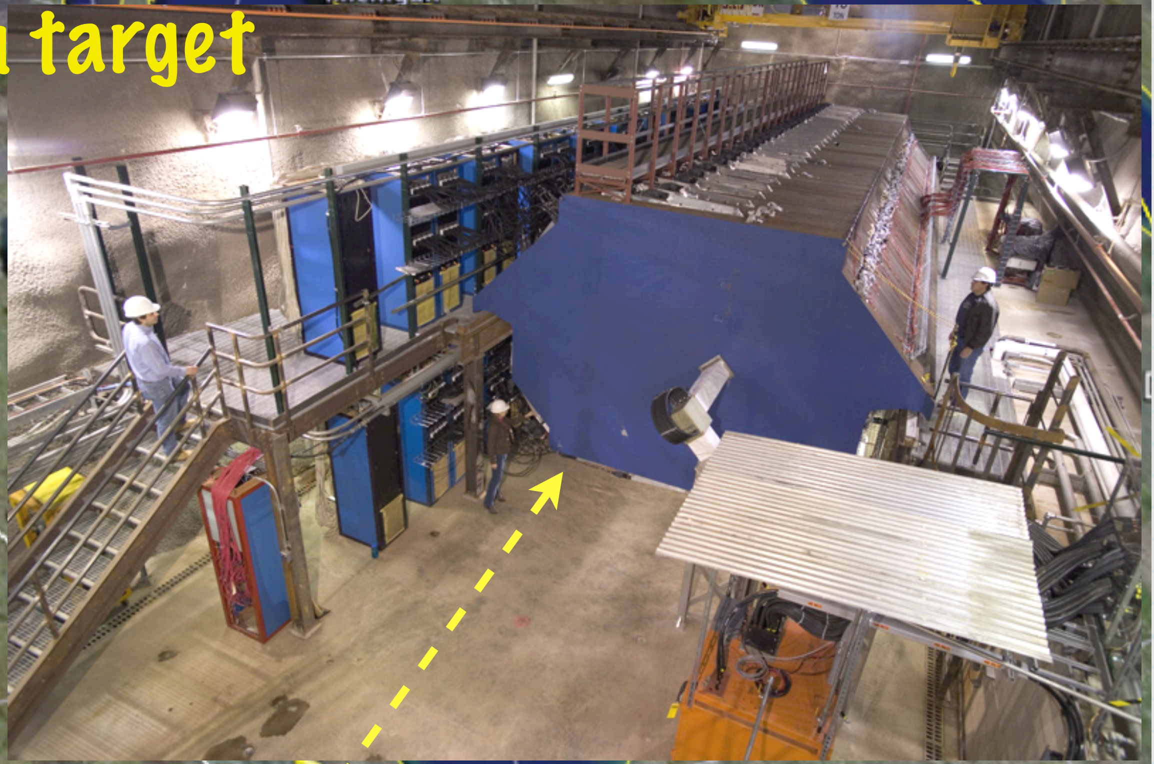

Both detectors are magnetic (~1.3 T) tracking calorimeters.

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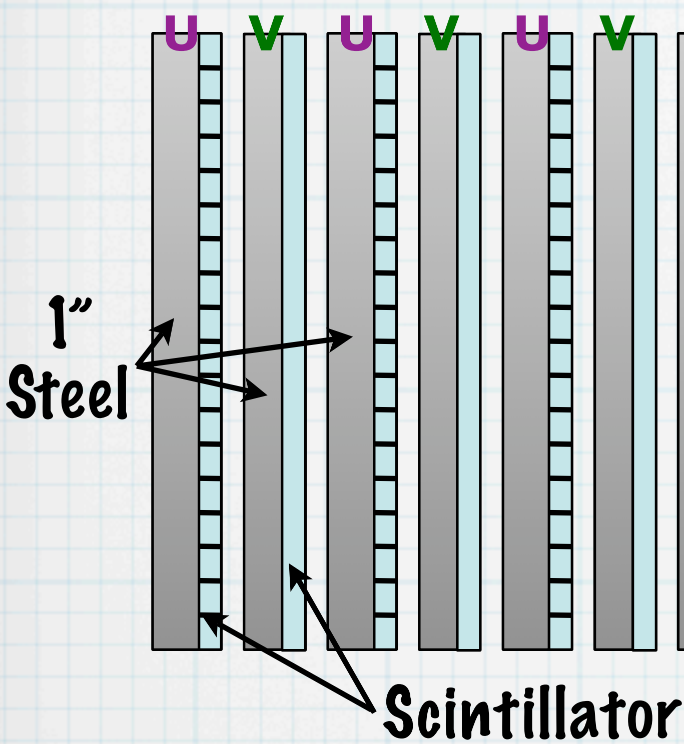
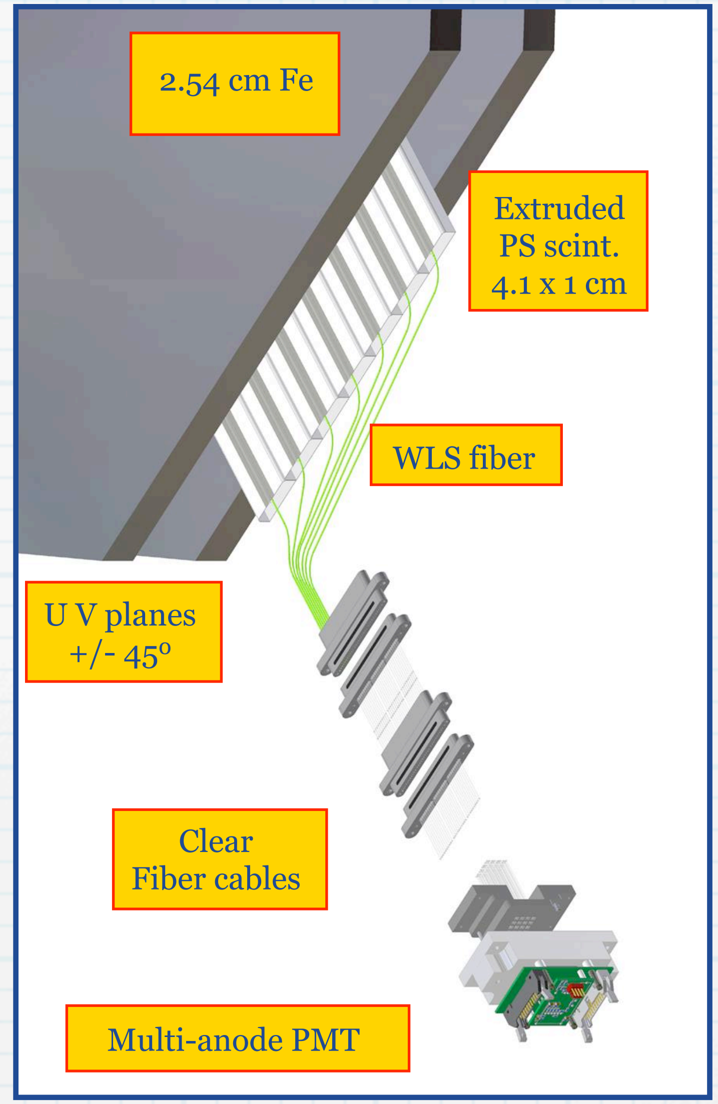
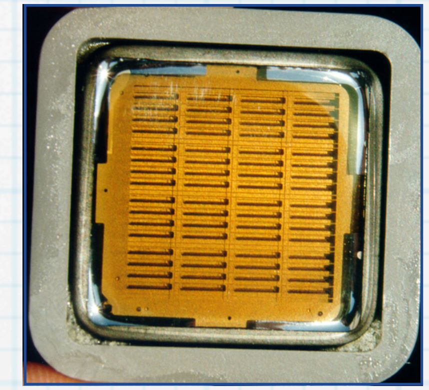
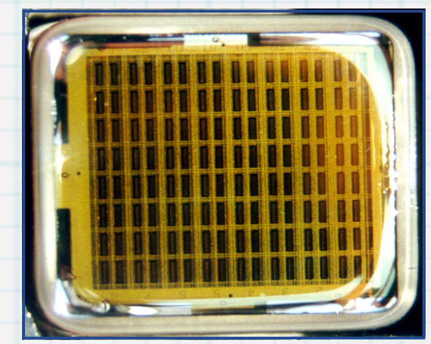
The MINOS Detectors







M16
Far Detector

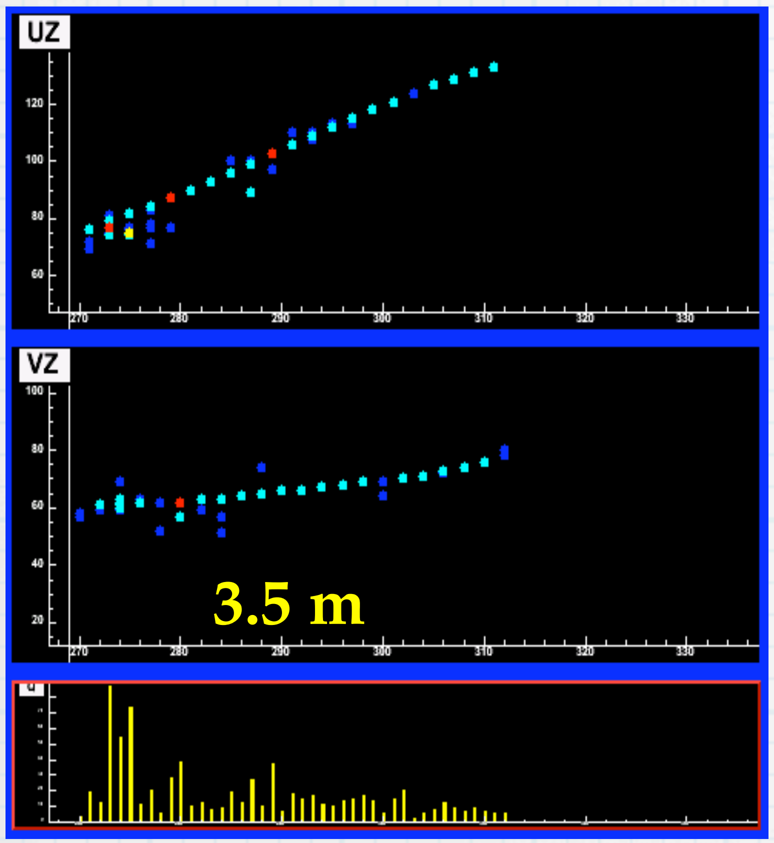


M64
Near Detector

- Both detectors have:
  - co-extruded polysterene scintillator strips
  - alternating planes with orthogonal orientations
  - optical fiber readout to multi-anode PMTs
- Differences between detectors:
  - PMTs & associated electronics
  - Event rates (pileup)
  - Fiducial volumes (and shapes)

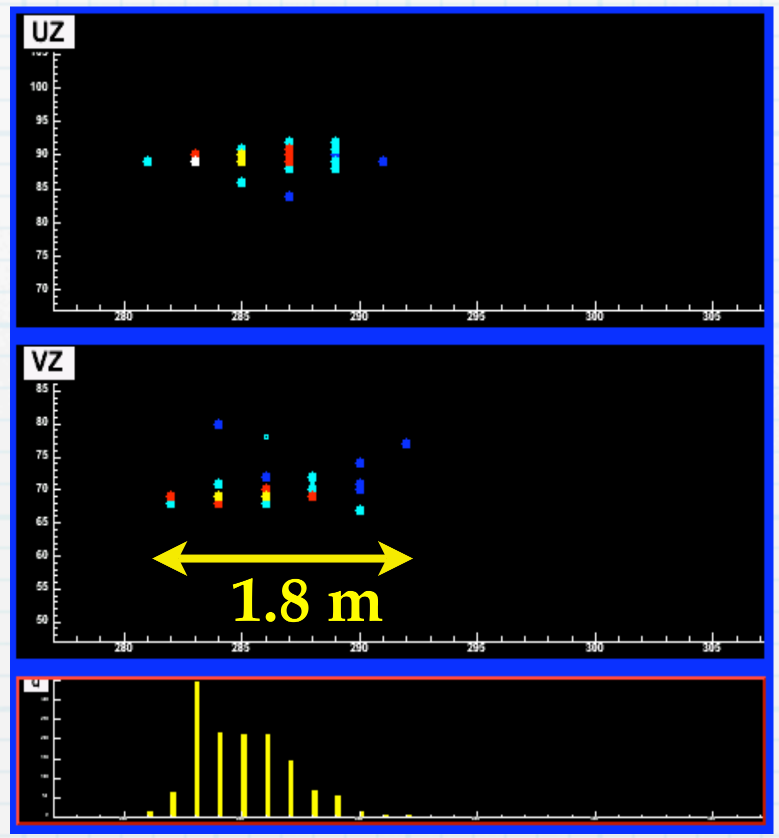
Identifying Events in MINOS

ν_μ CC event



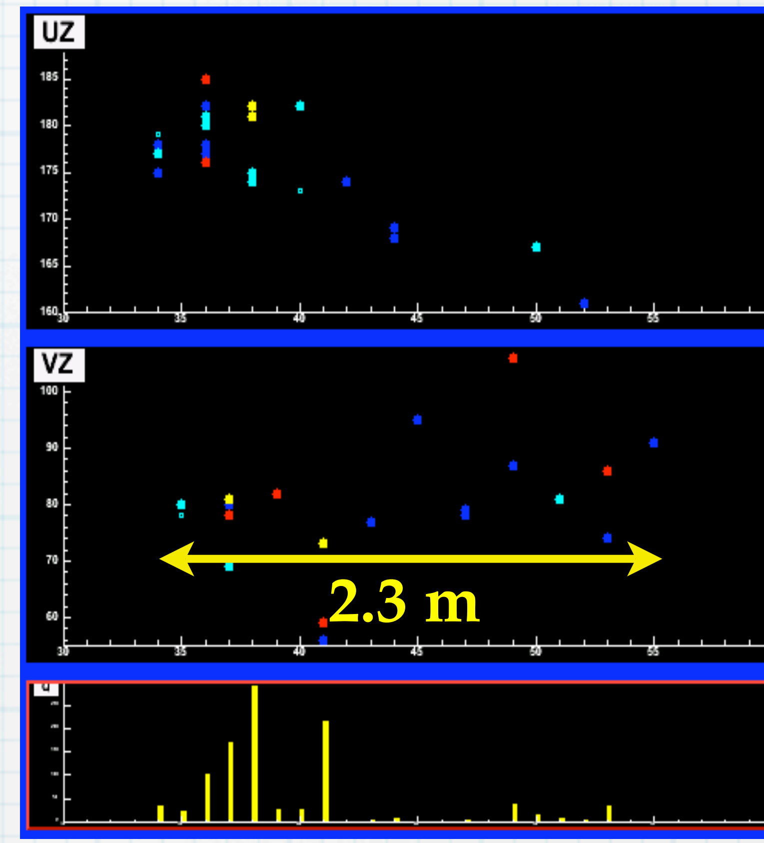
Long μ track + shower at vertex

ν_e CC event



Short event with EM shower profile.

NC event

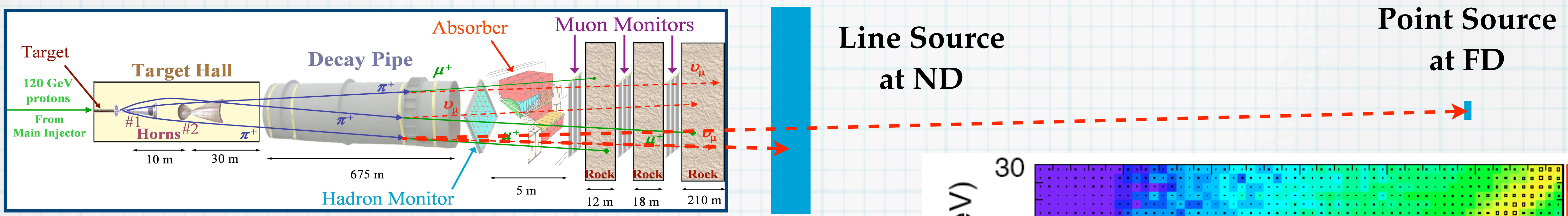


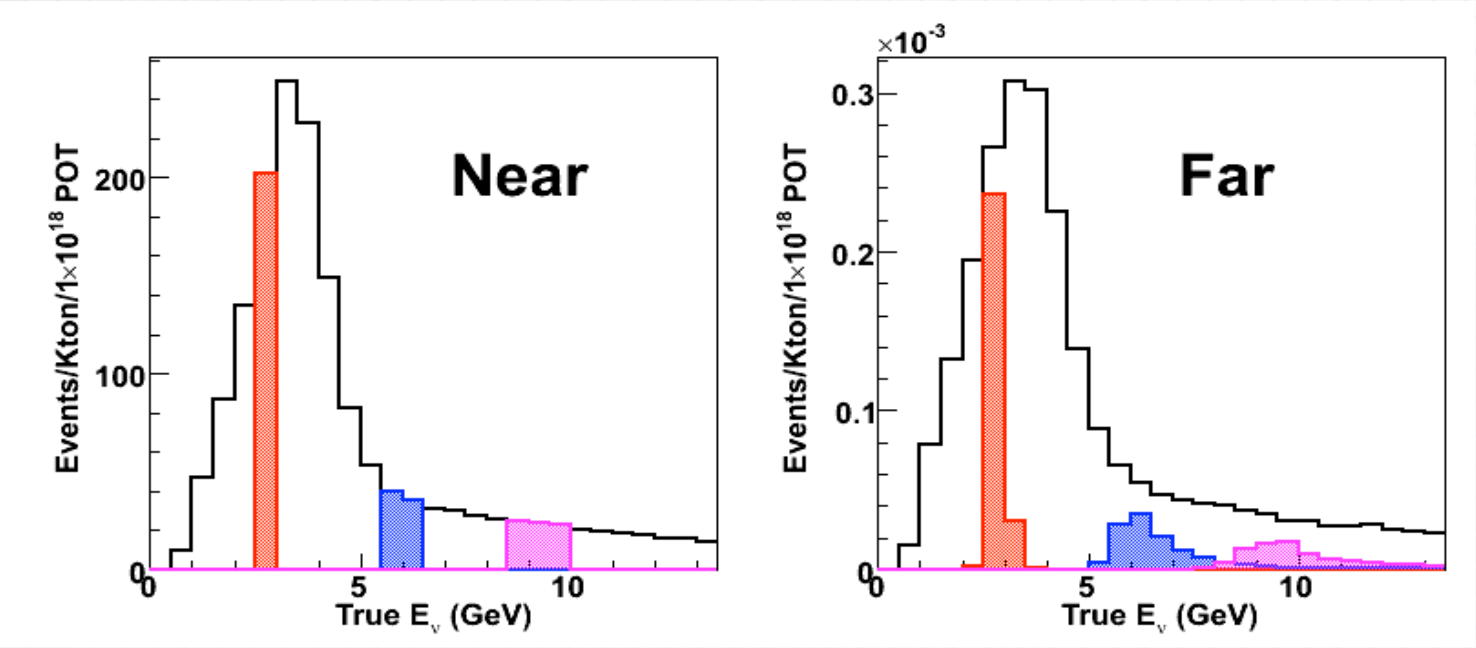
Short, diffuse event.

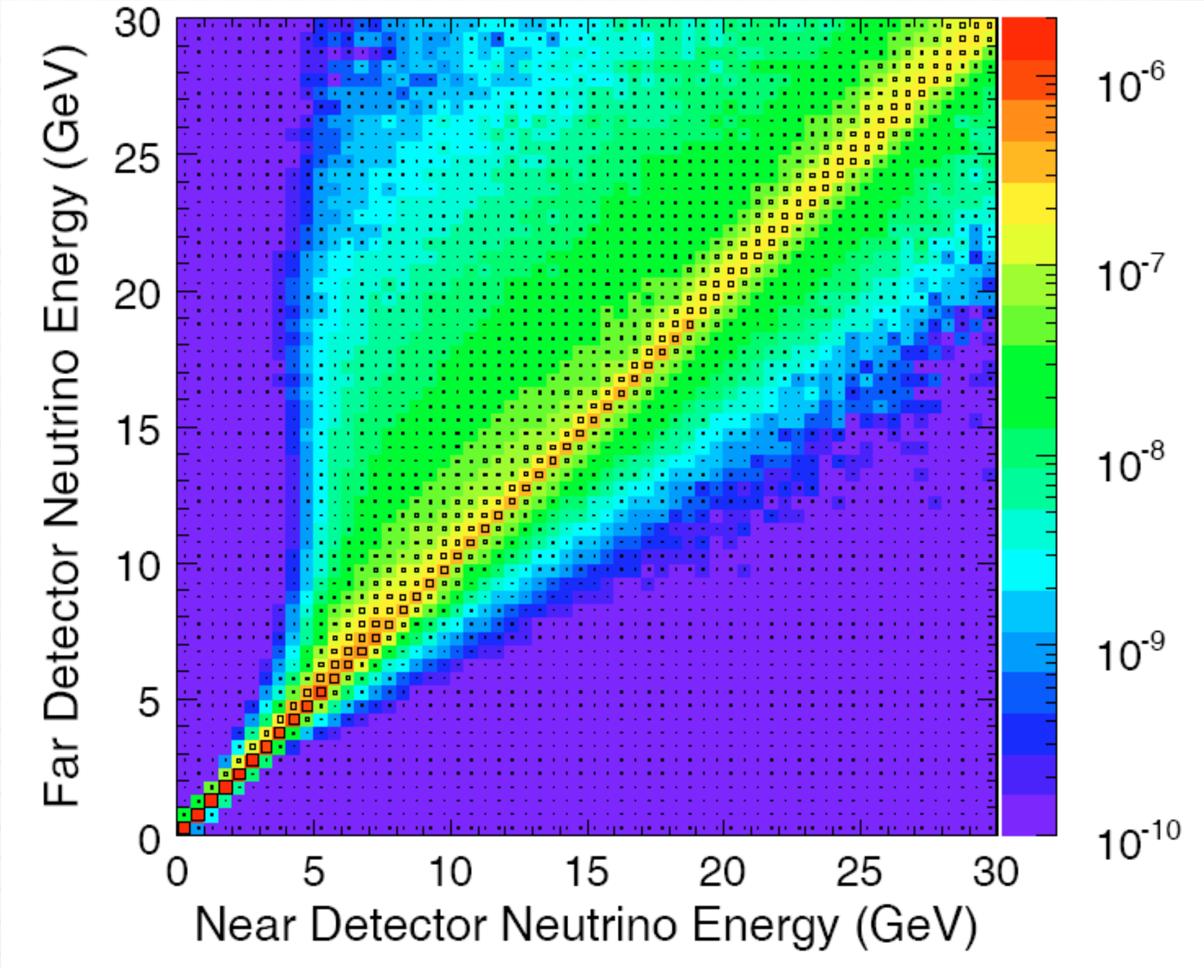
$$E_\nu = E_{shower} + E_{\mu,e}$$

$\delta E_{shower} = 55\%/\sqrt{E}$ $\quad$ $\delta E_\mu = 6\%$ range, 10% curvature

Predicting the FD Spectrum

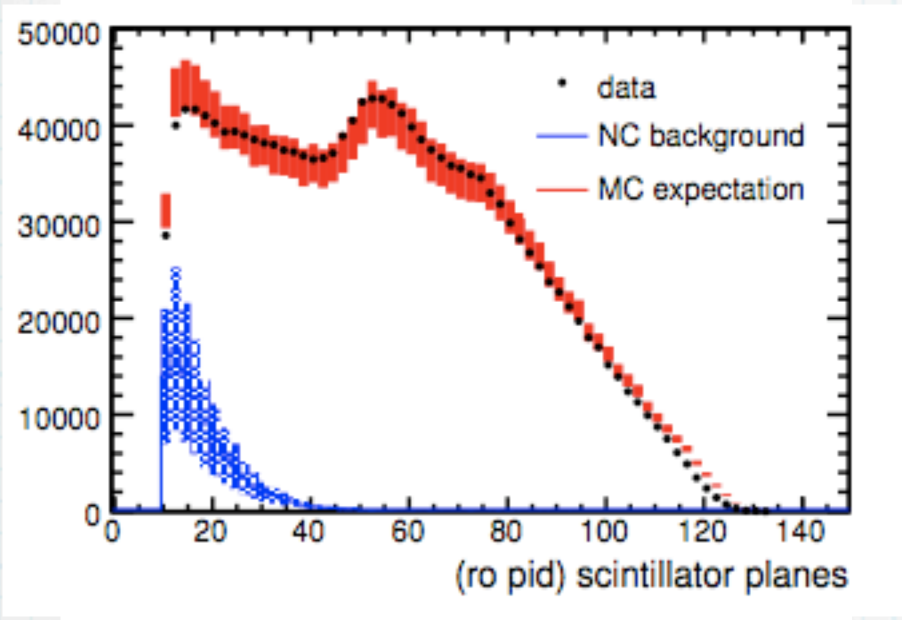






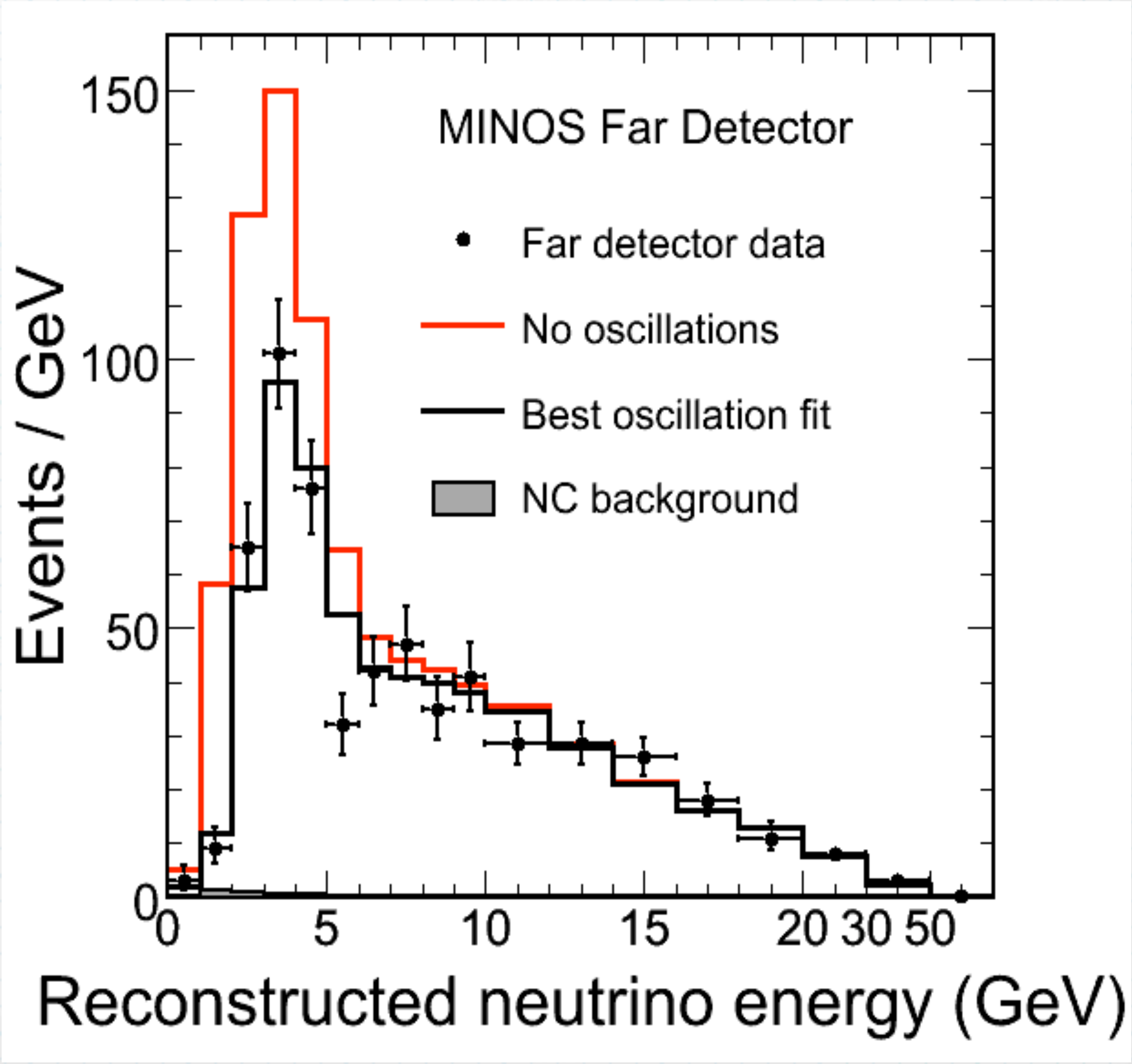
- Near detector spectrum is extrapolated to the far detector
- Use MC to provide energy smearing and acceptance corrections

MINOS Measurement of Δm^2 and $\sin^2(2\theta)$



* CC/NC event separation achieved using a selection based on track length, mean pulse height, fluctuation in pulse height and transverse track profile.

* FD energy spectrum is only looked at after performing:
  * low-level data quality checks
  * procedural checks
* 848 events observed in the FD
* 1065 ± 60 expected with no oscillations
* We fit the energy distribution to the oscillation hypothesis.



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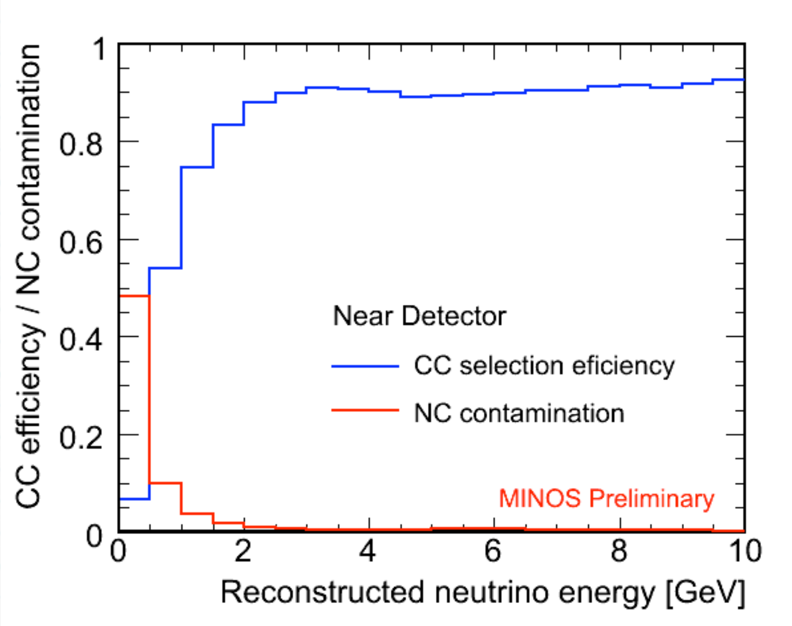

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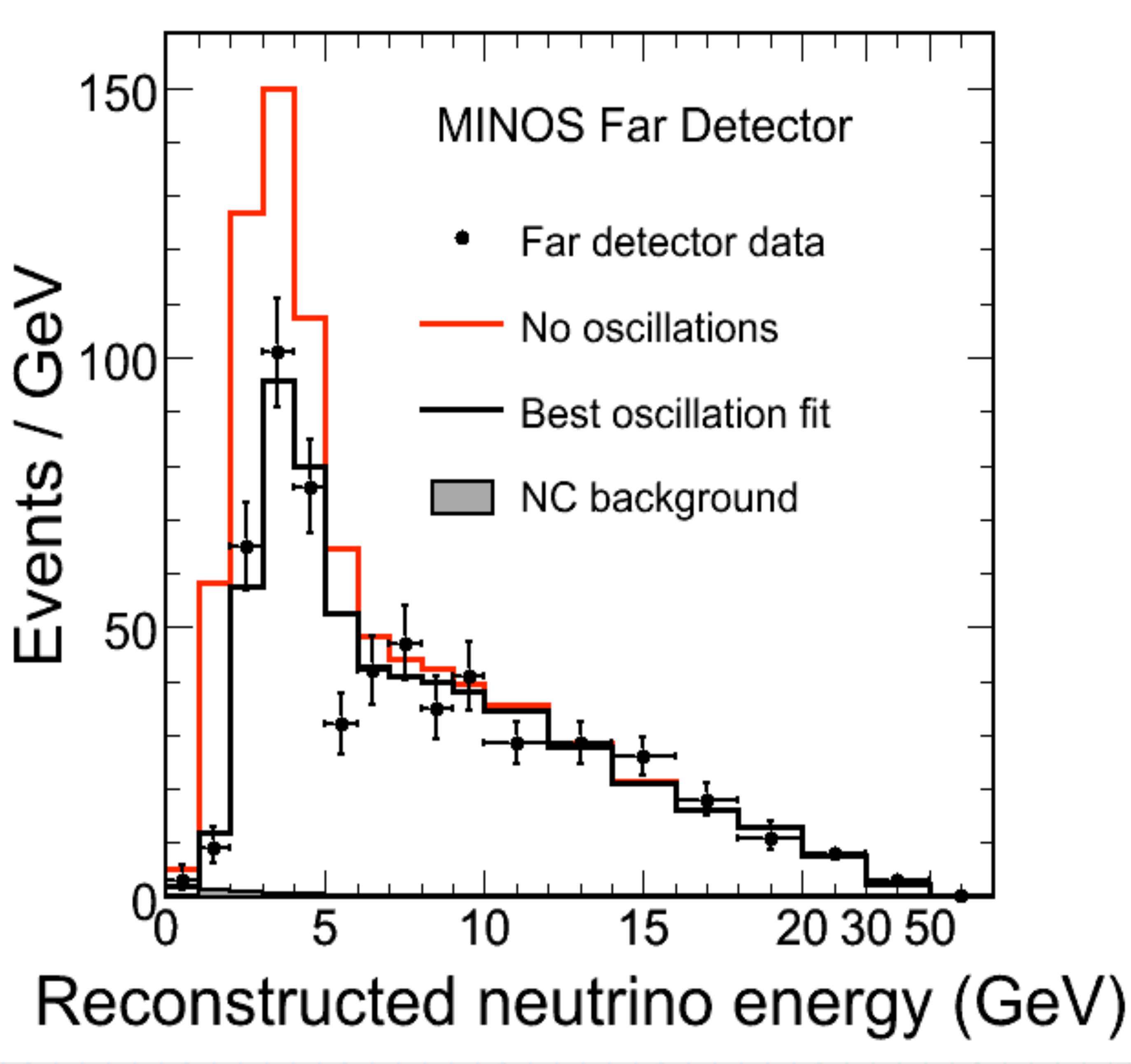
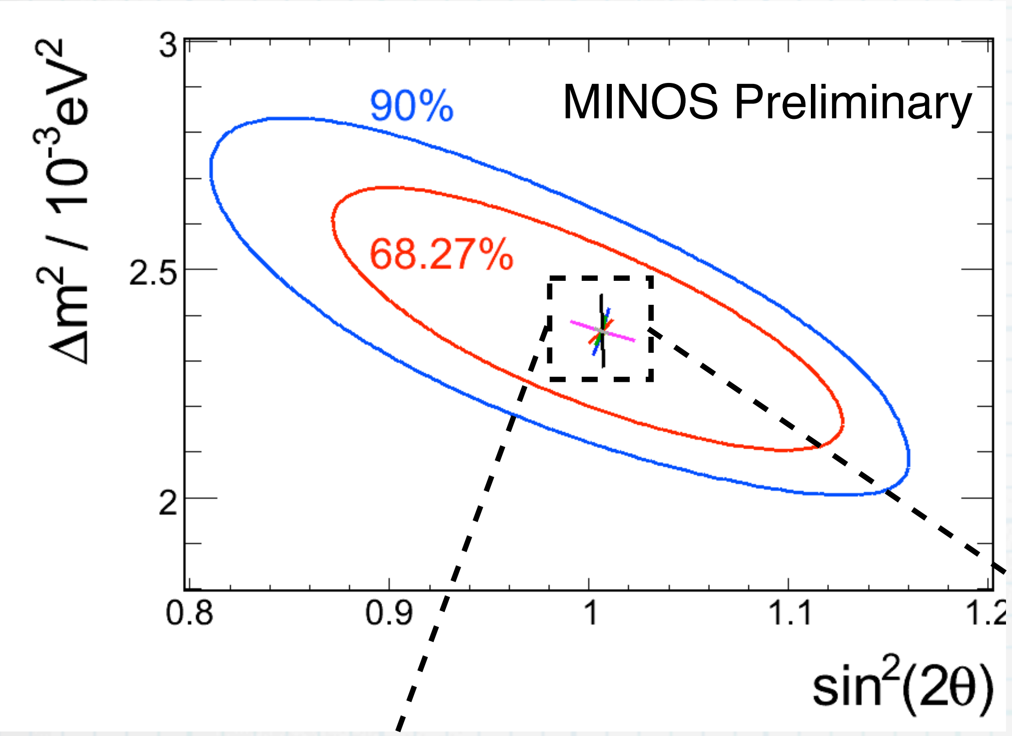
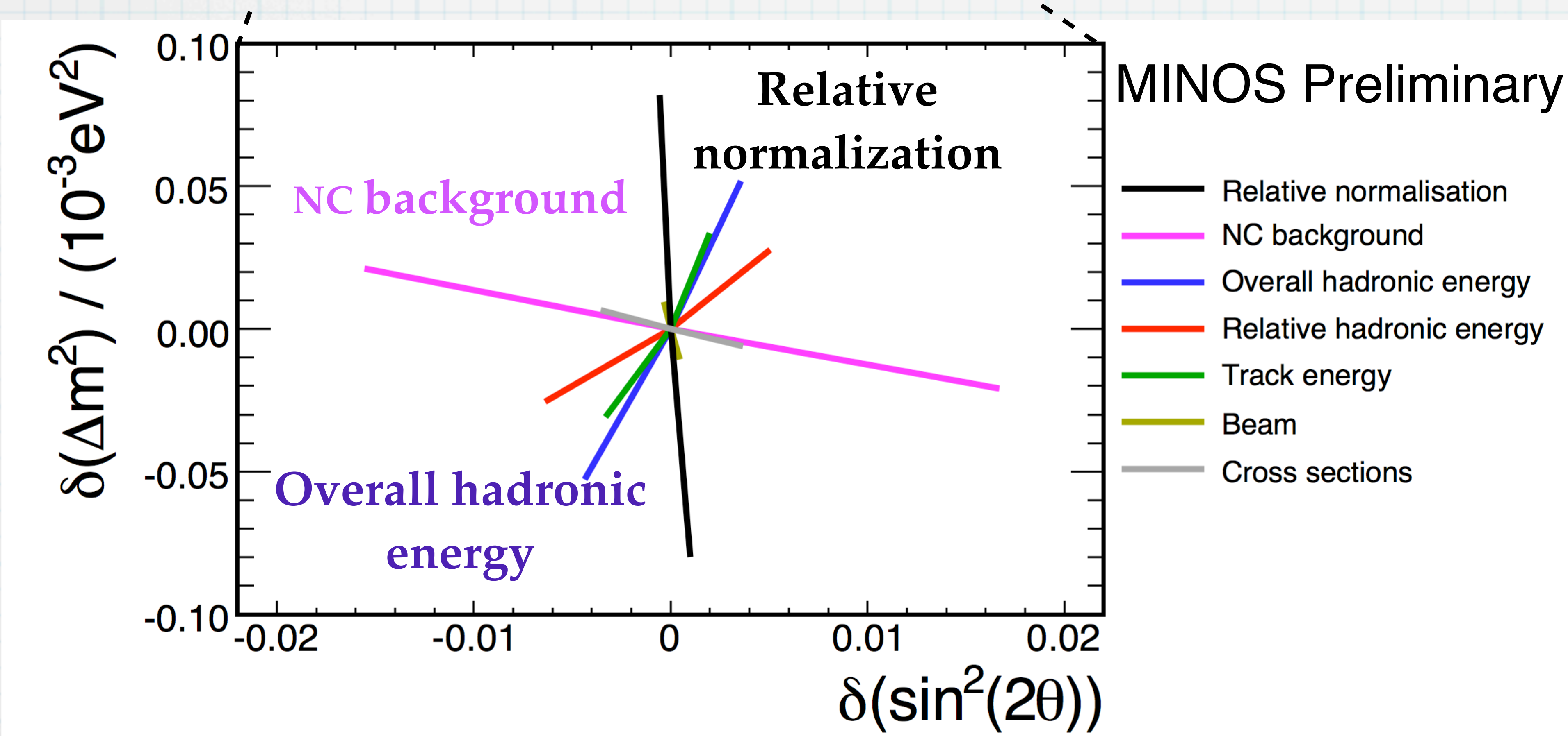


MINOS Δm^2 and $\sin^2(2\theta)$ Systematics

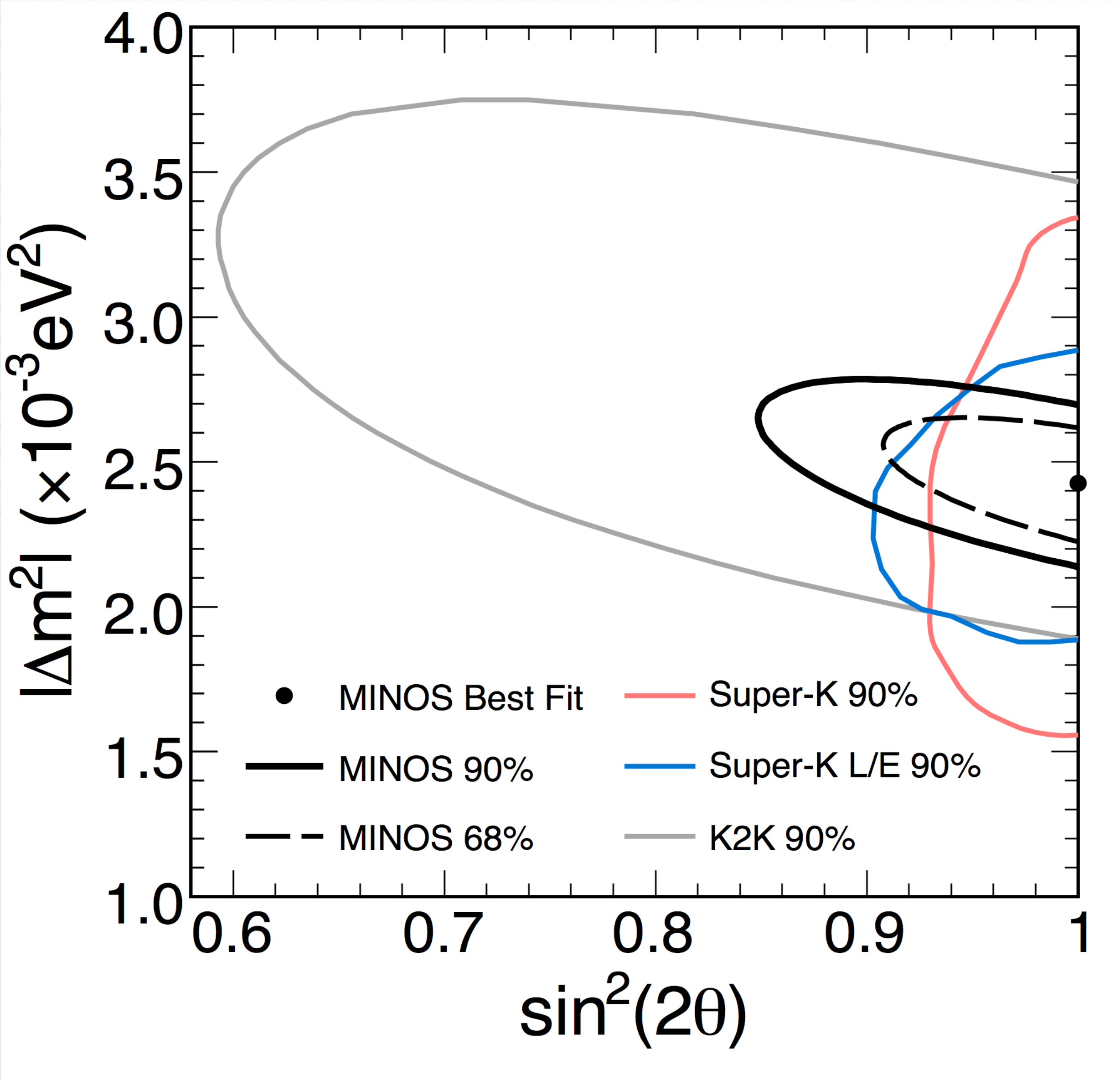


- Systematic uncertainties estimated by fitting modified MC in place of data.
- ν_μ CC measurement is statistics-limited.
- Dominant uncertainties:
  - ND/FD normalization (Δm^2)
  - Overall hadronic energy calibration (Δm^2)
  - NC background ($\sin^2(2\theta)$)

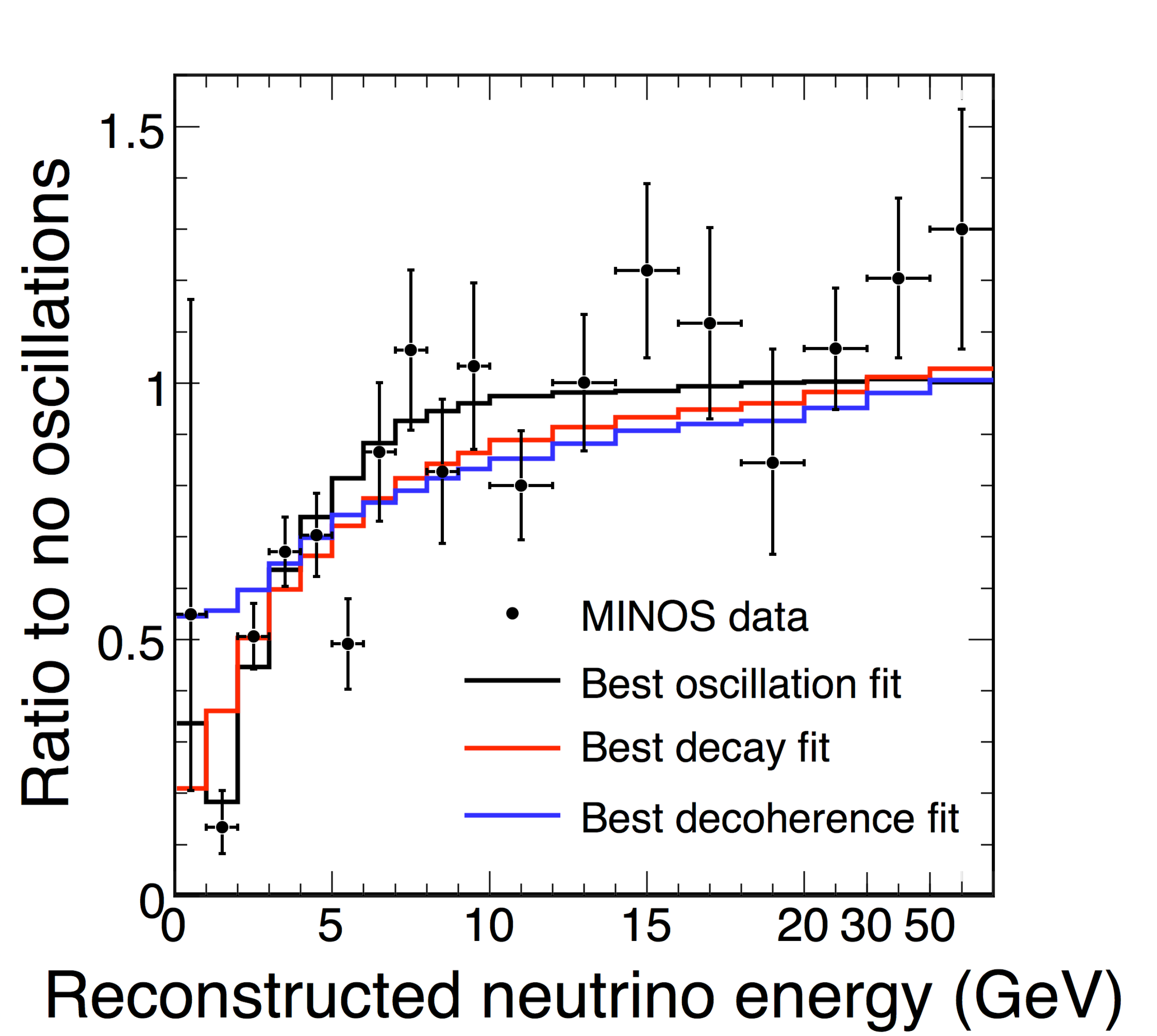


- These systematic effects are included in the final fit as nuisance parameters.

MINOS Δm^2 and $\sin^2(2\theta)$ Results



* $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL)
* $\sin^2(2\theta) > 0.90$ (90% CL)
* χ^2/ndof = 90/97



* Decay Model (V. Barget *et. al.*, PRL82:2640 (1999)) disfavored at 3.7 σ
* Decoherence Model (G.L. Fogli, *et. al.*, PRD67:093006 (2003)) disfavored at 5.7 σ

MINOS Antineutrino Analysis

* MINOS is unique in its ability to separate ν_μ from $\bar{\nu}_\mu$ events.
* Do ν_μ and $\bar{\nu}_\mu$ oscillate the same way? Test of CPT.
* Do ν_μ oscillate to $\bar{\nu}_\mu$? Possible via some exotic beyond-SM processes and/or Majorana nature of neutrinos.
* NuMI beam consists of ~7% $\bar{\nu}_\mu$.
* Most $\bar{\nu}_\mu$ are higher energy and come from low p_T π^-'s that travel straight through the focusing horns; all other π^-'s are defocused and don't reach the decay pipe.

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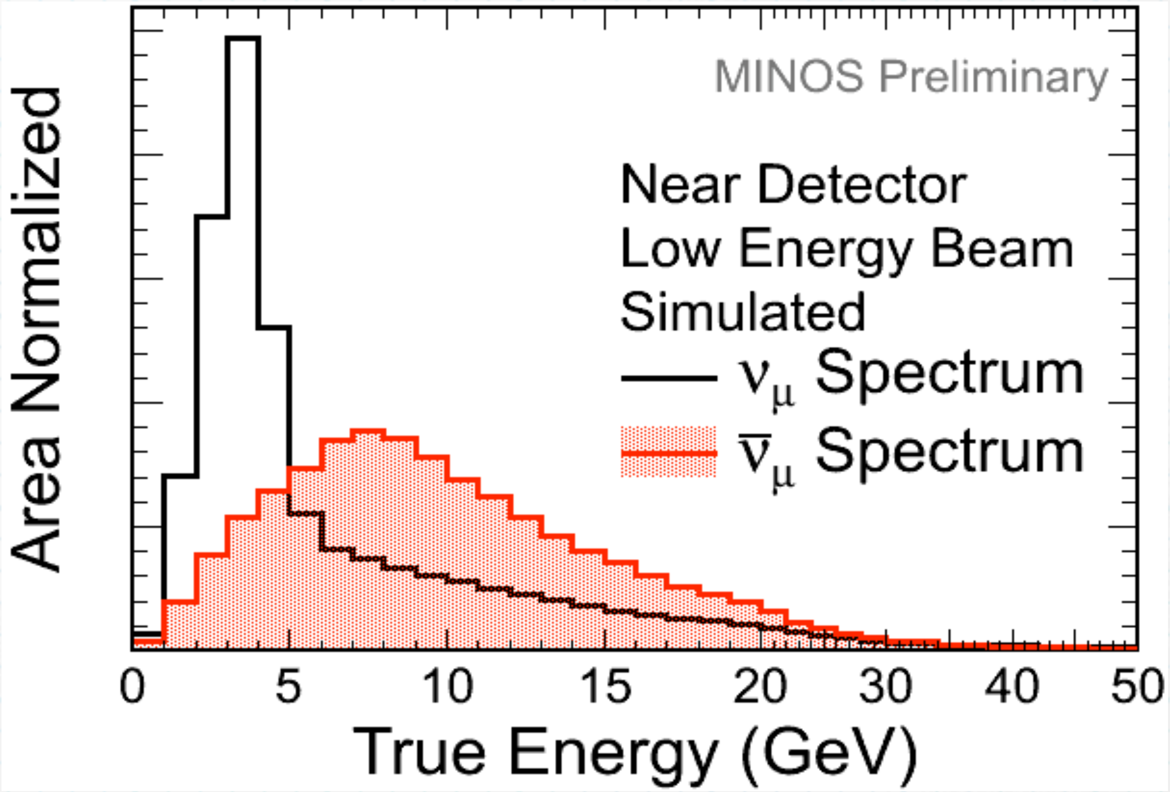
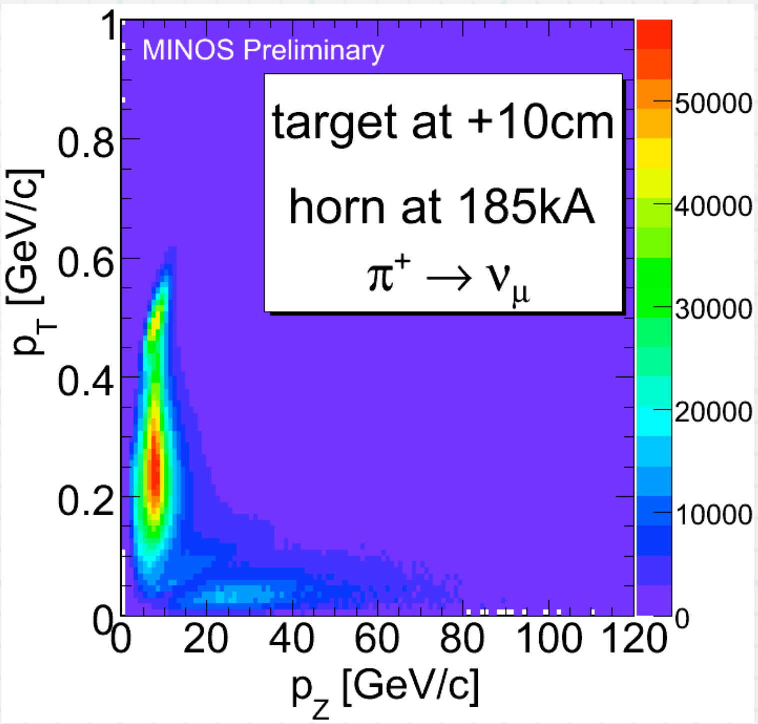
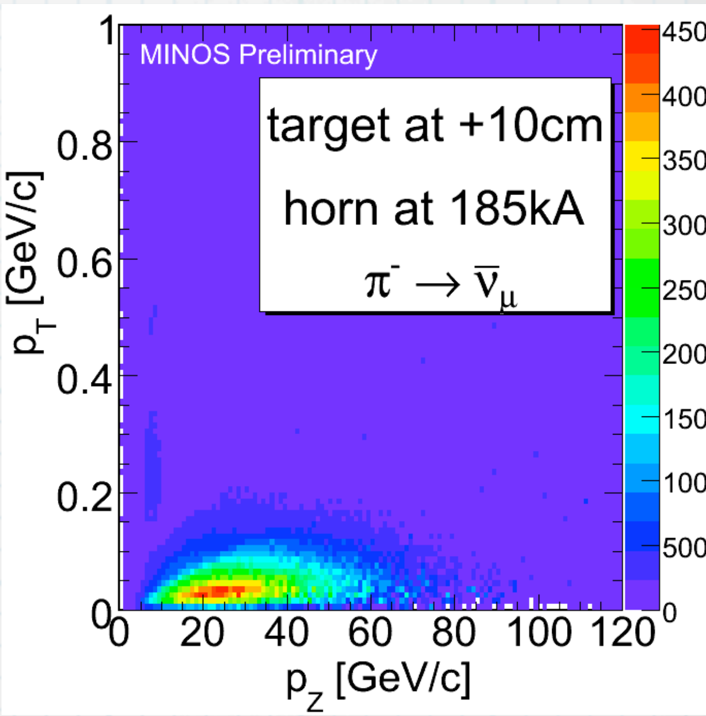
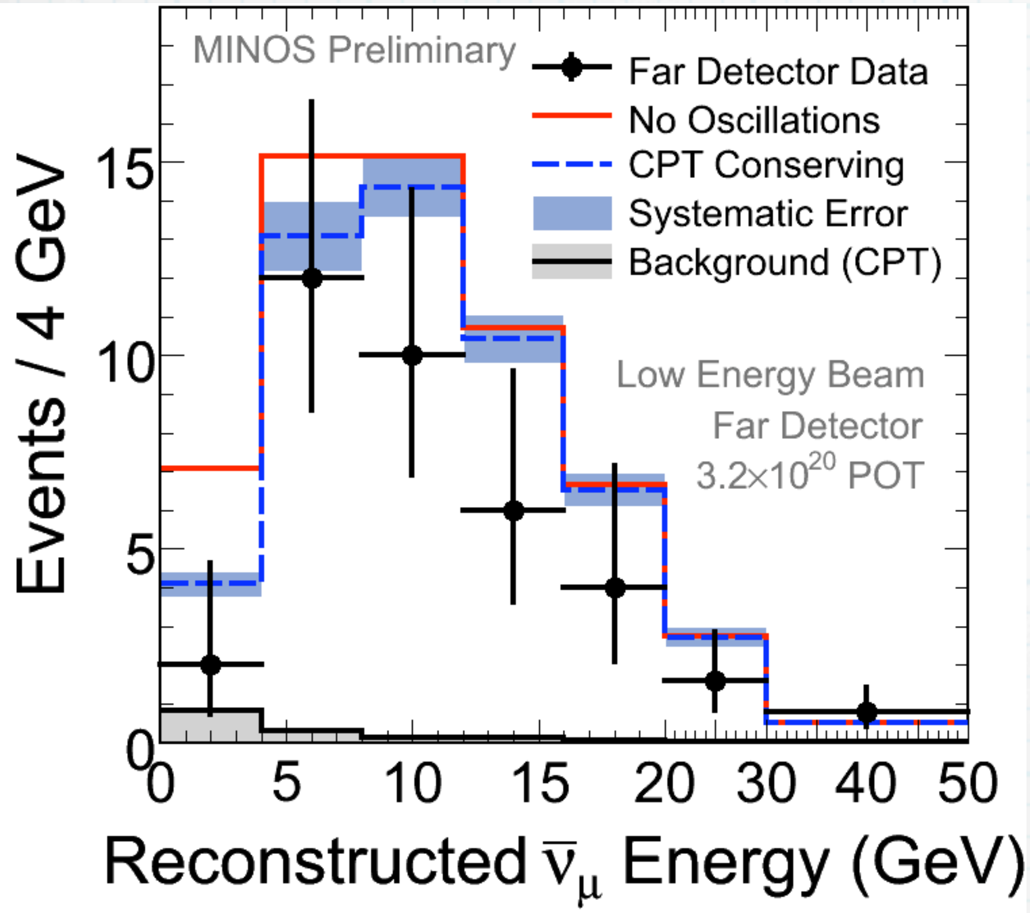






MINOS Antineutrino Results

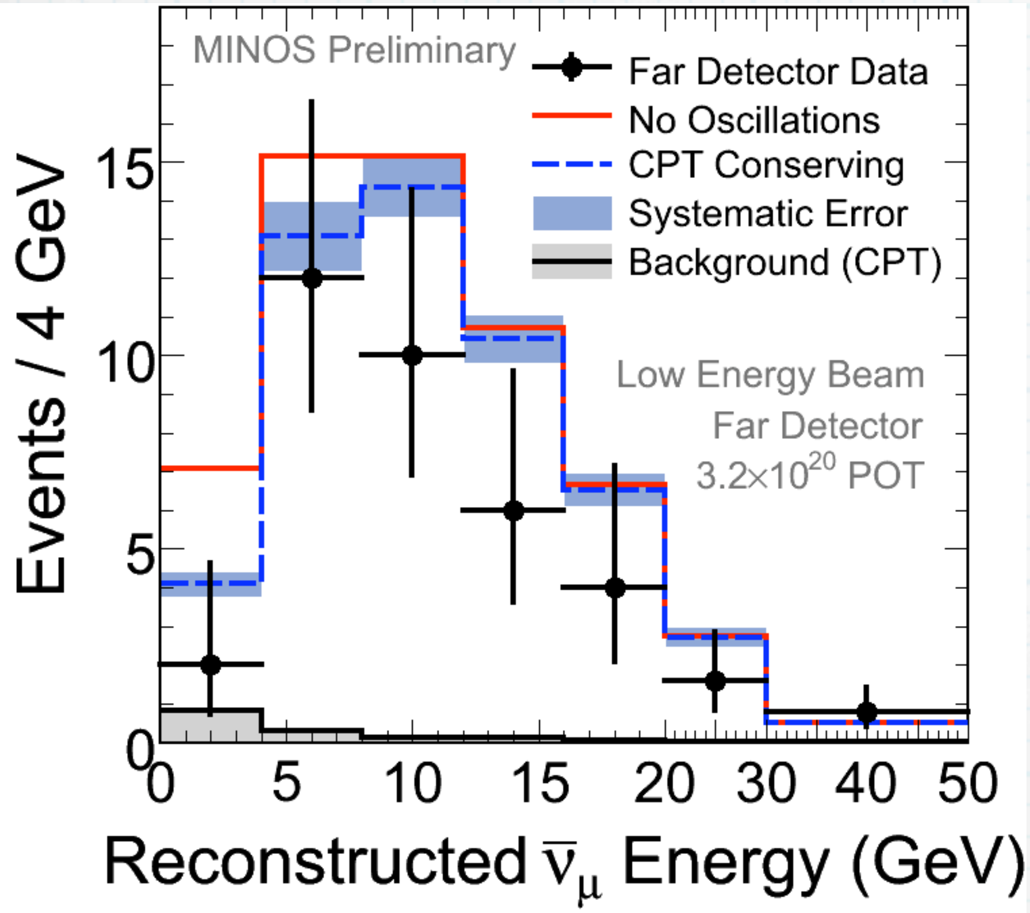


* Events are selected based on track length, pulse height fraction in track, pulse height per plane, track fit charge sign significance, and track curvature.
* Observe 42 events in the FD
* Predicted w/ CPT conserving oscillations:

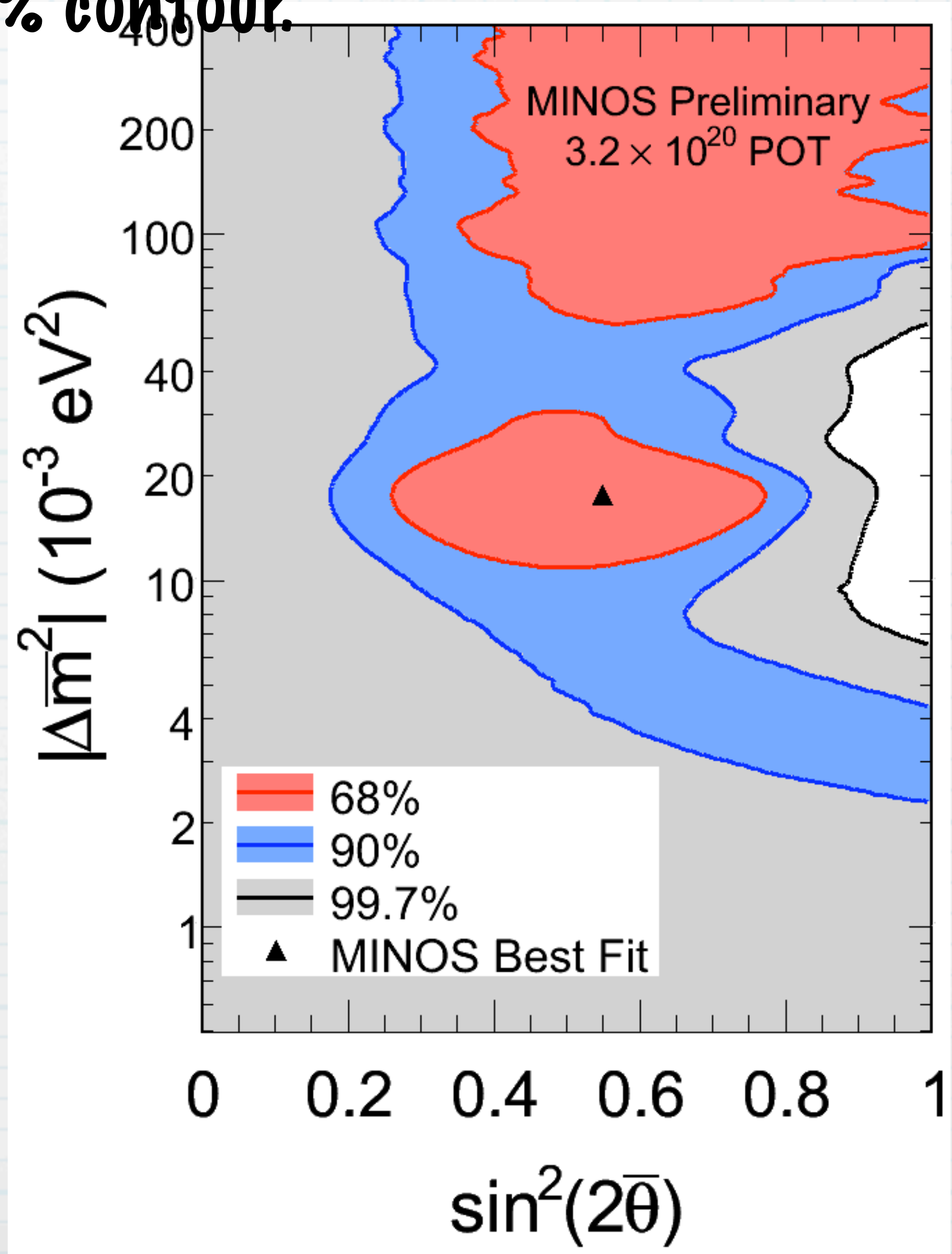
  58.3 ±7.6 (stat) ±3.6 (syst.)
* Predicted w/ no oscillations:

  64.6 ± 8.0 (stat) ± 3.9 (syst.)

MINOS Antineutrino Results



* MINOS excludes at maximal mixing:(5.0 < Δm^2 < 81)x10^{-3} eV^2 (90% CL)
* Null oscillation hypothesis excluded at 99%.
* CPT conserving point from ν_μ analysis falls within 90% contour.



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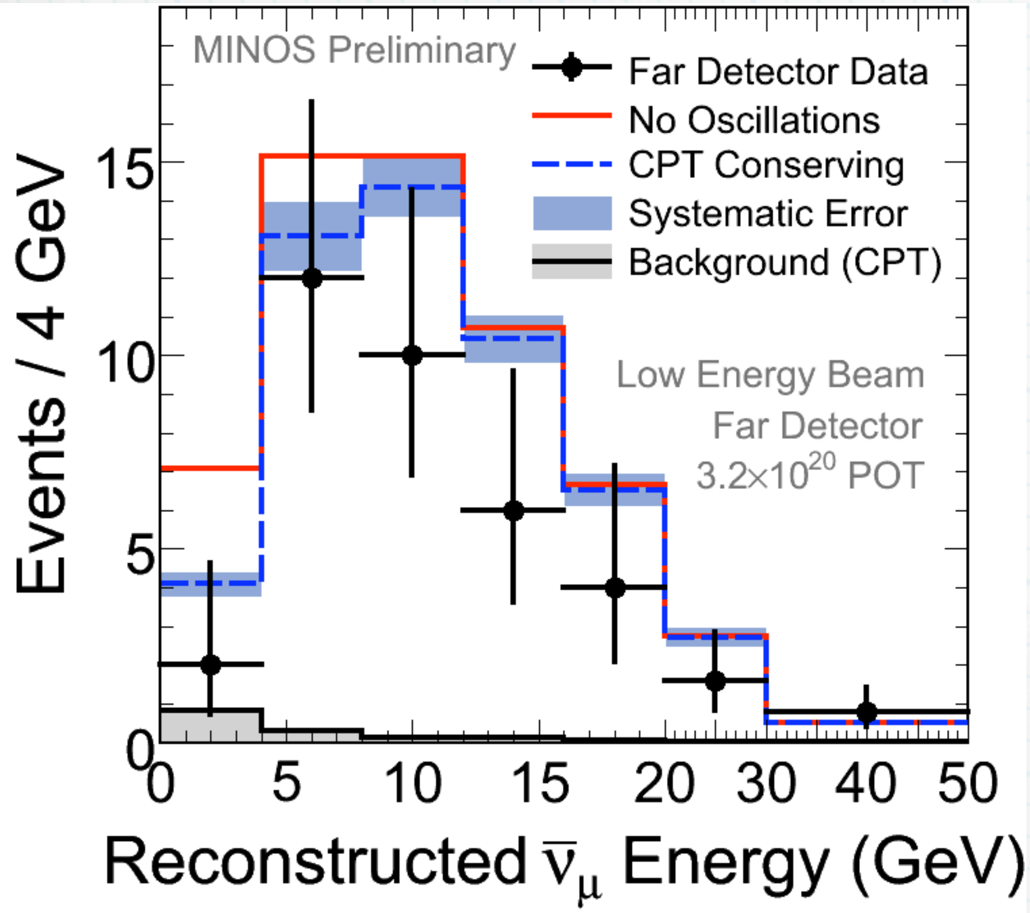
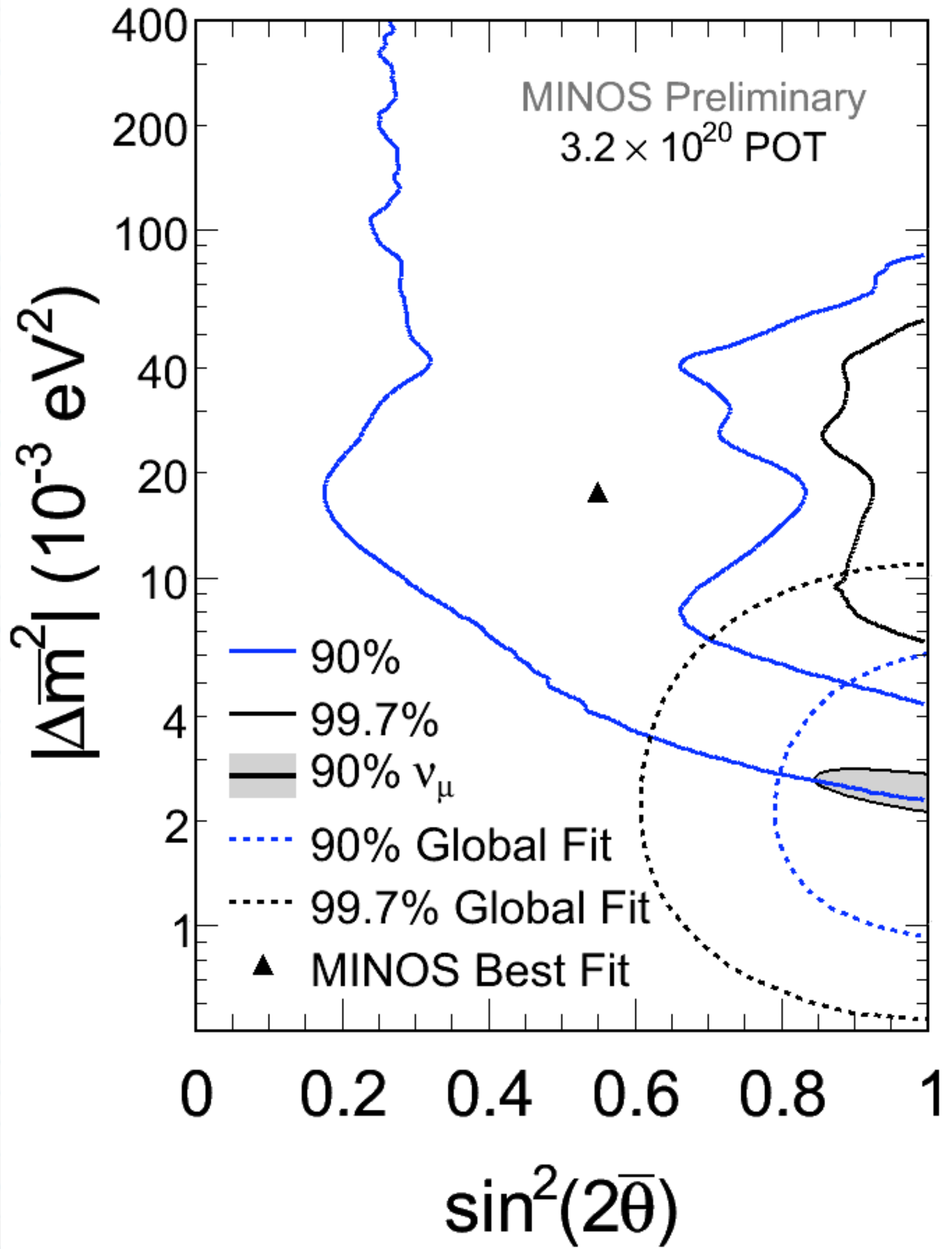


- M.C. Gonzalez-Garcia & M. Maltoni, Phys. Rept. 460 (2008) performed global fit using previous data (dominated by SK-I and SK-II).
- This result excludes previously allowed CPT violating regions of parameter space.



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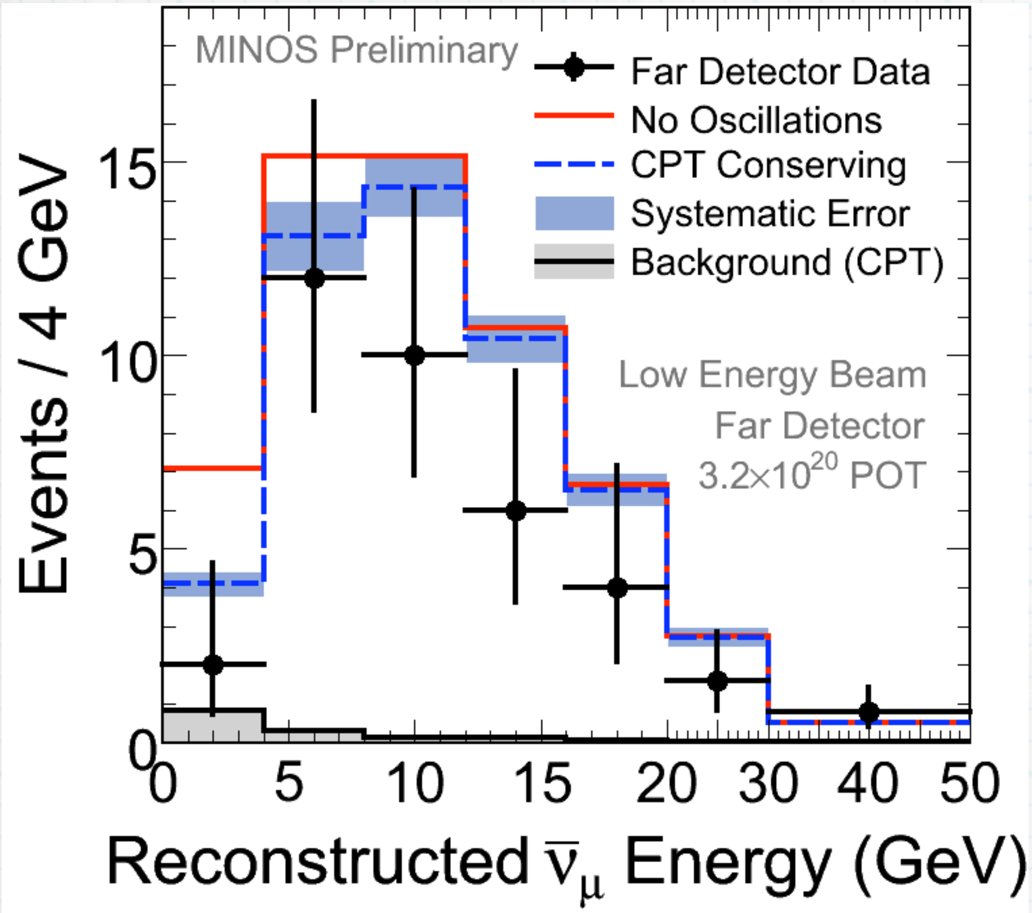

- MINOS observes no excess of ν_μ events in the FD.
- 1-parameter fit for α

$$P(\nu_\mu \rightarrow \overline{\nu_\mu}) = \alpha \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

gives limit: α< **0.026 (90% CL)**

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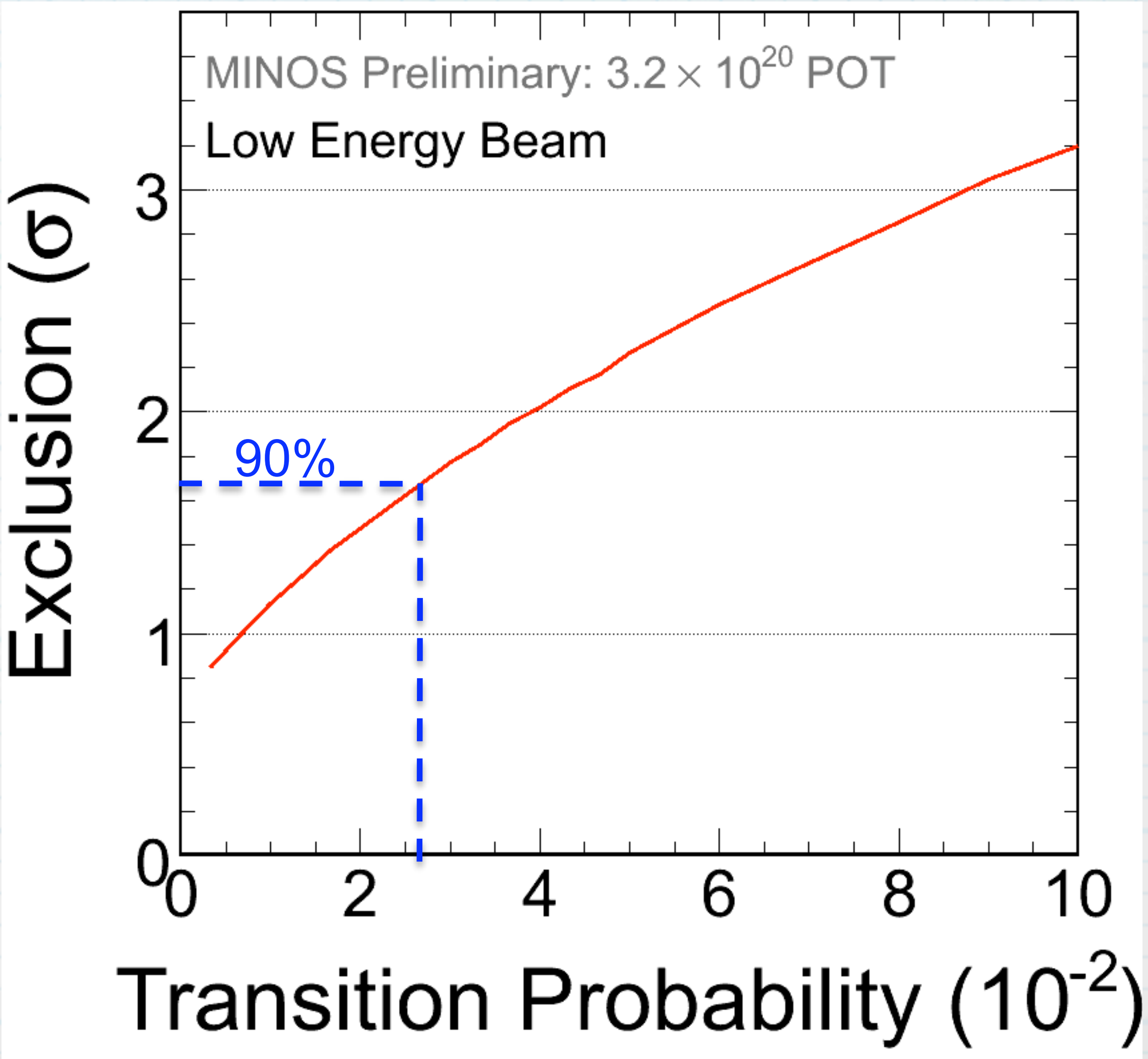
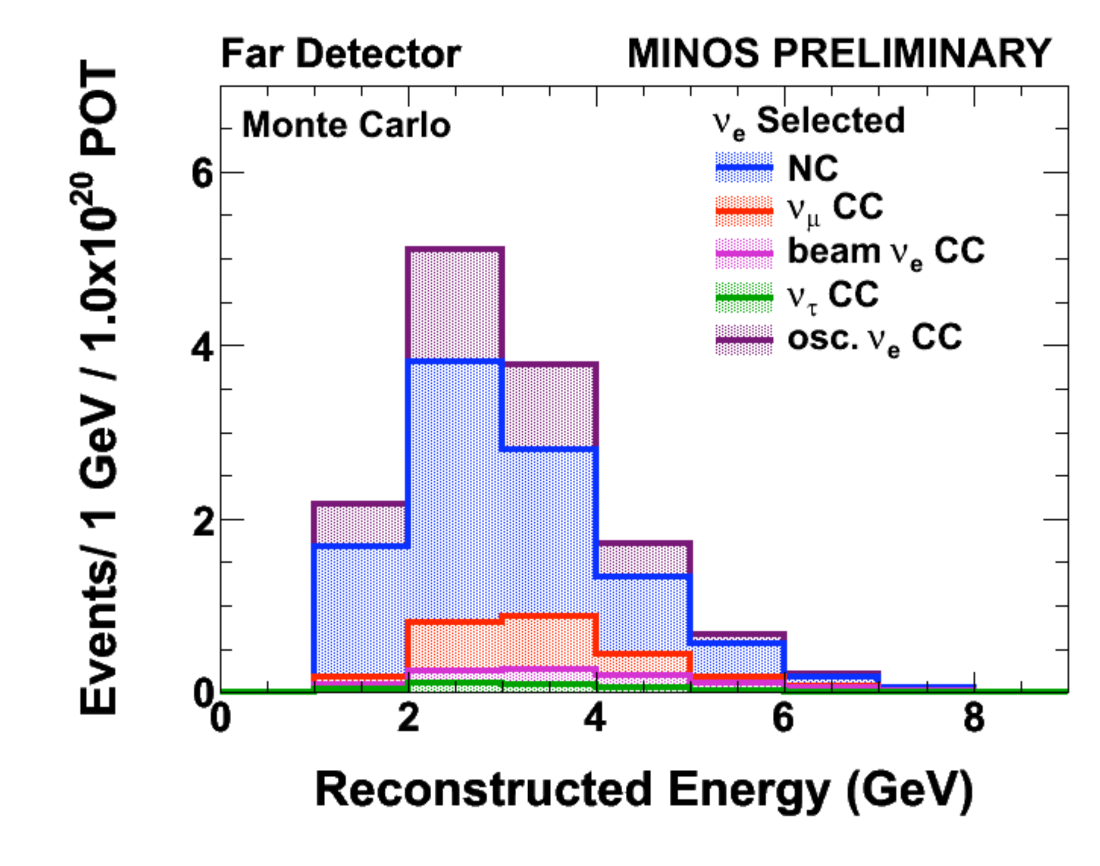
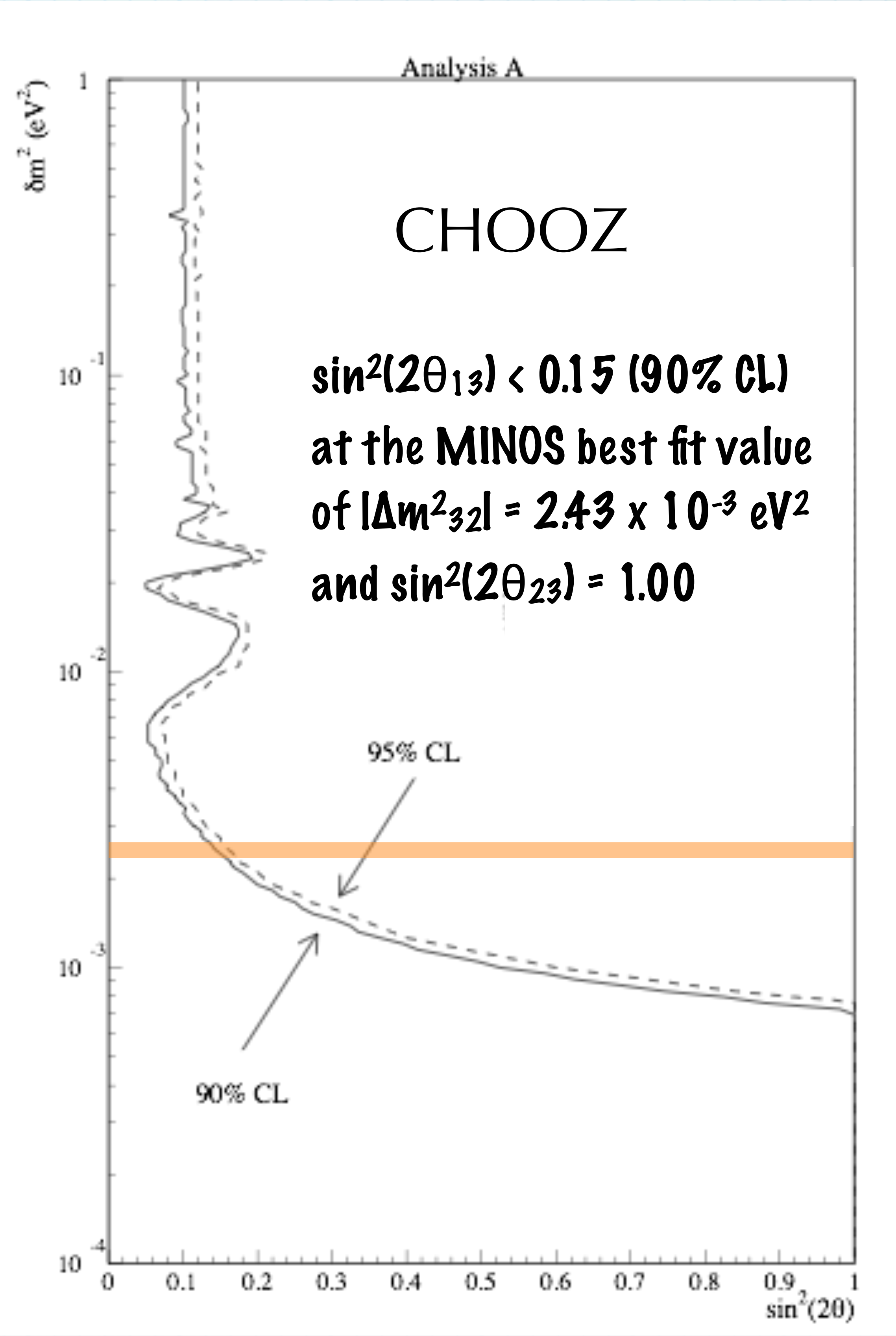


MINOS ν_e Appearance Analysis

- CHOOZ reactor experiment has current best limit on θ_{13}.
- Because of its long baseline, MINOS is sensitive to δ_{CP} and mass hierarchy.
- MINOS detectors were optimized to detect muons, not electrons.
- Main background components are NC, low-energy ν_μ CC and beam ν_e CC events.





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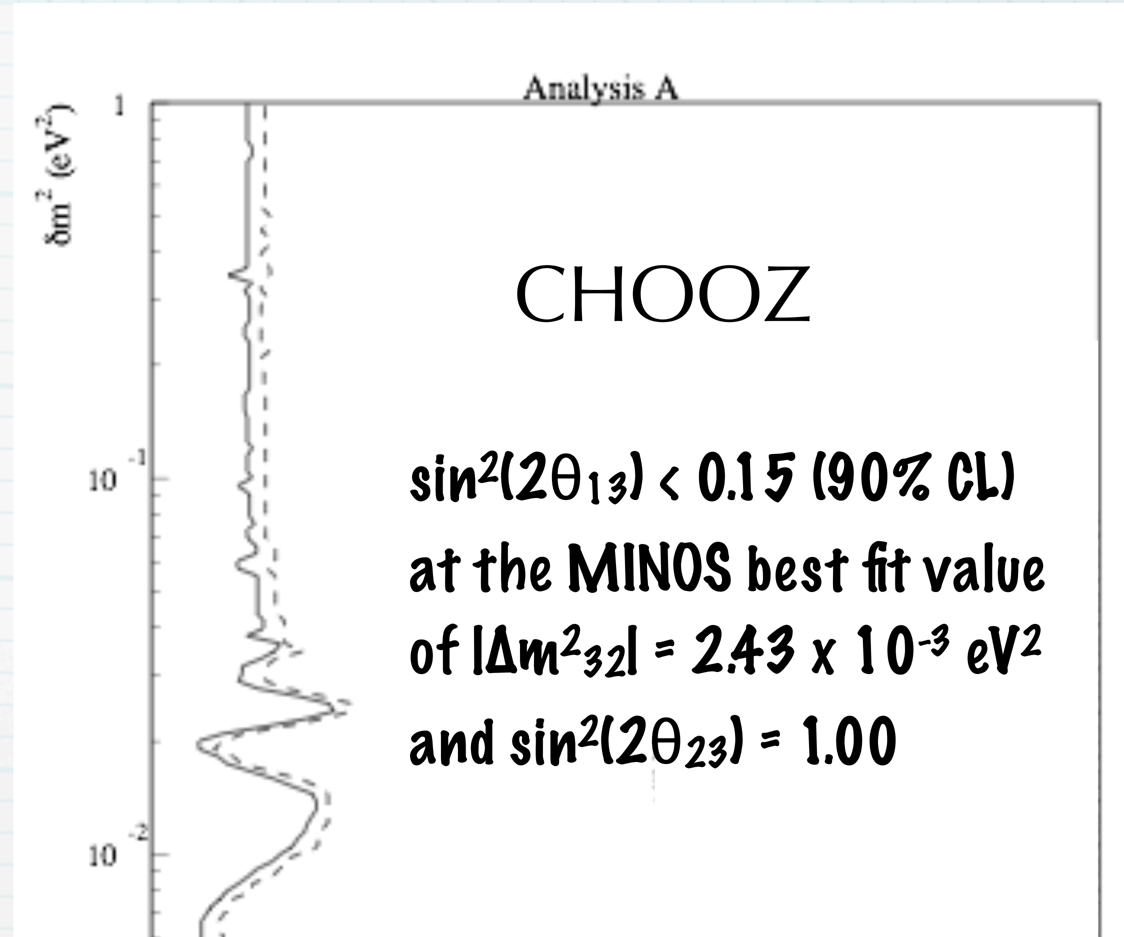
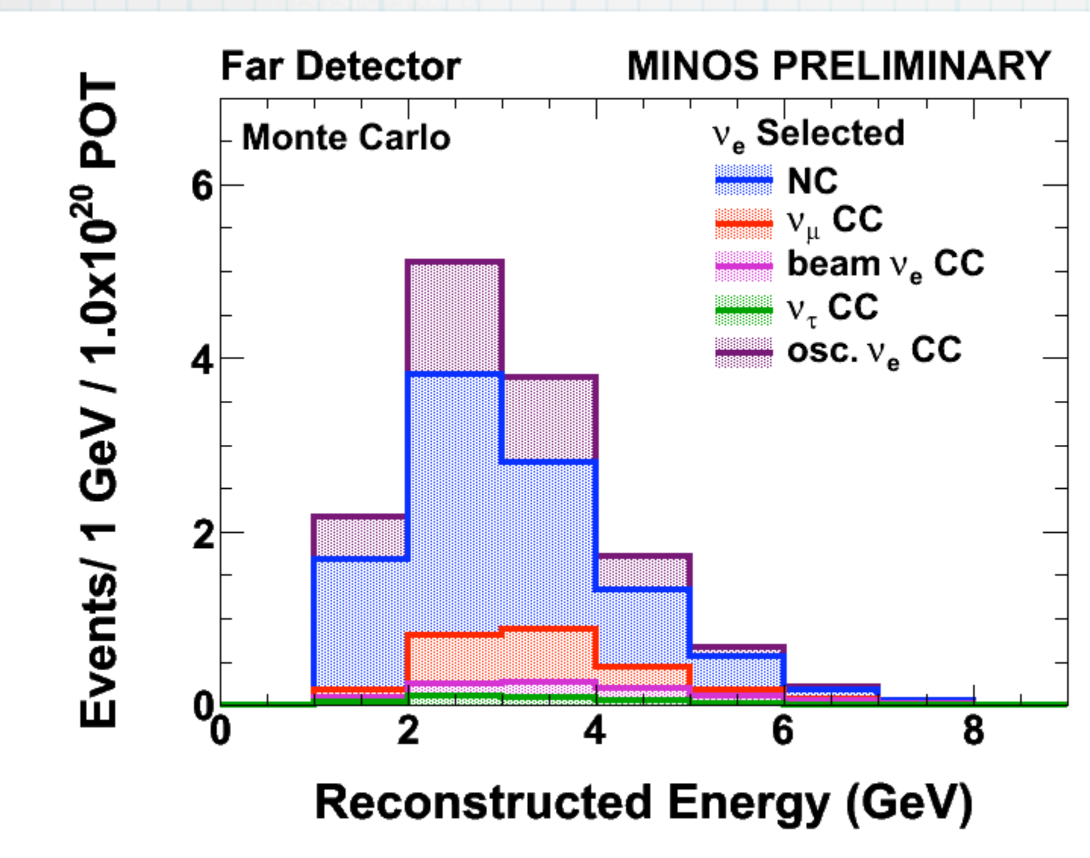
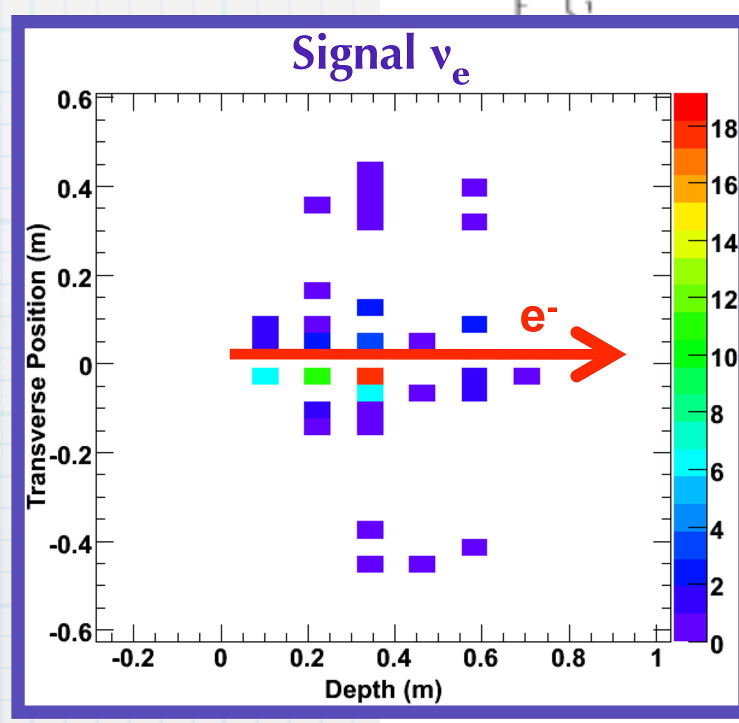
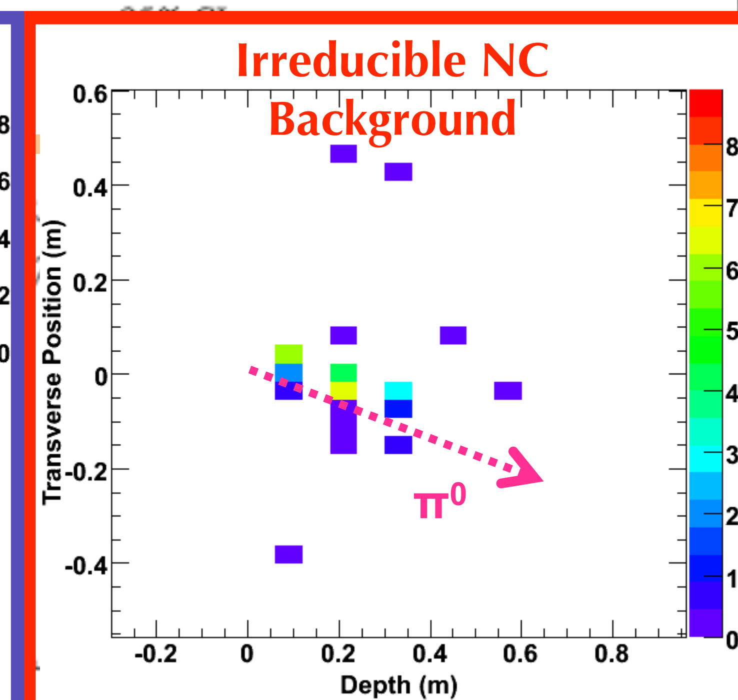


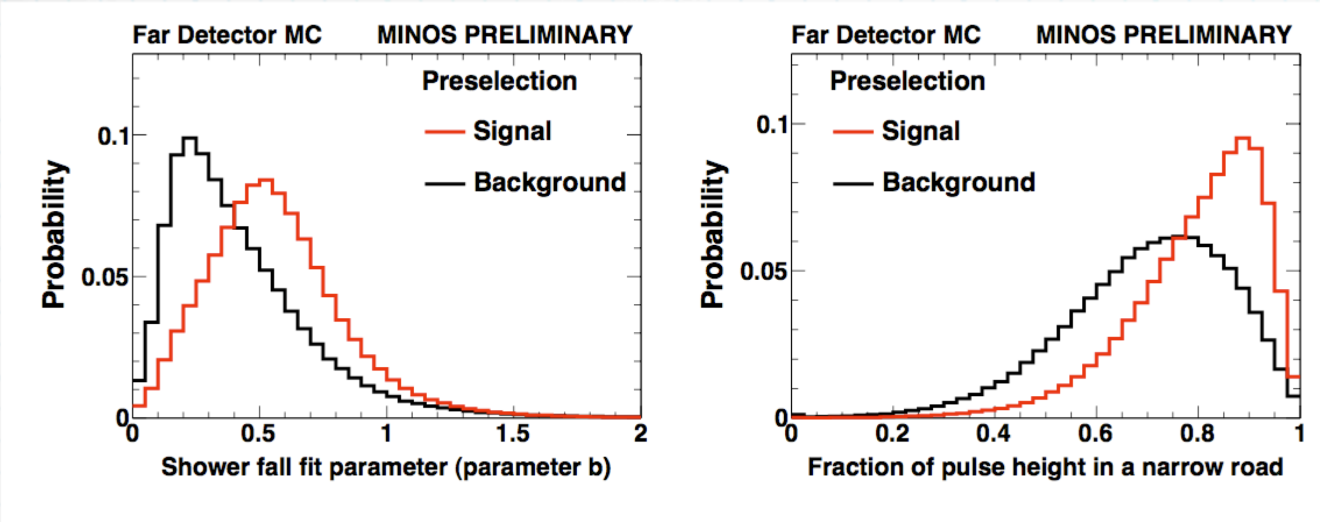
$\sin^2(2\theta_{13}) < 0.15$ (90% CL) at the MINOS best fit value of $|\Delta m^2_{32}| = 2.43 \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) = 1.00$







MINOS Event Selection and MC Tuning for ν_e Analysis



- "Shower-like" events were selected with energies between 1 and 8 GeV.
- 11 variables were used in a neural network to select EM-like shower profiles.
- Before selection, S/B = 1/55; after event selection, S/B = 1/4.

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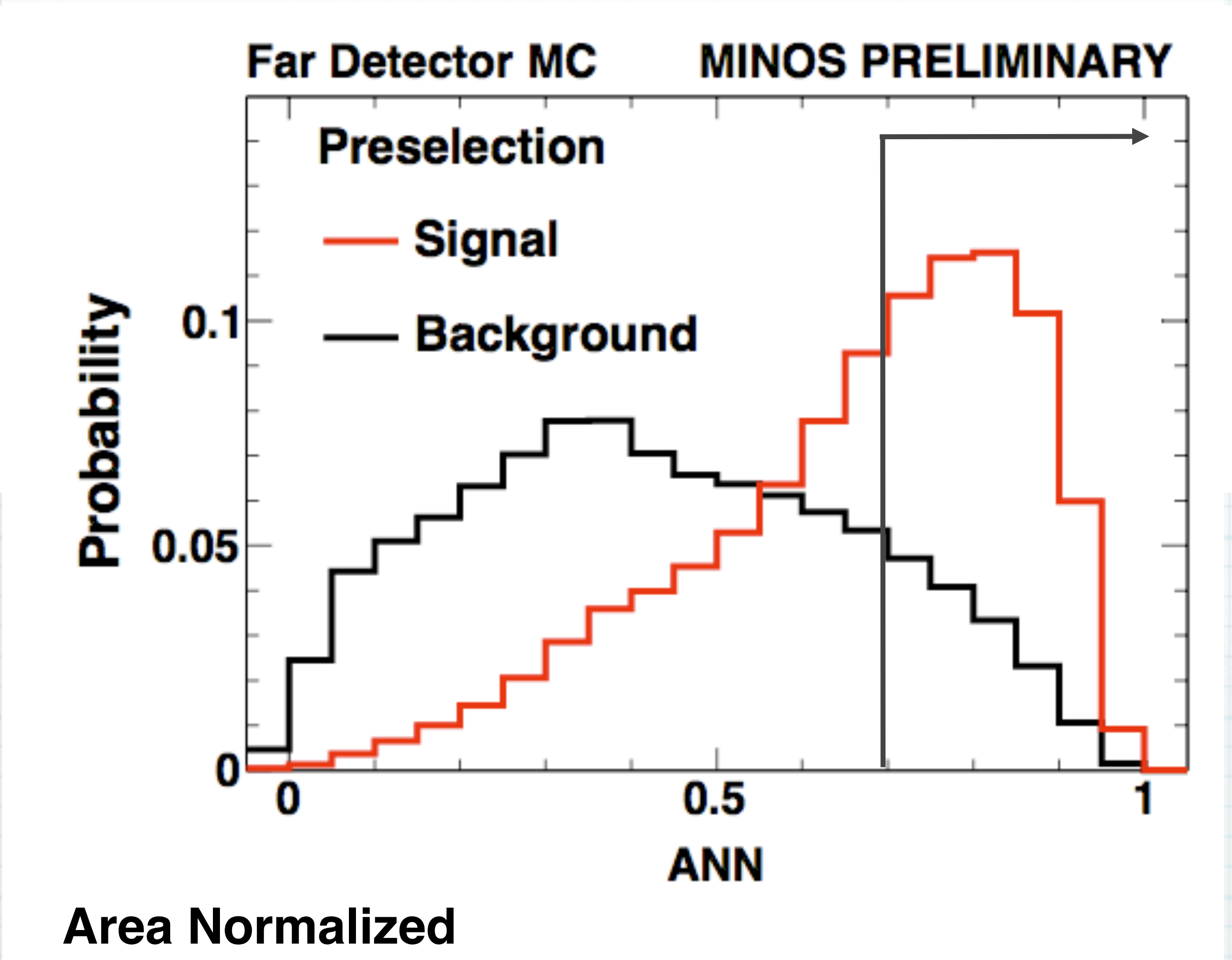

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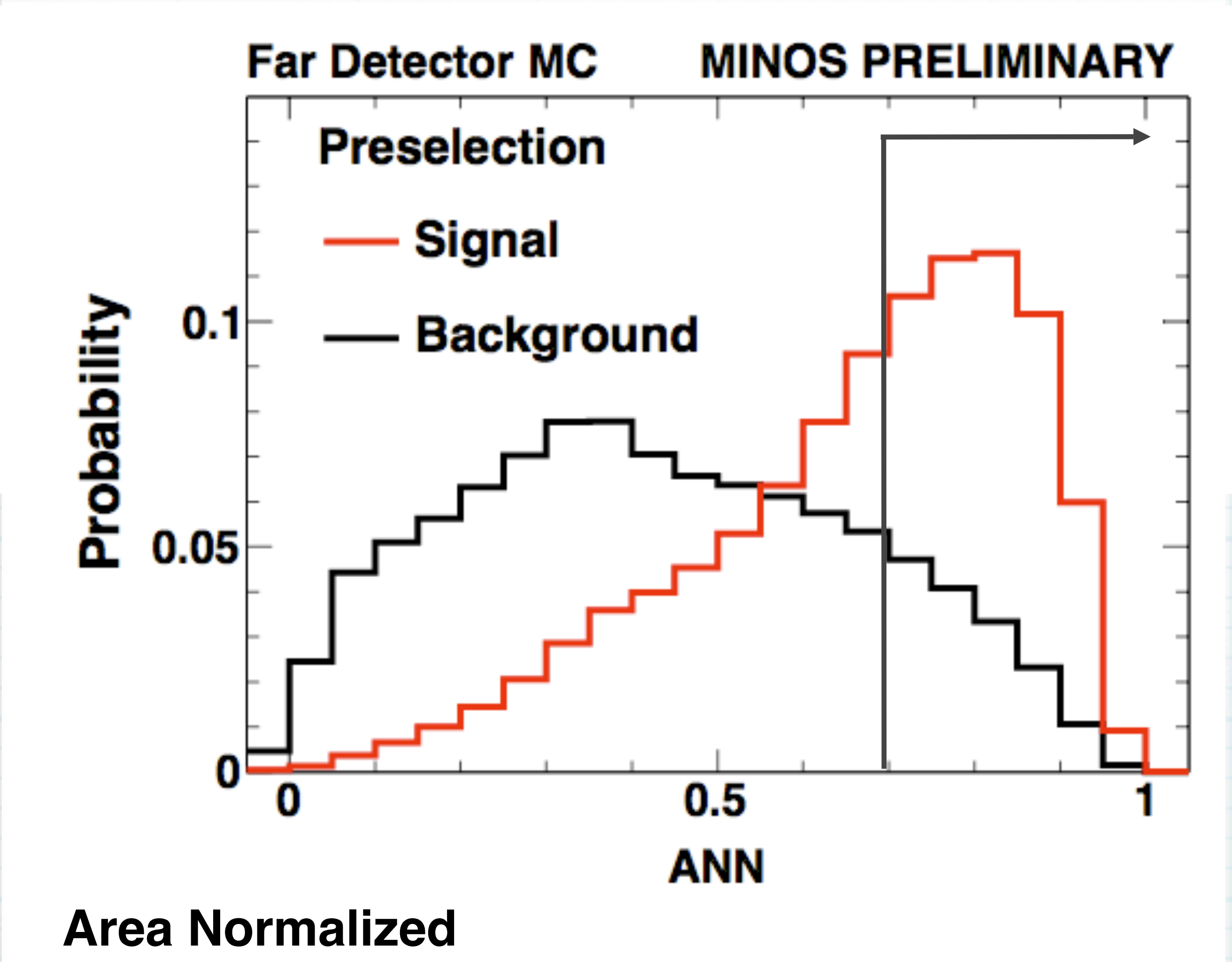

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* Not suprisingly, MINOS found very large disagreements between data and MC after event selection.
* Two data-driven methods were developed to correct the MC to match the data.

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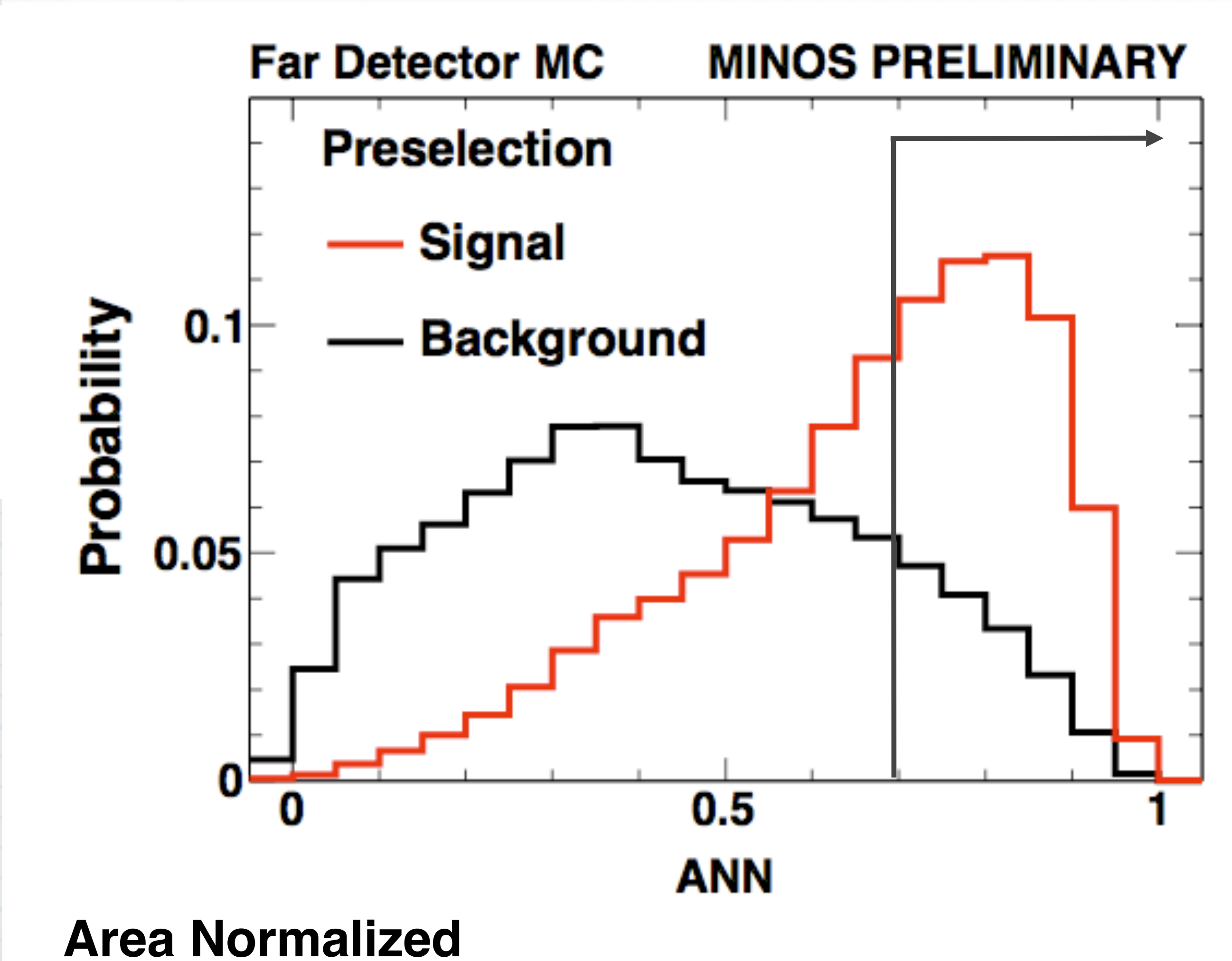

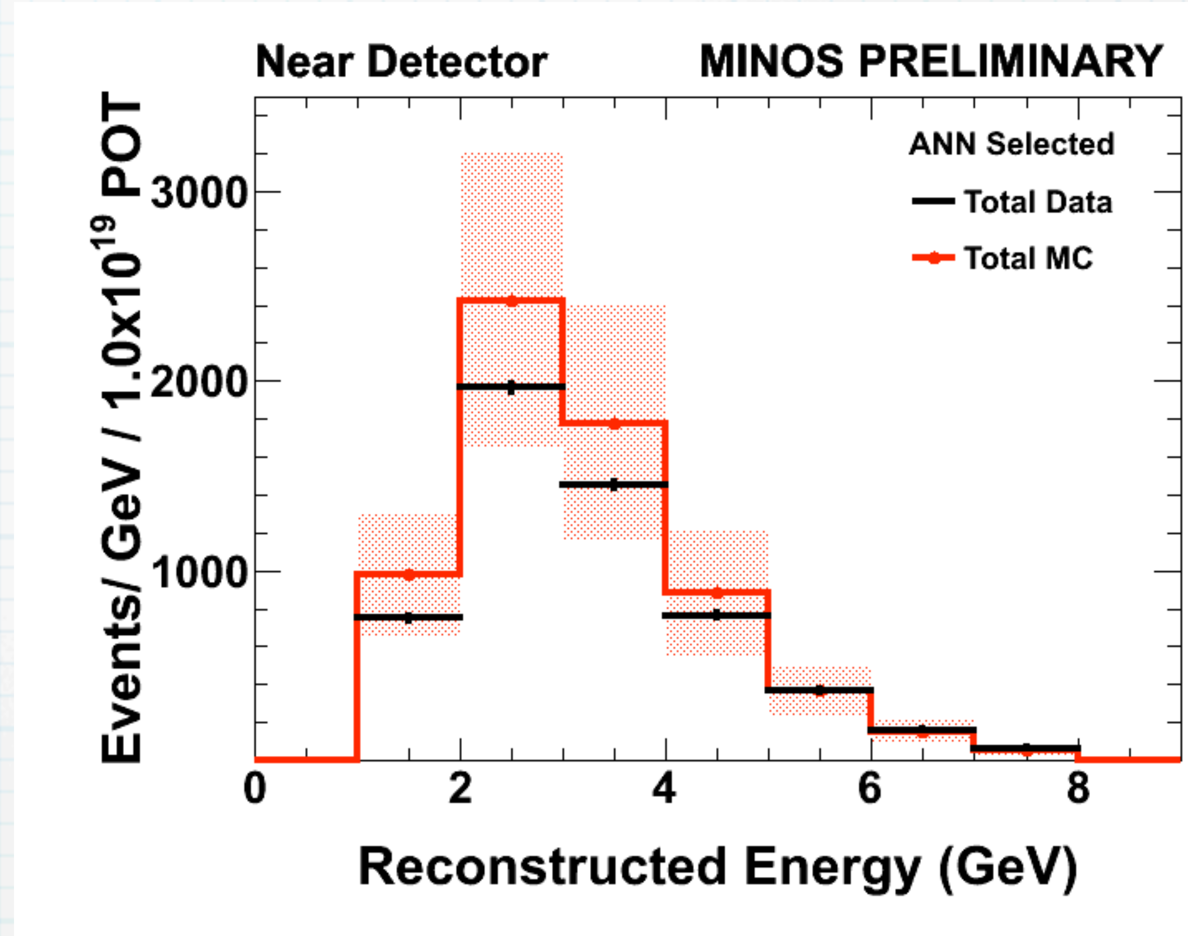

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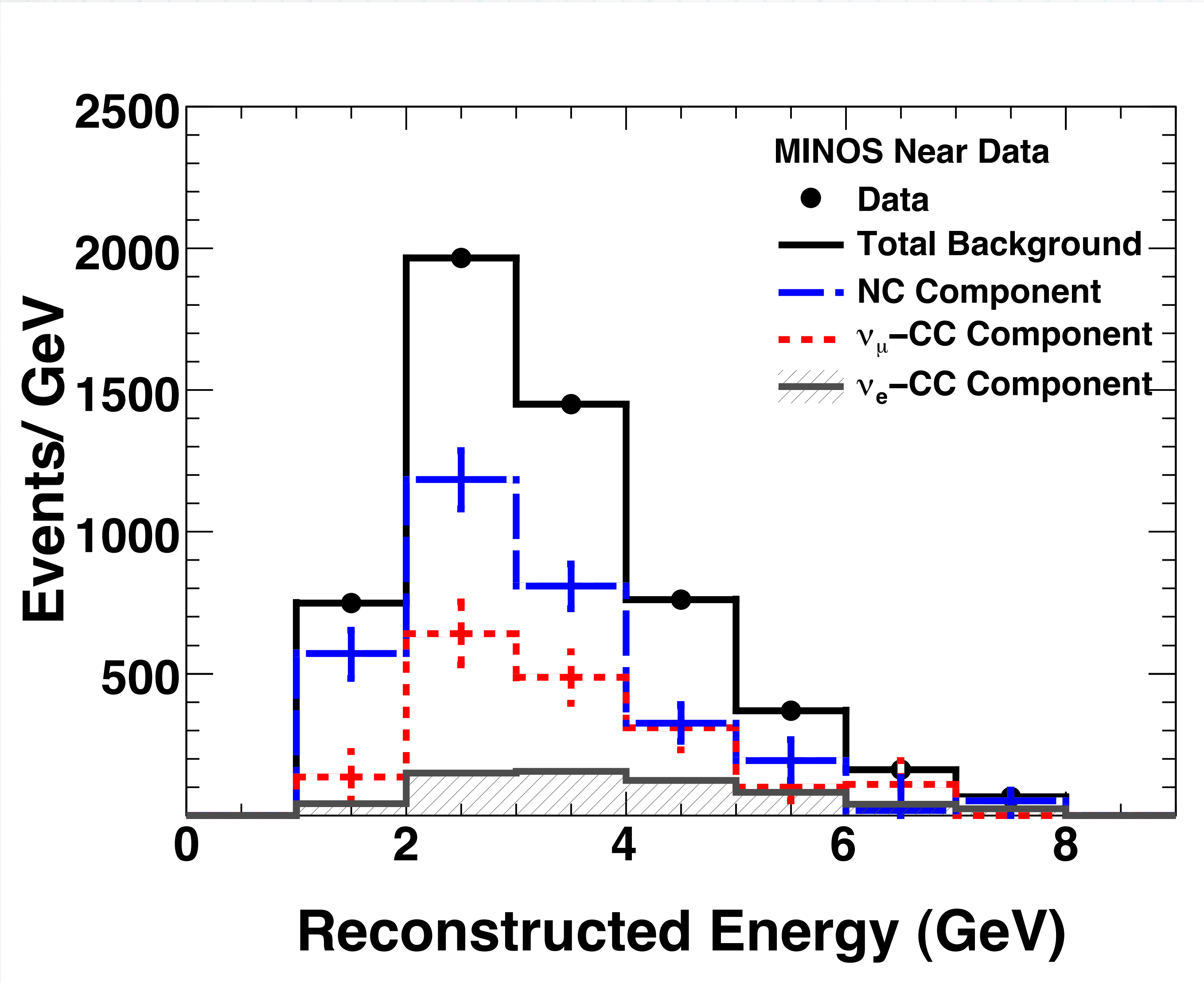
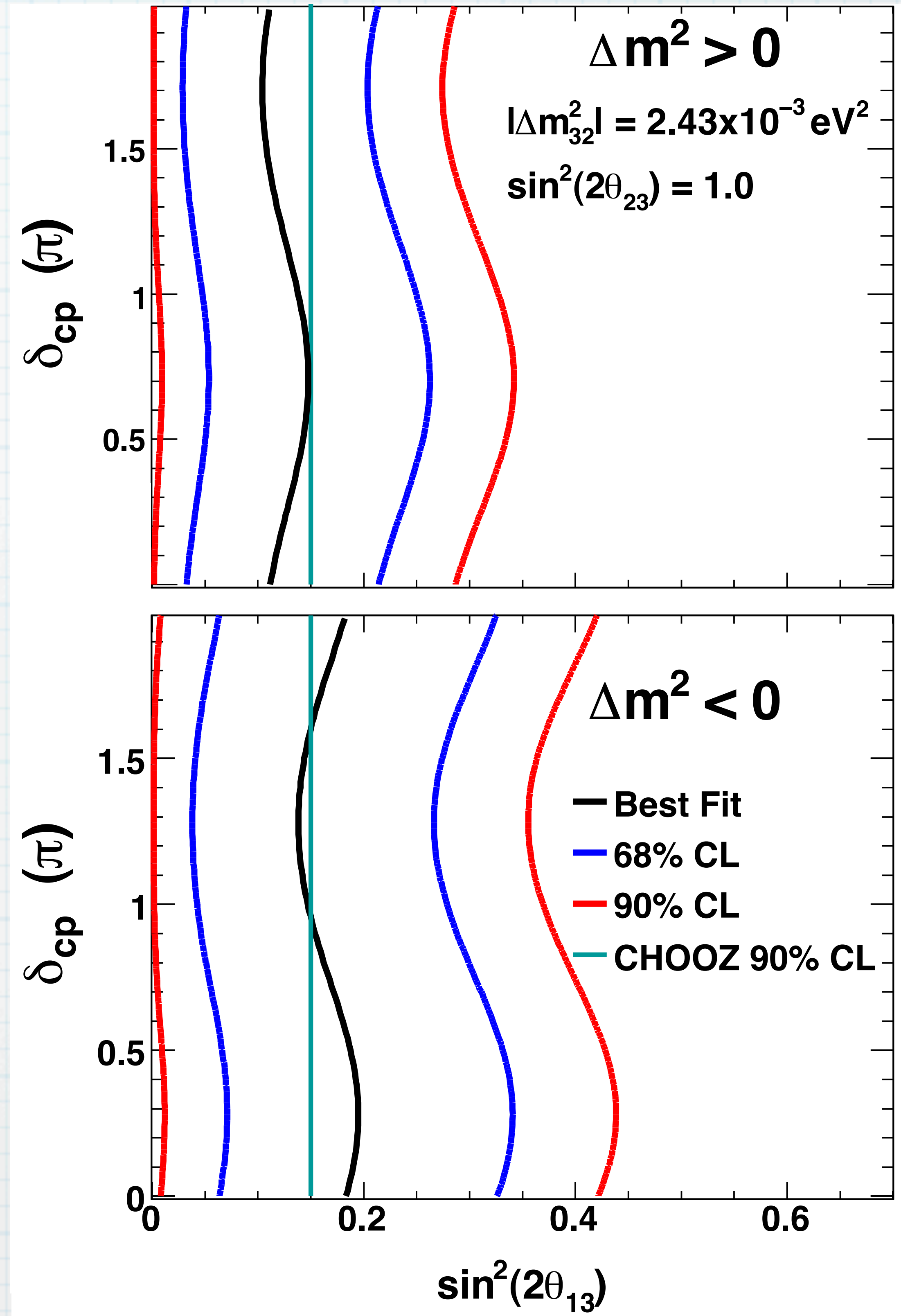
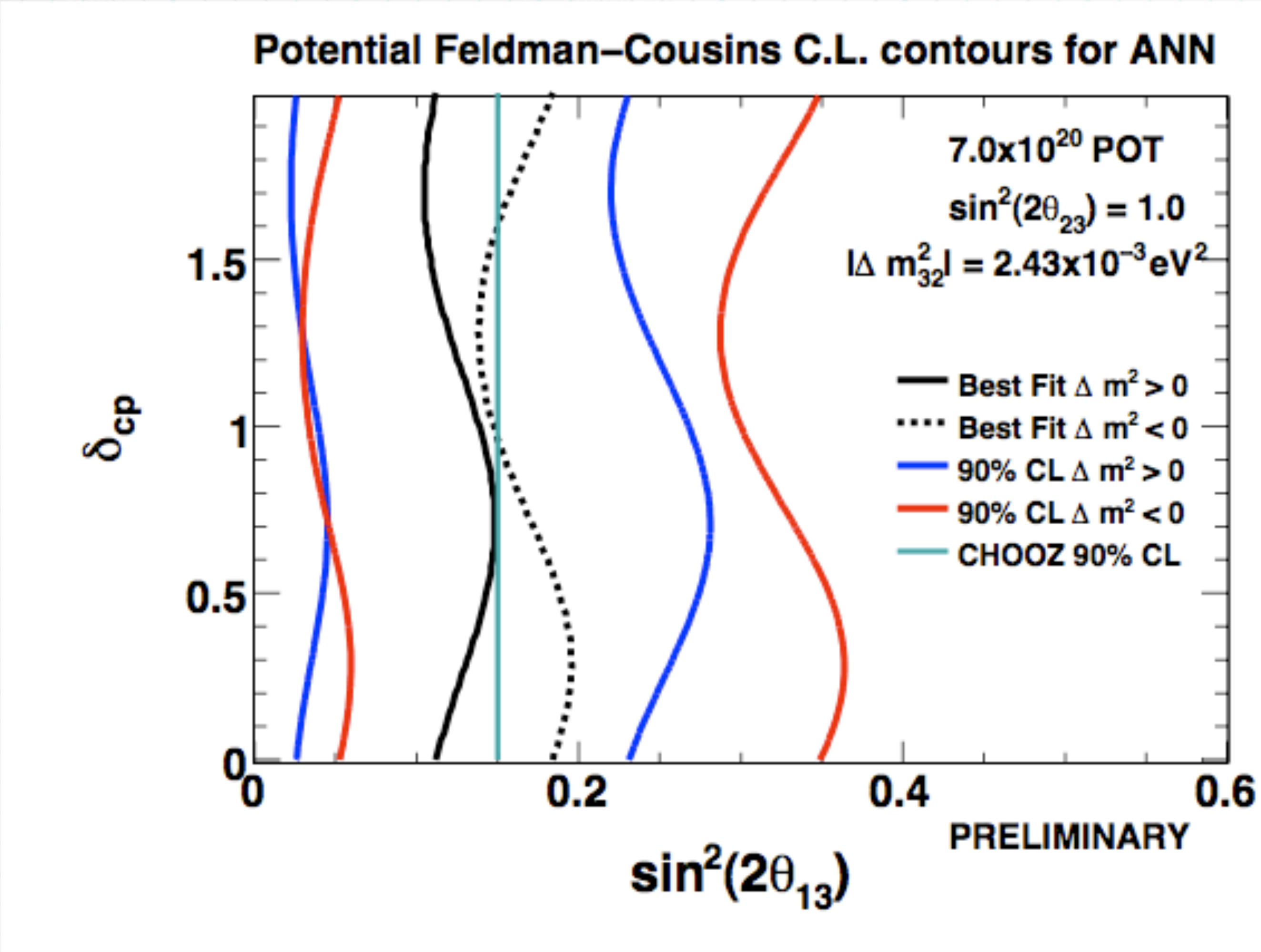
MINOS ν_e Analysis Results

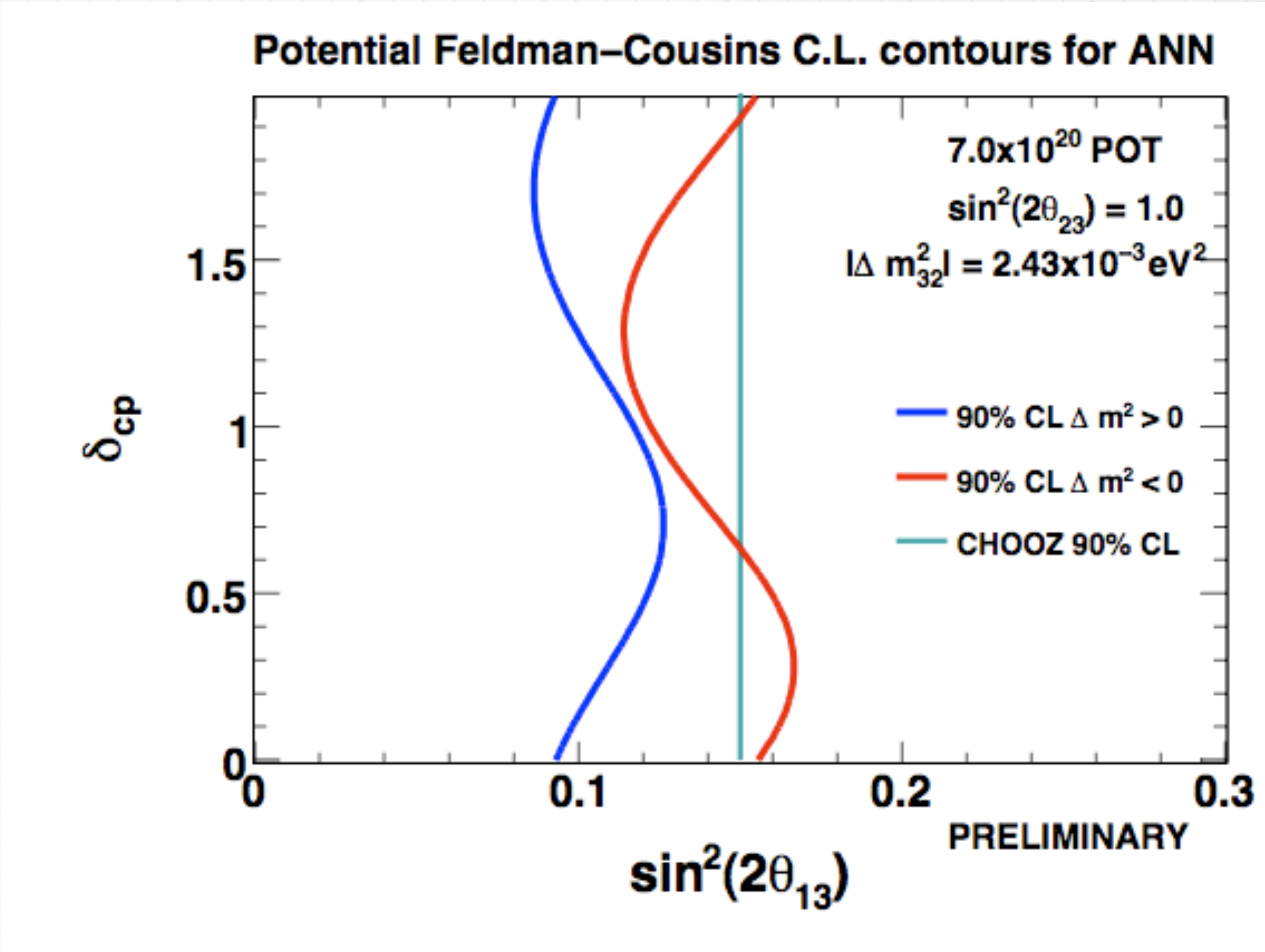




- MINOS has measured a 1.5σ excess of data compared to the expected background.
- Dominant backgrounds are NC and low-energy ν_μ CC events.

MINOS ν_e Analysis Future Sensitivities





If data excess persists...

If data excess vanishes...

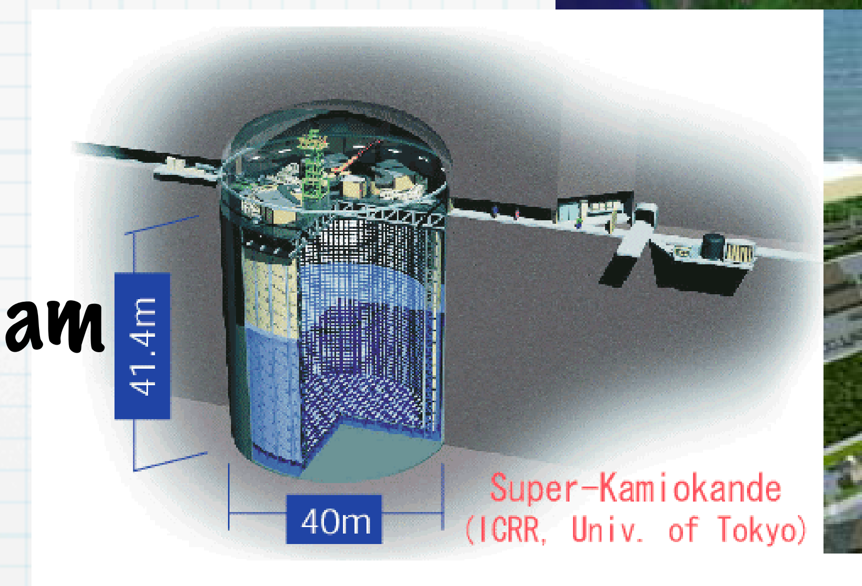
- MINOS has ~2x data in the can, analysis is underway.
- Systematics are expected to be lower with improvements in reconstruction and analysis.

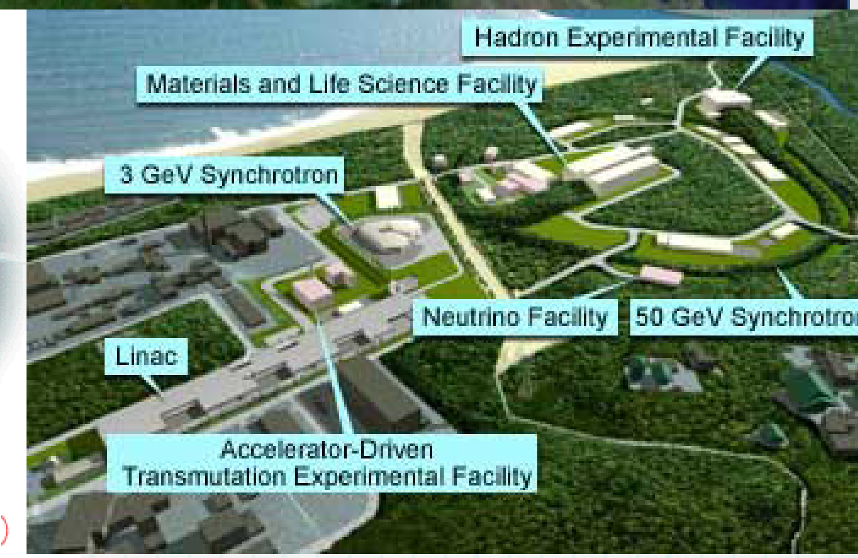
MINOS Future Run Plans

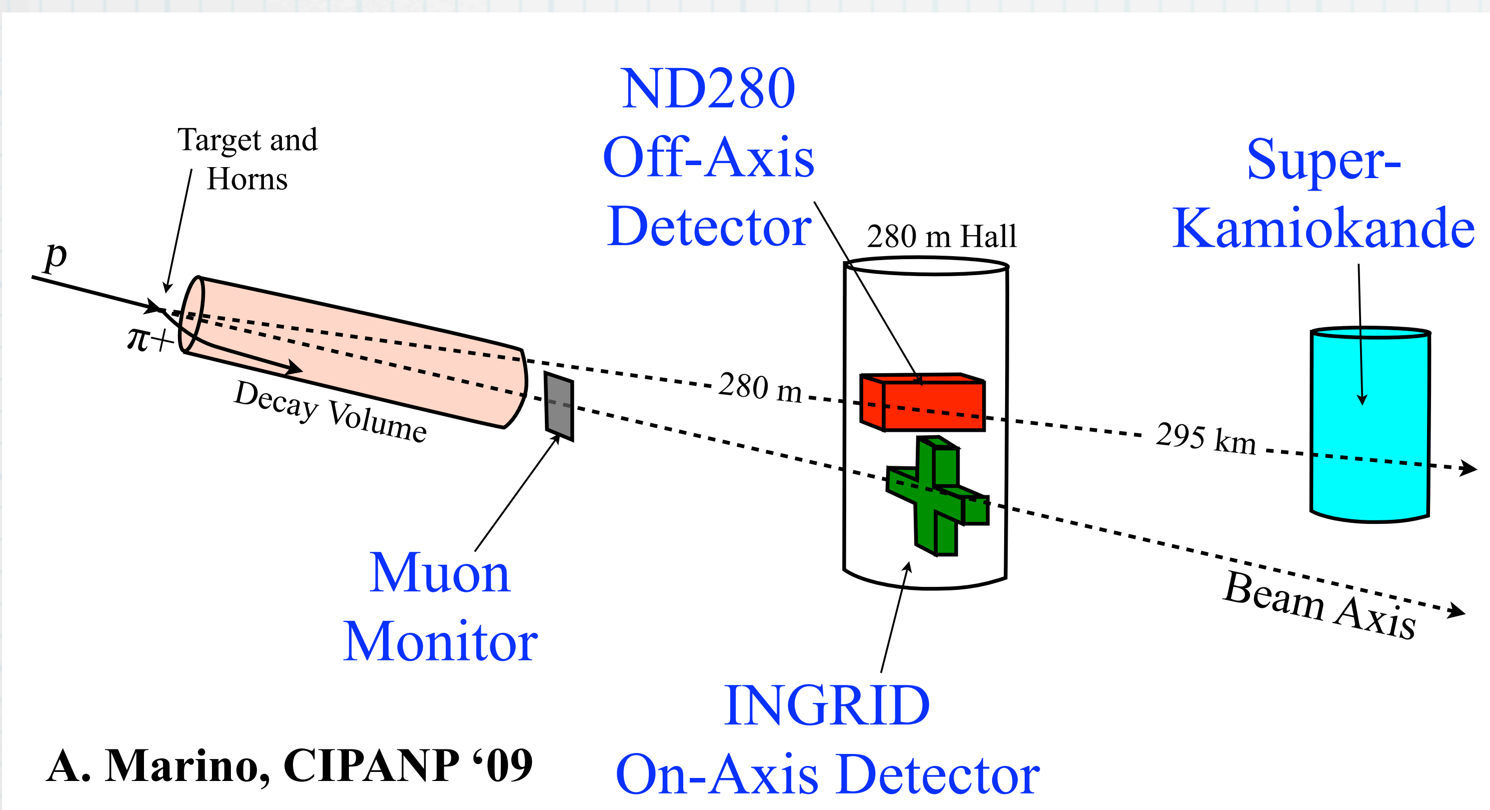
* MINOS will continue to collect data until the accelerator shutdown in 2011.
* Current plan is to run in anti-neutrino mode for about 8 months (about 2×10^{20} POT). Will re-evaluate next summer.
* Many new/updated results are expected by next summer; improvements in both statistical and systematic uncertainties on Δm^2_{32}, $\sin^2(2\theta_{23})$, $\sin^2(2\theta_{13})$, and many other measurements.

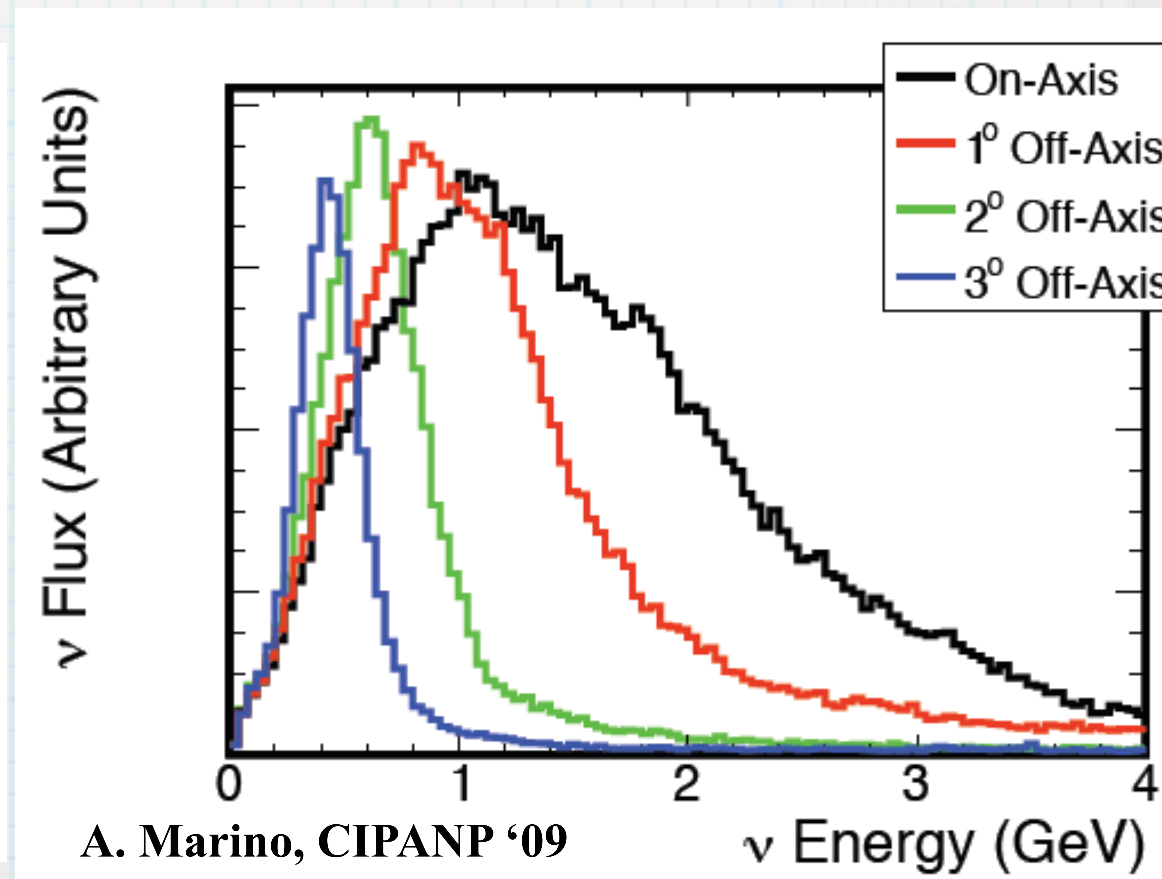
T2K: Tokai to Kamioka

* Long baseline neutrino experiment: J-PARC (Tokai) to Kamioka.
* Detector is off-axis (2.5°), providing narrow-band beam peaked at ~500 MeV.

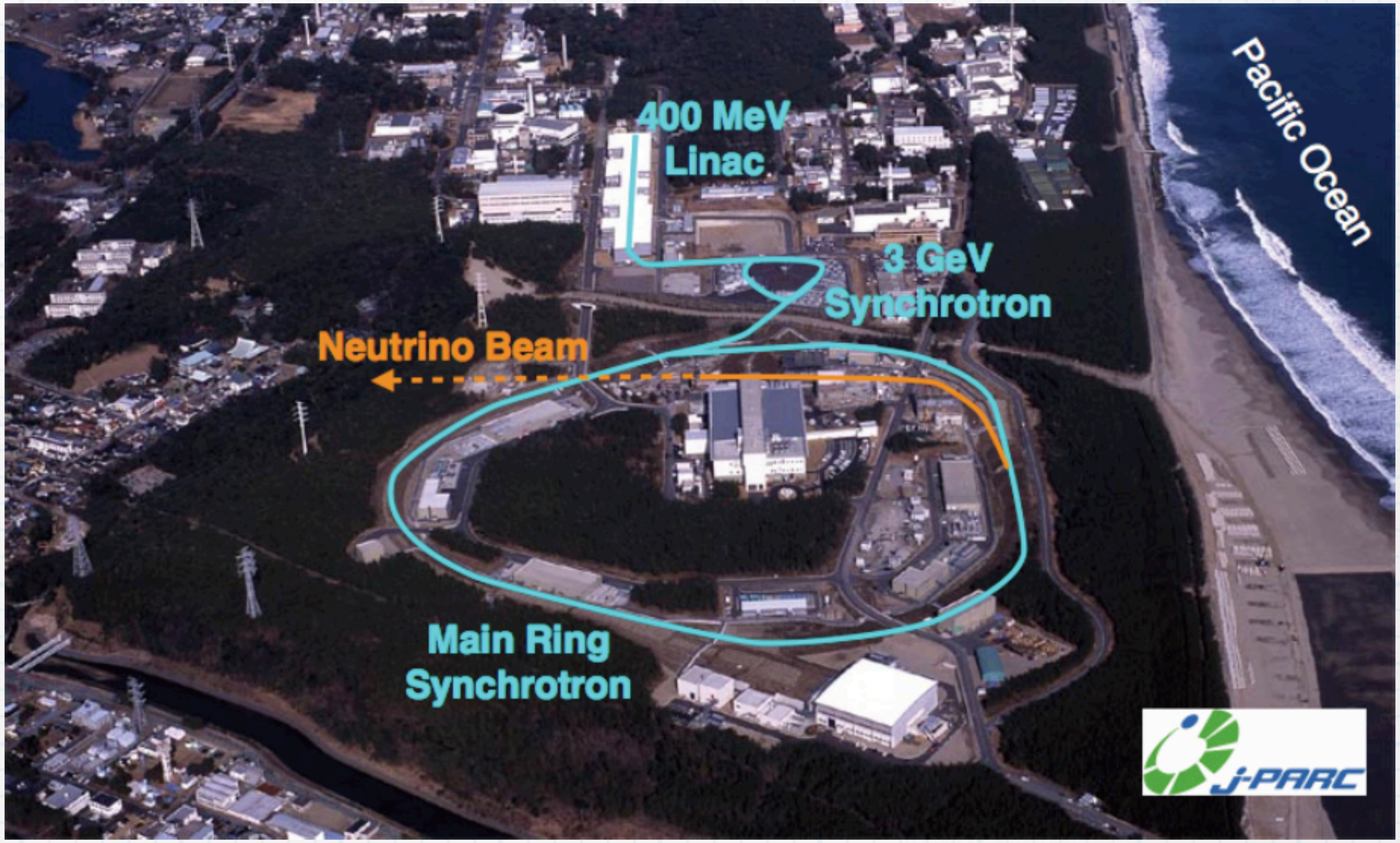




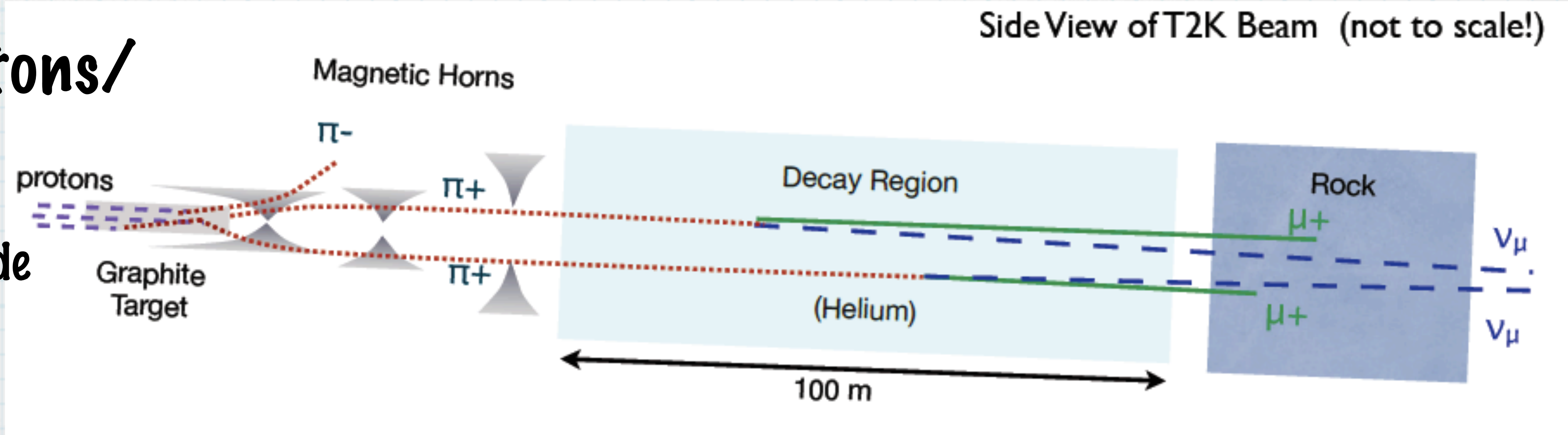




The T2K Neutrino Beam

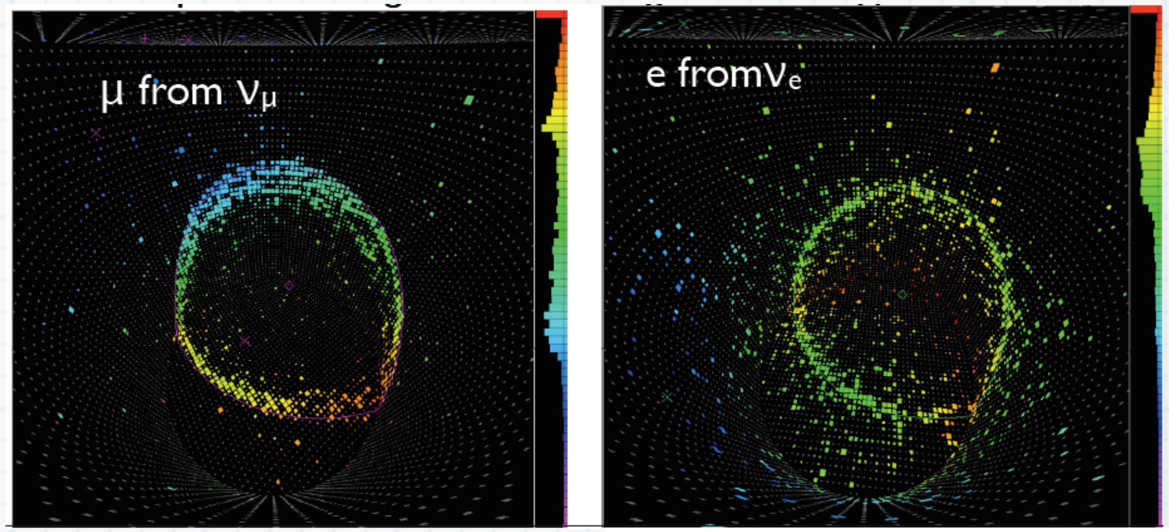


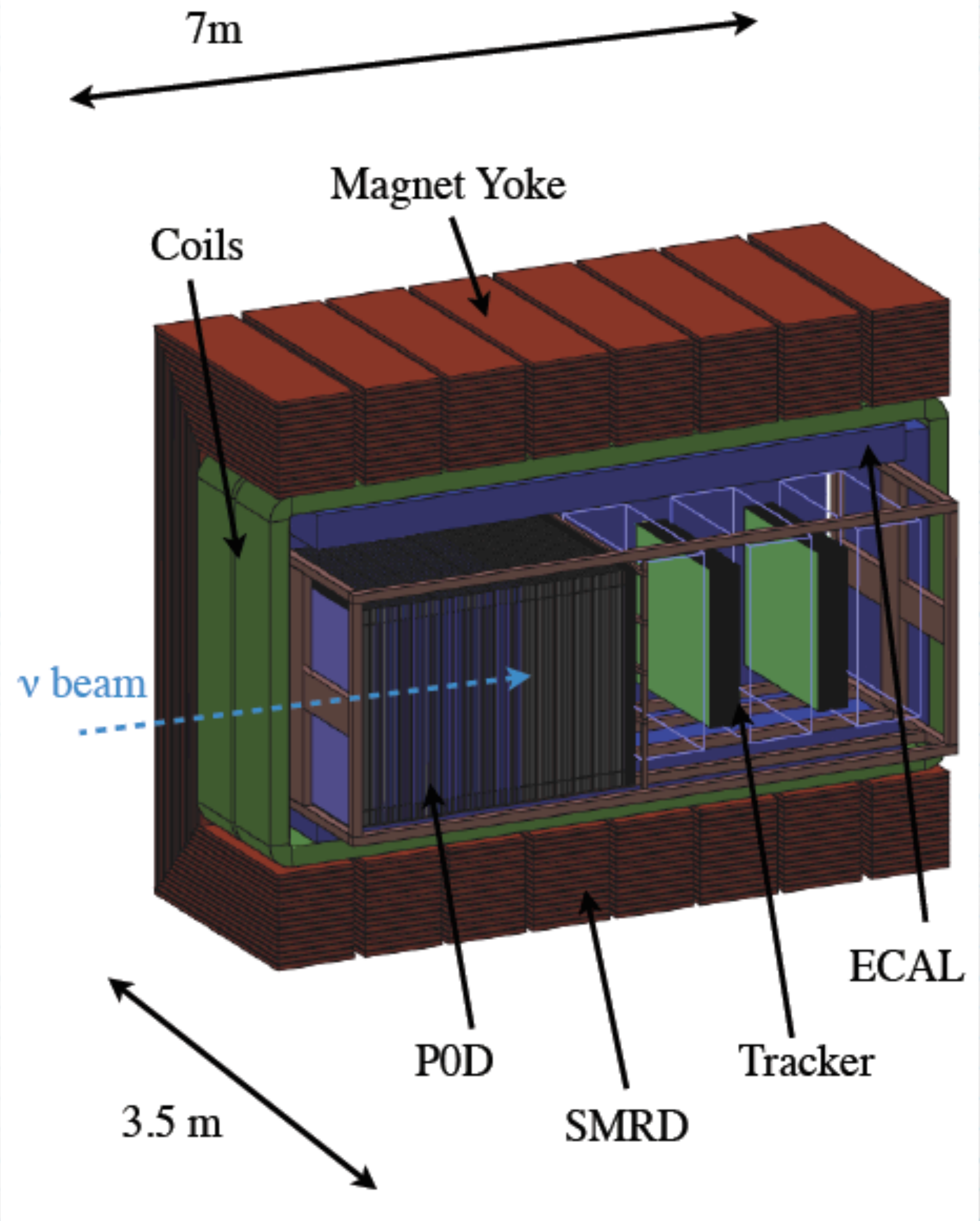
* Similar approach as NuMI beamline, but lower energy proton beam (30 GeV).
* 3 magnetic horns focus the secondary π's and K's.
* 100 m long decay region; rock used to stop decay muons.
* 3.3 x 10^{14} protons/pulse
  * pulse is 5.2 μs wide
  * 1 pulse/3.5 s



The T2K Detectors

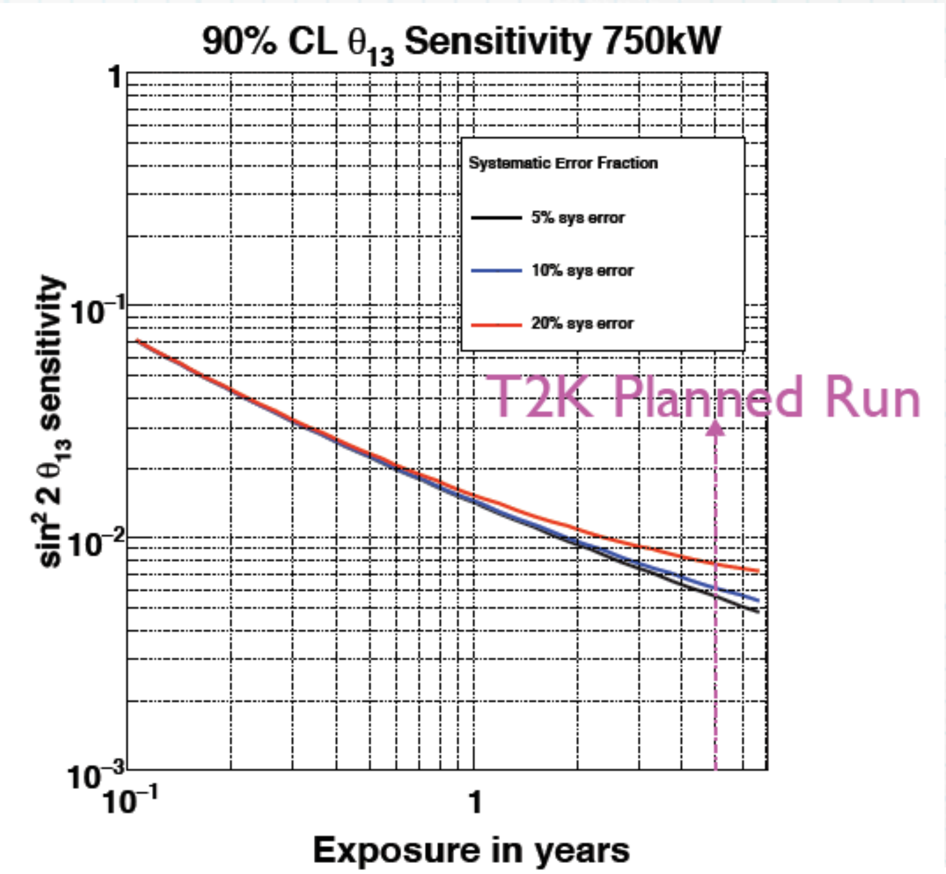
* Far detector: Super-K
* Near detector :
  * Off-axis
  * Uses UA-1 magnet
  * Tracker (3 TPCs + 2 fine-grained scintillator detectors) measures momentum and distinguishes e from μ
  * Pi-Zero Detector to measure π^0 production
  * ECAL to catch γ's that don't interact elsewhere in detector
  * Side Muon Range Detector measures momenta of lateral muons and serves as a muon trigger for calibration.

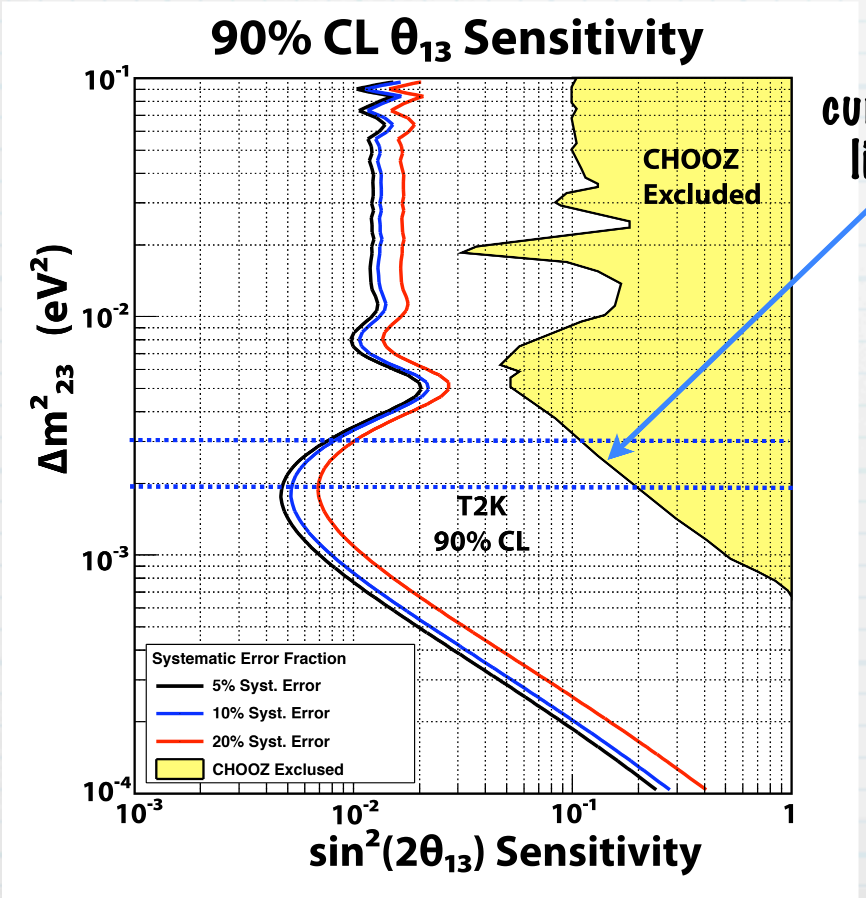




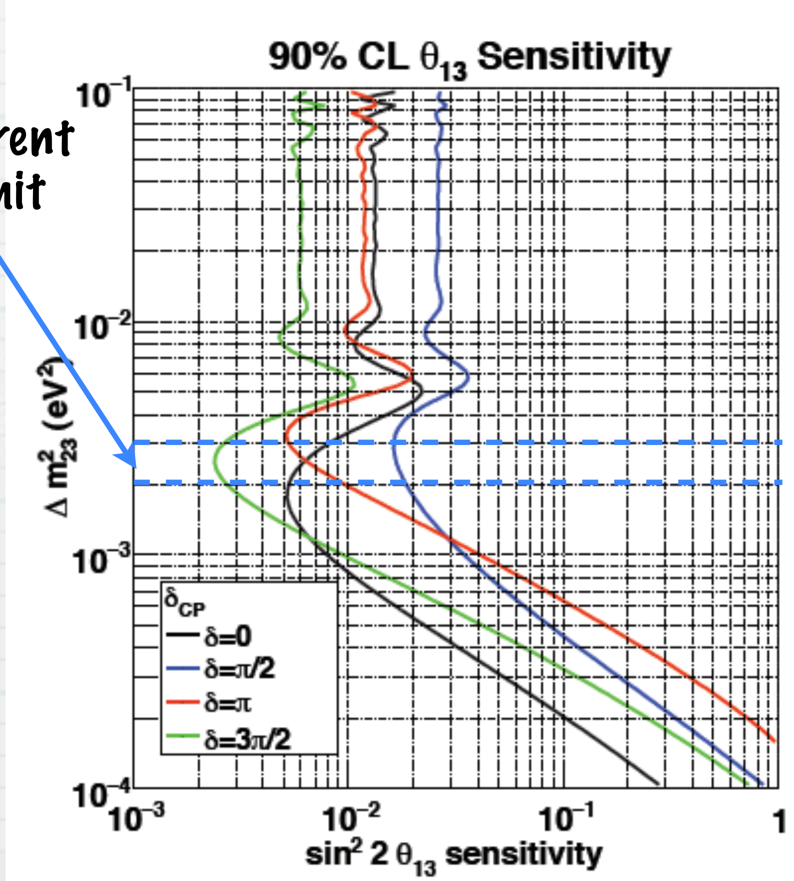
T2K Sensitivities

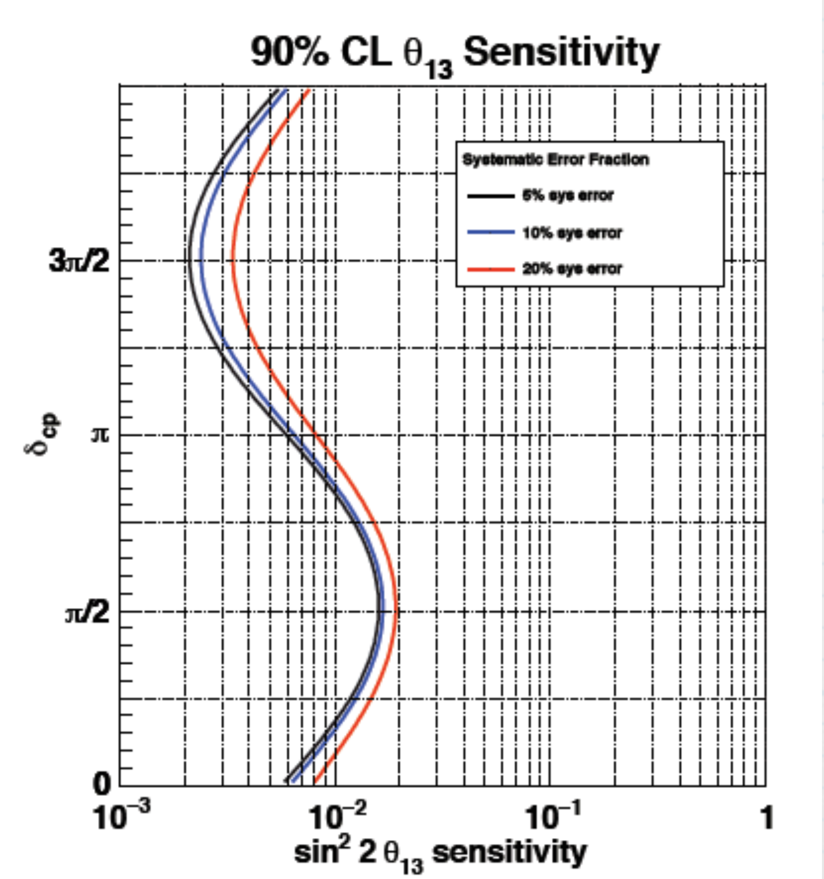
* Five year run planned.
* Will have an improved limit within just a few months after the run begins!
* Largest background from beam ν_e's.
* Measurement is sensitive to δ_{CP}; currently there are no plans to run in antineutrino mode.





current limit

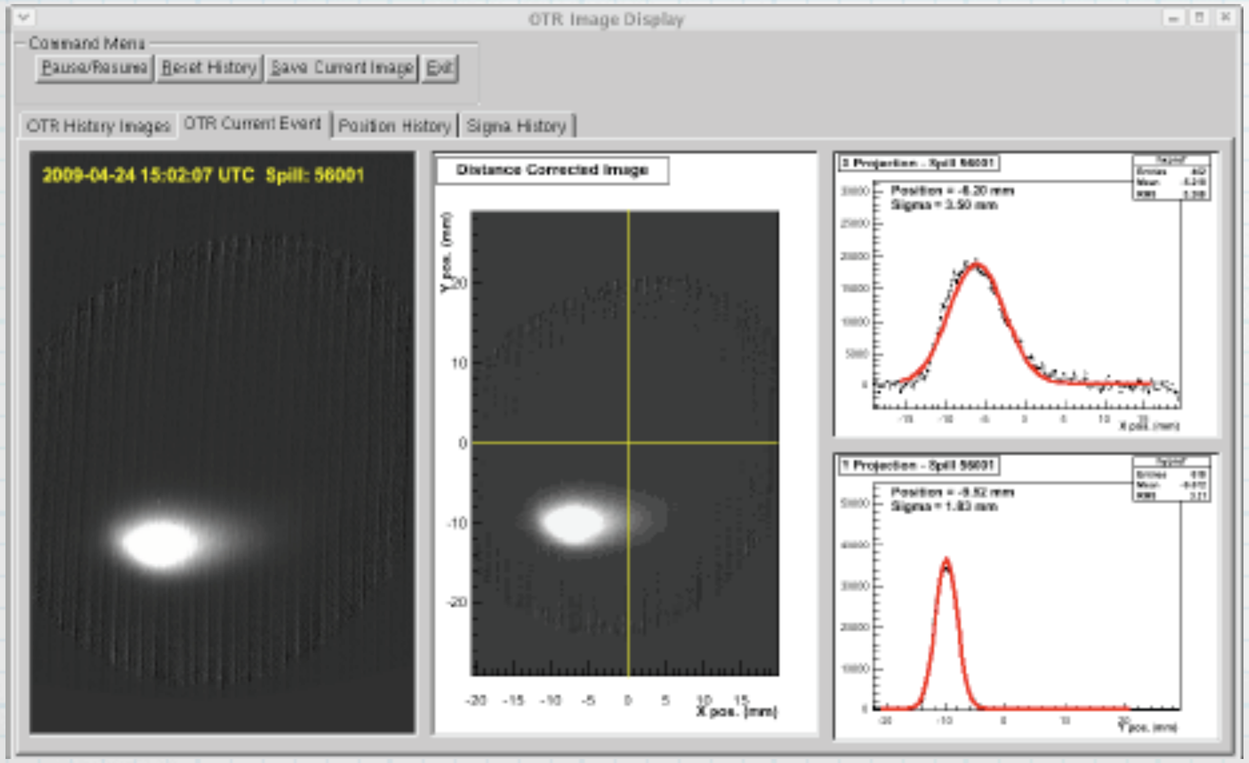


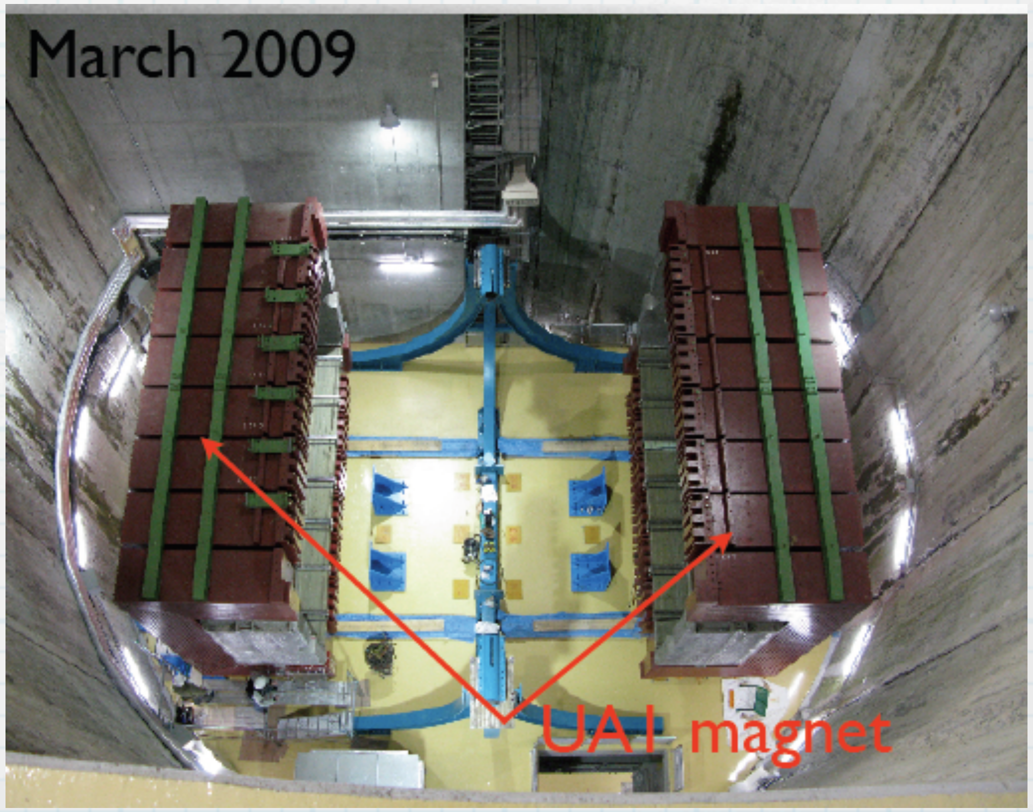


All figures taken from A. Marino, CIPANP '09

T2K Schedule

* Target hall and beam absorber completed and installed in 2008.
* Target and horn installed in Jan. 2009
* UA1 magnet installed in March, 2009.
* First proton on target April 24, 2009!
* All detectors expected to be online by end of 2009; first neutrino events in 2010!





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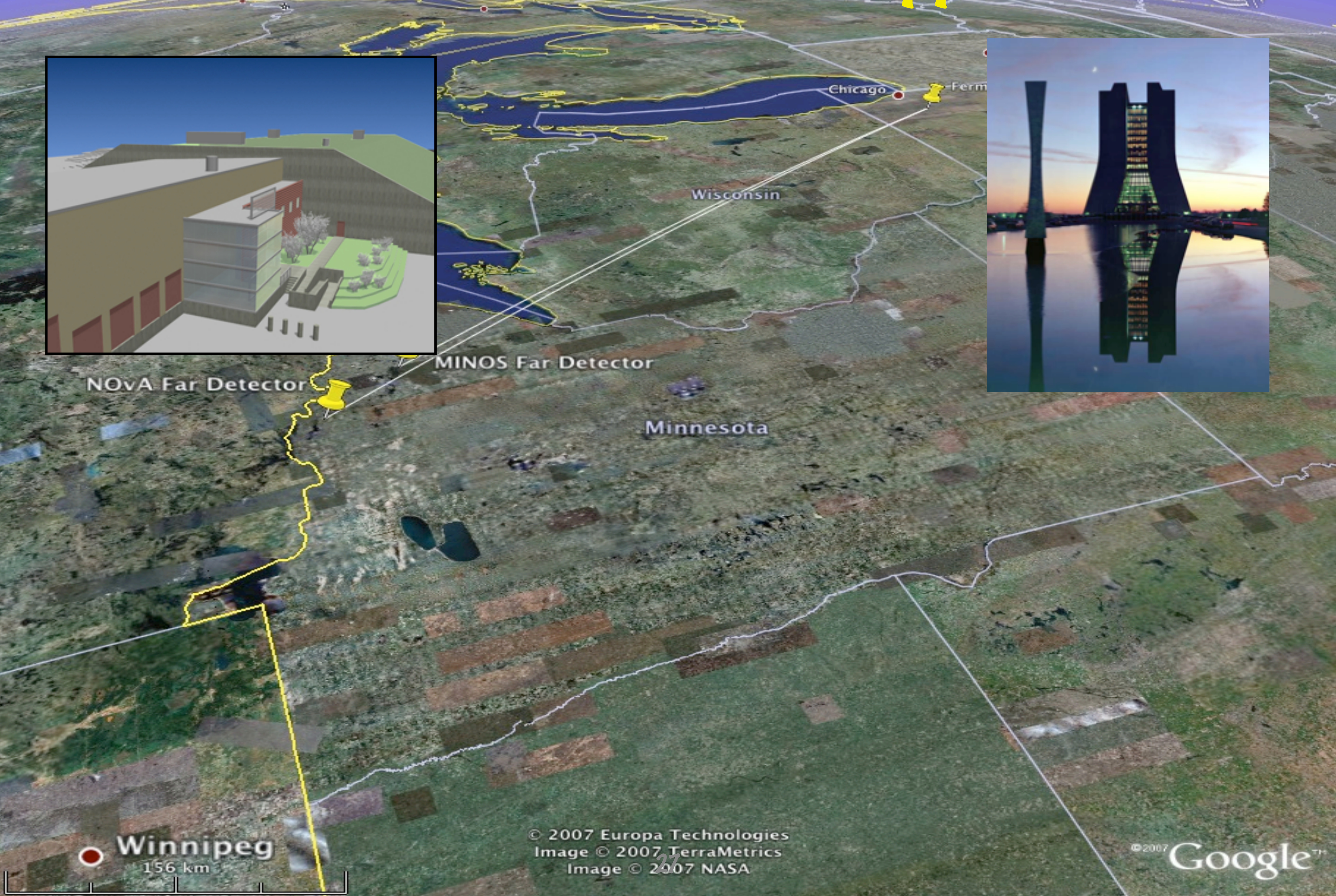
NOvA - NuMI Off-Axis ν_e Appearance



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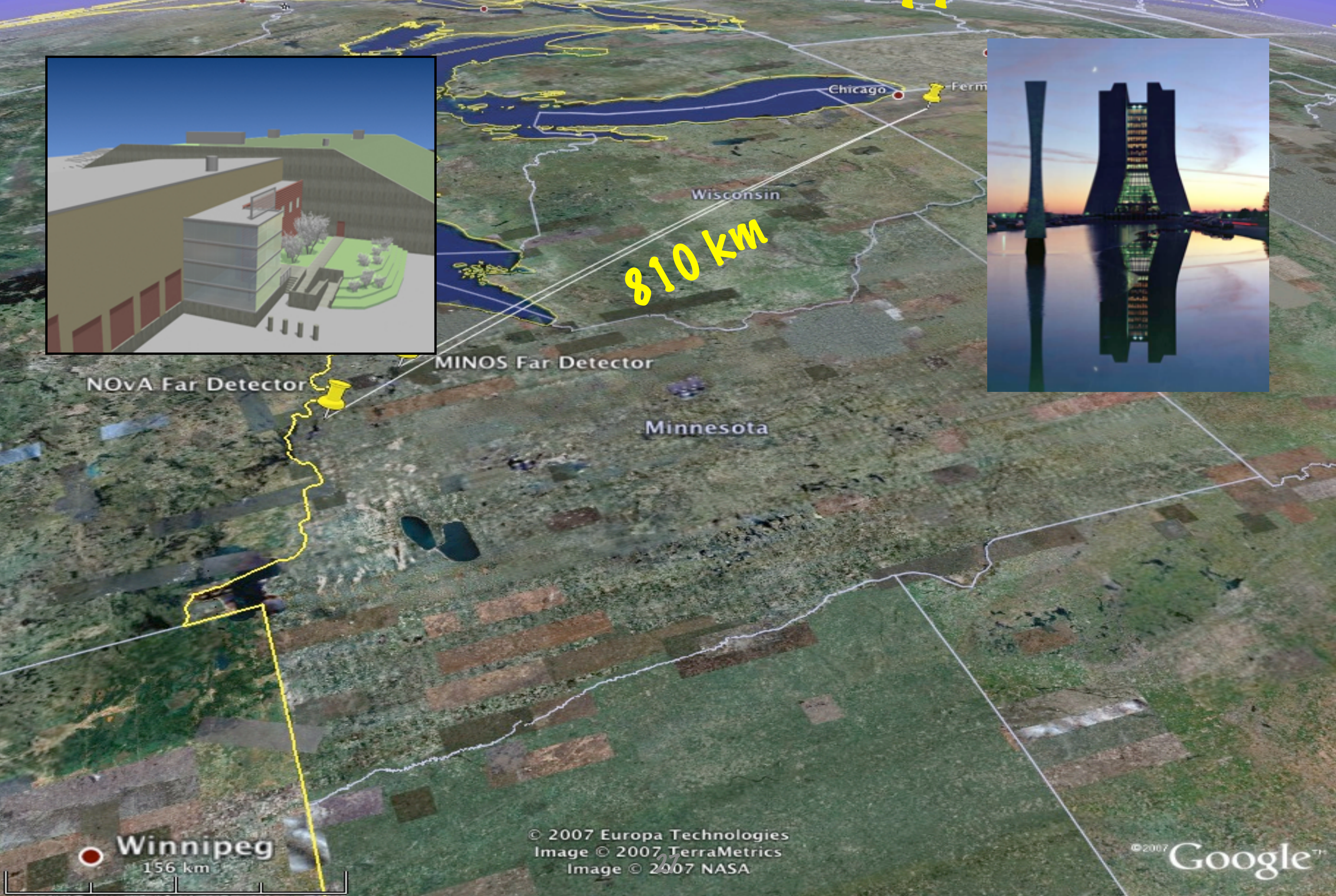

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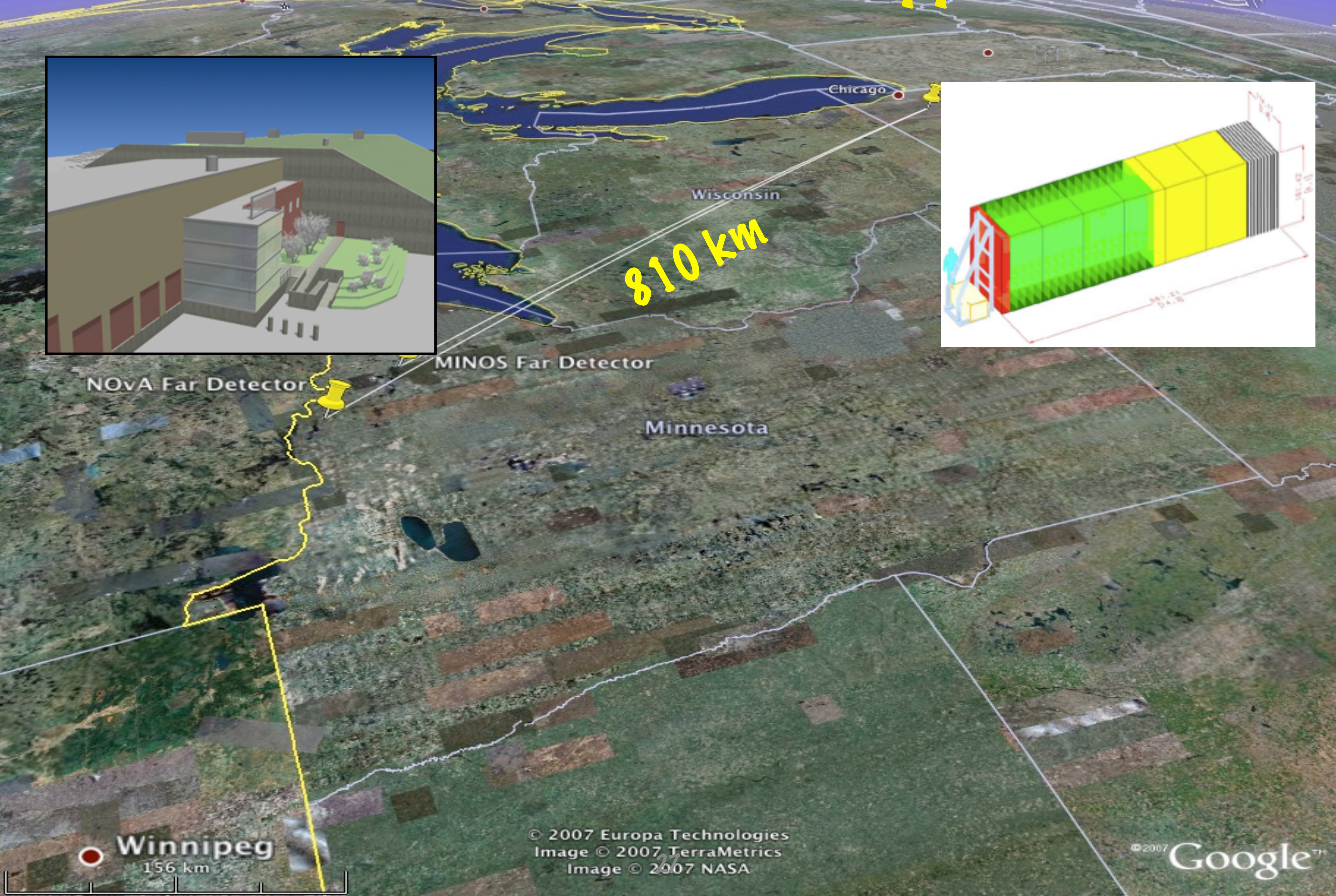

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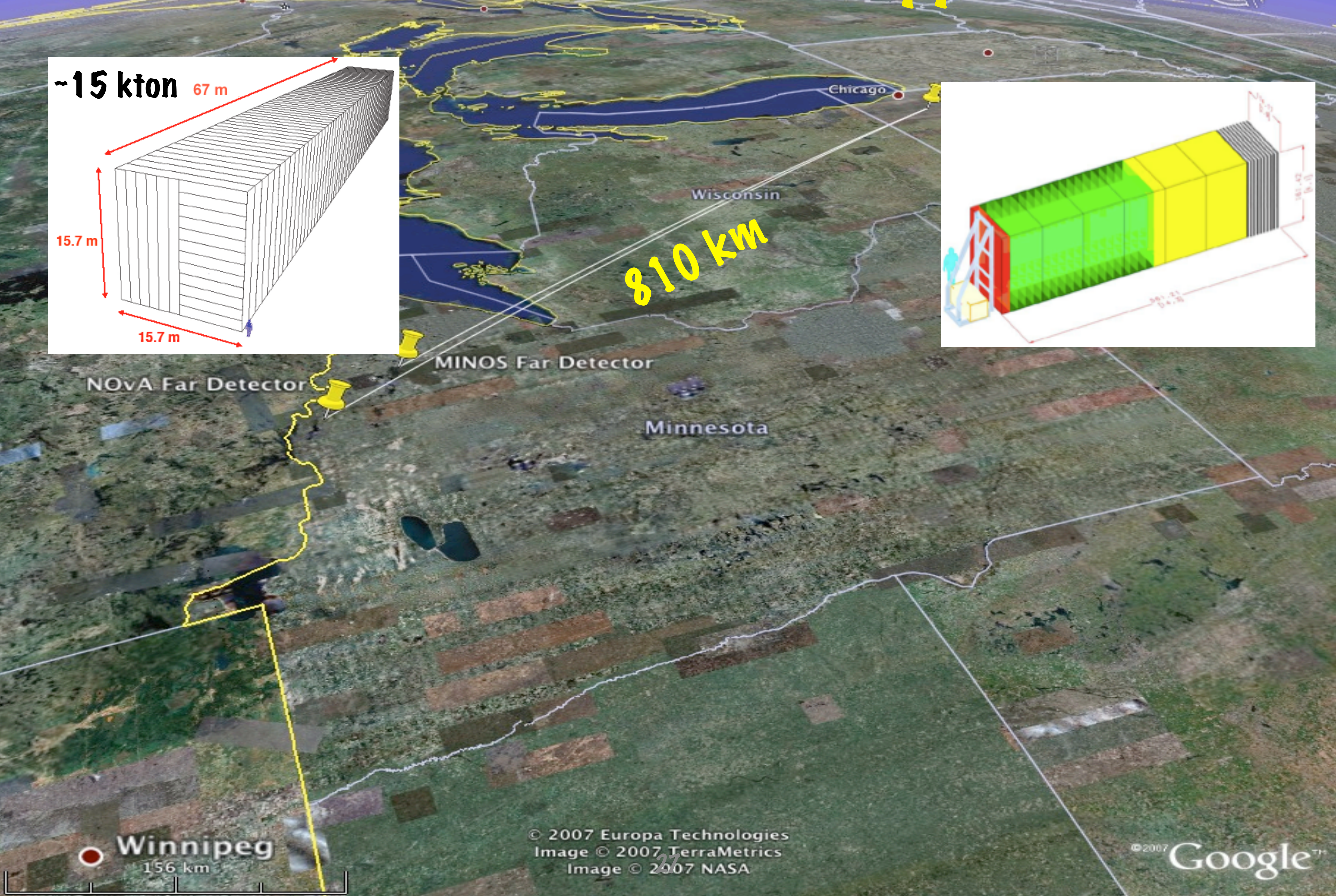

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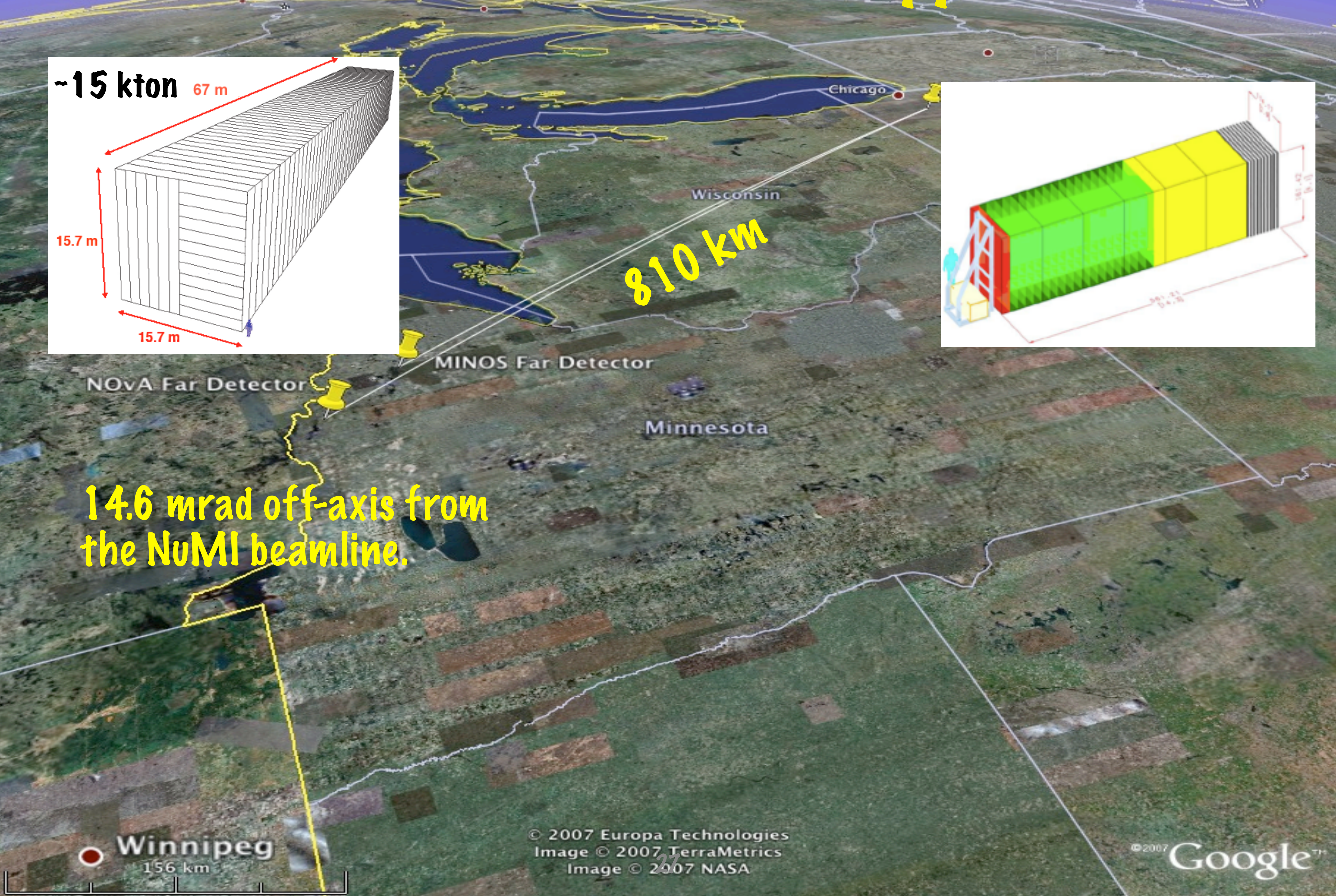

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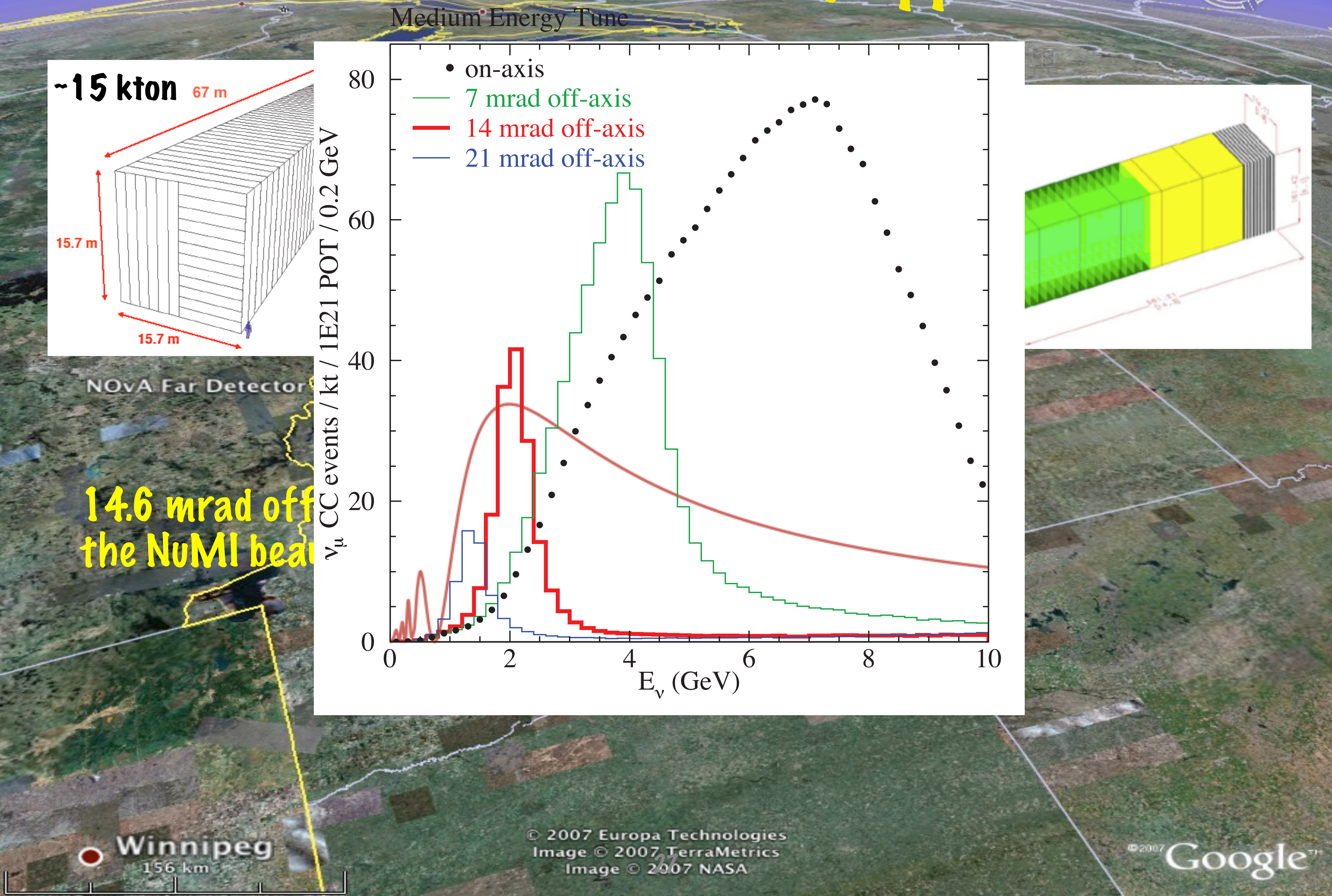

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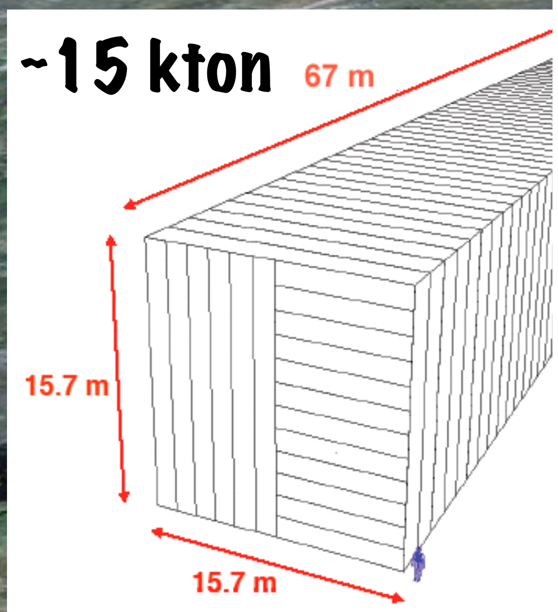

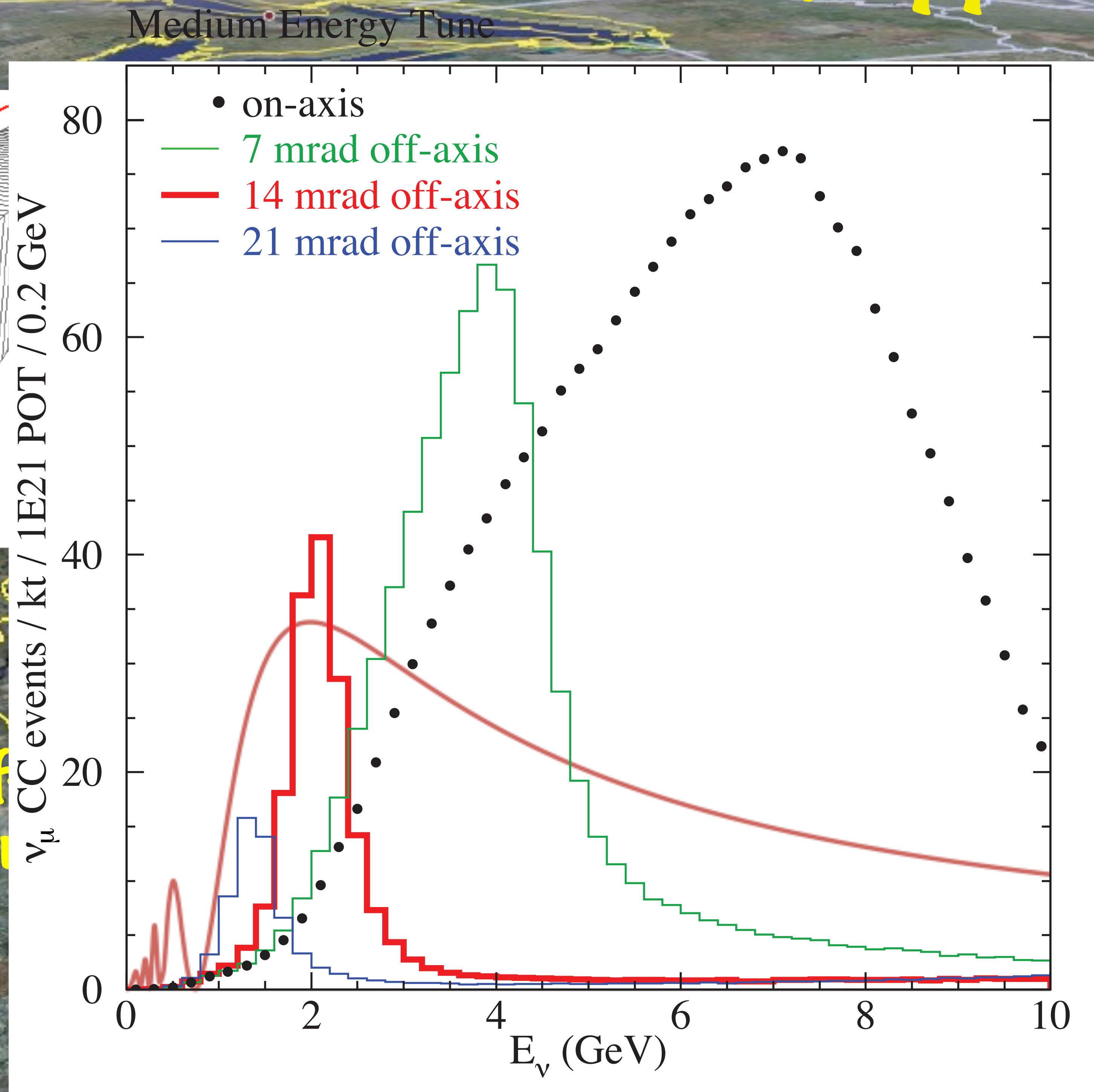

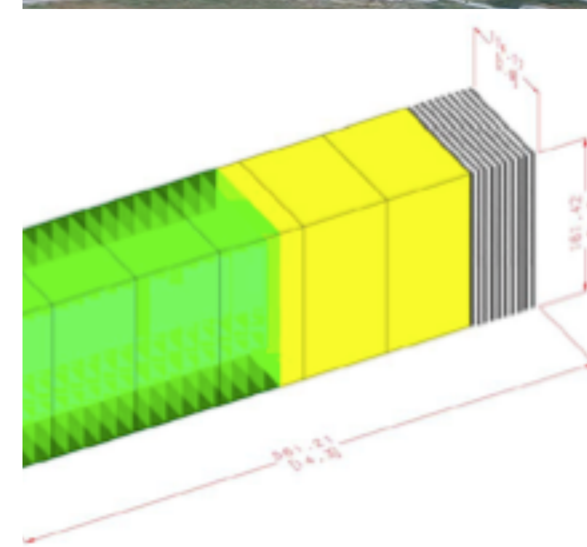

NOvA Far Detector

14.6 mrad off
the NuMI bea

The off-axis neutrino energy spectrum is peaked close to the oscillation maximum, and is narrow, allowing for background rejection based on event topology.

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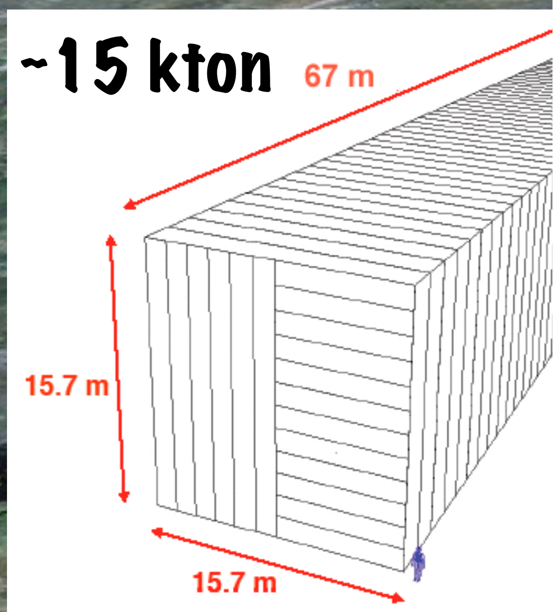

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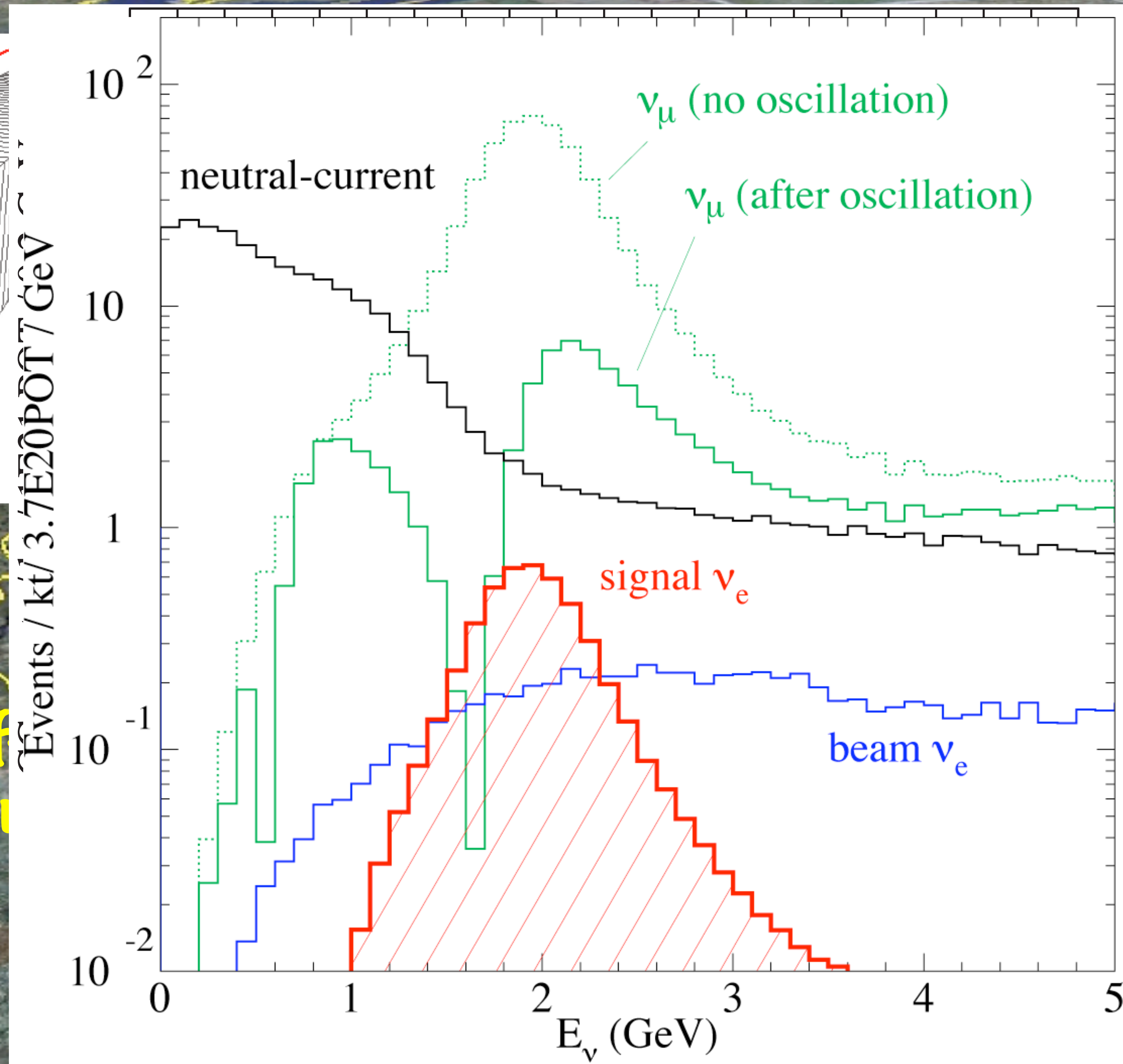

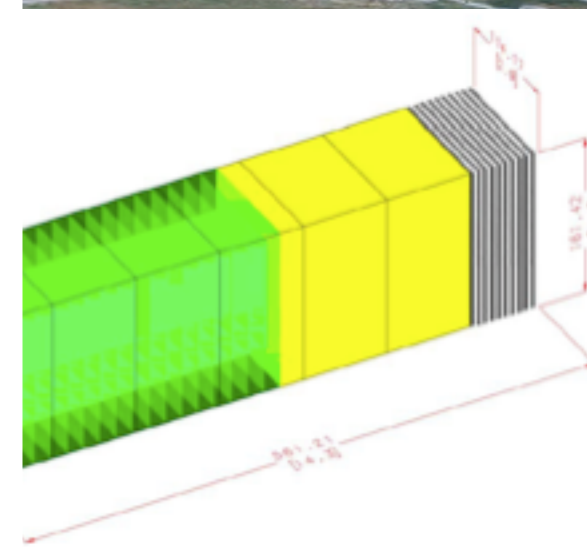

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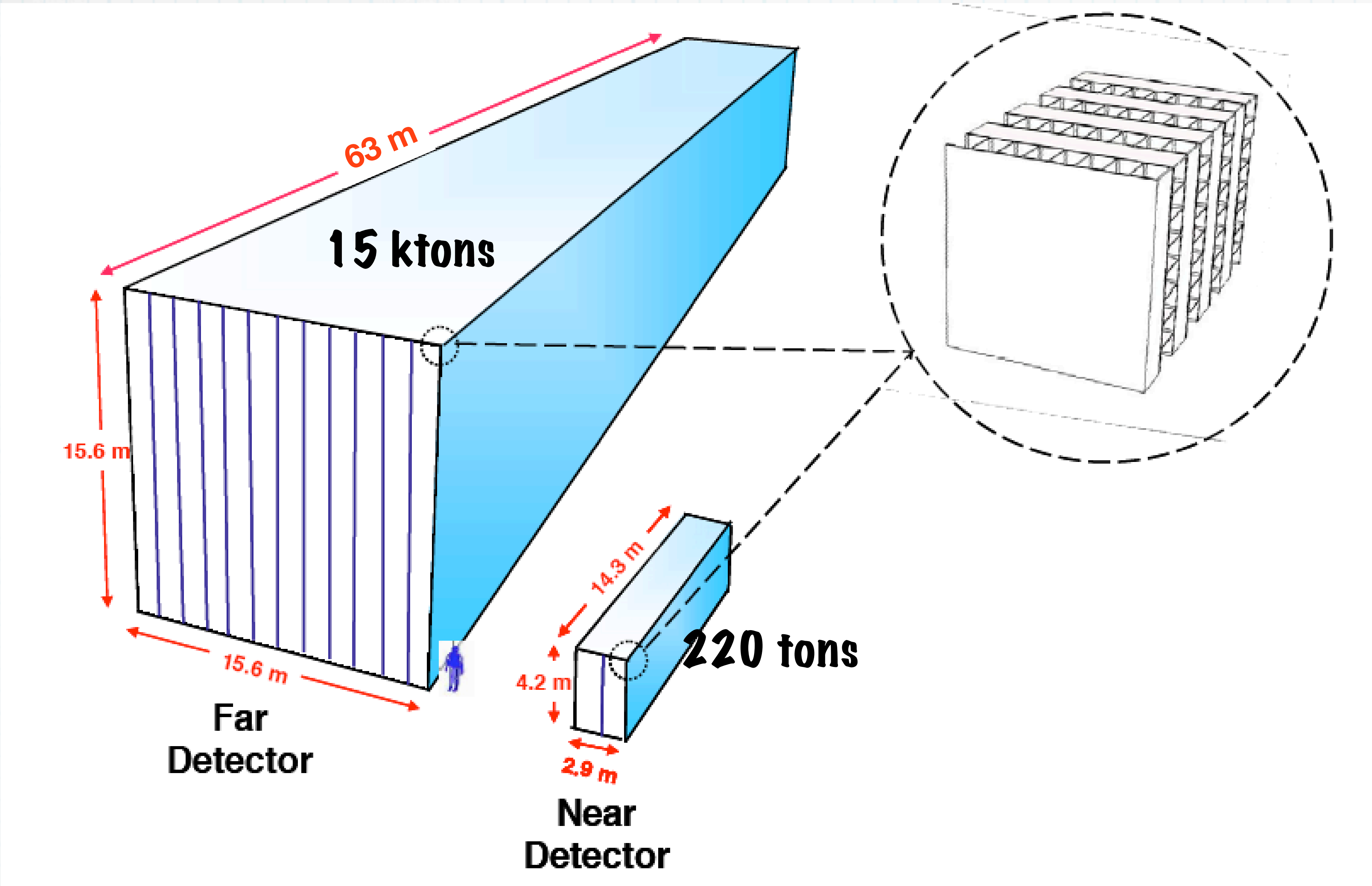
NOvA - Goals

* Observe $\nu_\mu \rightarrow \nu_e$ oscillations and measure the neutrino mixing angle θ_{13}.
* To take advantage of long baseline, NOvA will run in both ν_μ and anti-ν_μ mode; this gives NOvA sensitivity to the neutrino mass hierarchy and δ_{CP}!
* ~10x improvement in measurement of $\sin^2 2\theta_{23}$: is θ_{23} maximal?
* To achieve these goals, NOvA needs:
  * Two detectors optimized to separate electron-showers from NC showers, with excellent energy resolution.
  * Accelerator upgrades to bring power up from 400 kW to 700 kW.
* NOvA is complementary to T2K and Daya Bay.

The NOvA Detectors



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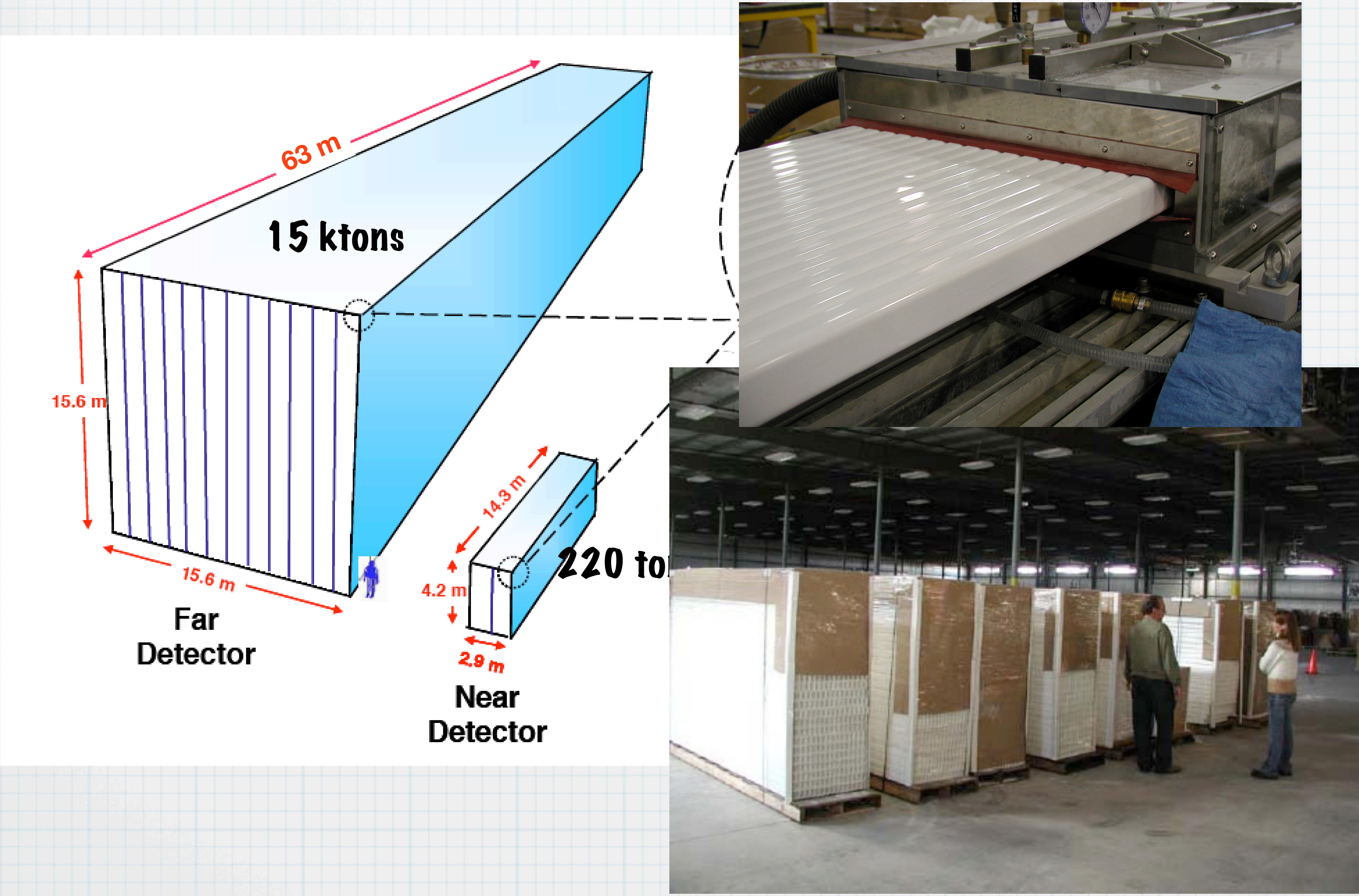

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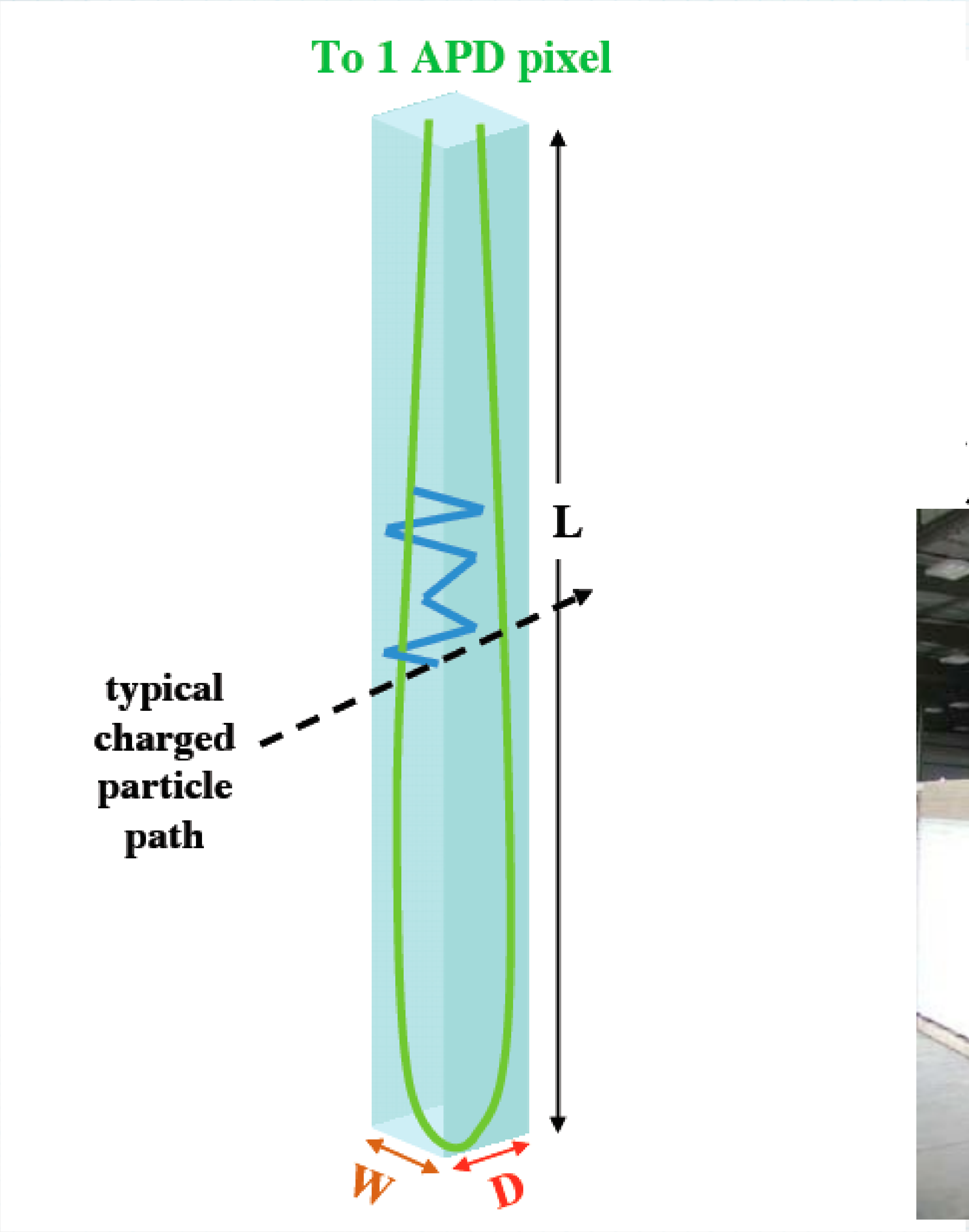

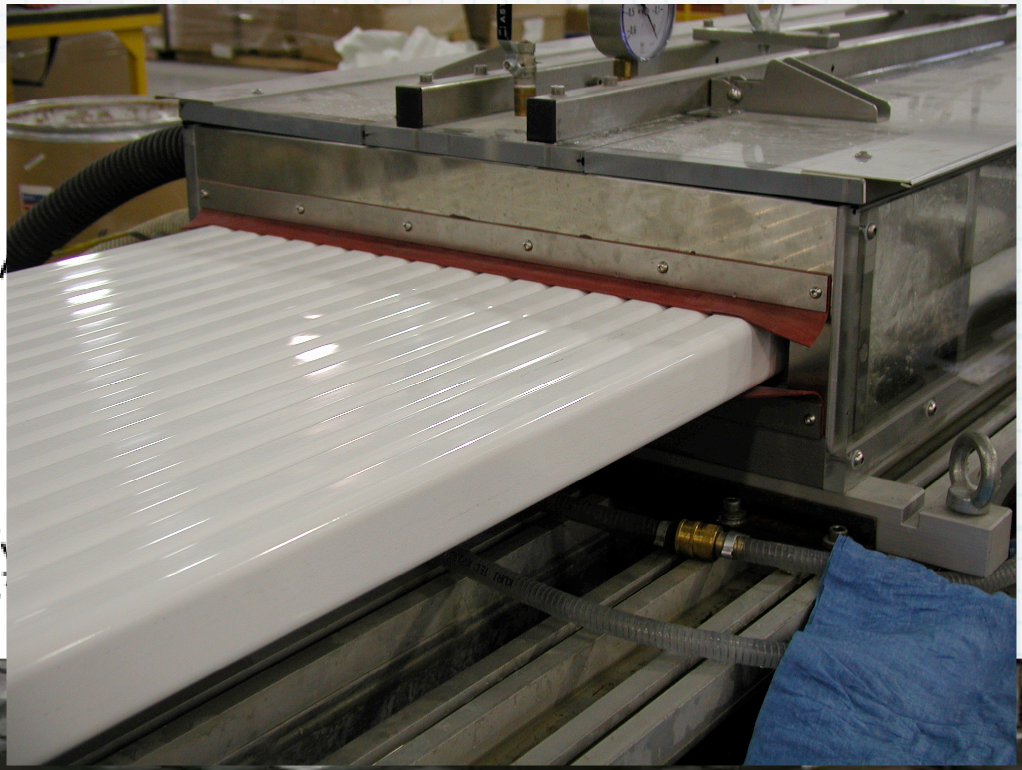

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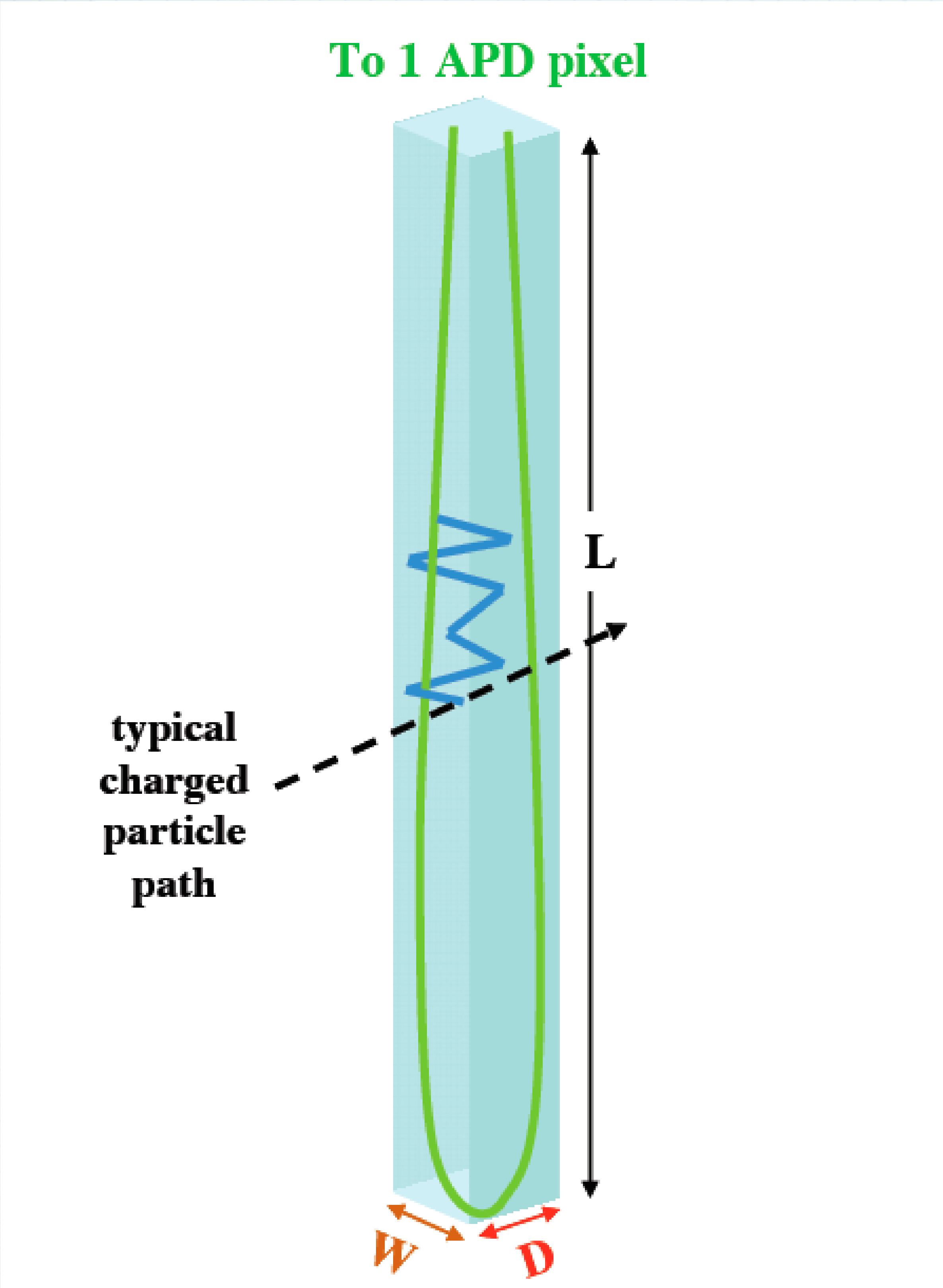

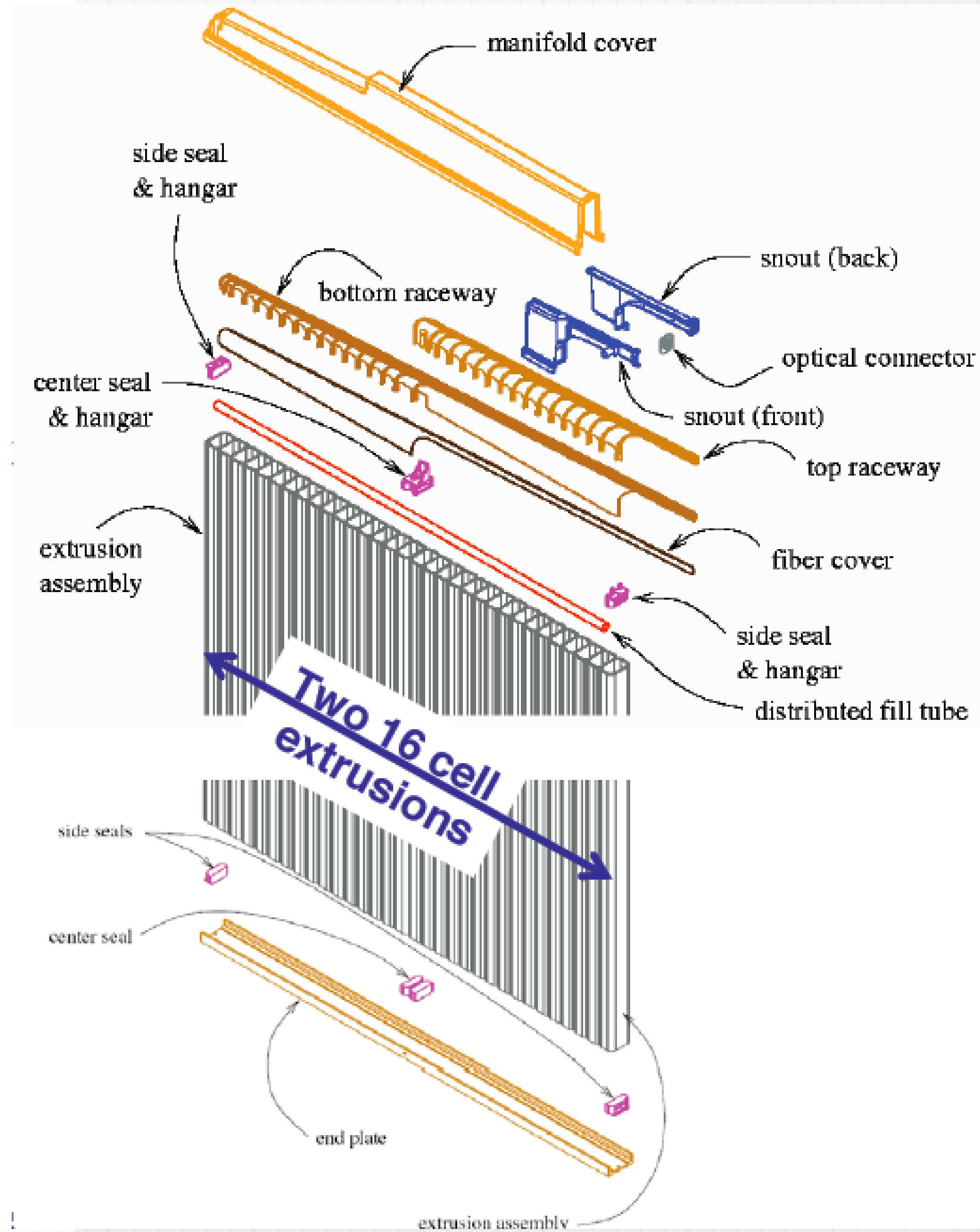

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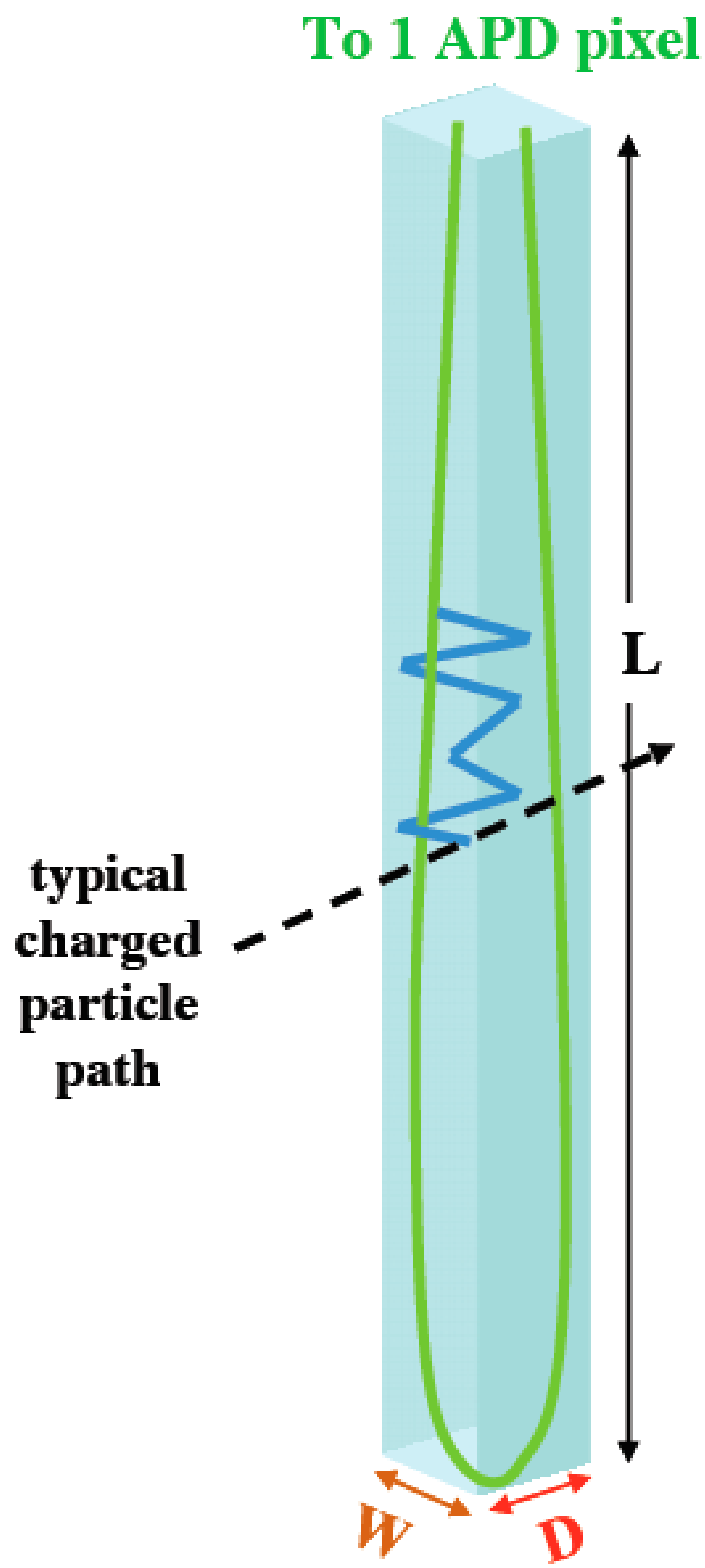
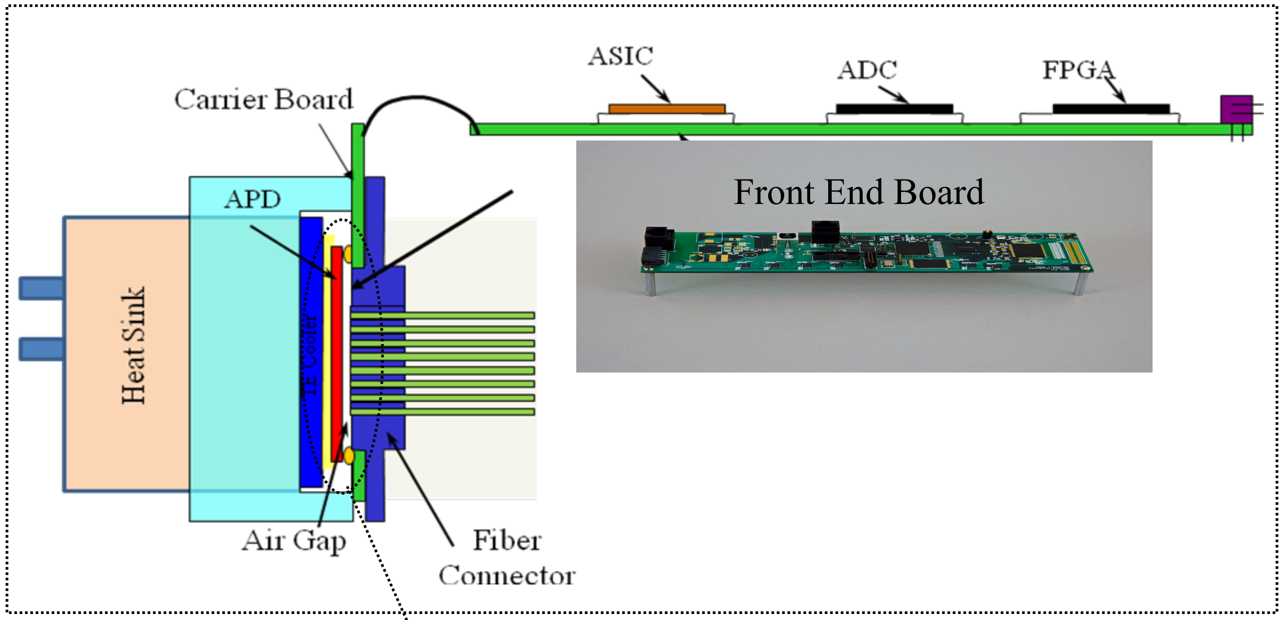
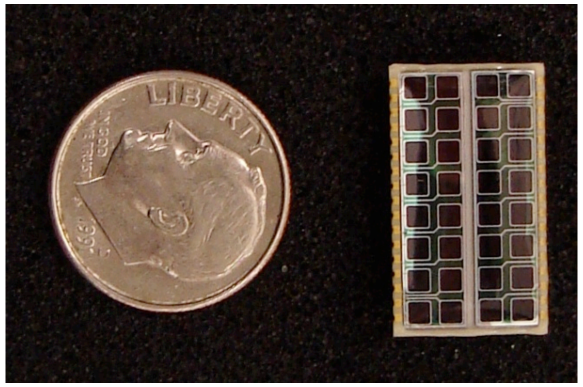
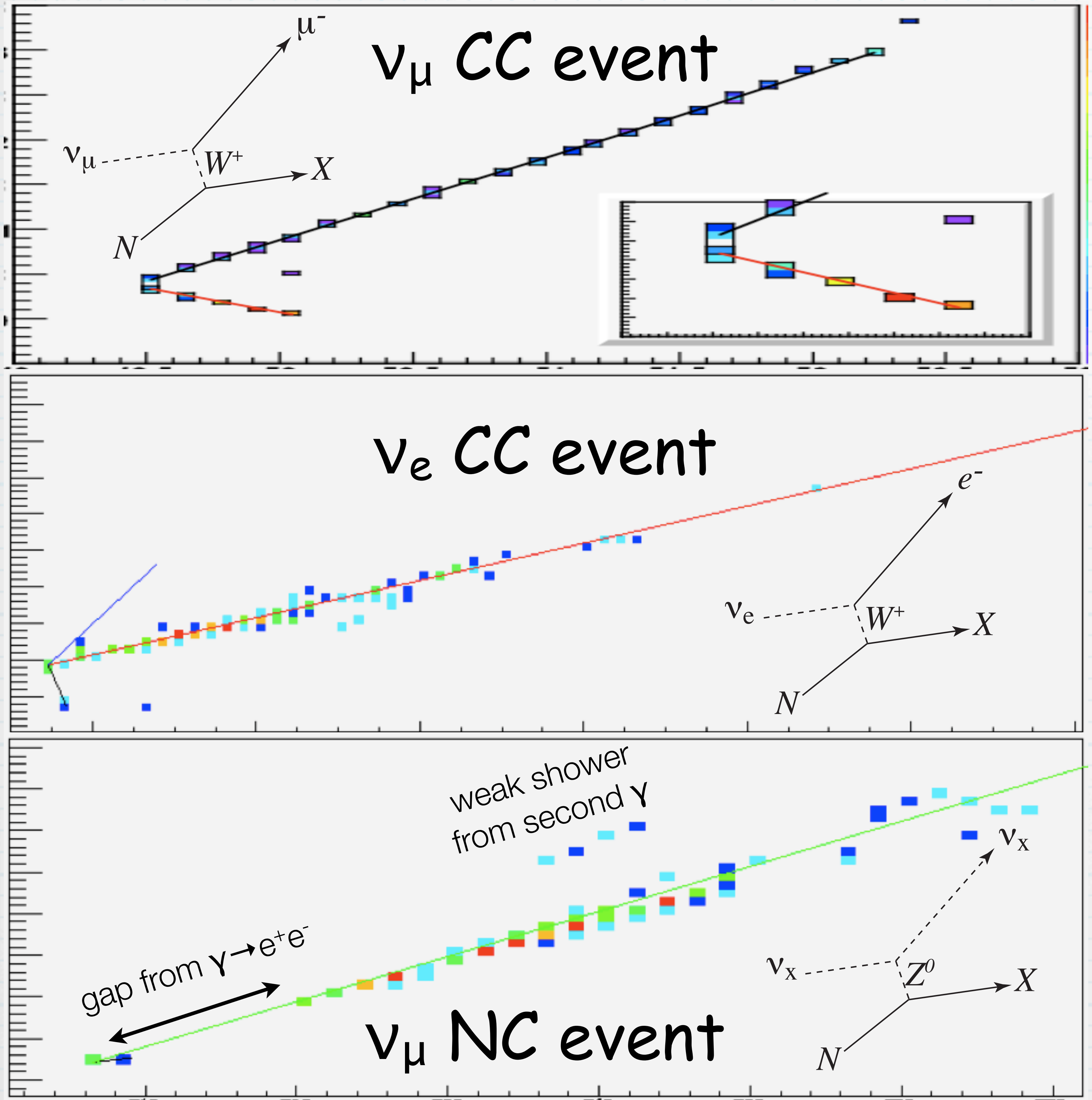




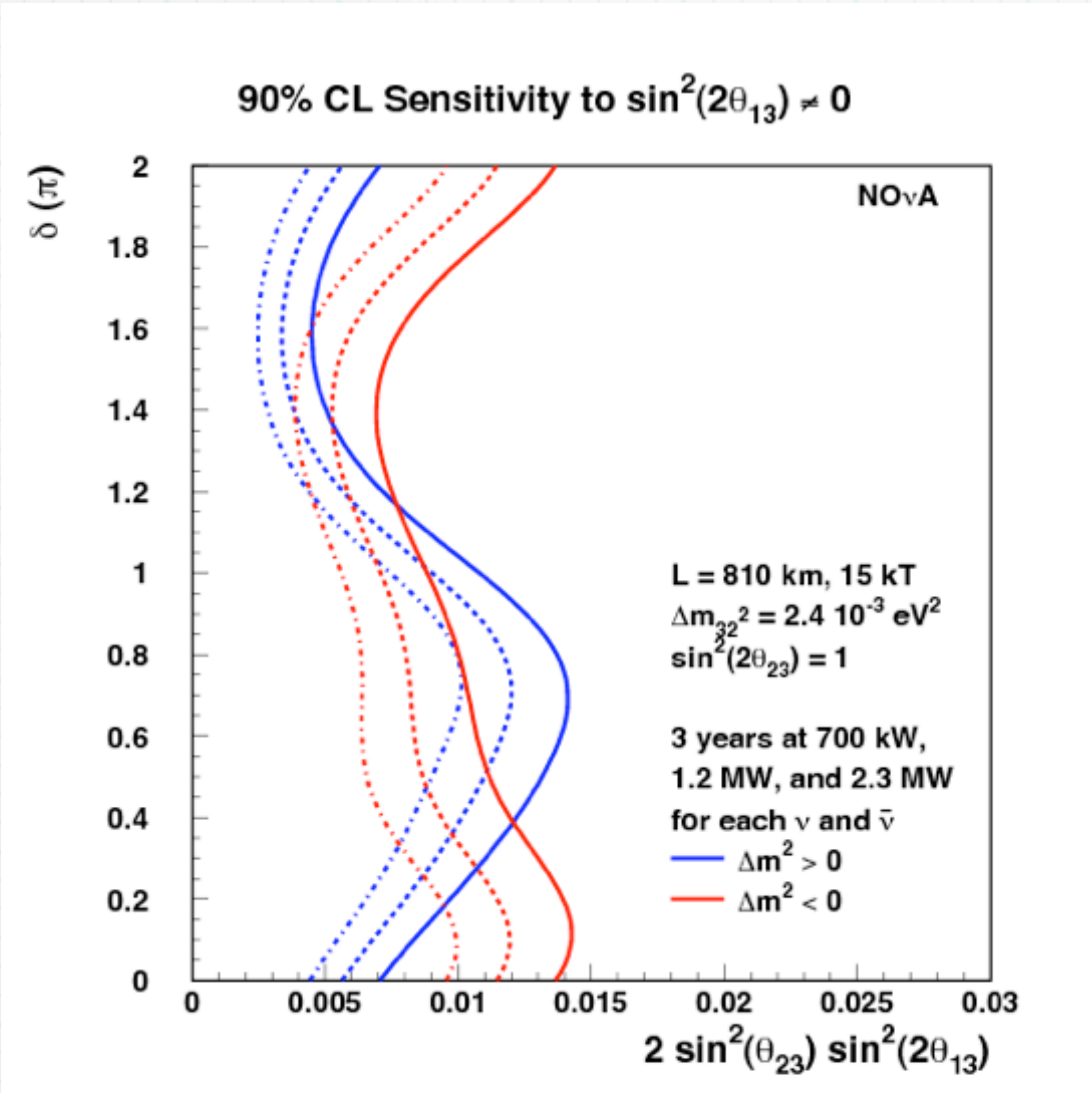


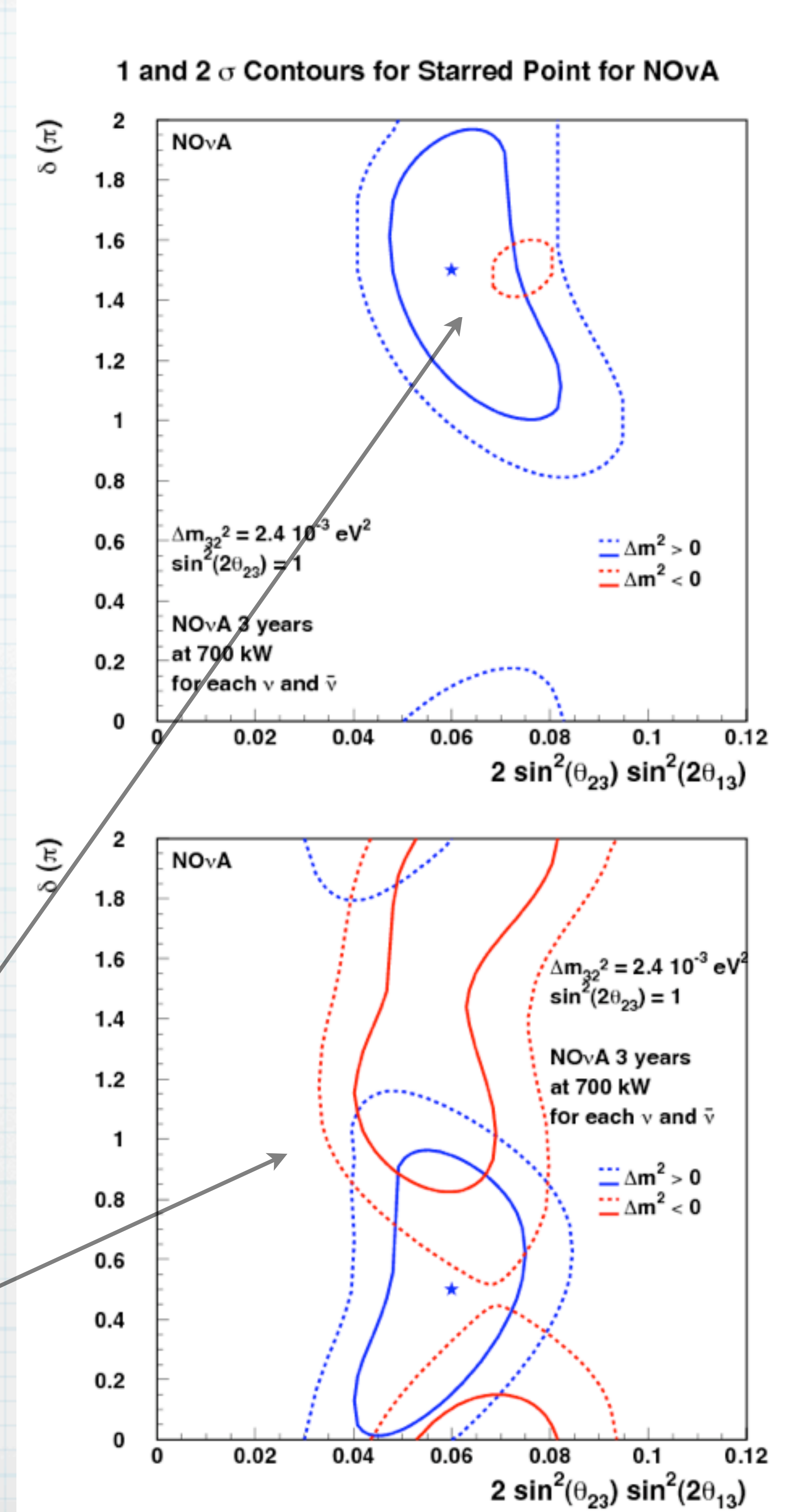
NOvA - Separating Events by Topology



* High granularity needed for required >100:1 background rejection.
* Each "pixel" is a single 4 cm x 6 cm cell of liquid scintillator.
* 35% efficiency for identifying ν_e CC events
* ν_e CC fake rate from NC events is ~0.1%
* Largest background comes from NC π^0s.

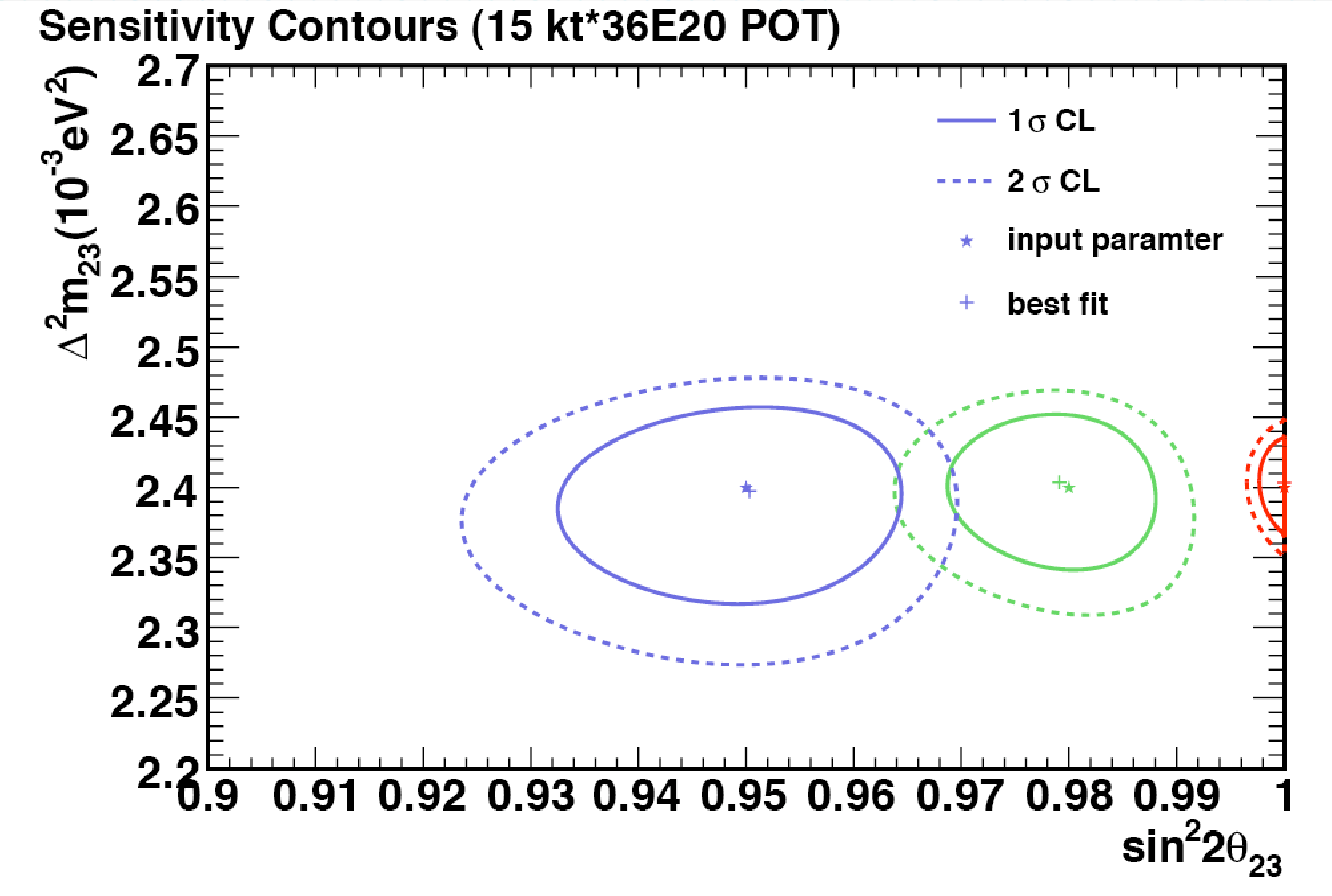
NOvA - θ_{13} Sensitivity





- NOvA will make ~10x improvement on current limit of $\sin^2 2\theta_{13}$.
- Depending on the value of δ_{CP}, NOvA may or may not be able to resolve the hierarchy.

NOvA - θ_{23} Sensitivity

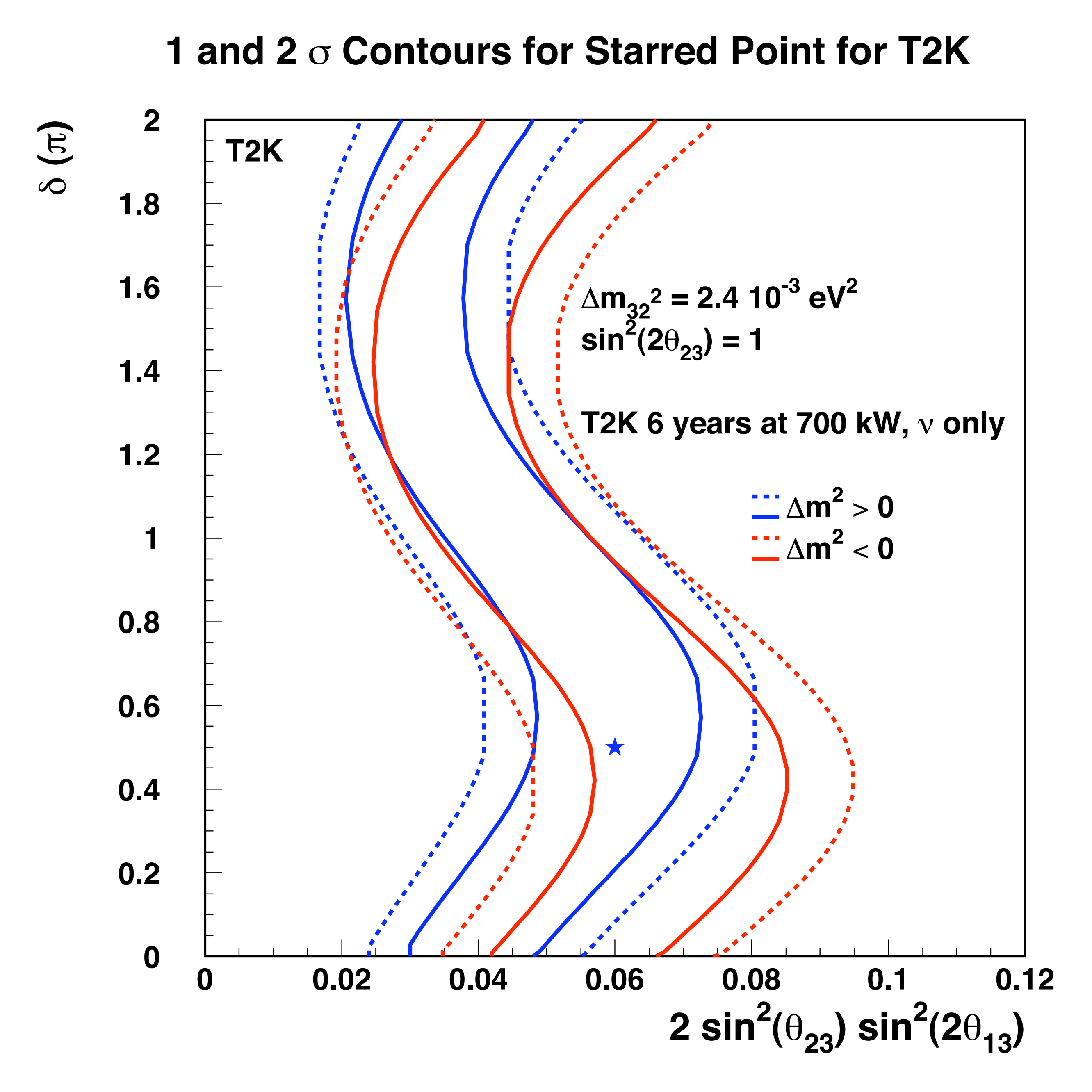


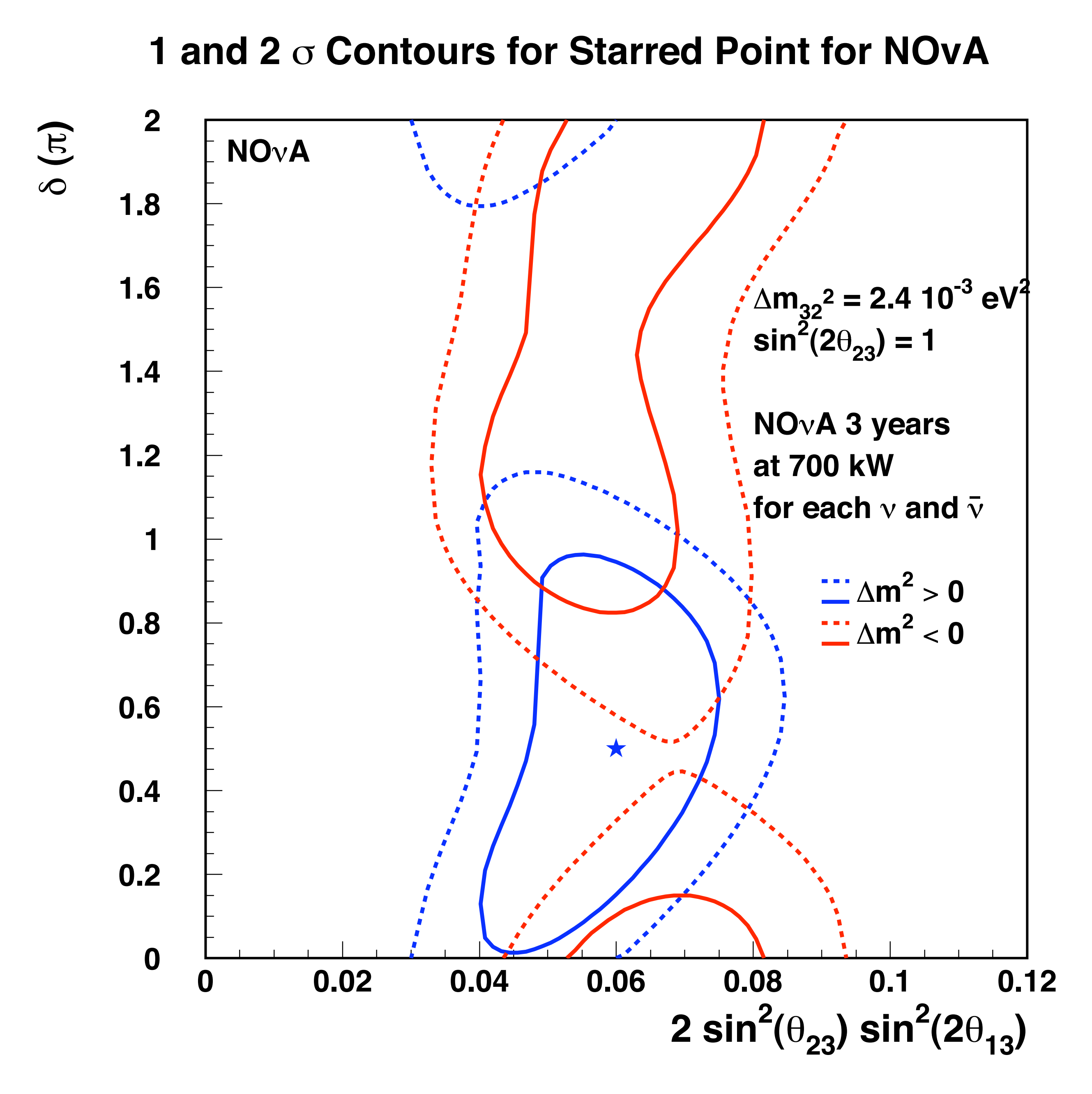
* NOvA will make ~10x improvement on $\sin^2 2\theta_{23}$.
* NOvA will make this measurement for both neutrino and anti-neutrino mode.

NOvA Schedule

* Construction has started on the far detector building. Should have occupancy next summer, allowing construction of far detector to begin. Building complete in November, 2010.
* Near Detector will be constructed over the next year. Data will be collected with partial ND on the surface at FNAL next summer.
* Recommended for CD3b in July. Last approval before NOvA is authorized for all procurements.
* Plan to run experiment while it's being constructed. First data in 2012 and a completed detector in 2013.

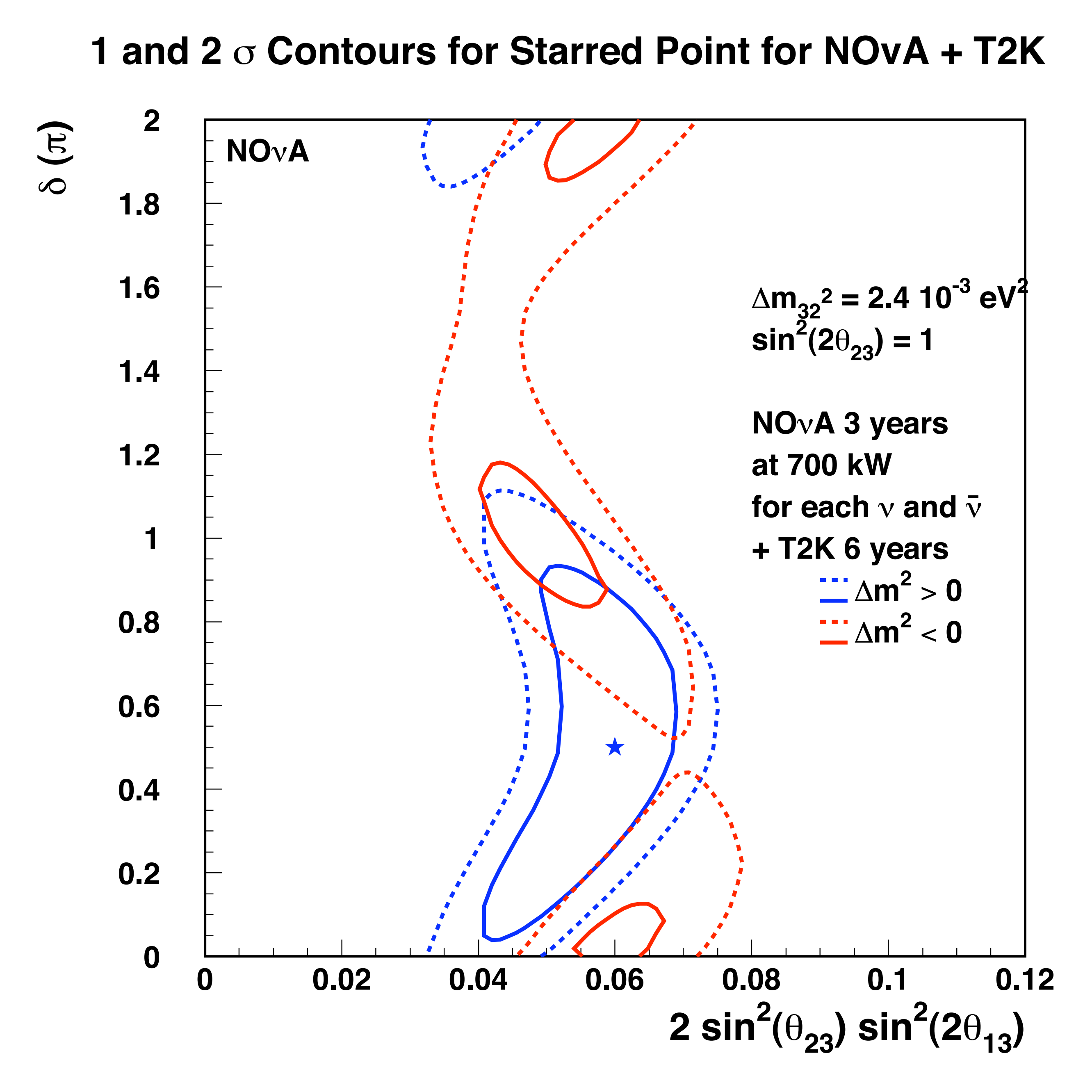
Combining T2K and NOvA

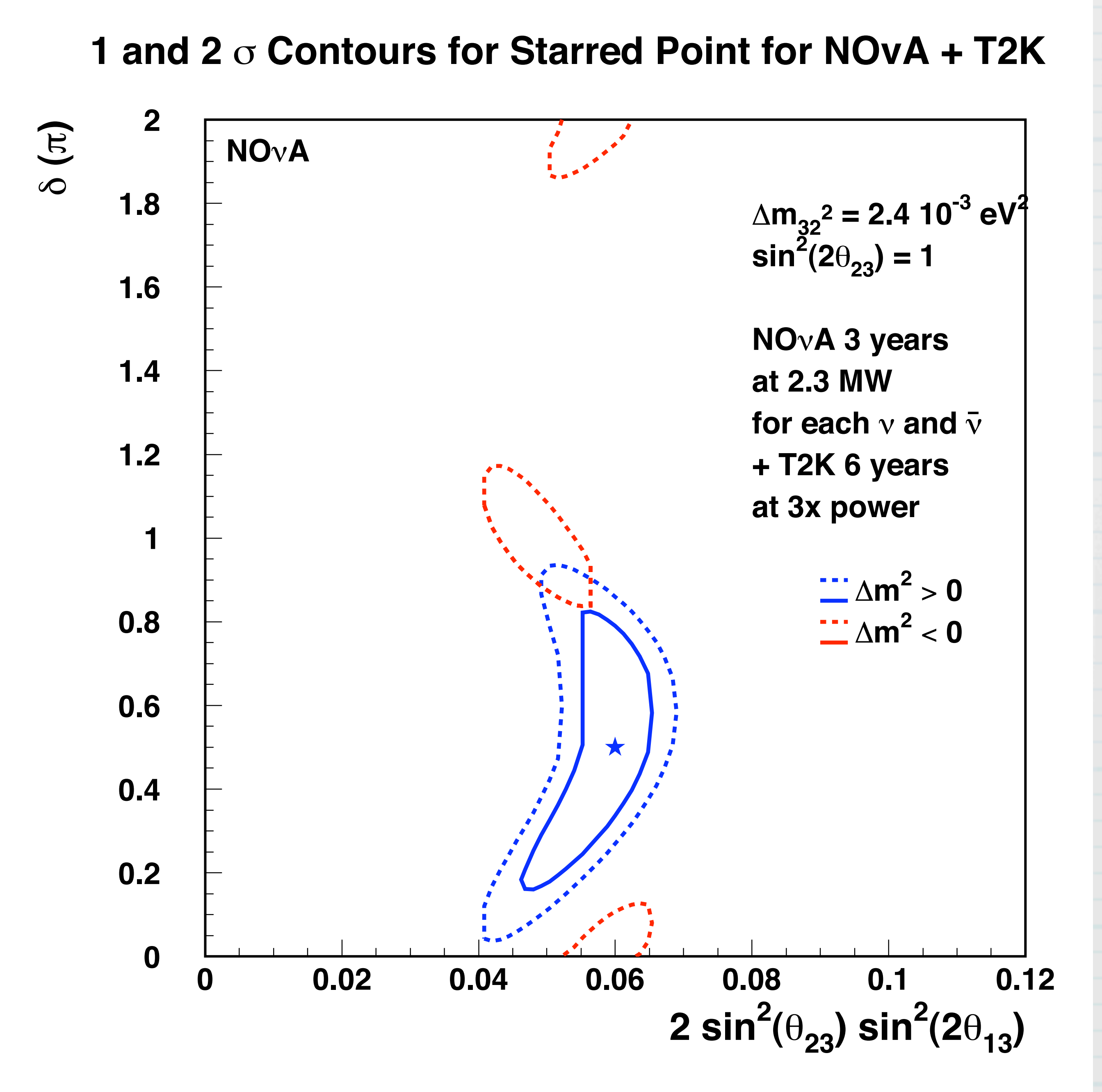




* Estimate for results from T2K true value at starred point. T2K has no sensitivity to either the CP phase or the mass hierarchy.
* Contours from NOvA for the same starred point. Hierarchy no resolved since 1 σ contours overlap (blue & red).

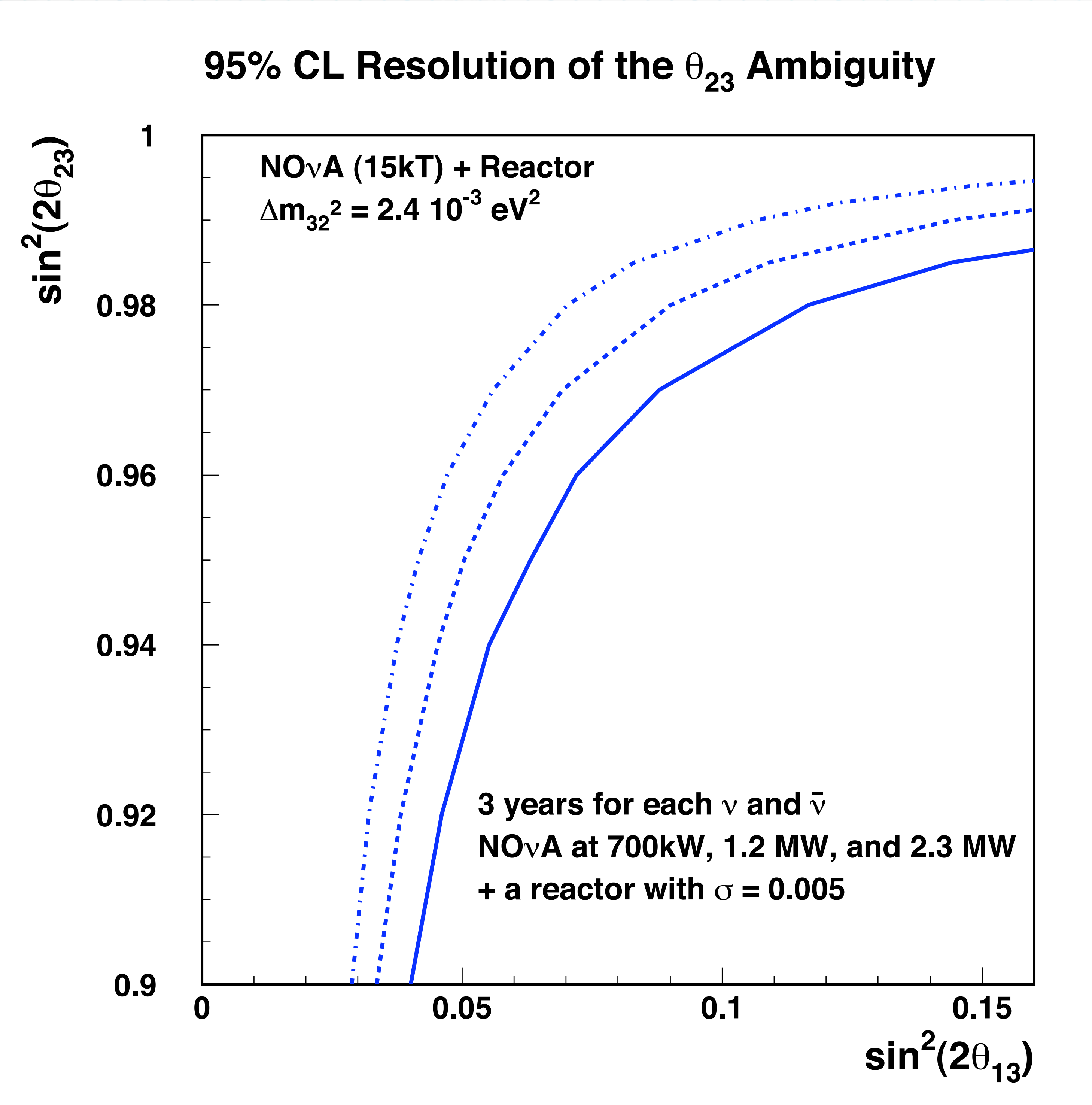
Combining T2K and NOvA





* Contours for combine T2K and NOvA analysis. Allowed phase-space for inverted hierarchy is greatly reduced.
* Contours for combined T2K and NOvA analysis, with beam upgrades in both.

Combining NOvA and Reactor



* The octant of the θ_{23} is uniquely determined by combining reactor (eg, Daya Bay) and NOvA results.
* If $\theta_{23} < 45^0$, then ν_μ couples more strongly with m_2 state.
* If $\theta_{23} > 45^0$, then ν_μ couples more strongly with m_3 state.

Summary

* Both appearance and disappearance measurements in long baseline neutrino oscillation experiments allow precise measurements of the oscillation parameters.

* MINOS has the most precise measurement of Δm^2_{32}, and has seen a slight excess of ν_e events in its far detector. All analyses will soon be updated/improved with greater statistics and smaller systematics.

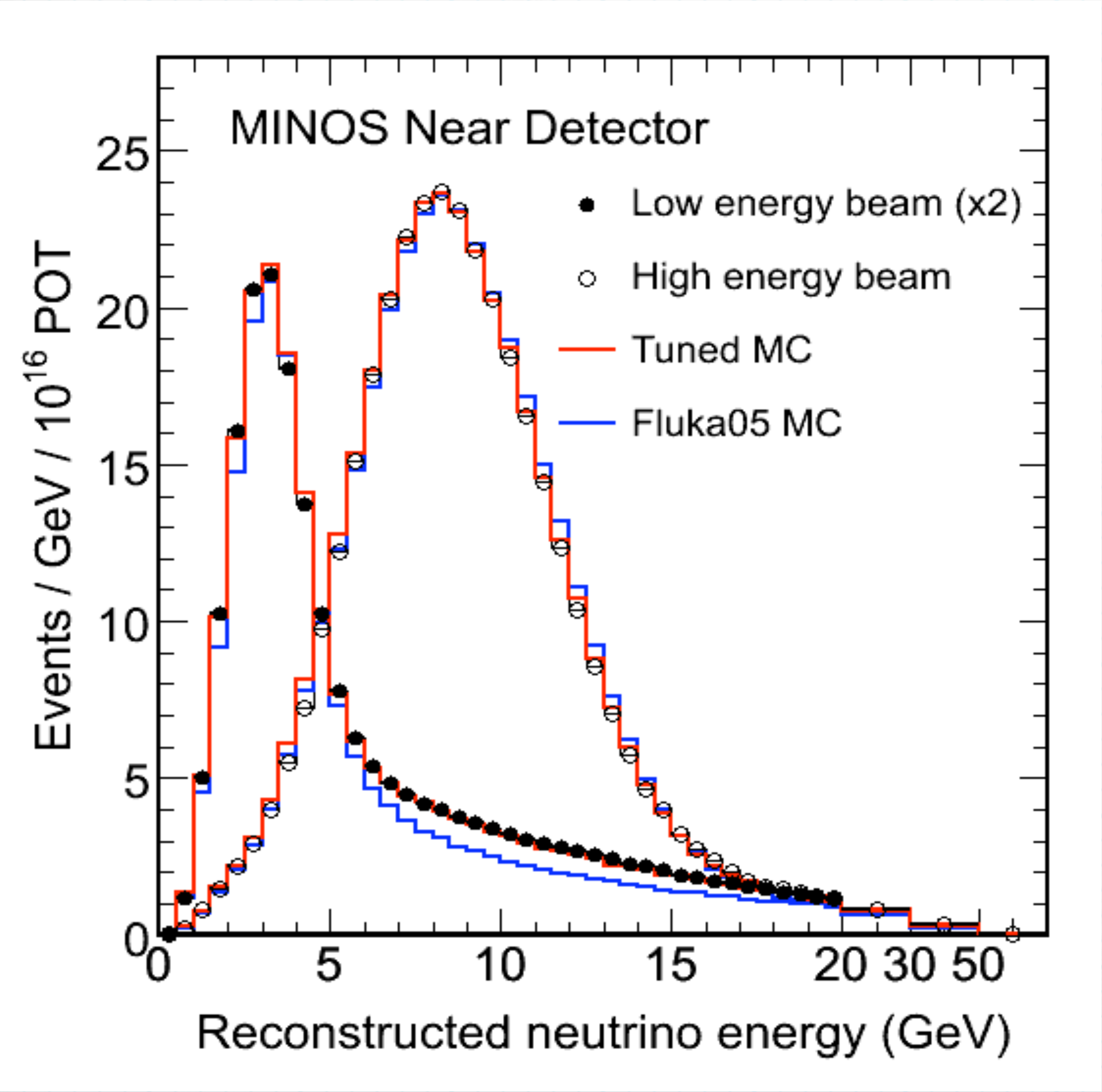
* NOvA will improve by ~10x the uncertainties/limits on θ_{23} and θ_{13} over a 6-year run, and may be able to resolve the mass hierarchy.

* T2K is very close to beginning their 5-year run. A new limit or possible discovery of a non-zero θ_{13} is possible within the next couple of years!

* T2K, NOvA and reactor experiments are all complimentary; combining results may open new windows into our understanding of the universe!

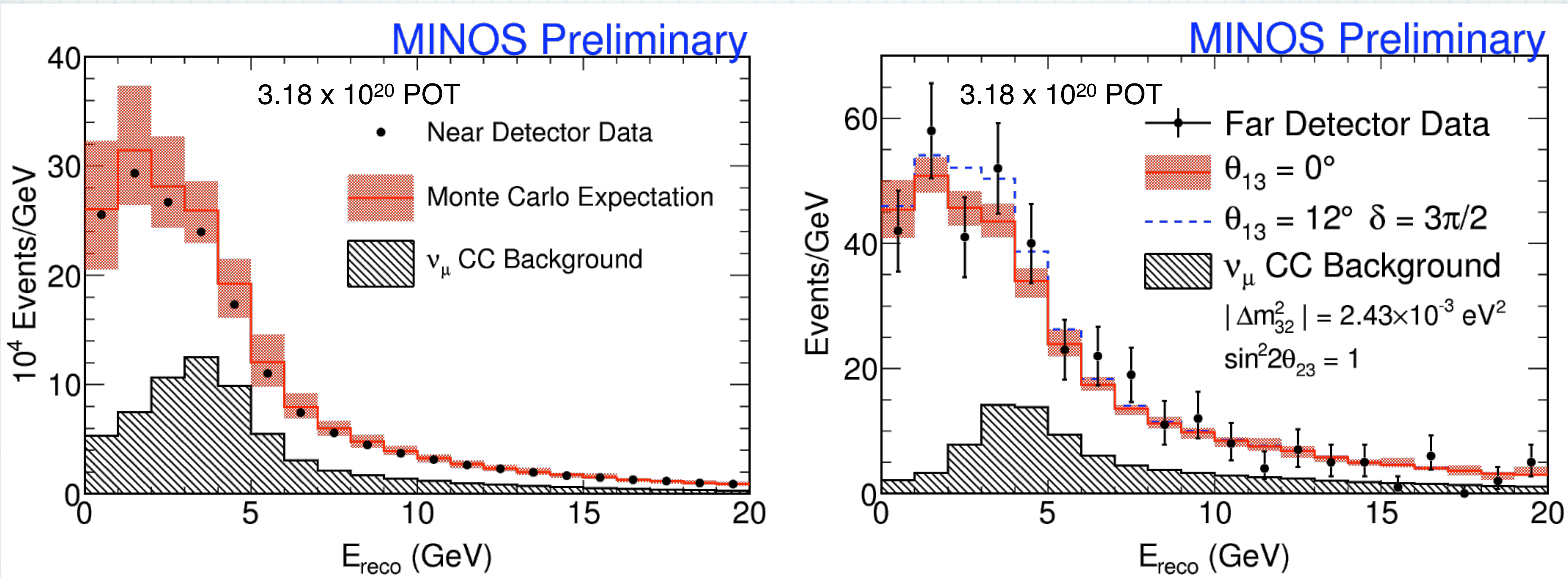
Backup Slides

Tuning the Flux Prediction



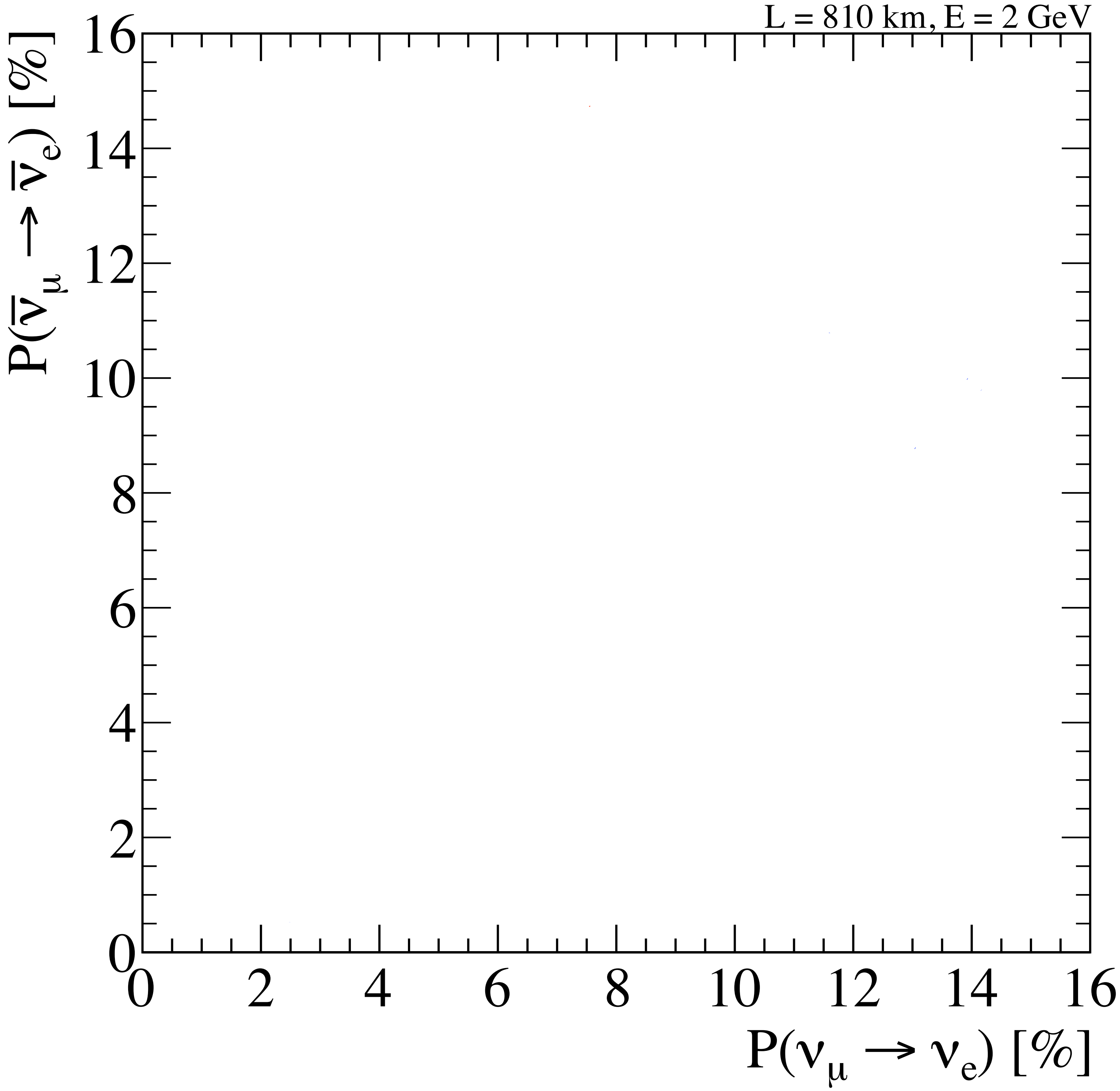
* MINOS uses Fluka MC to predict the ν flux.
* Uncertainty on flux is ~30% due to lack of hadron production data.
* To improve our data-to-MC agreement, we tune the Fluka MC to ND energy spectra of different beam configurations.
* These beam-reweighted spectra are used in all analyses discussed today.

MINOS Sterile Neutrino Analysis



- Search for sterile neutrinos: since NC events probe all active flavors, a depletion of NC events in the FD can only be explained by ν_s.
- Select reconstructed "shower-like" events.
- Result: $f_s = P(\nu_\mu \rightarrow \nu_s)/(1-P(\nu_\mu \rightarrow \nu_\mu))$

  $f_s < 0.51$ ($0.55\ \nu_e$) (90% CL)



Using a muon neutrino beam, we have two basic observables

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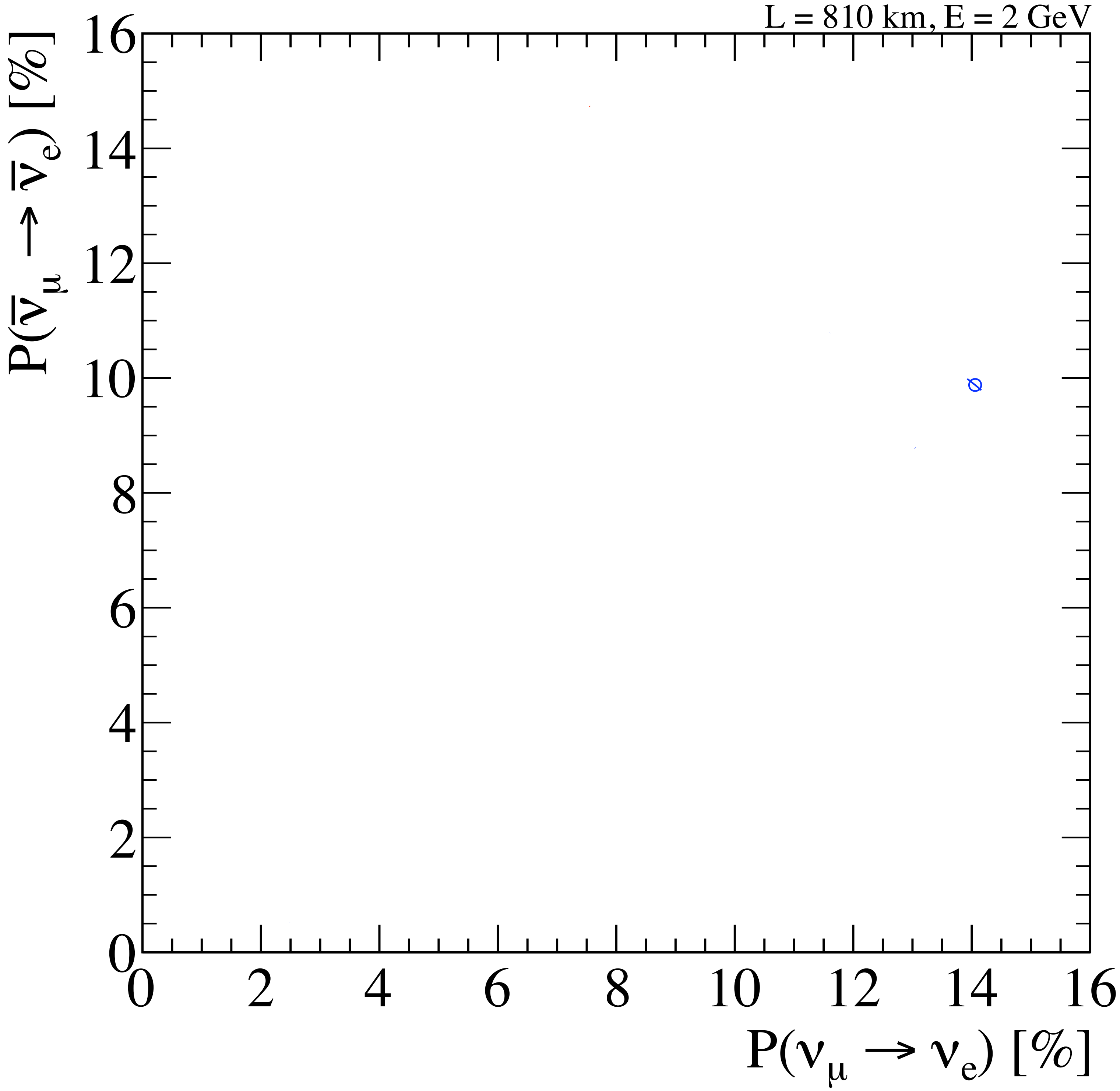
We can plot these two observables as a function of the remaining unknowns θ_{13}, δ_{CP} , and mass hierarchy.

Perfect measurements of the two oscillation probabilities answer all remaining questions if θ_{13} is large enough.

For small θ_{13} there are inherent ambiguities between hierarchy choice and δ_{CP}. However, even in these cases we learn something about δ_{CP}.

Principle of the NOvA Experiment



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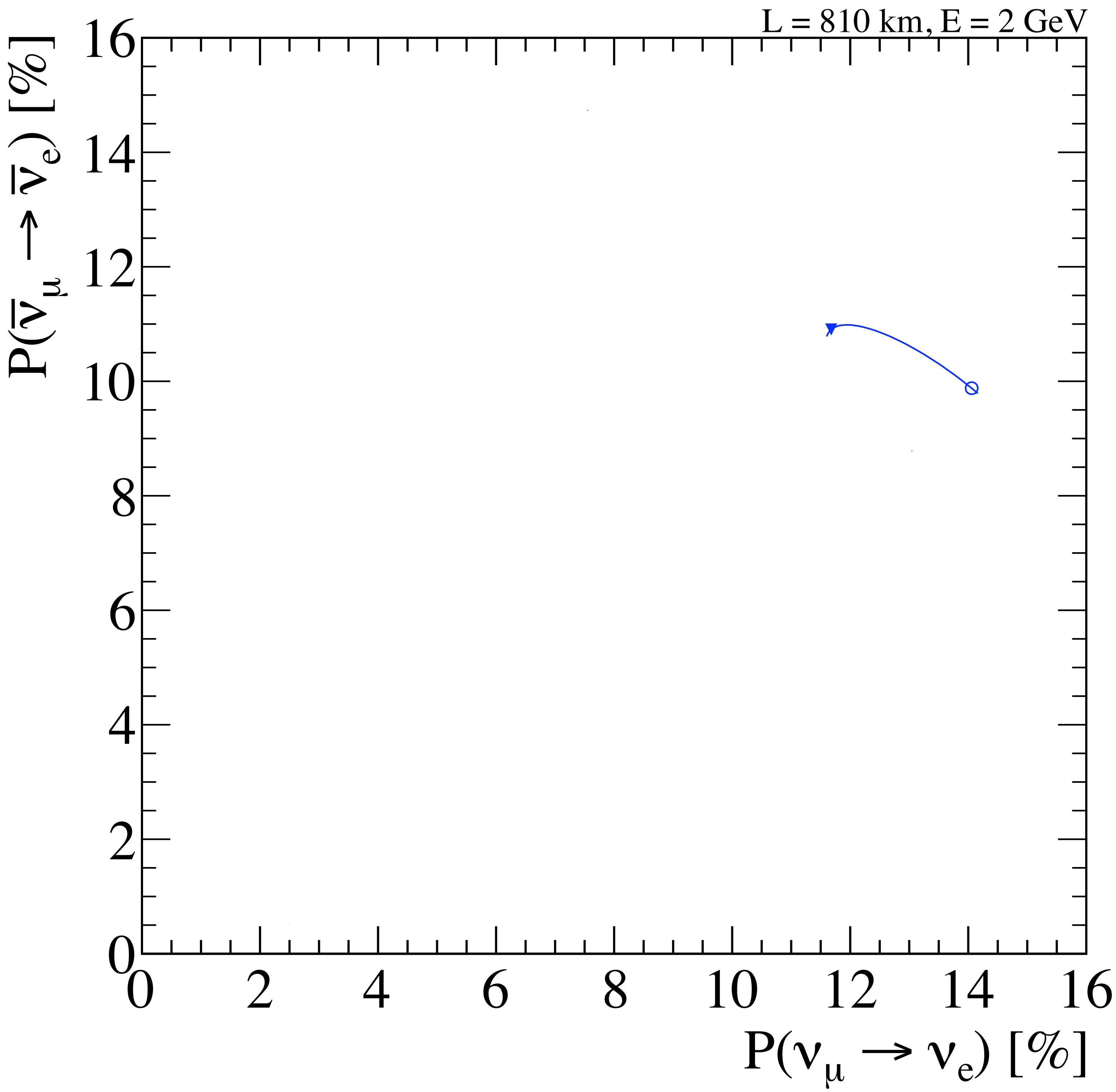

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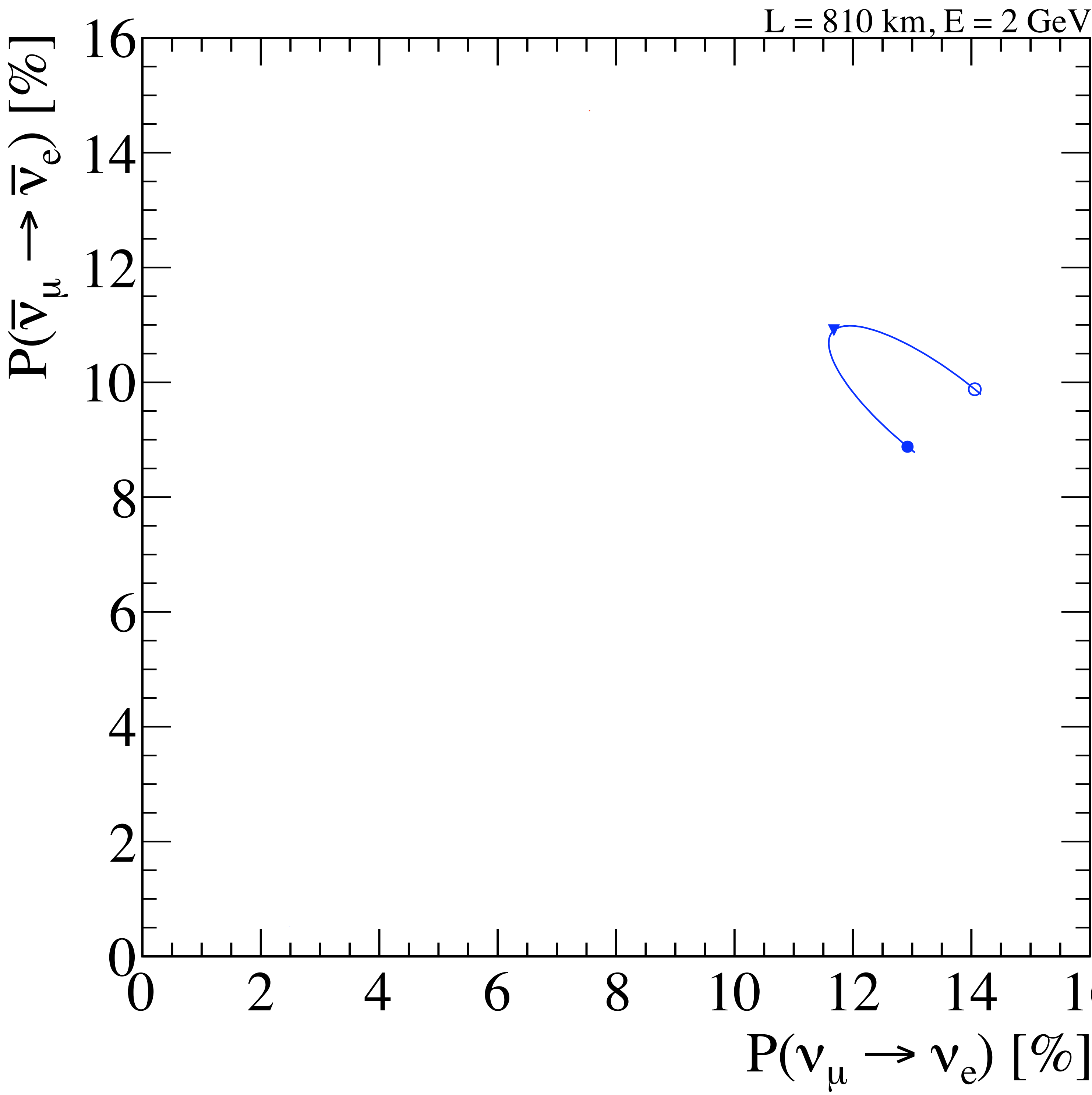

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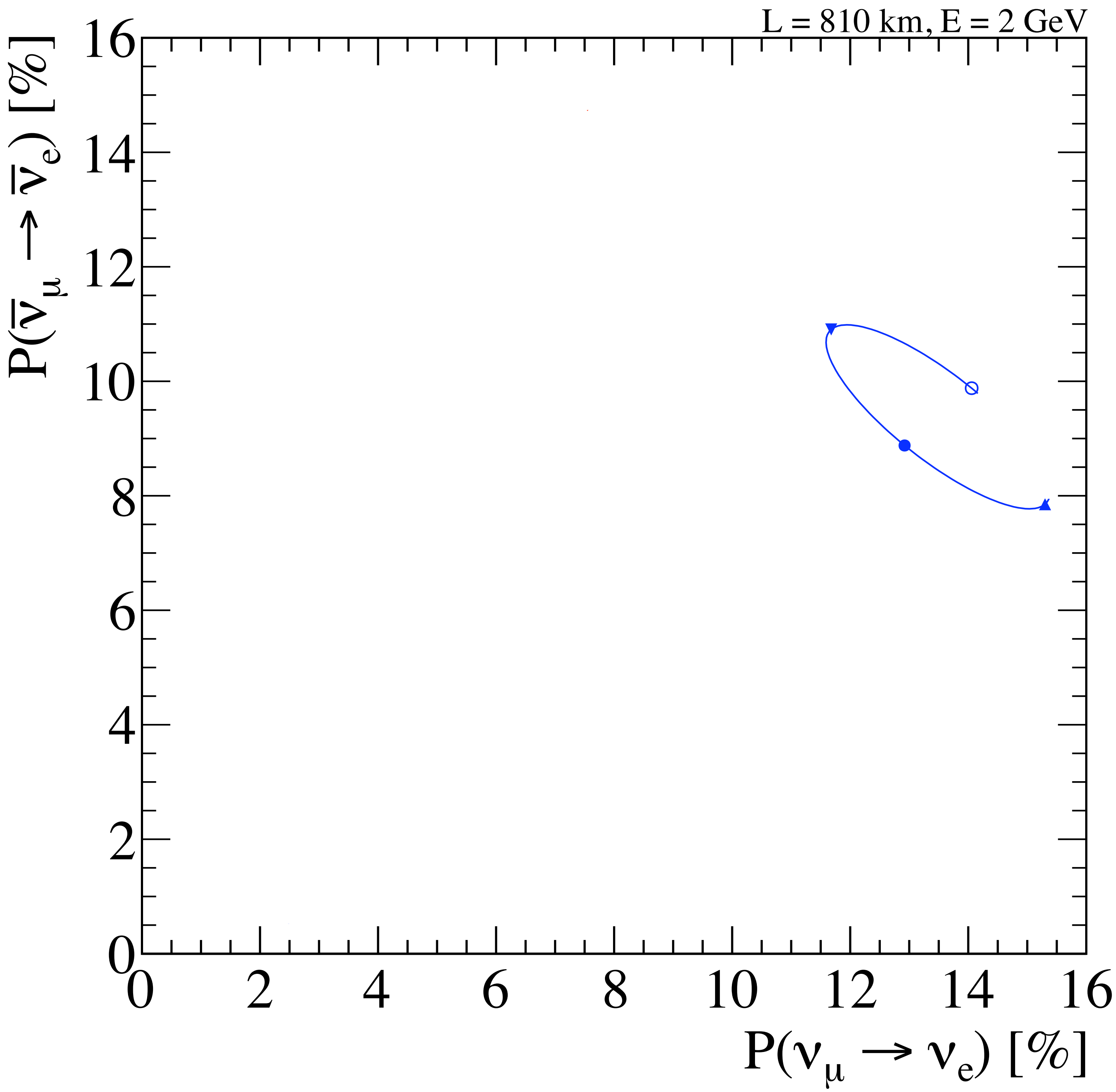

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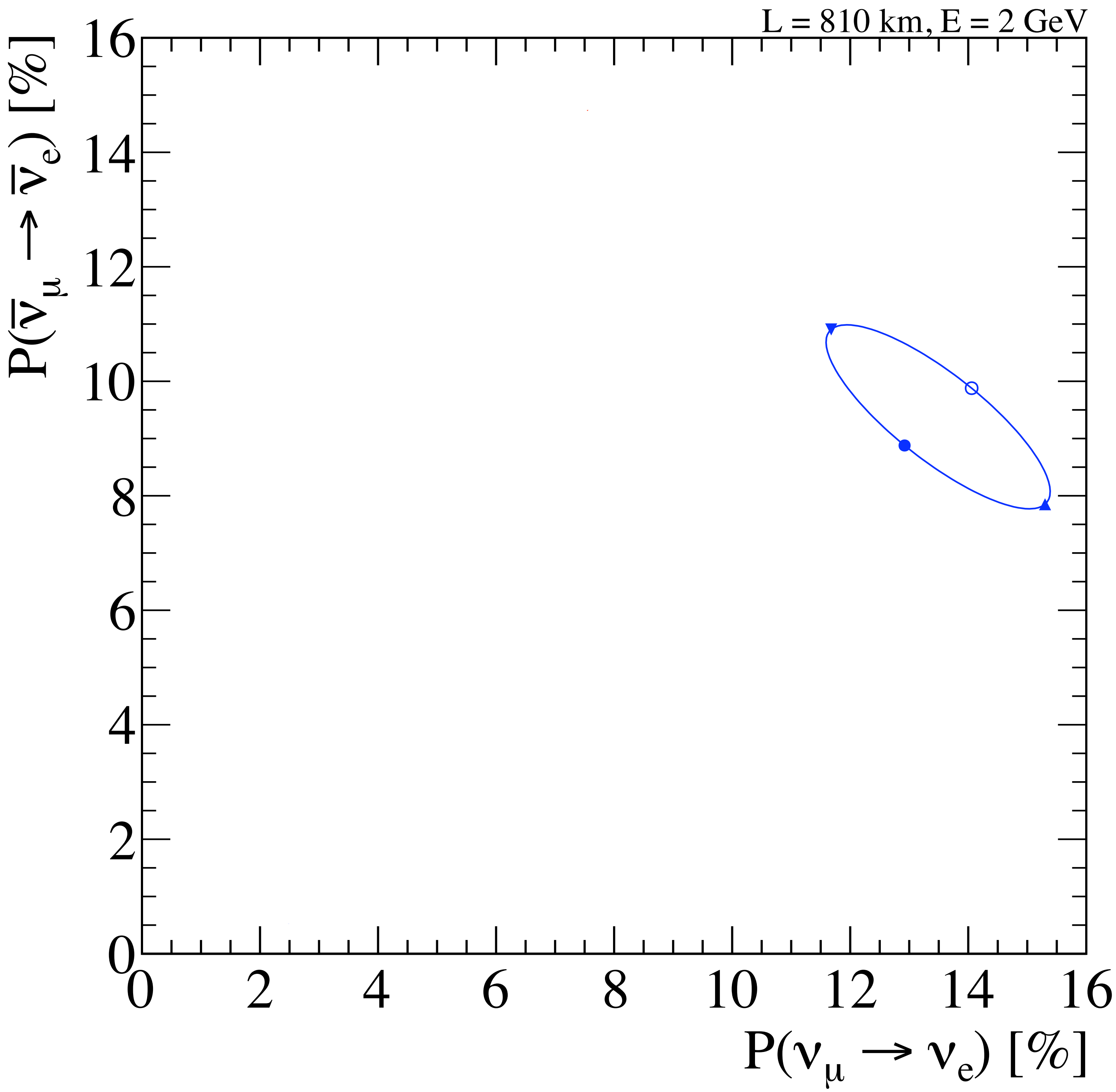

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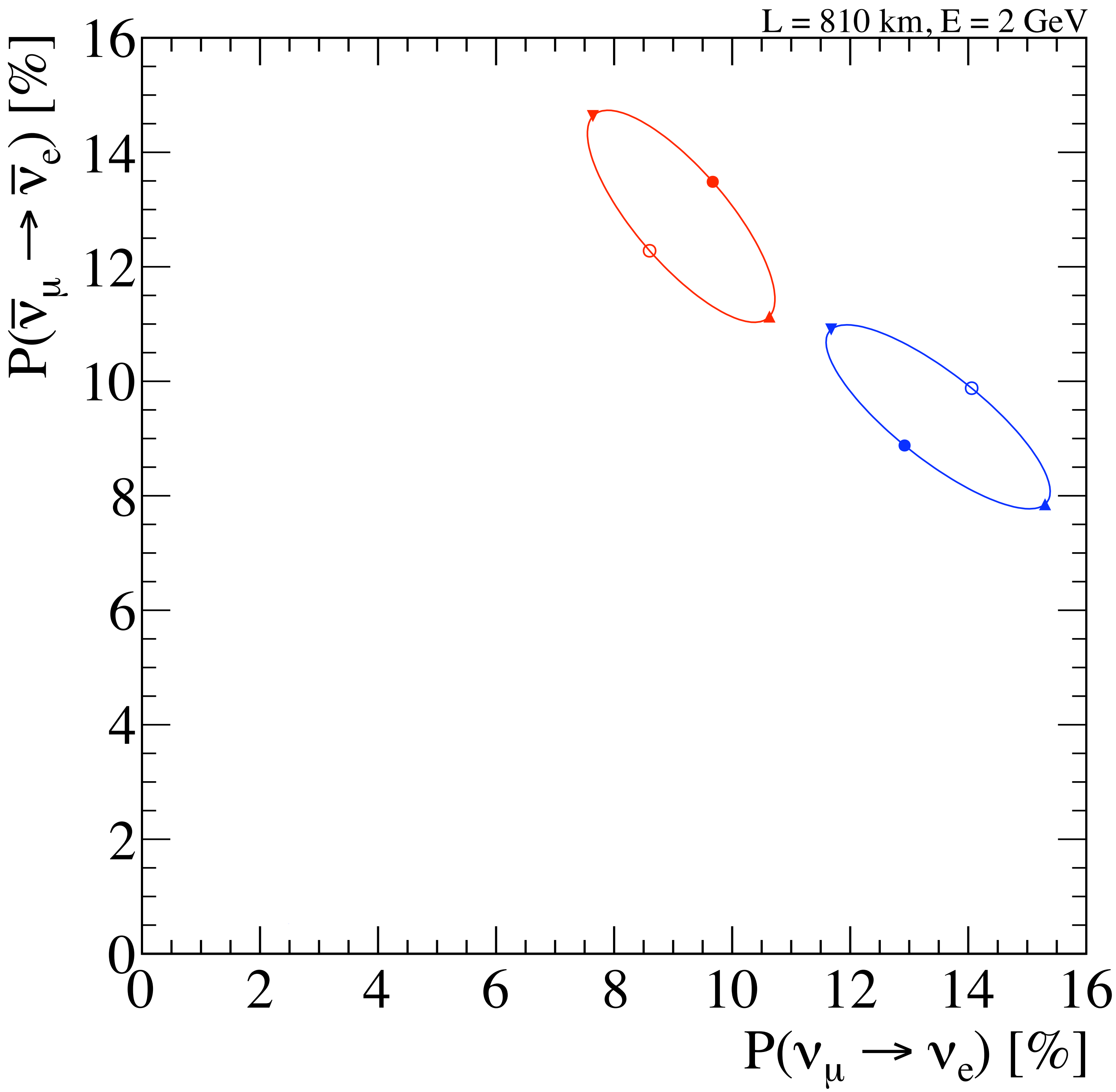

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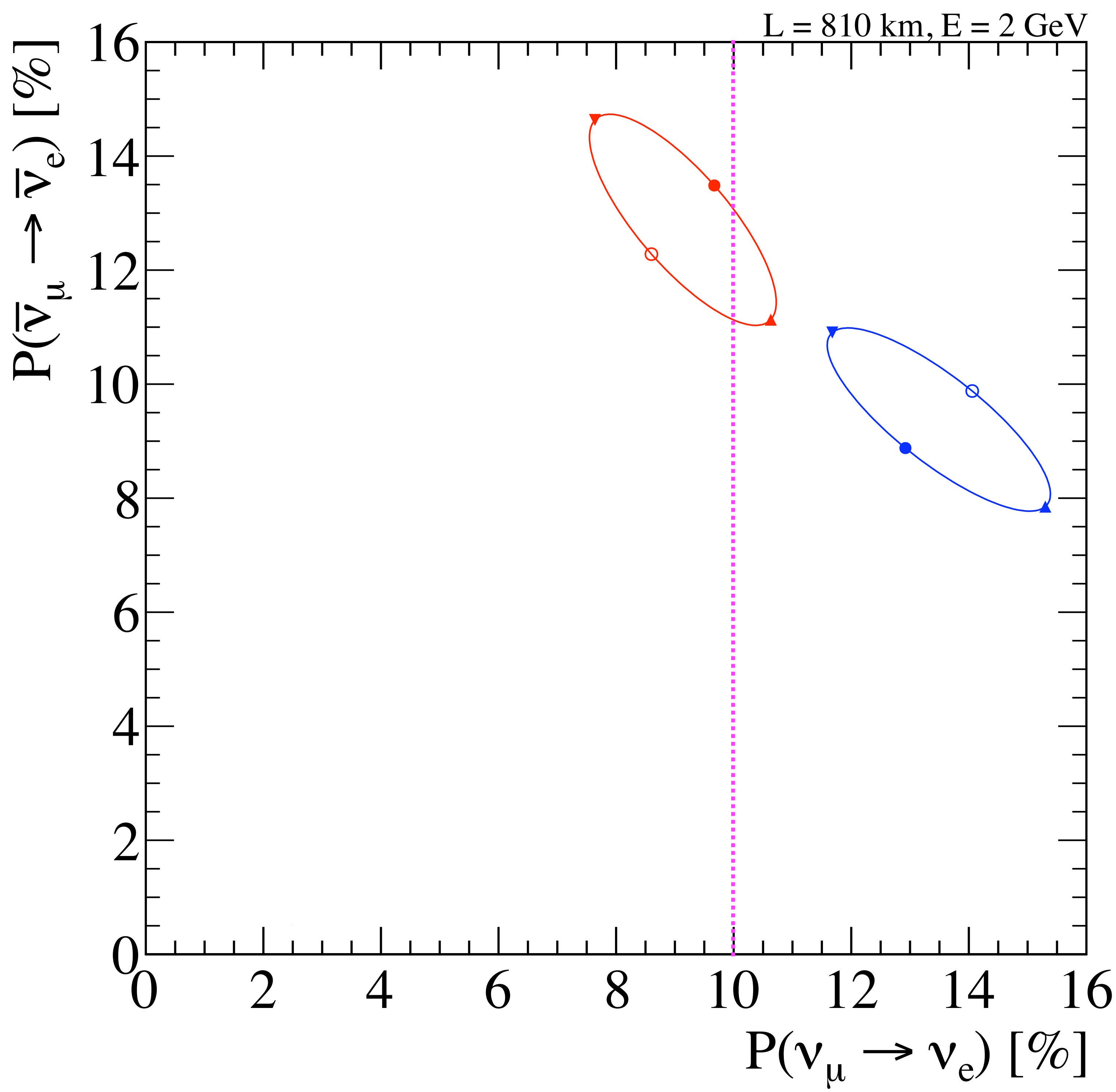

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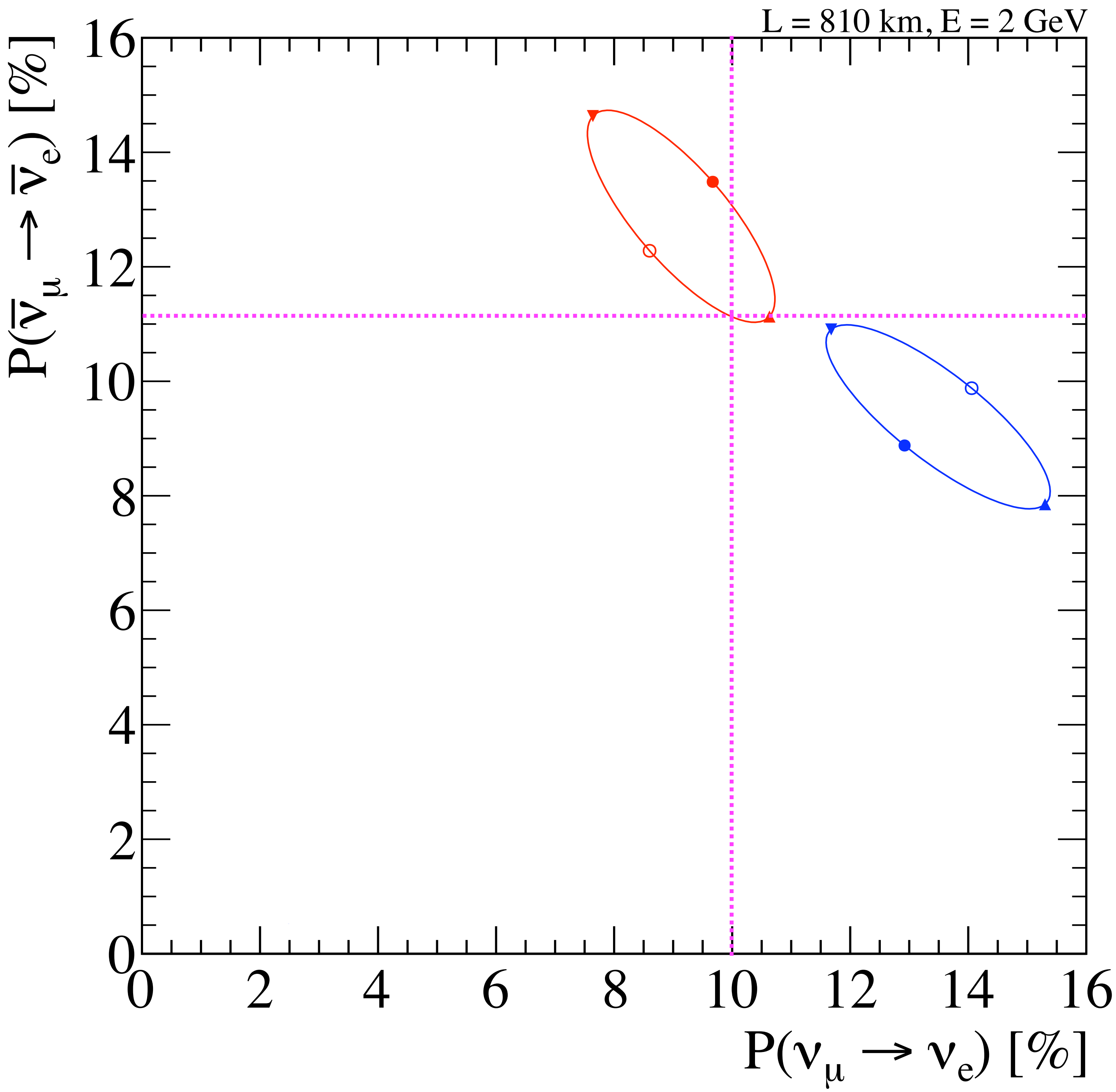

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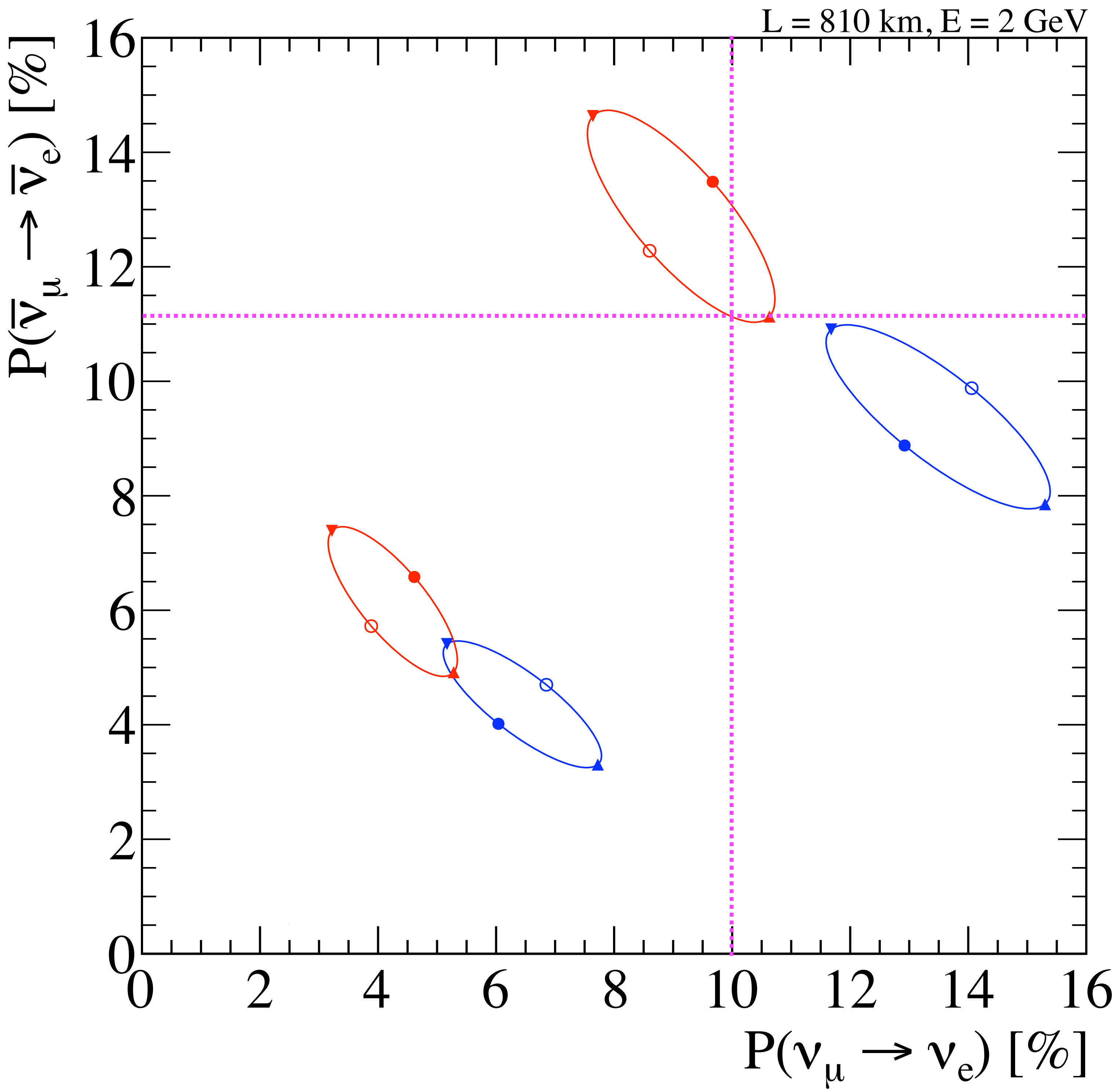

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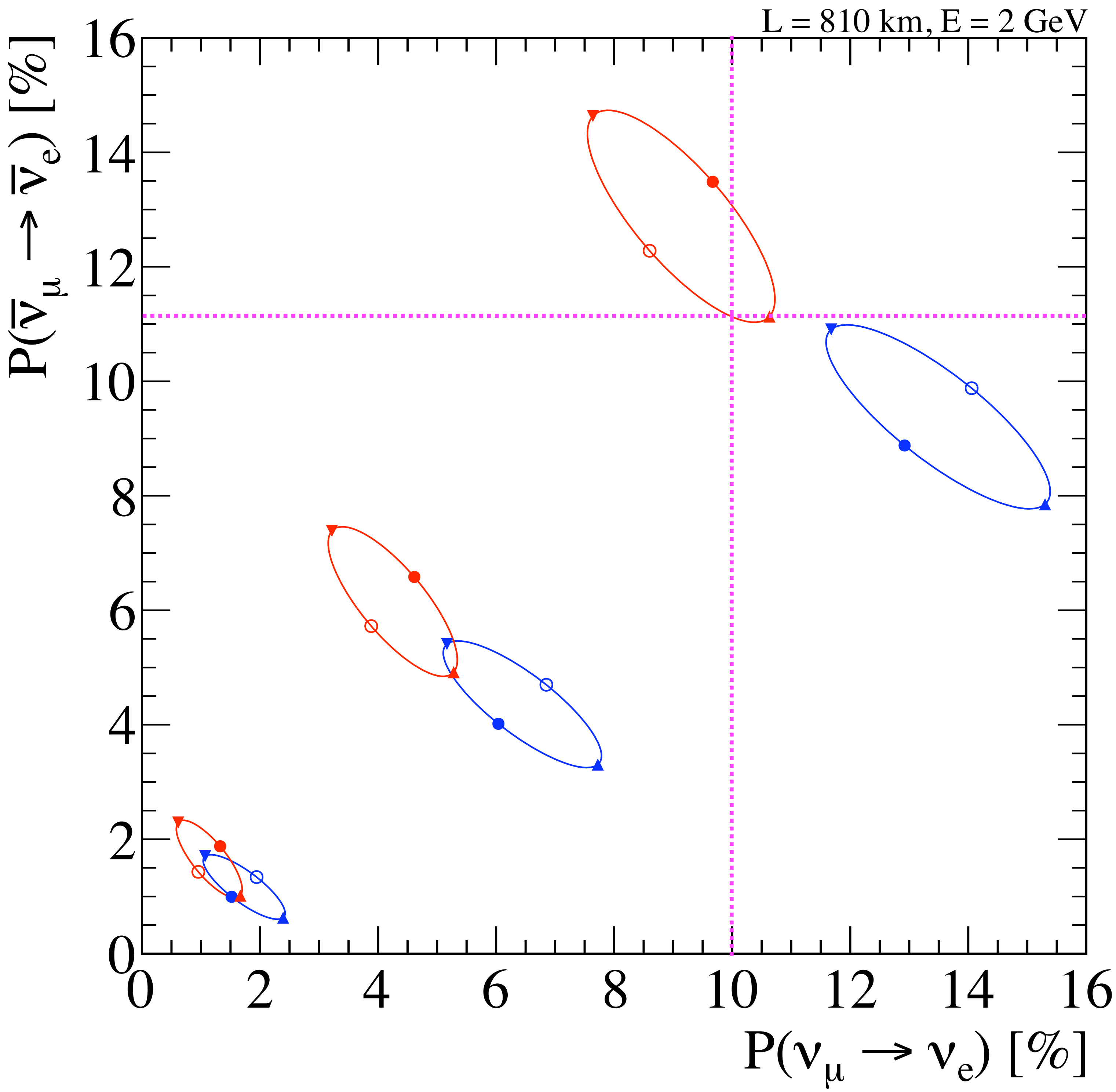

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θ_{13} = 15°, 10°, 5°

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δ_{CP} = 0, ▼π/2, ● π, ▲3π/2, 2π

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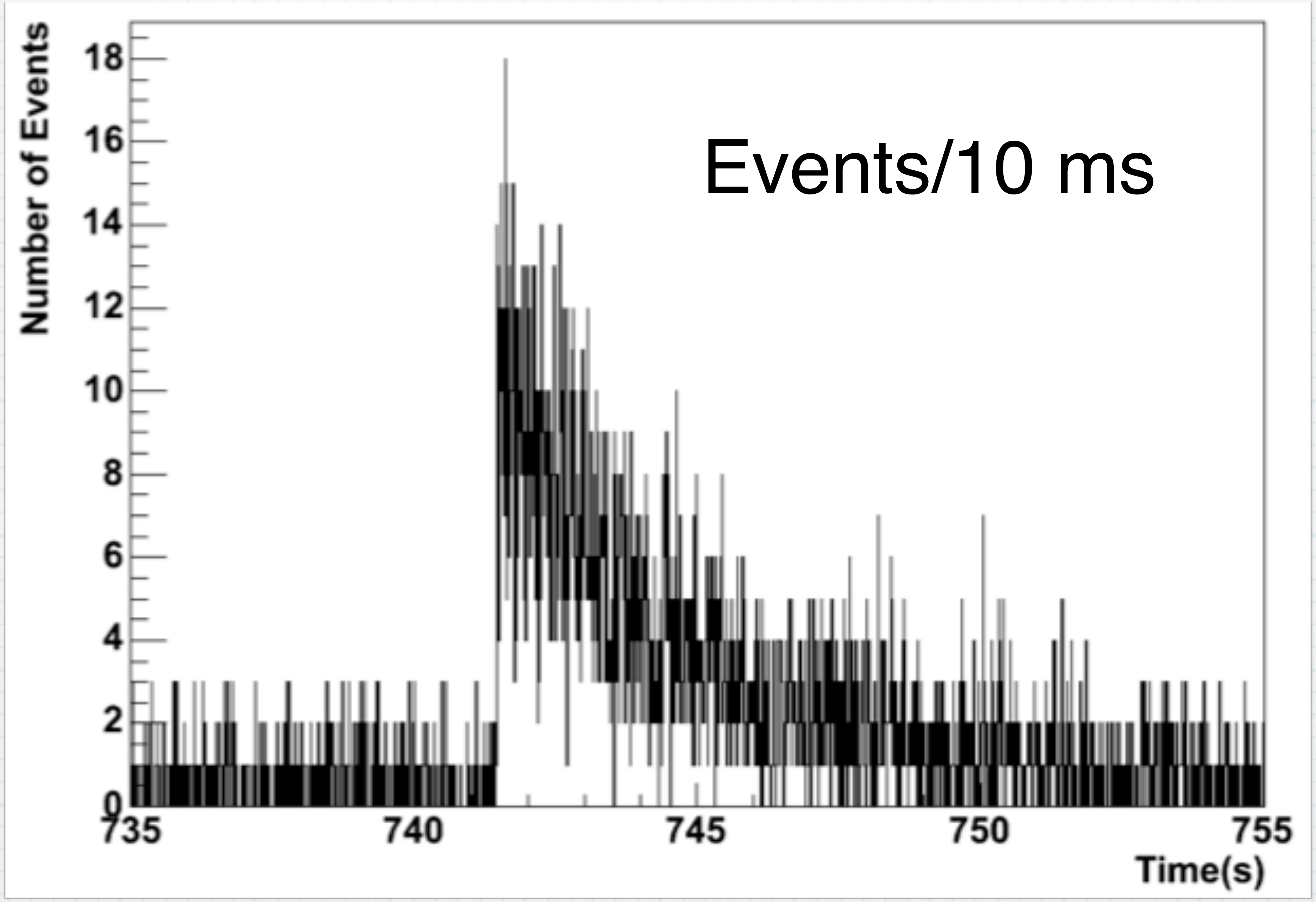
Principle of the NOvA Experiment

Side note: Supernova Signal in NOvA



* NOvA would see ~5000 events for a supernova at the center of the galaxy.
* Plans to build trigger tied into the SNEWS (Supernova Early Warning System).