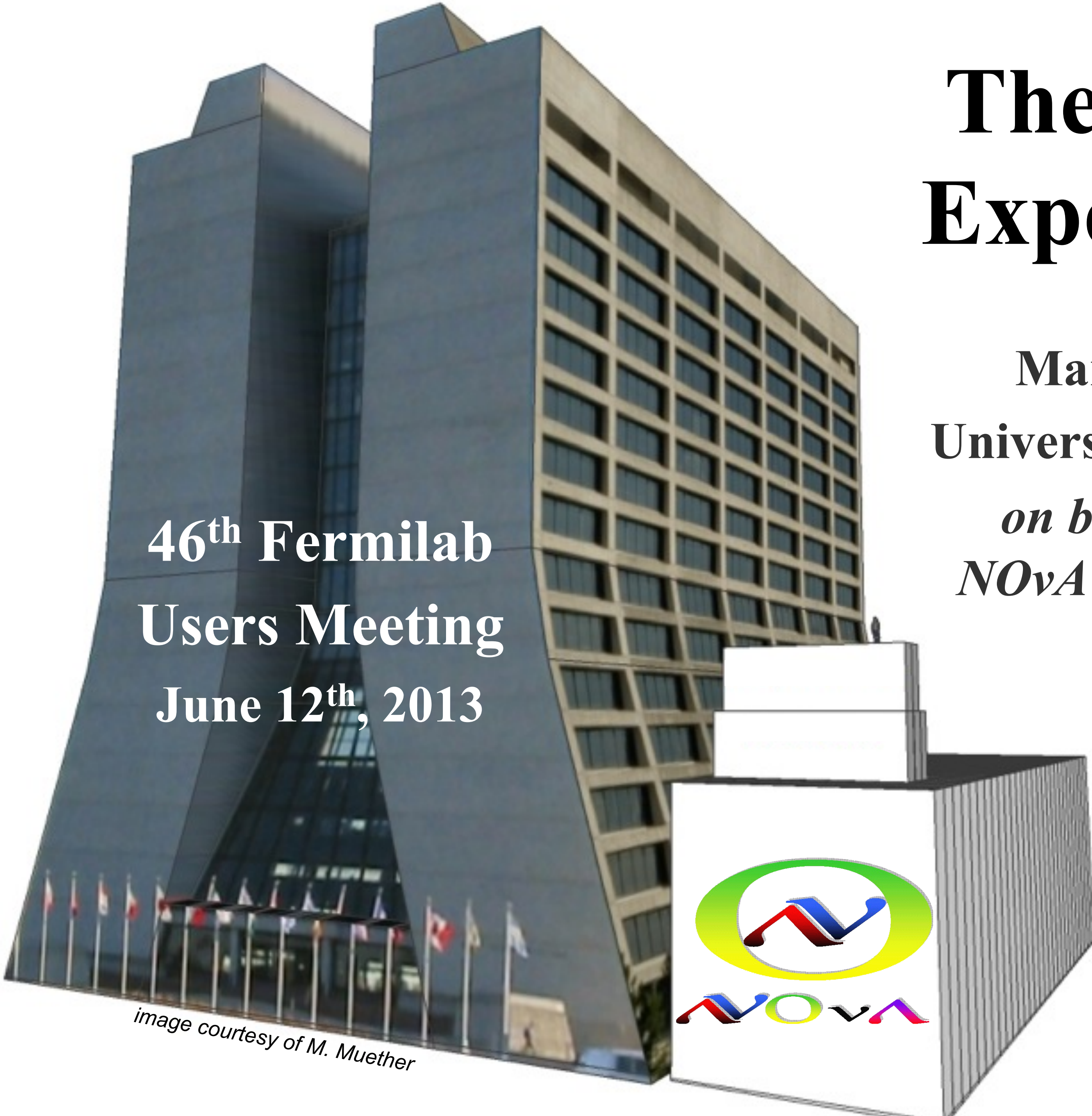
The NOvA Experiment

Martin Frank
University of Virginia
on behalf of the NOvA Collaboration



46th Fermilab Users Meeting
June 12th, 2013

image courtesy of M. Muether

Physics

- NOνA:
  - NuMI: Neutrinos at the Main Injector (ν_μ)
  - Off-Axis: monoenergetic beam (2 GeV)
  - ν_e Appearance

$$P(\nu_\mu \to \nu_e) = f(\theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}, \text{mass hierarchy}, \ldots)$$

- Physics Goals:
  - measure θ_{13}, θ_{23}, Δm^2_{32}
  - resolve θ_{23} octant
  - measure δ_{CP}
    CP-violating phase angle
  - resolve mass hierarchy

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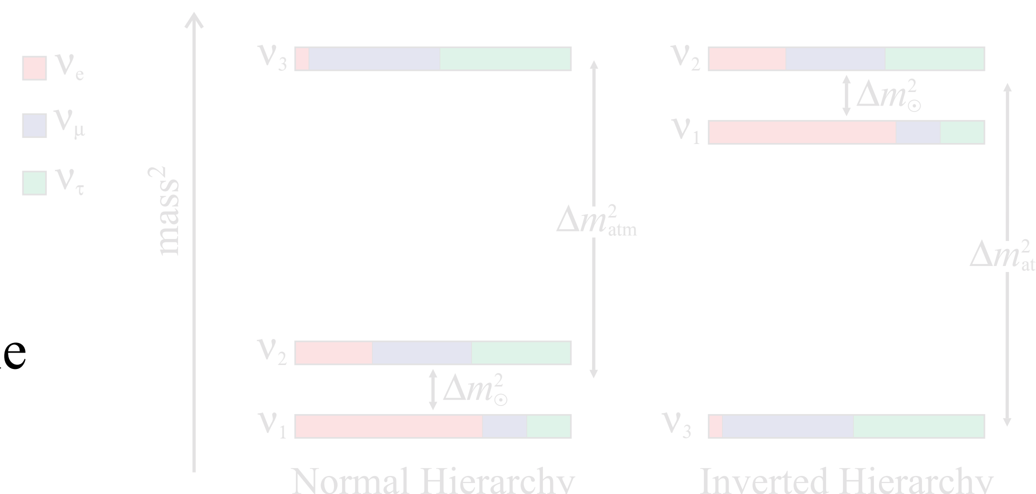

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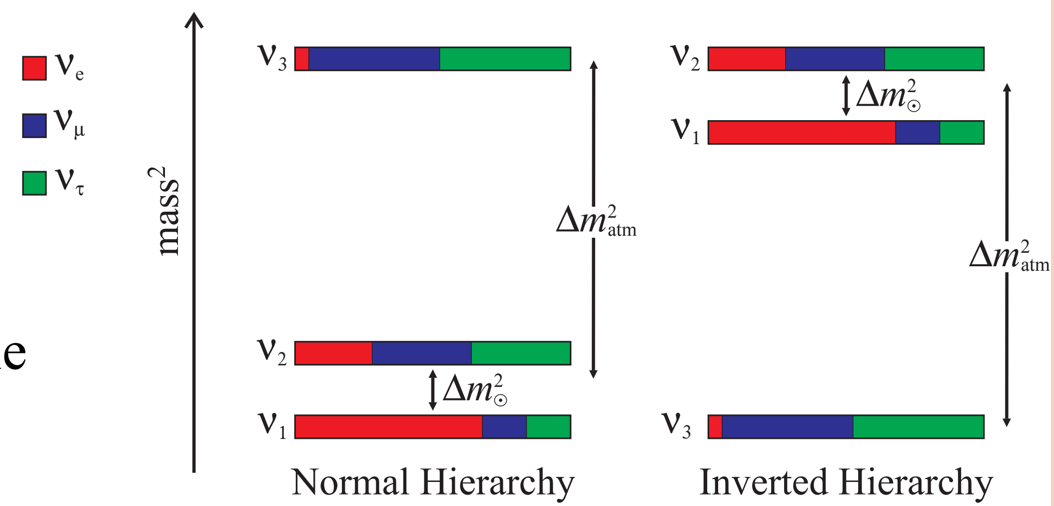
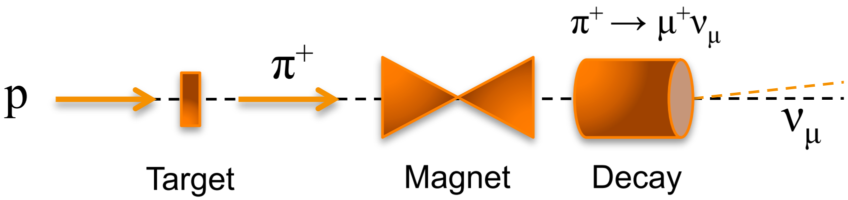
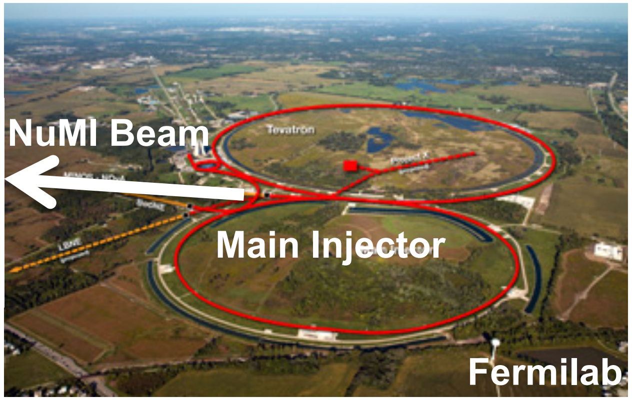
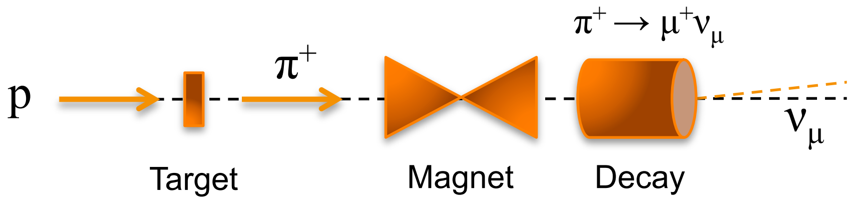






NuMI Beamline

- NuMI: Neutrinos at the Main Injector
- Beam delivered to several neutrino experiments since 2005:
  - MINOS, MINERνA, and ArgoNeut
- Beam upgrade work since May 2012:
  - increase beam power from 300 kW to 700 kW
  - upgrade graphite target and magnetic focusing horns
- **Beam returns at the end of this month (June 2013)!**



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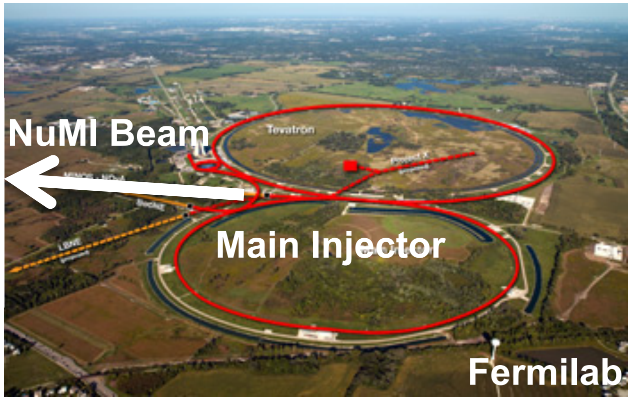

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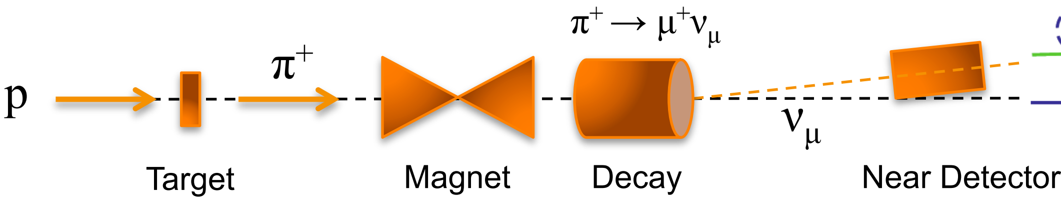
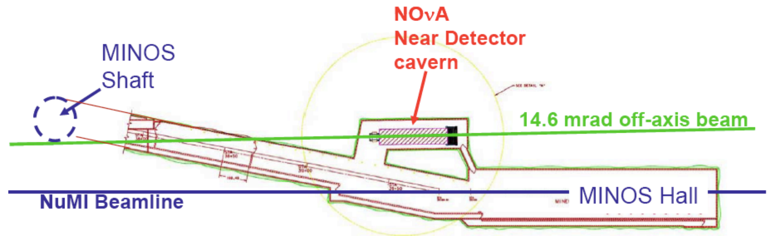
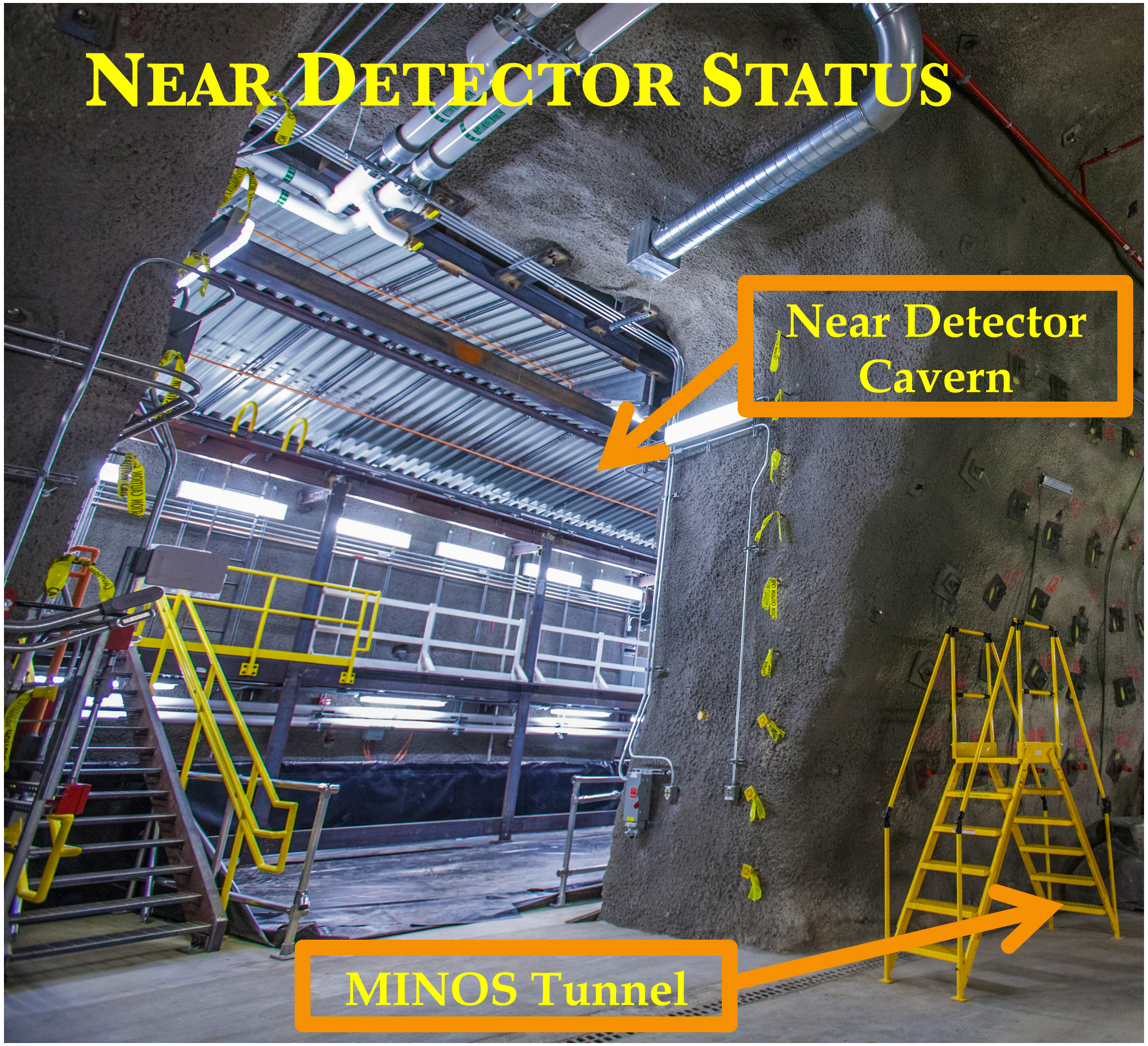
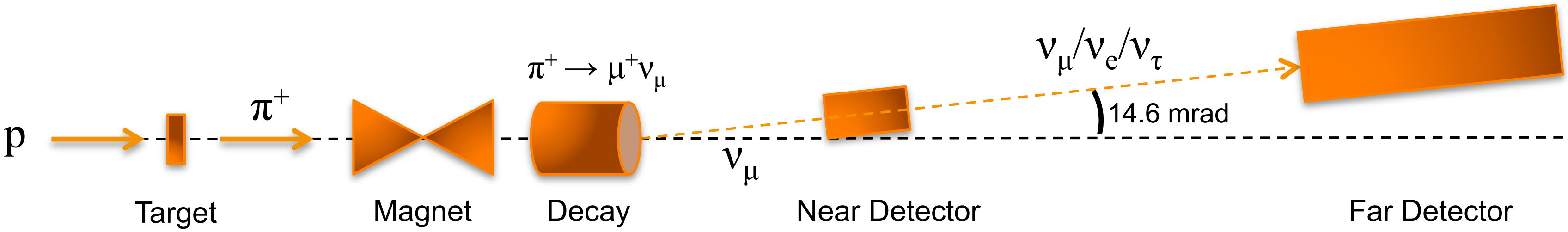
NEAR DETECTOR STATUS







- 105m underground
- Cavern Completed!
- Received Beneficial Occupancy in May.
- Assembly starts this month (June).
- Outfitting during summer and fall.
- Start data taking with half of the detector in December.

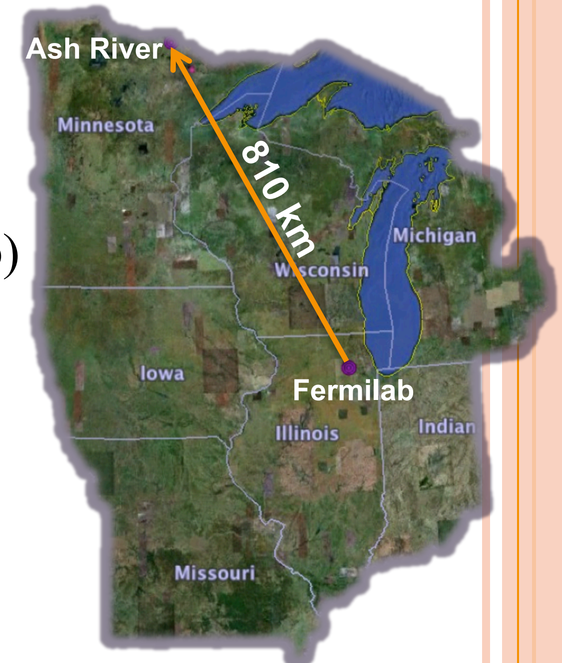


The Beam

Baseline (L = 810 km)

The neutrino beam travels from here (Fermilab) to Ash River, MN through the earth's crust.

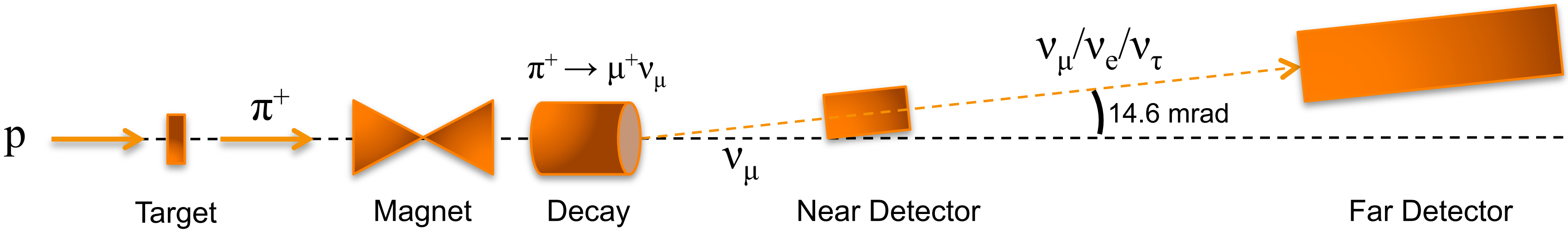
Longest baseline experiment!



Energy (E_ν = 2 GeV)

We can achieve a narrowly distributed neutrino energy by placing the far detector 14.6 mrad off the beam axis.

This is also the $\nu_\mu \rightarrow \nu_e$ oscillation peak.



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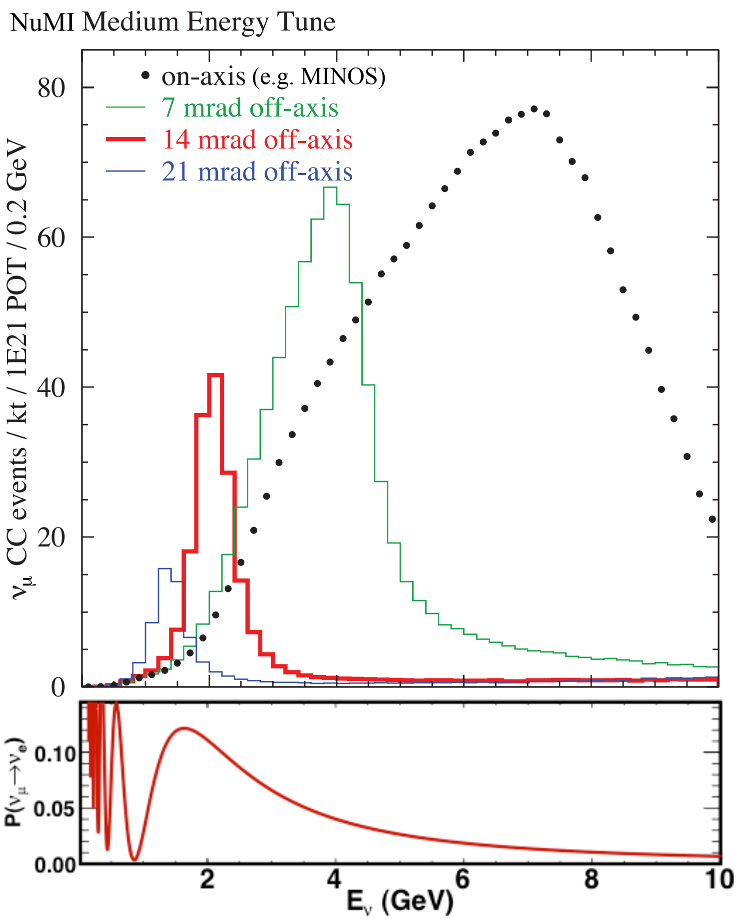

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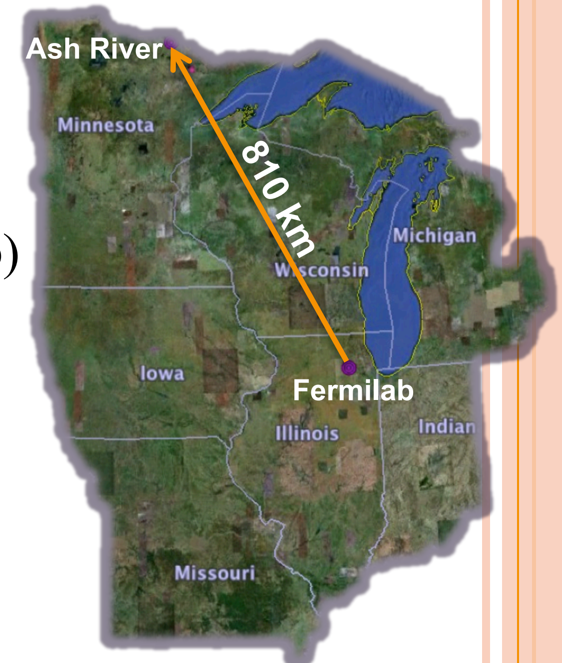

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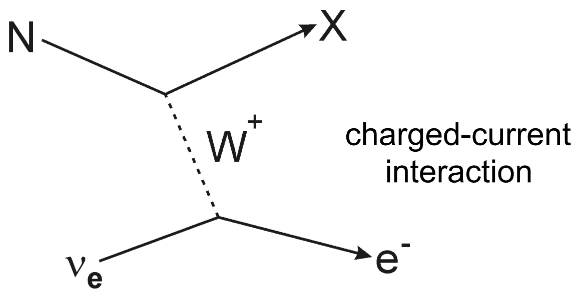
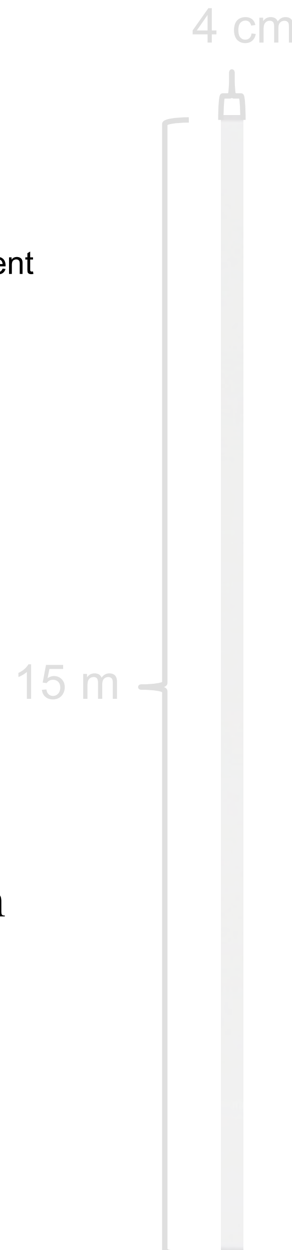


- We want to detect weakly-interacting electron neutrinos (ν_e).
- This requires:
  - large detector mass
  - good electromagnetic (EM) shower resolution

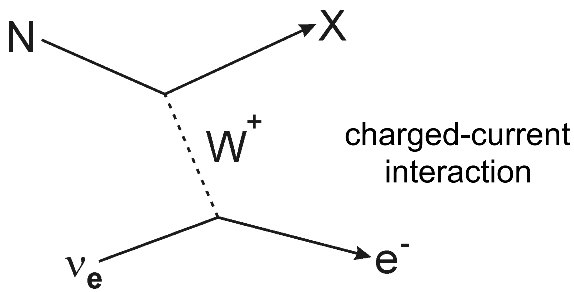


"Fully" Active Detector

- PVC extrusions (long tubes)
- filled with liquid scintillator
- provide a radiation length of ~ 40 cm.
- 2 GeV muon travels 10 m!
- Each extrusion contains one loop of wavelength-shifting fiber.

1 Channel

DETECTOR



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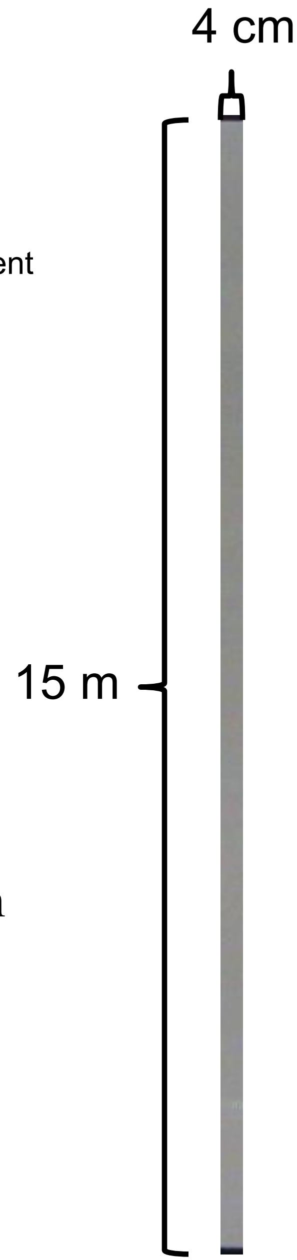

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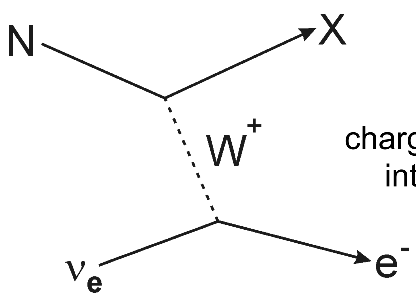

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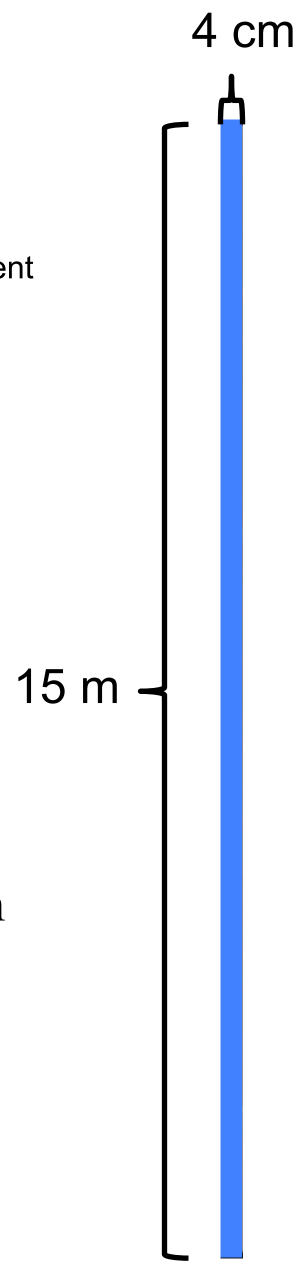

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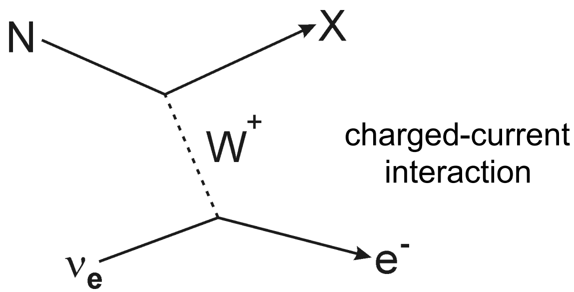

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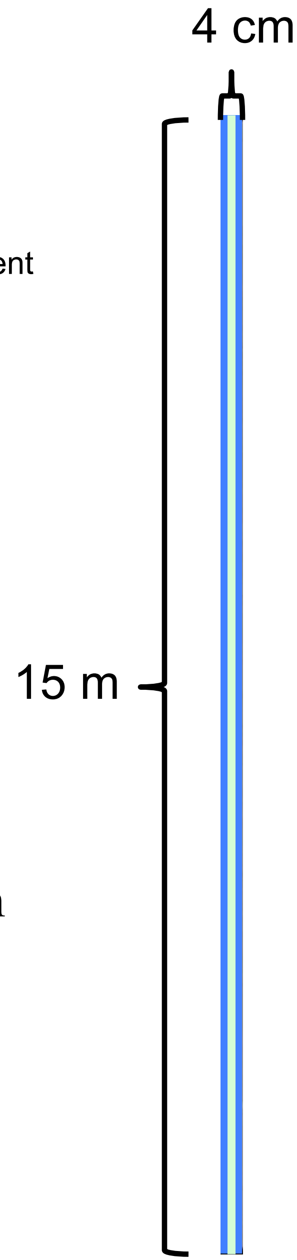

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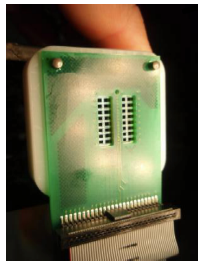
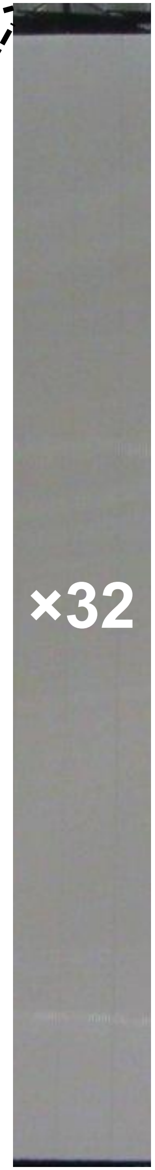


Avalanche Photo-Diode

15 m

32 channels → 1 module

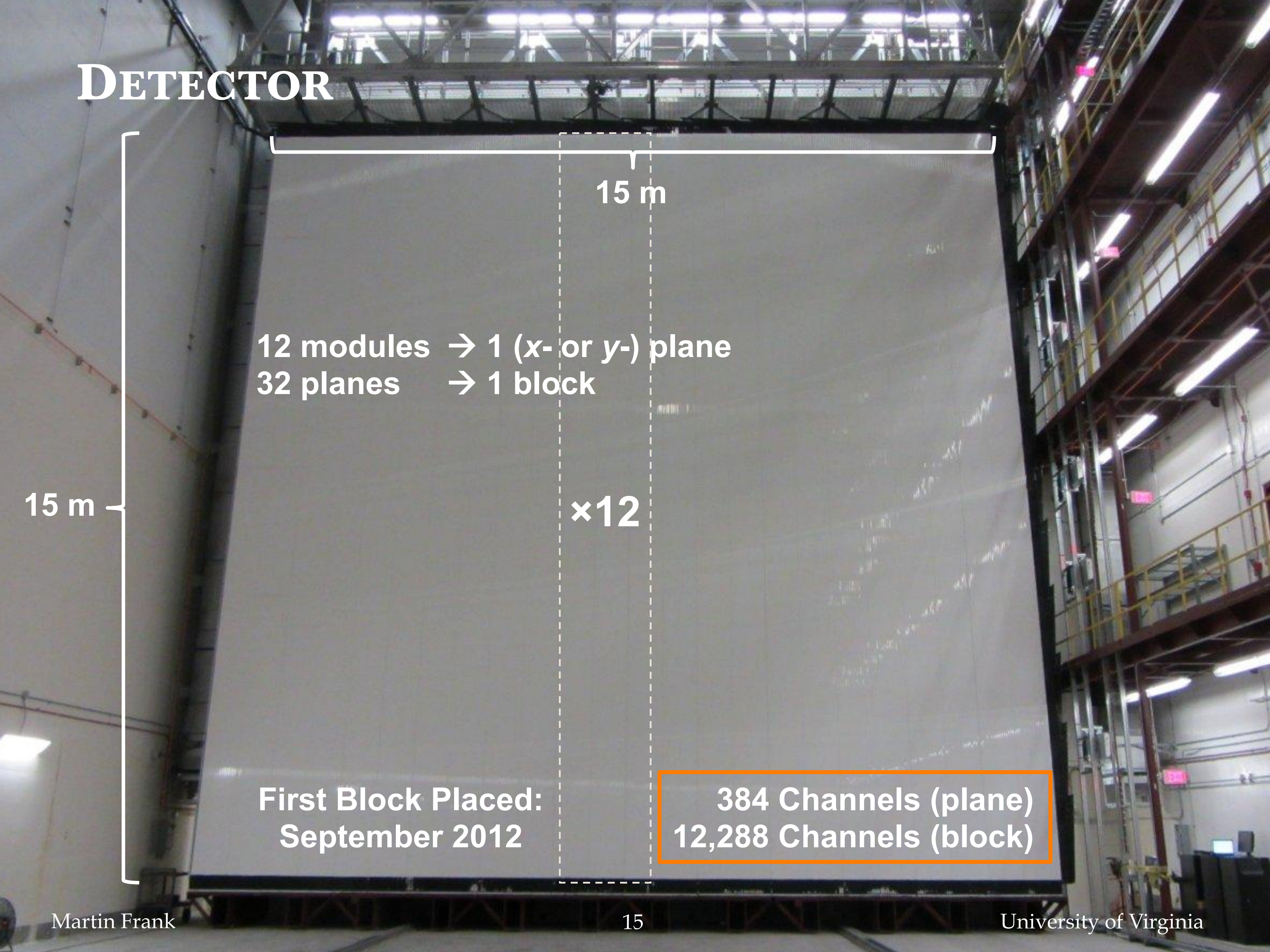


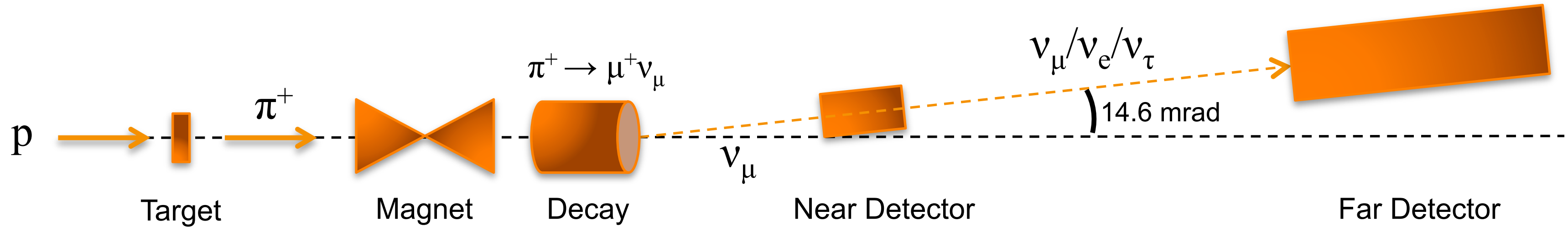
"Fully" Active Detector

- PVC extrusions (long tubes)
- filled with liquid scintillator
- provide a radiation length of ~ 40 cm.
- 2 GeV muon travels 10 m!
- Each extrusion contains one loop of wavelength-shifting fiber.
- 32 channels are read out by one avalanche photo-diode (APD).

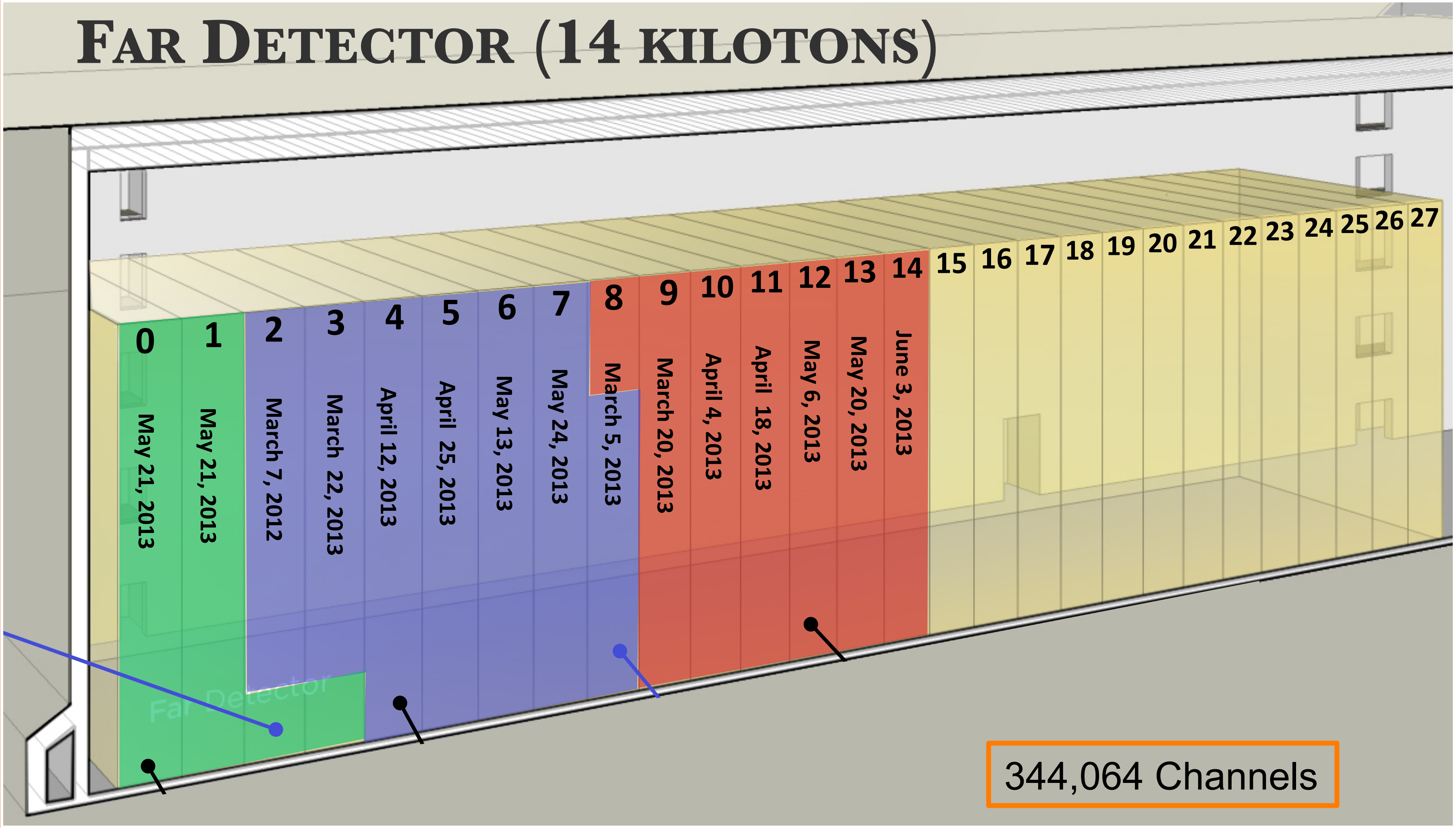
32 Channels

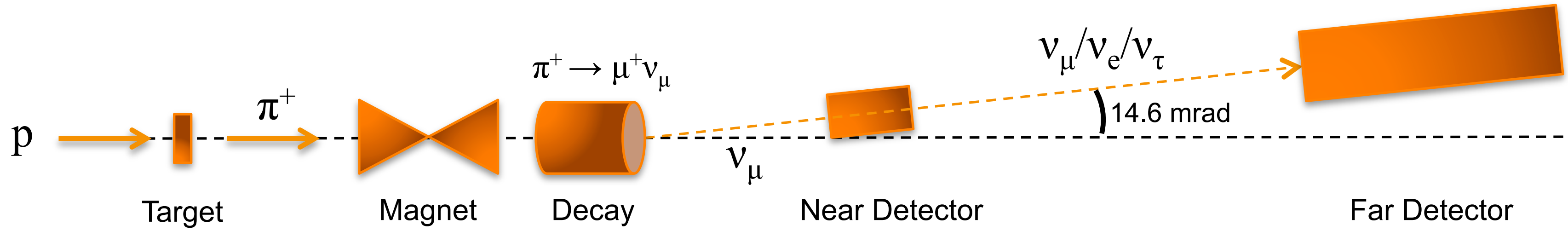
DETECTOR


15 m
15 m
12 modules → 1 (*x*- or *y*-) plane
32 planes → 1 block
×12
First Block Placed:
September 2012
384 Channels (plane)
12,288 Channels (block)



Far Detector (14 kilotons)





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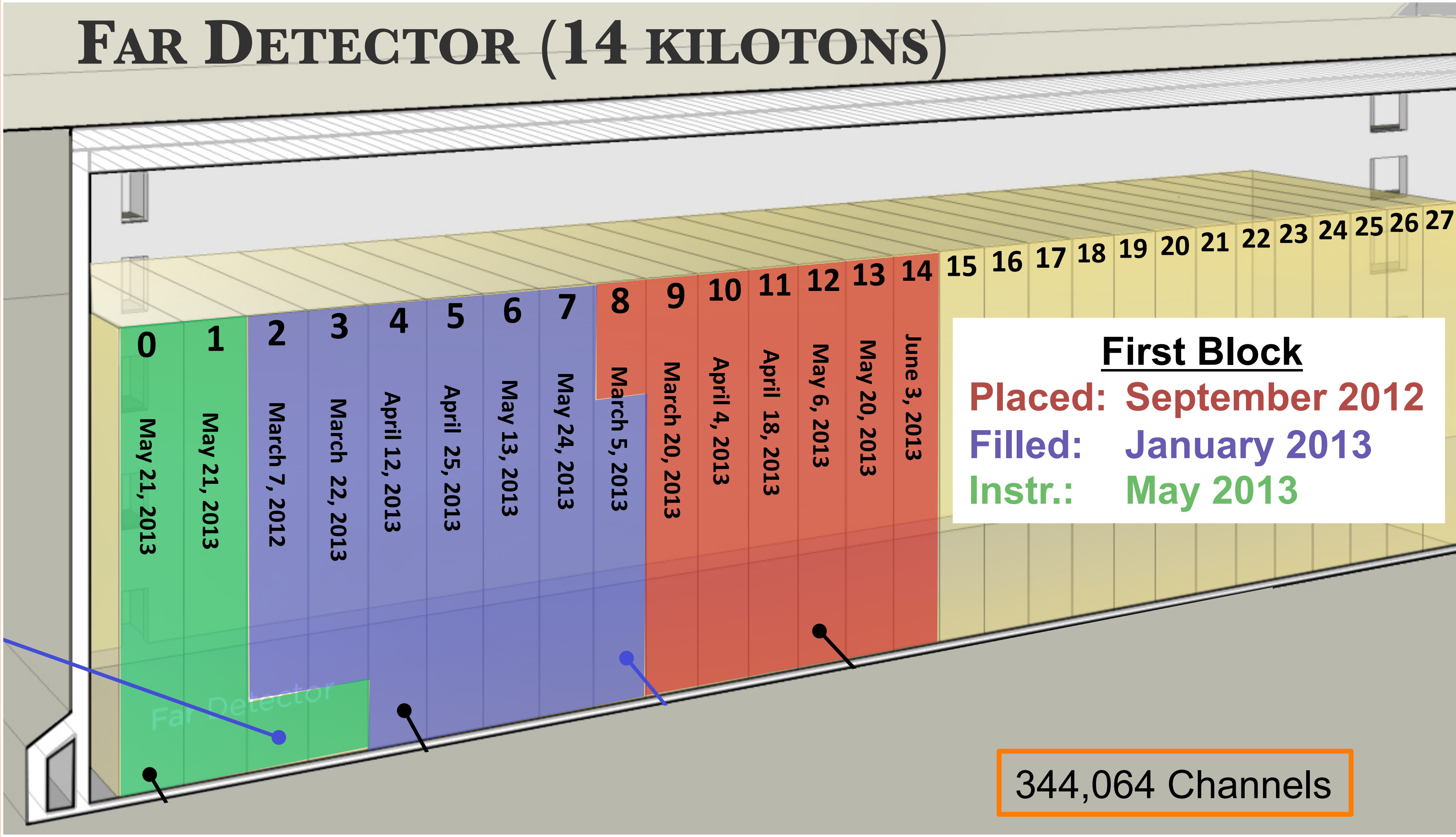
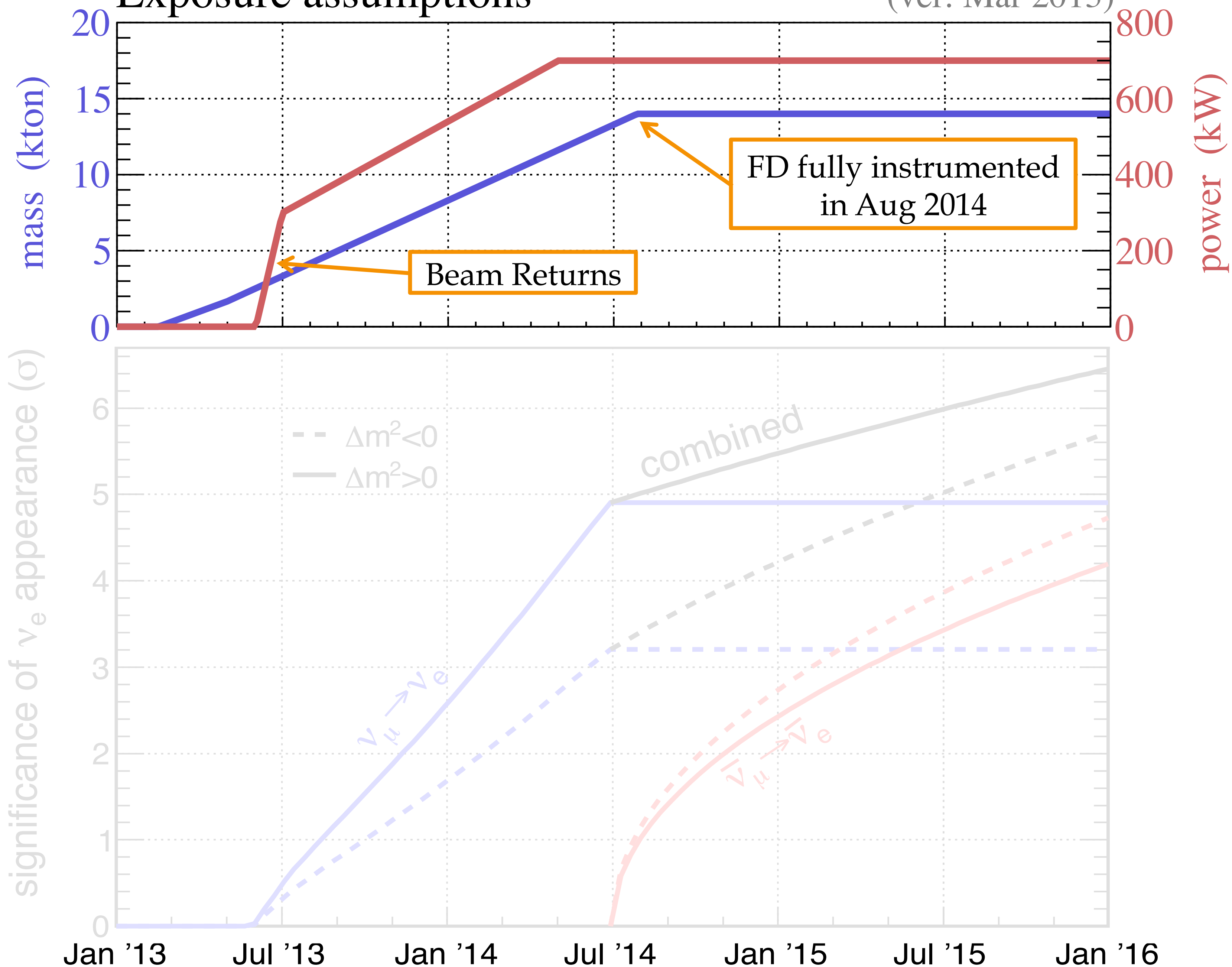


Exposure assumptions

(ver: Mar 2013)



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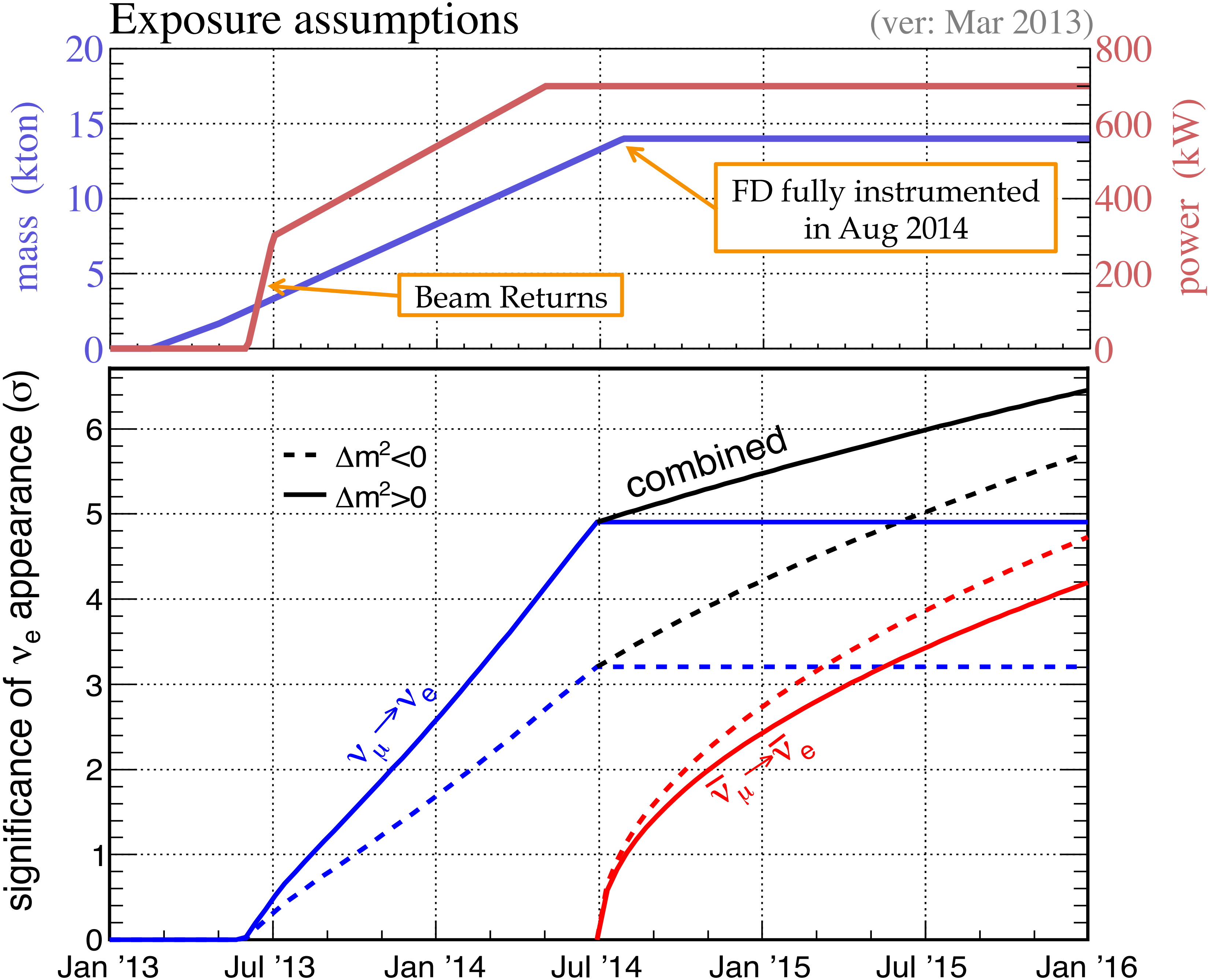

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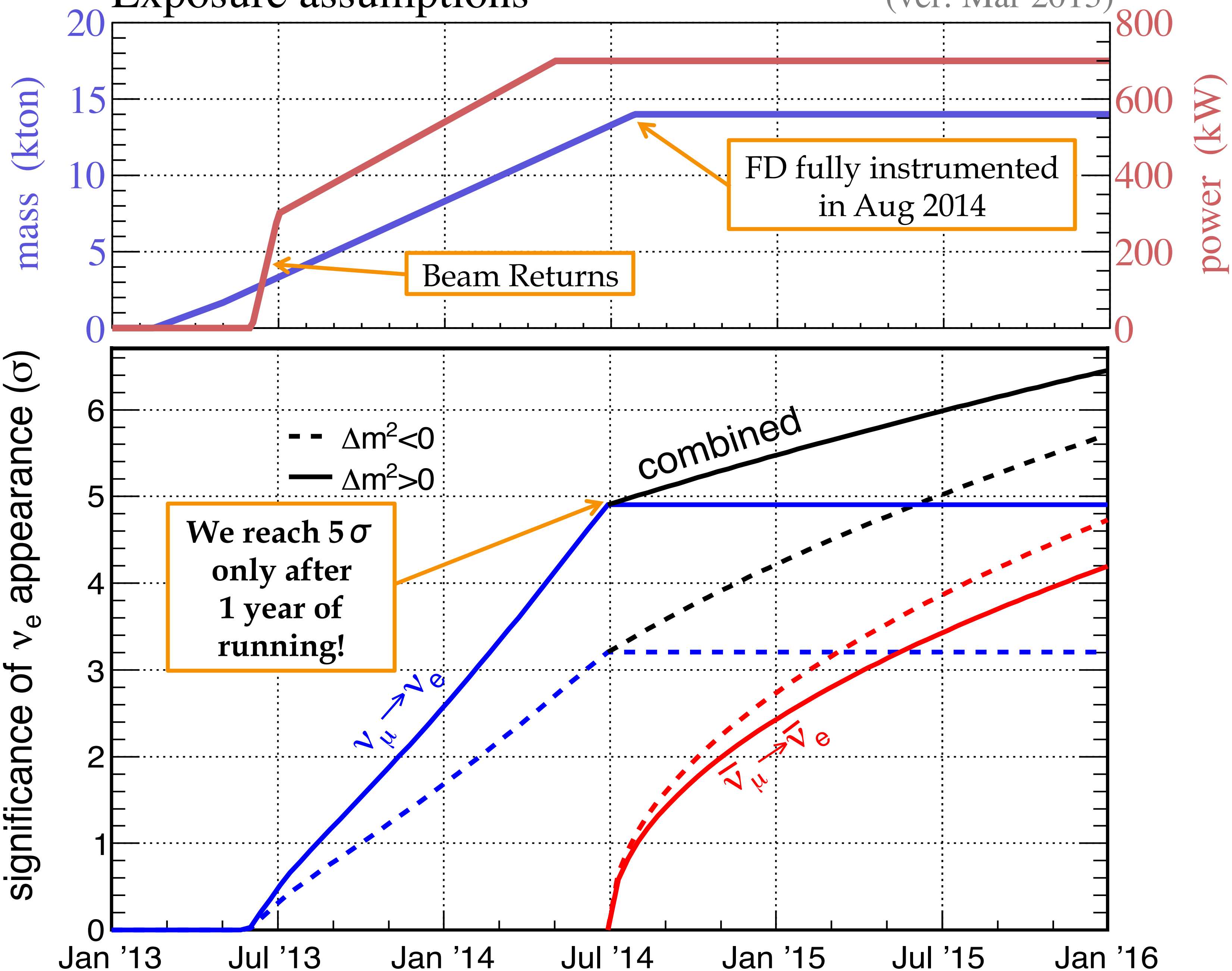

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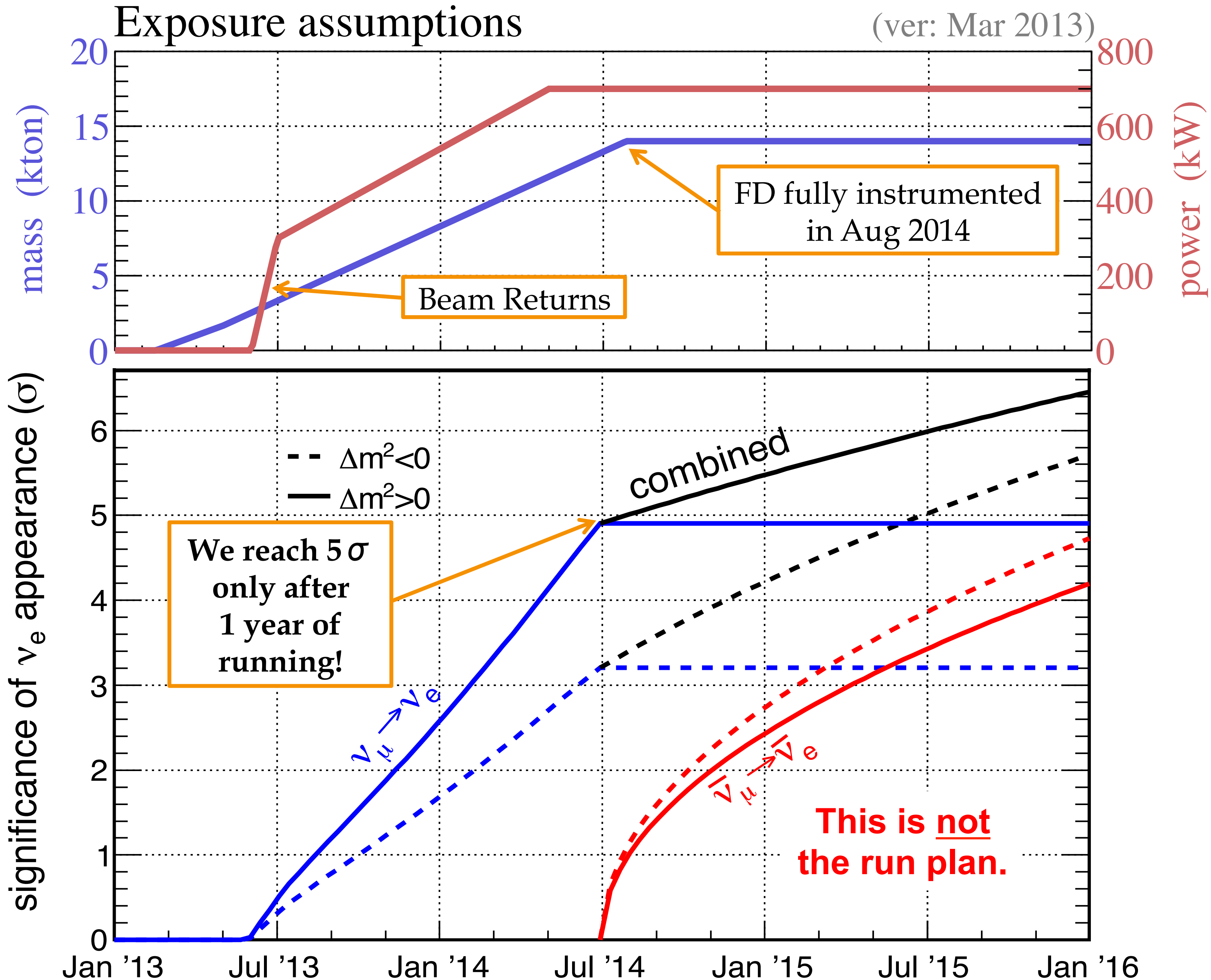
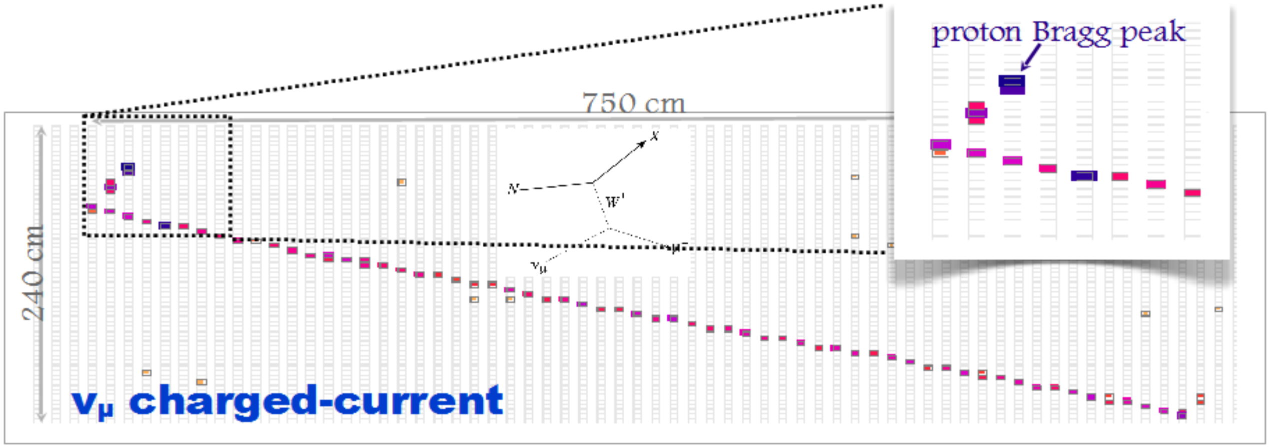
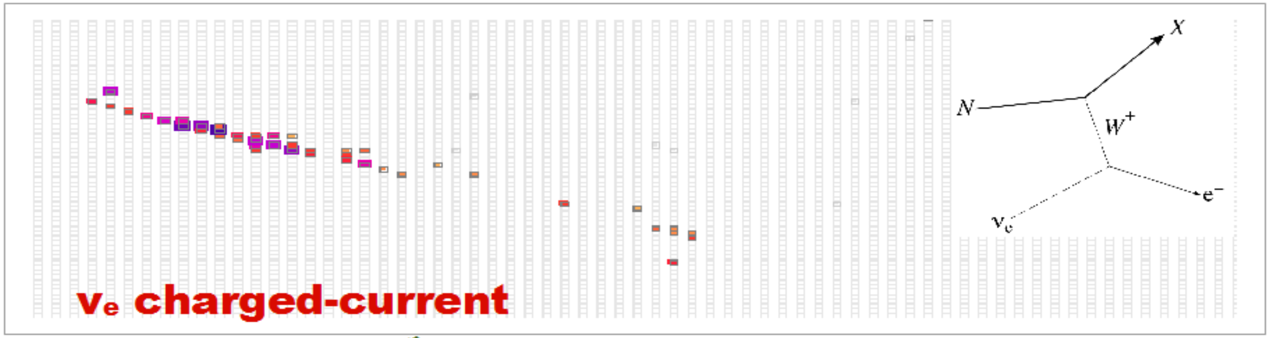


Simulated Event Signatures



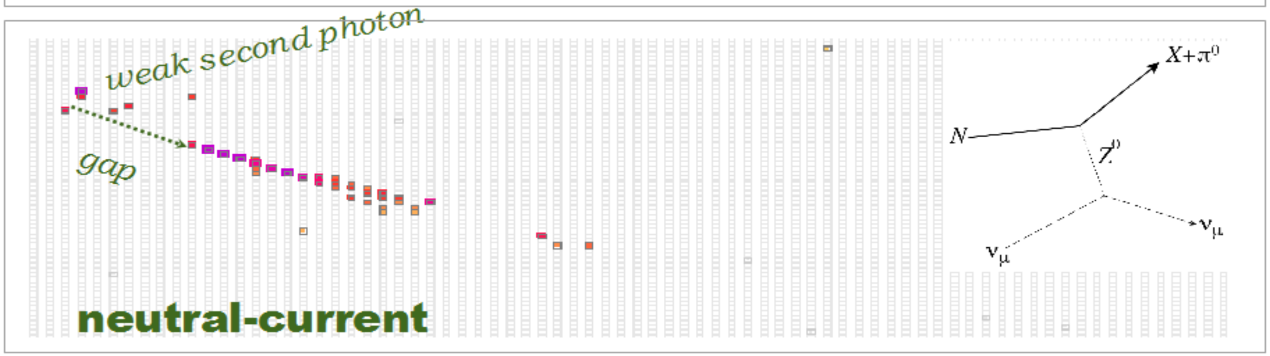
ν_μ charged-current

- ✓ long muon track
- ✓ short proton track



ν_e charged-current

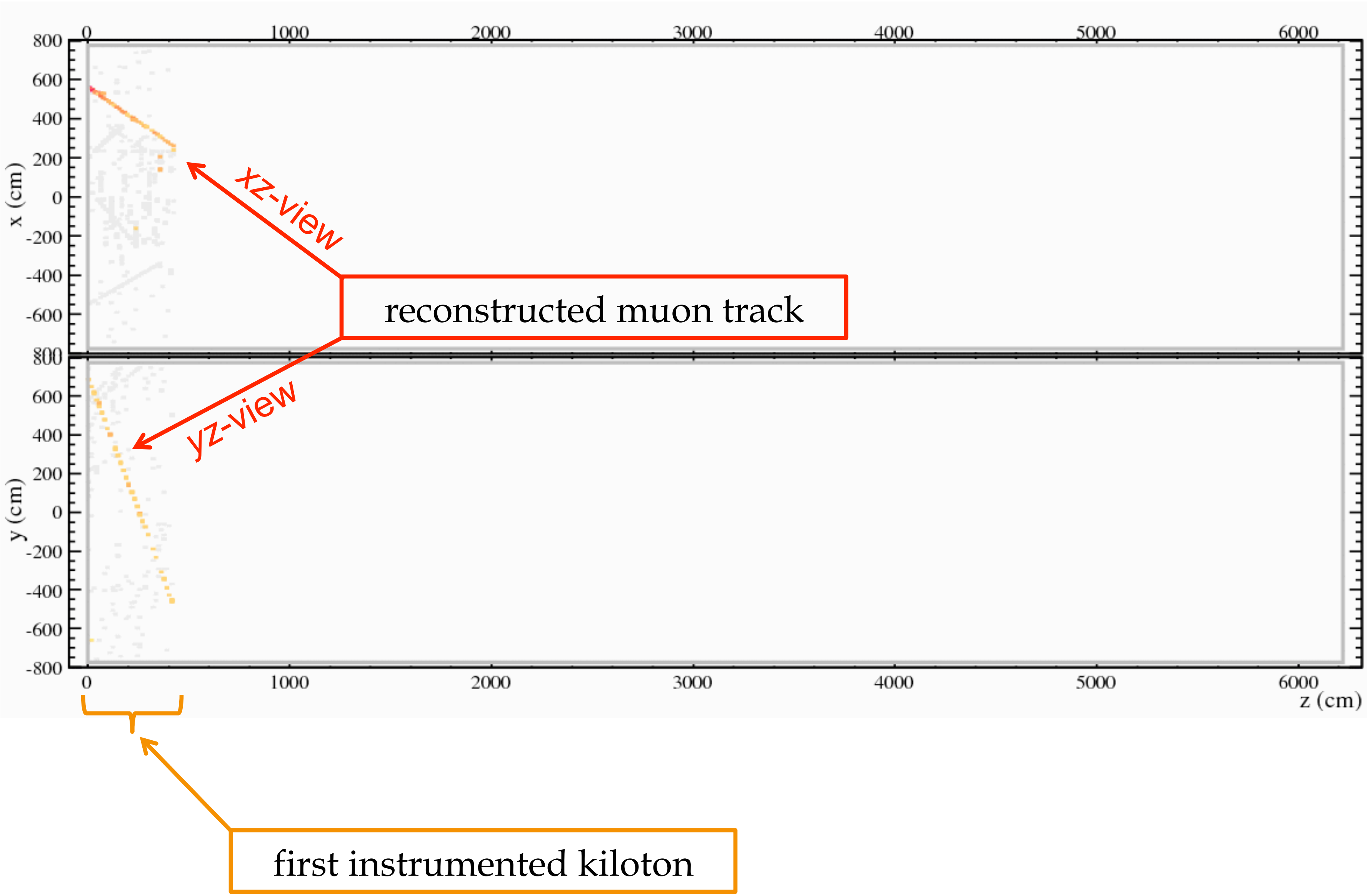
- ✓ single EM shower



neutral-current with π^0 final state

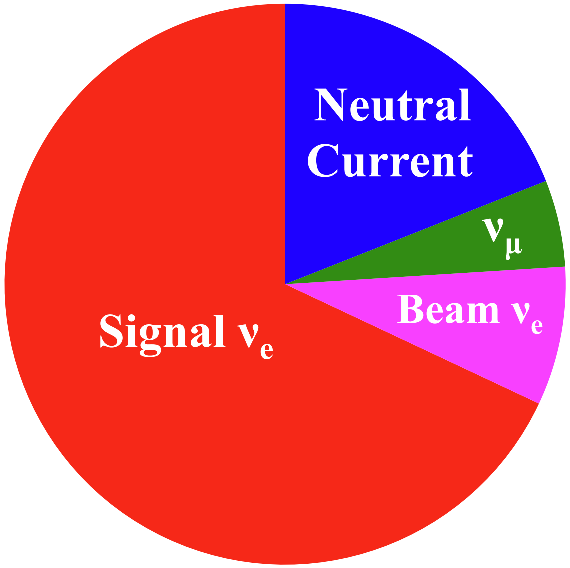
- ✓ multiple EM showers
- ✓ gaps near vertex

First Far Detector Cosmic Ray Data



ν_e SELECTION

- 3 years of running in neutrino mode:



Backgrounds

- We designed a suite of particle ID techniques:
  - ANN: Likelihood ratios for particle hypotheses.
  - LEM: Matching to MC library events.
  - BDT: Boosted decision tree on simple reconstructed quantities.
- The plots on the right show promising ν_e signal/background separation.

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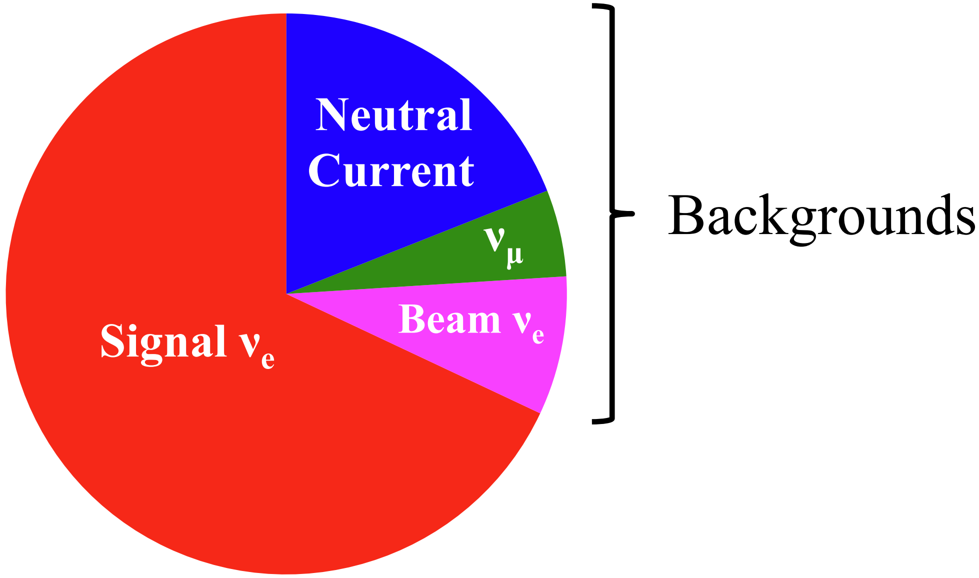

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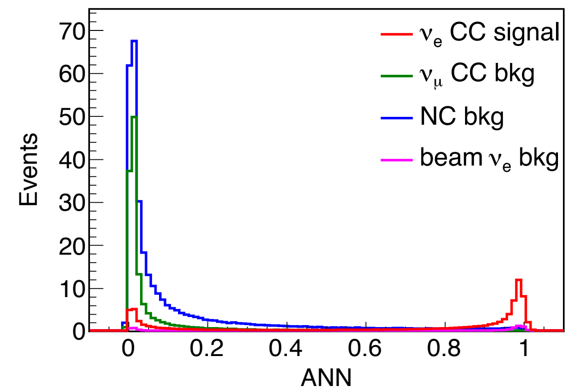

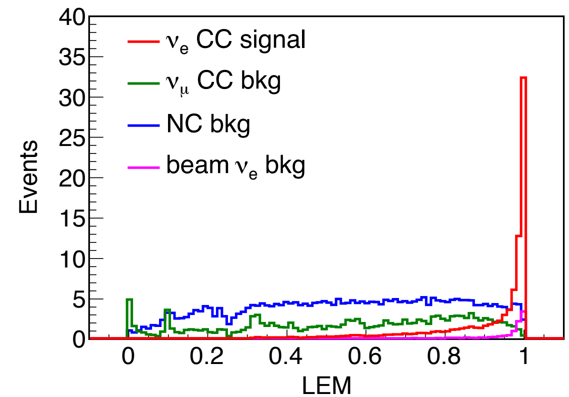

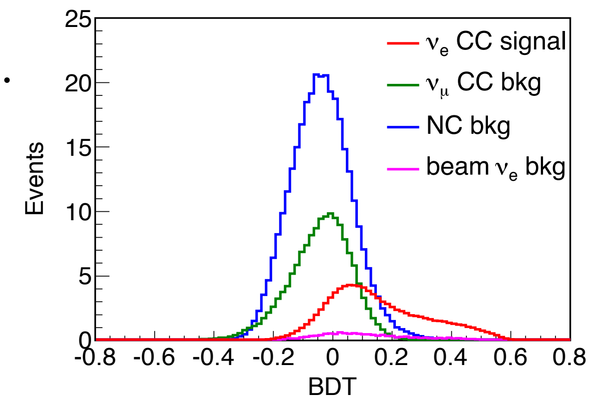

Extracting Nature's Parameters

$$P(\nu_\mu \to \nu_e) \quad P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})f^{\pm}(L, E, \Delta m^2_{31})$$

$$+ \{\cos\delta_{CP}\cos\frac{\Delta m^2_{31}L}{4E} \mp \sin\delta_{CP}\sin\frac{\Delta m^2_{31}L}{4E}\}$$

$$\times\ 2\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin(\theta_{13})g^{\pm}(L, E, \Delta m^2_{31}, \theta_{12}, \theta_{23})$$

± neutrino mode

∓ anti-neutrino mode

- The **NOvA baseline** (L = 810 km) and **neutrino beam energy** (E = 2 GeV) place our detector at the first $\nu_\mu \rightarrow \nu_e$ oscillation peak.
- **$\sin^2 2\theta_{13}$**: the leading term in this equation has already been measured and it is large!
- **$\sin^2\theta_{23}$**: we can glean information about the θ_{23} octant from the leading term.
- **δ_{CP}**: using the measured value of θ_{13}, we can determine the CP-violating phase angle.
- **mass hierarchy**: depending on the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$, the oscillation probability is either enhanced or suppressed. This difference can be determined by comparing neutrino running with anti-neutrino running.

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$$+ \left\{\cos\delta_{CP}\cos\frac{\Delta m^2_{31}L}{4E} \mp \sin\delta_{CP}\sin\frac{\Delta m^2_{31}L}{4E}\right\}$$

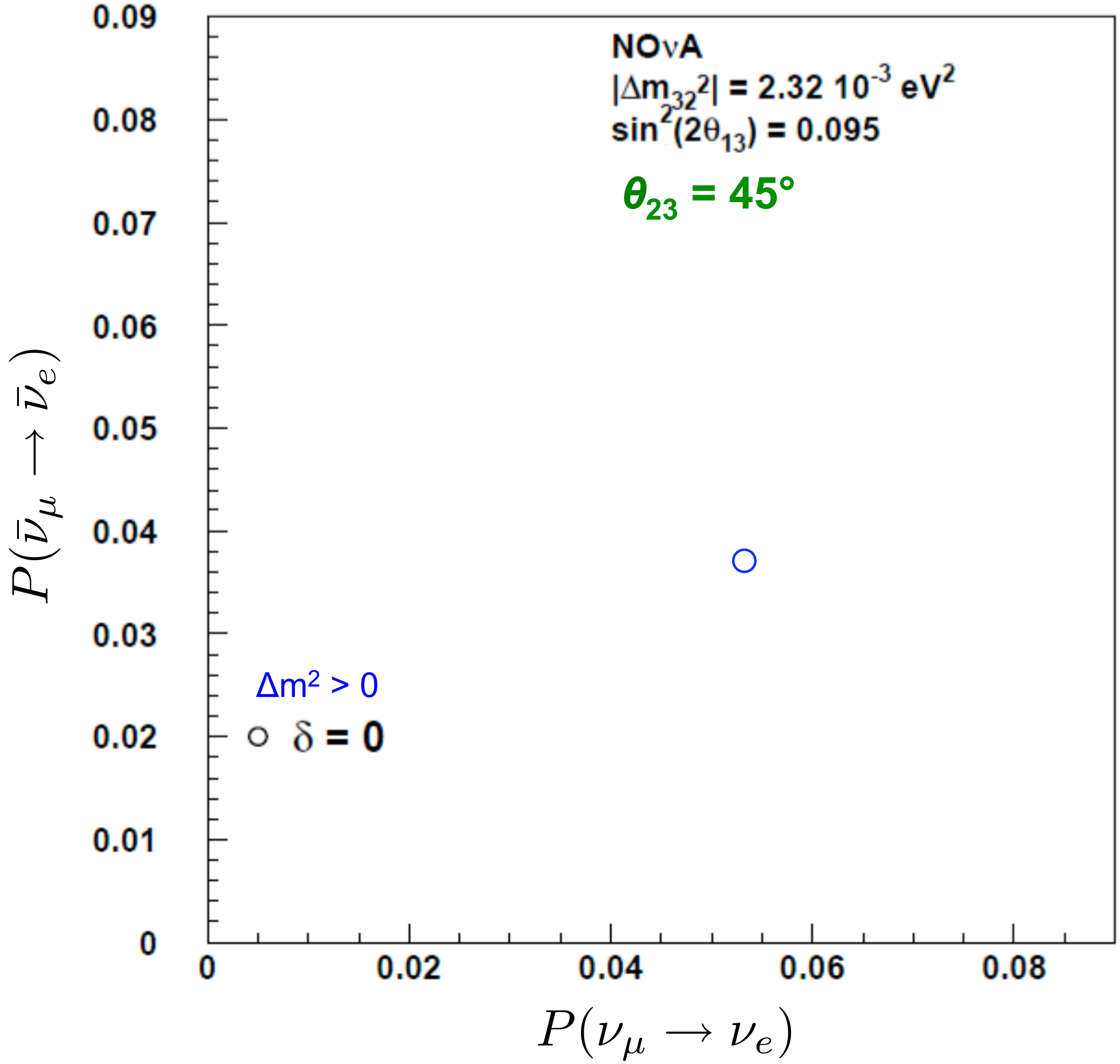
$$\times\ 2\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin(\theta_{13})g^{\pm}(L, E, \Delta m^2_{31}, \theta_{12}, \theta_{23})$$

± neutrino mode

± anti-neutrino mode

- The **NOνA baseline** (L = 810 km) and **neutrino beam energy** (E = 2 GeV) place our detector at the first $\nu_\mu \to \nu_e$ oscillation peak.
- **$\sin^2 2\theta_{13}$**: the leading term in this equation has already been measured and it is large!
- **$\sin^2\theta_{23}$**: we can glean information about the θ_{23} octant from the leading term.
- **δ_{CP}**: using the measured value of θ_{13}, we can determine the CP-violating phase angle.
- **mass hierarchy**: depending on the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$, the oscillation probability is either enhanced or suppressed. This difference can be determined by comparing neutrino running with anti-neutrino running.

PHYSICS REACH (BI-PROBABILITY PLOTS)



- Using the previous equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

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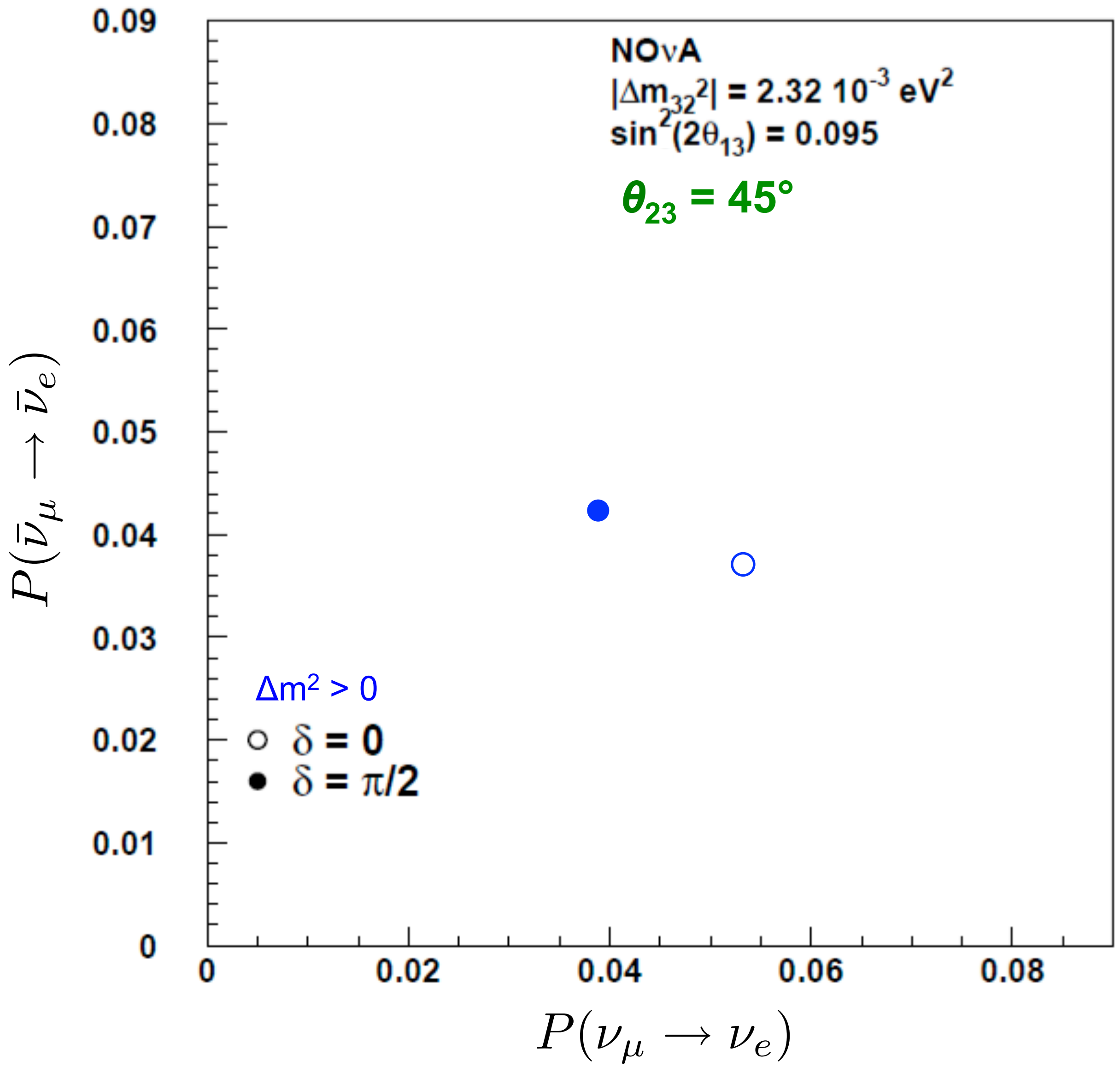

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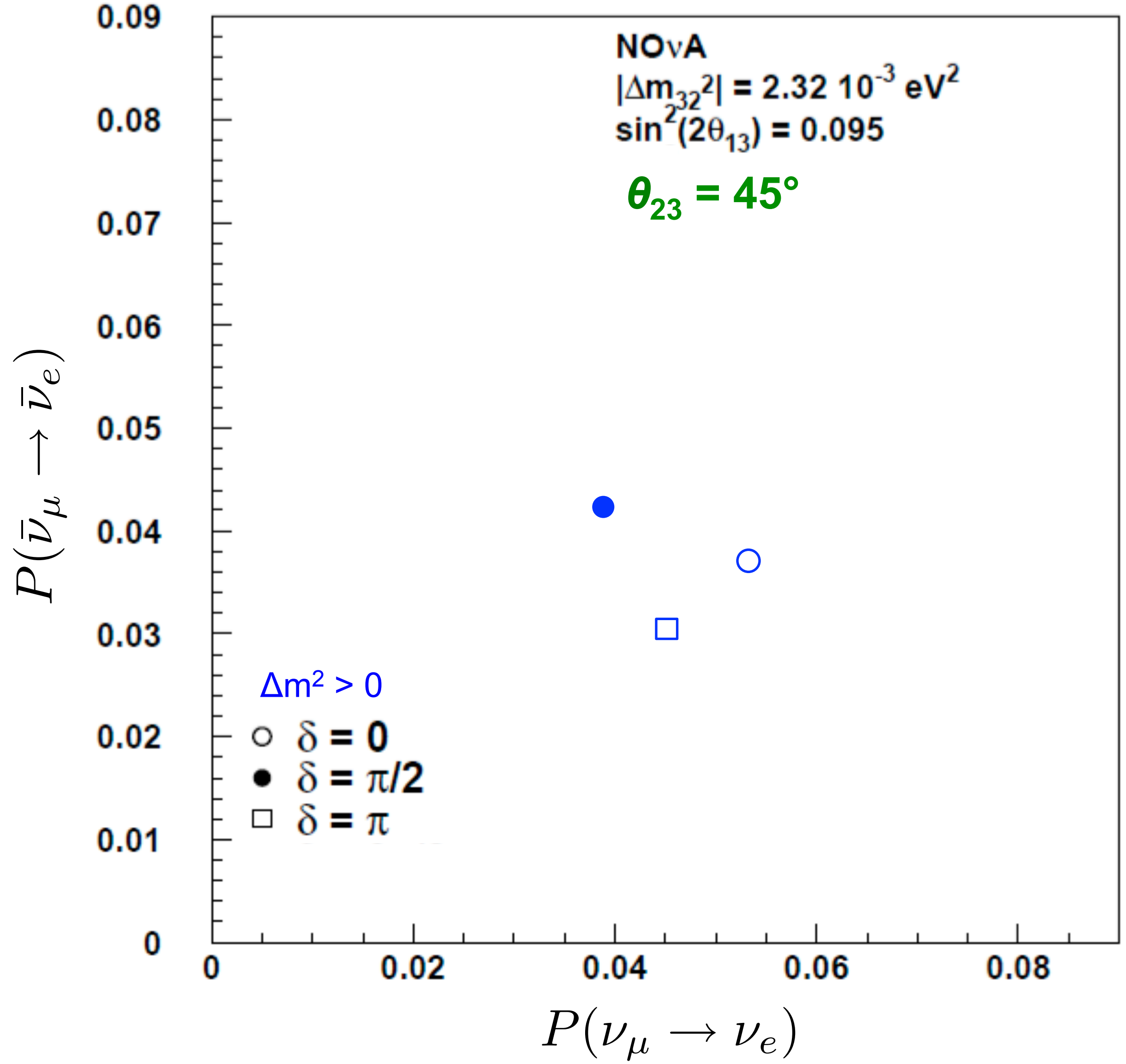

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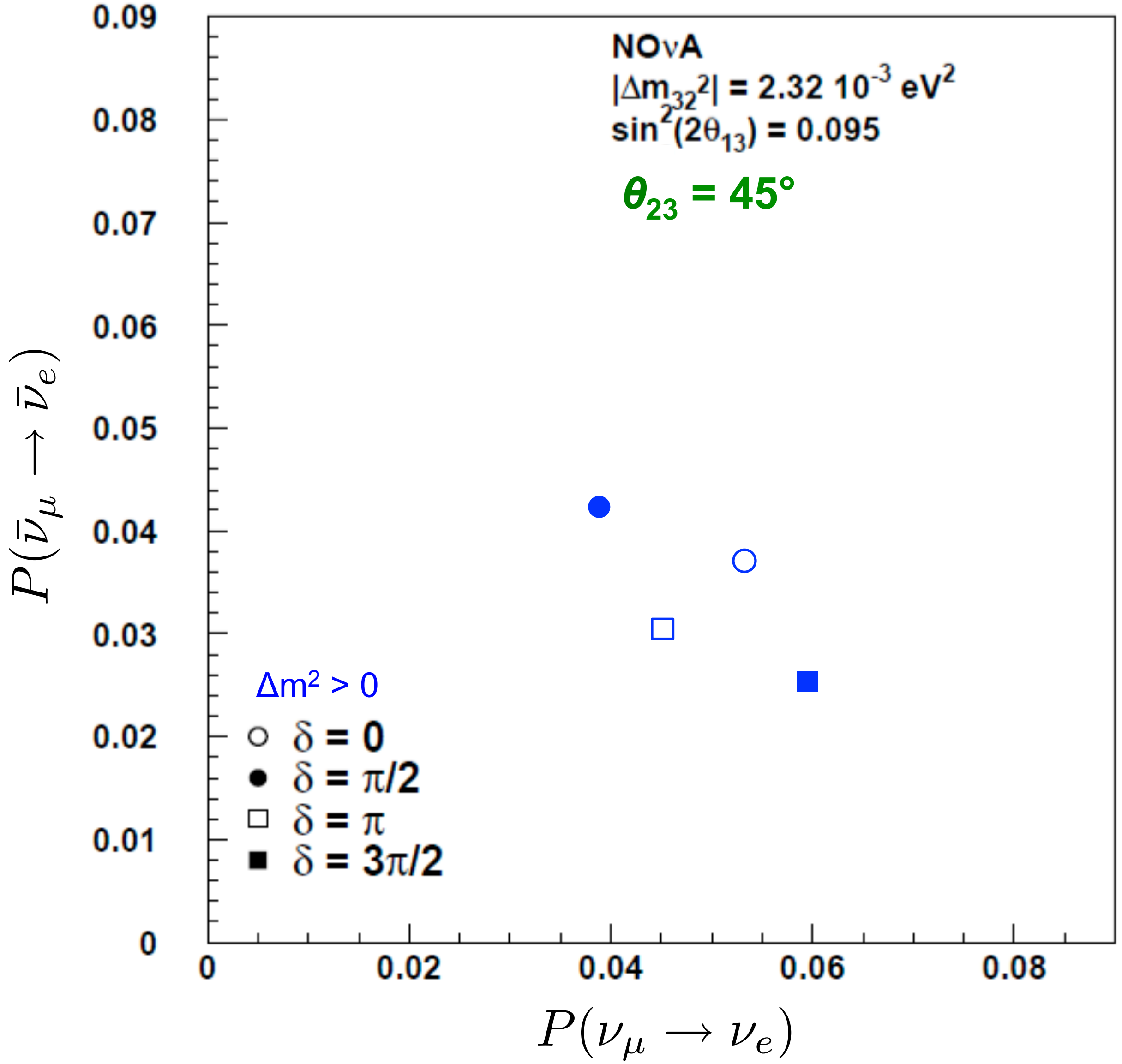

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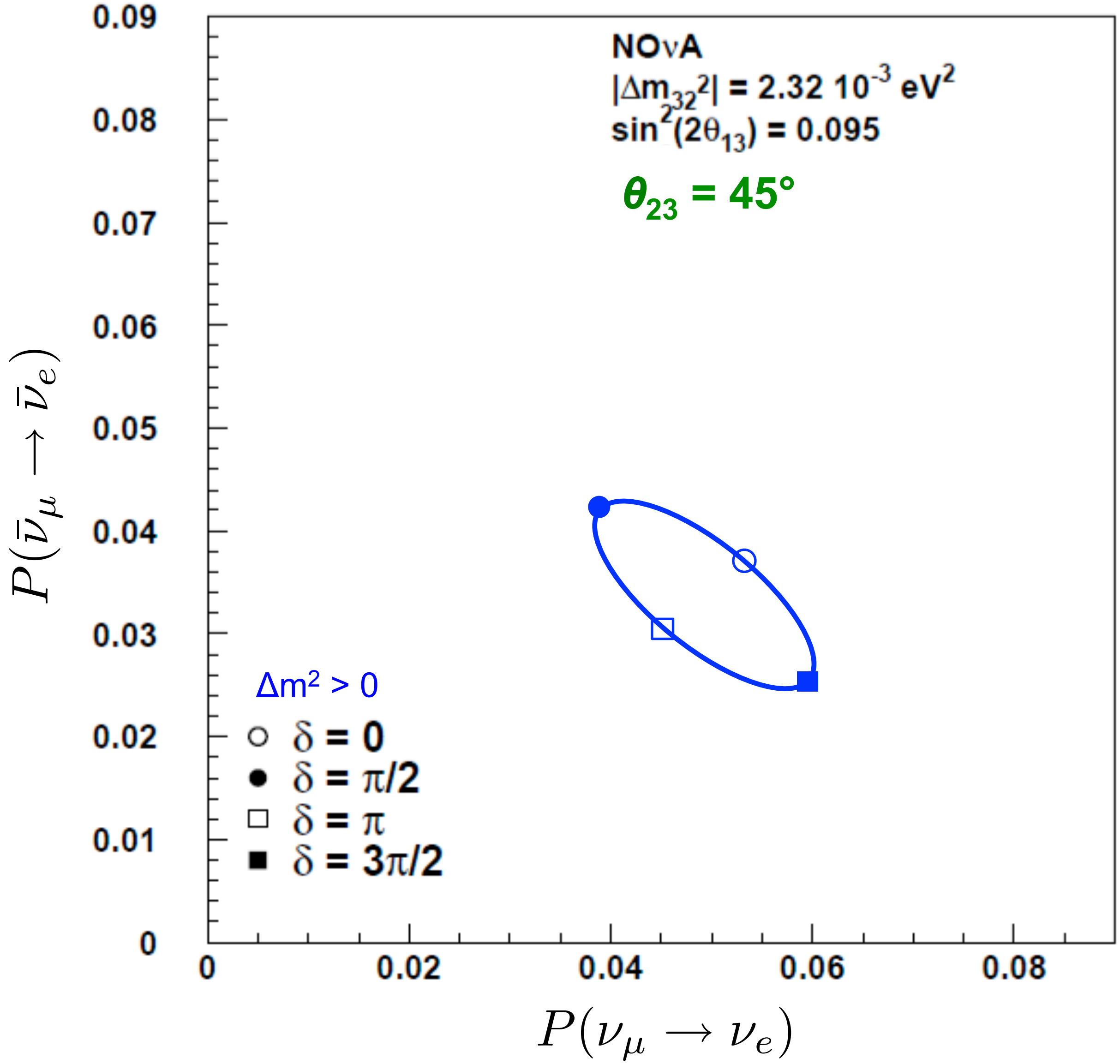

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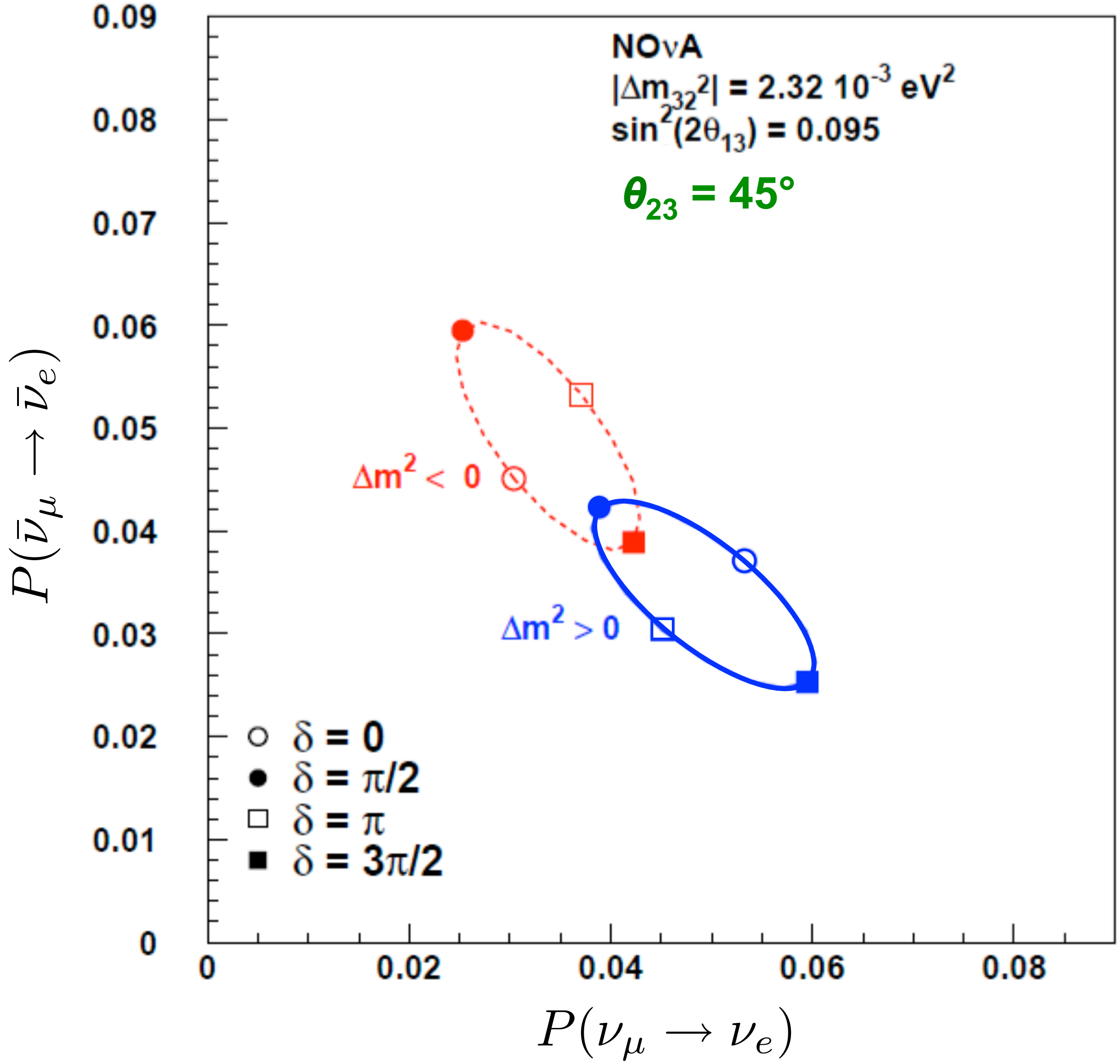

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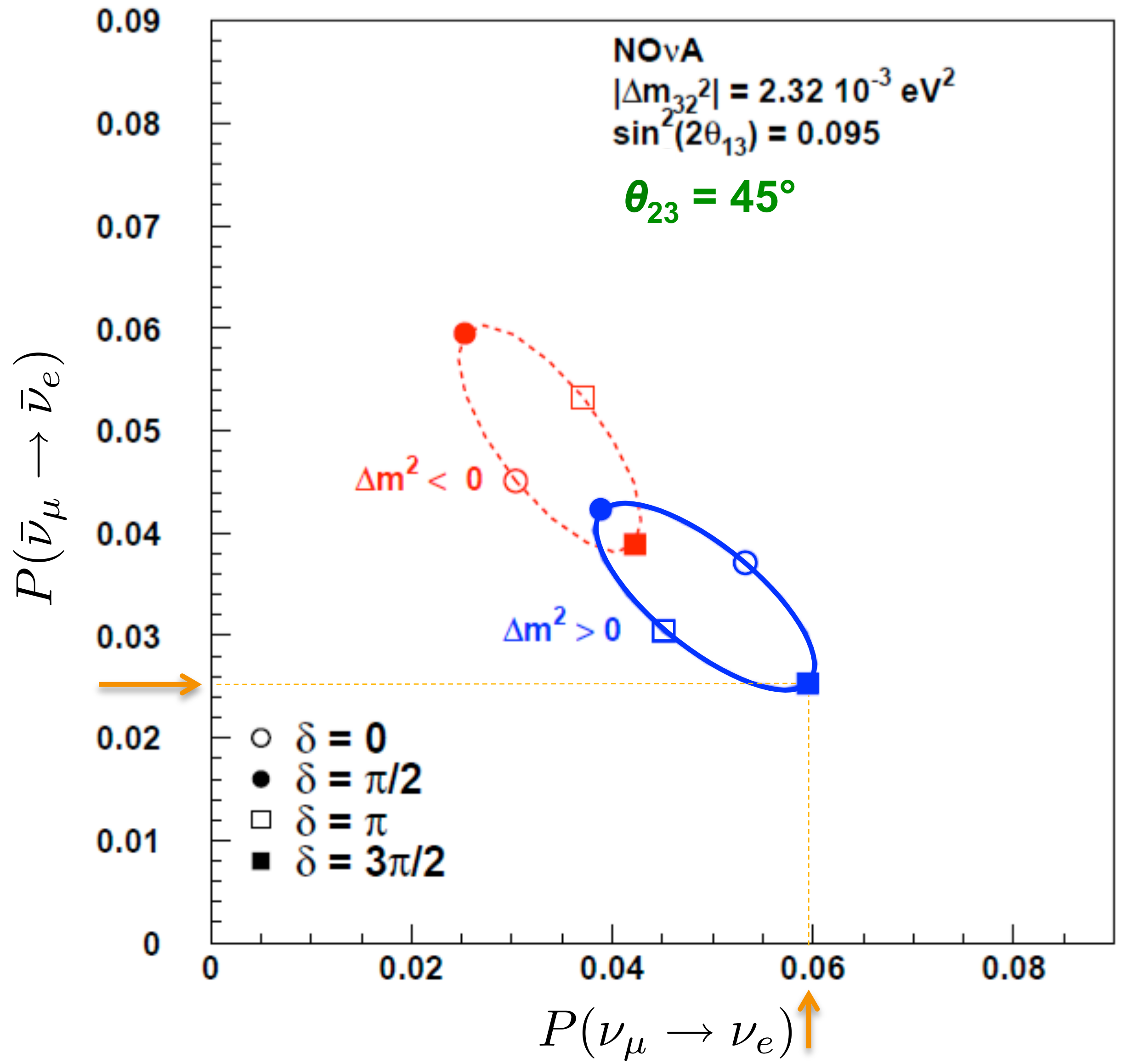

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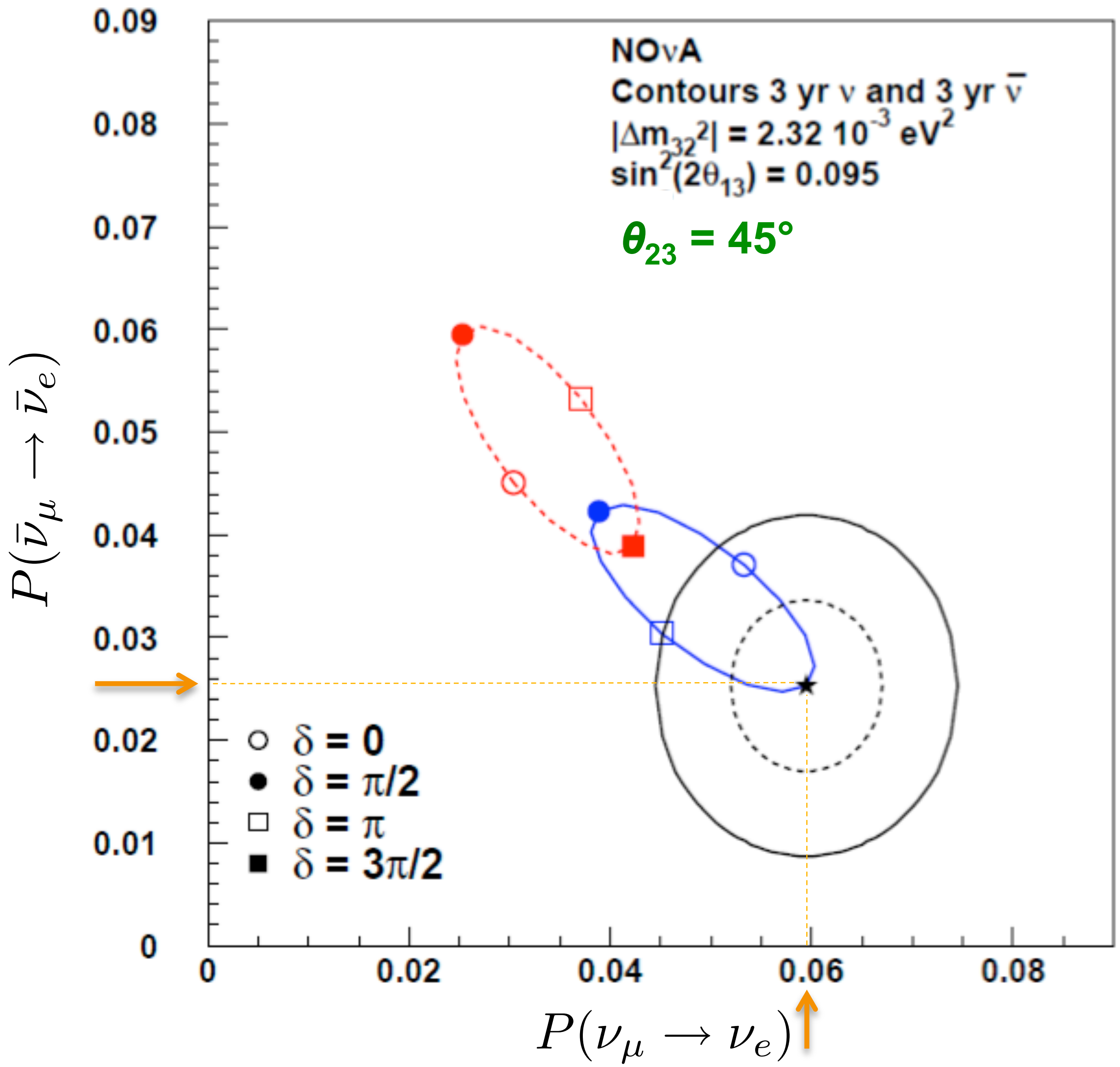

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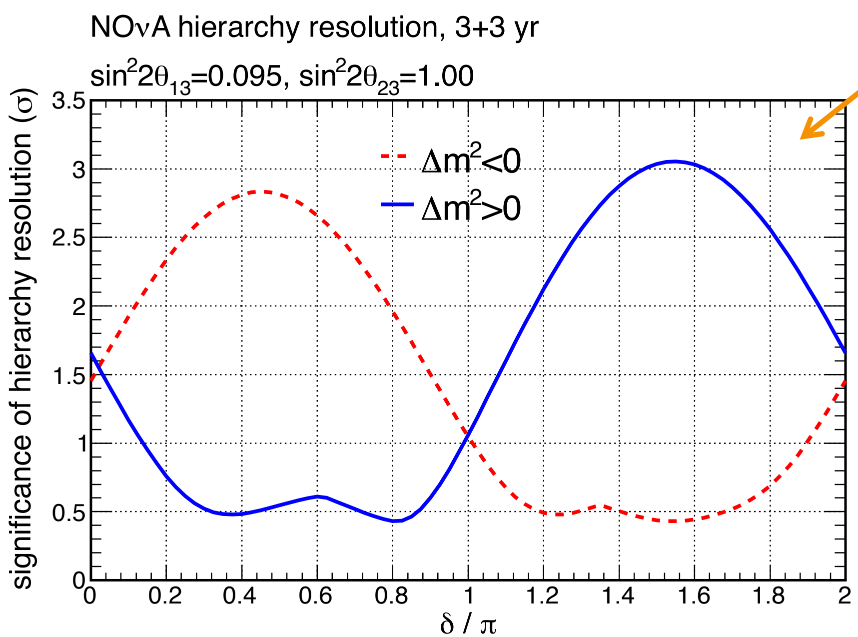
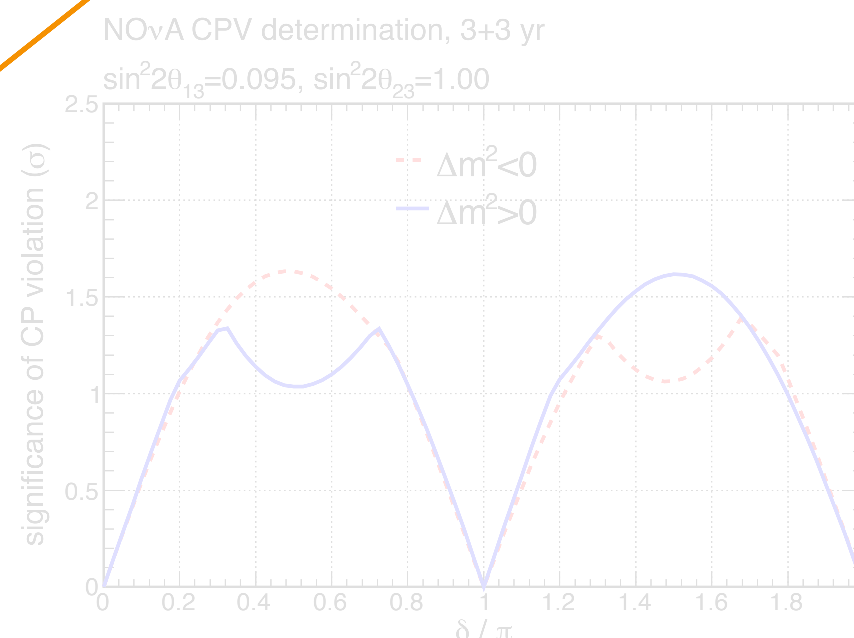
MASS HIERARCHY AND δ_{CP} SENSITIVITY

- Given the bi-probability plots from the previous slides **and using latest analysis framework**, we can determine how sensitive we will be to resolve the:
  - Mass Hierarchy (even better with T2K)
  - CP-violating phase angle (δ_{CP})

Results from full simulation, reconstruction, and selection!





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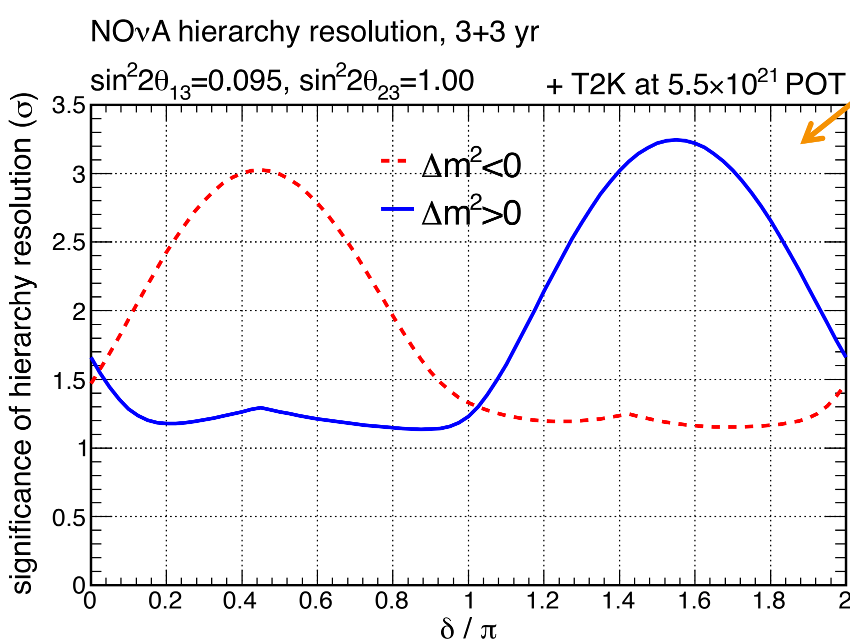

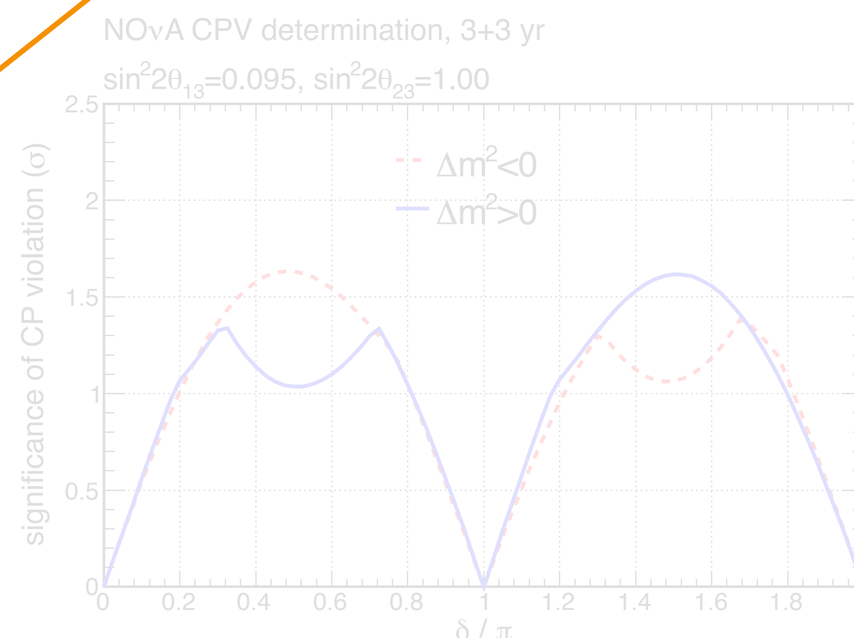

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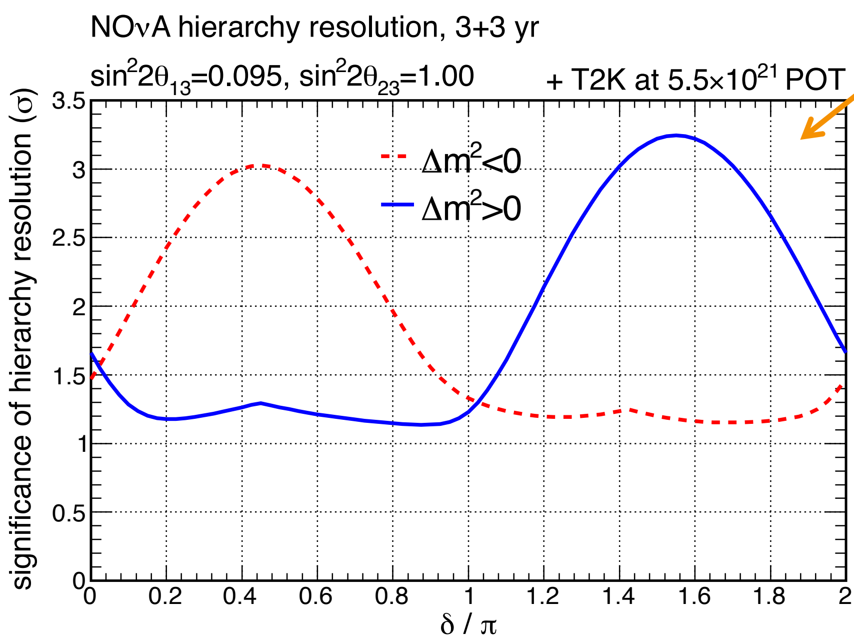
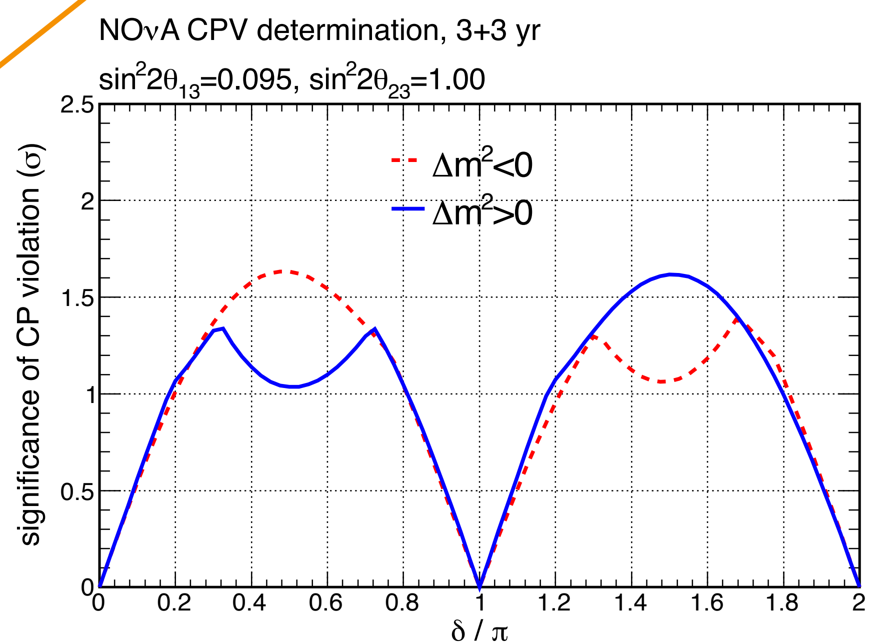
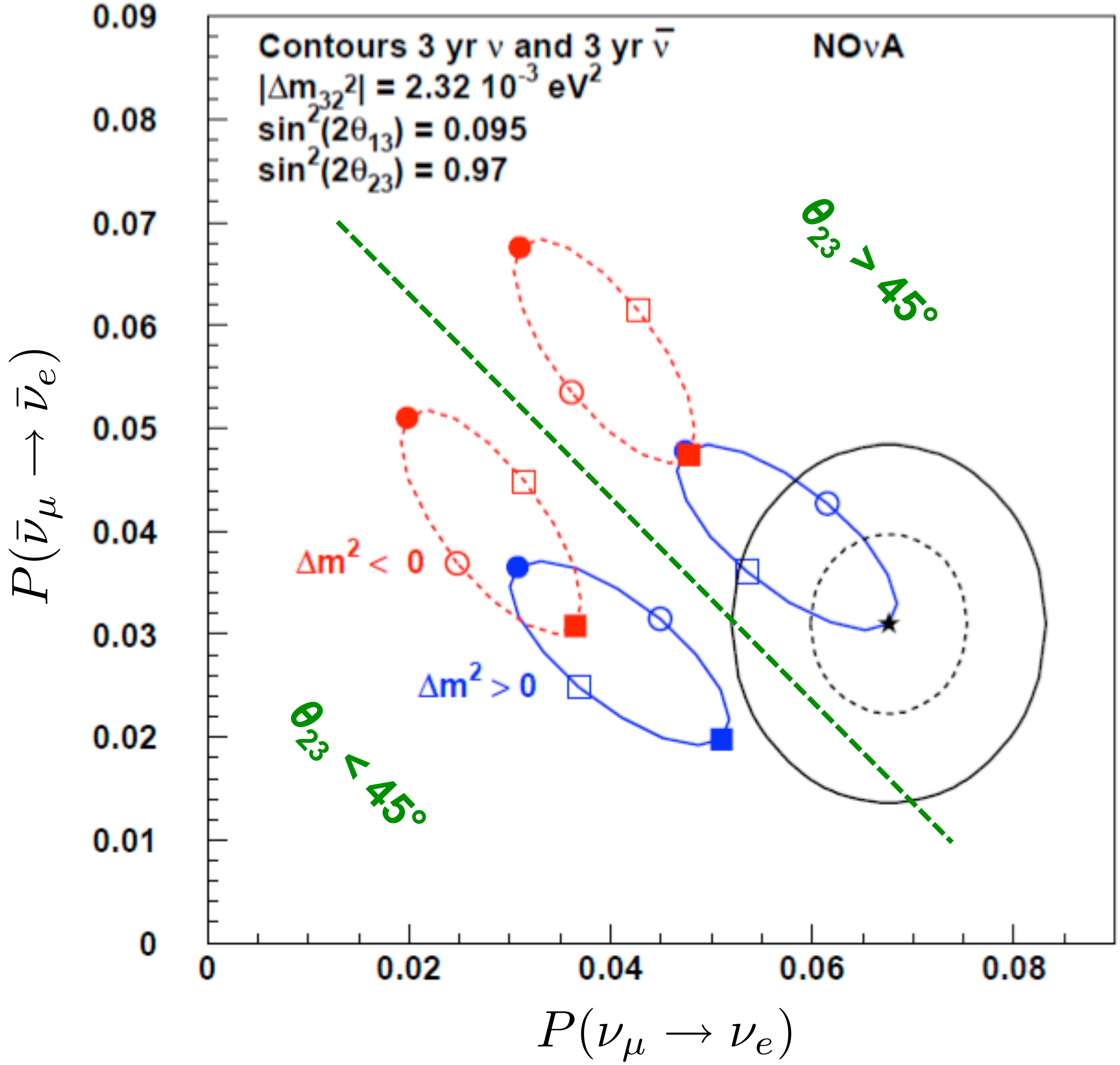




First glimpse at (δ_{CP})!

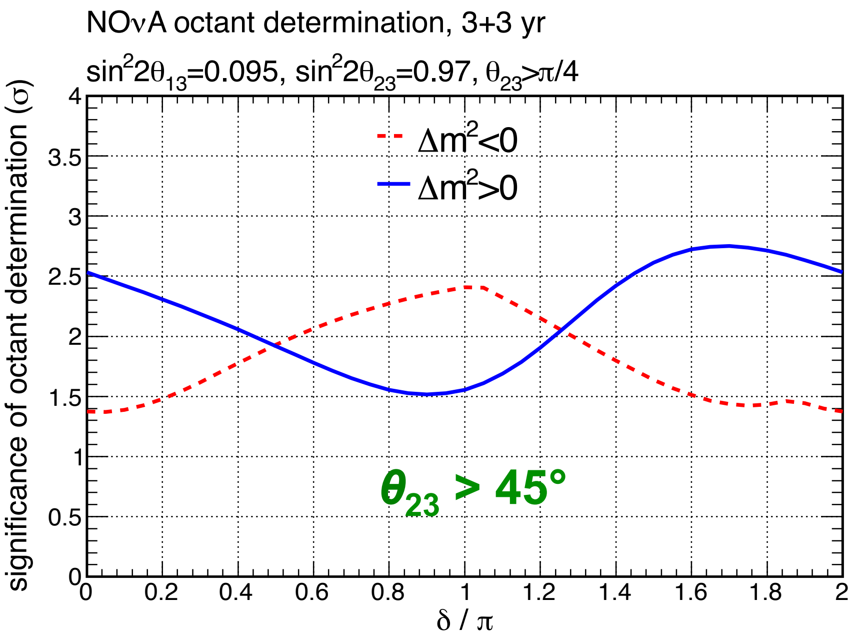
PHYSICS REACH (θ_{23} Octant)

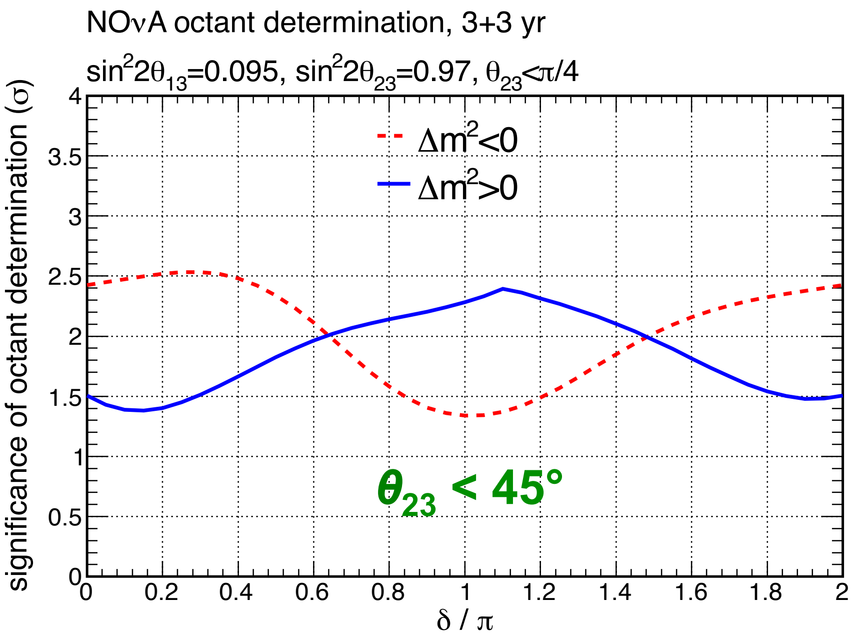


- We know that $\sin^2(2\theta_{23})$ is close to unity, but what octant does θ_{23} fall in?
  - $\theta_{23} > 45°$
  - $\theta_{23} < 45°$
- The probability ellipses are given for both scenarios separated by the green dotted line.

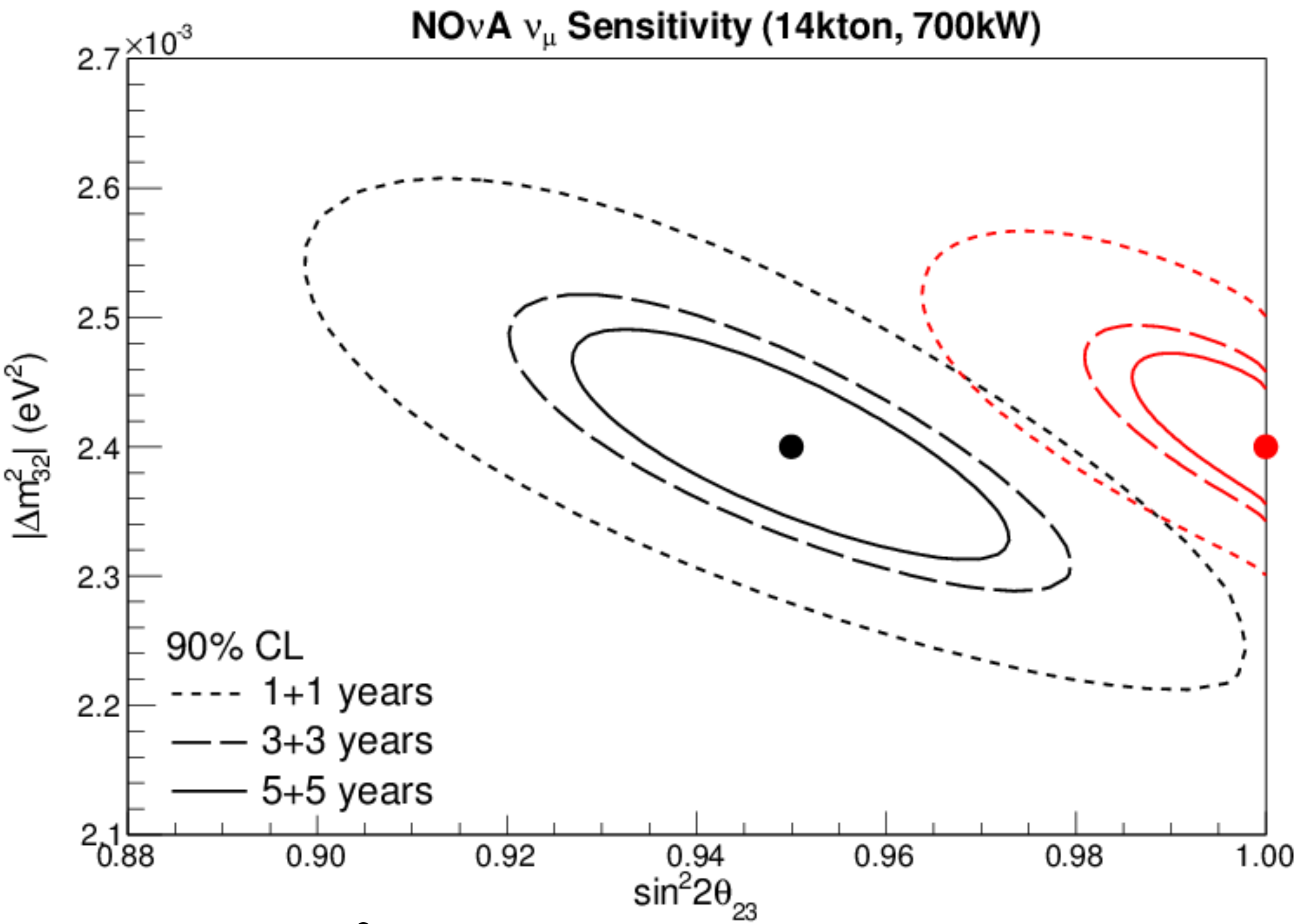
θ_{23} Octant Sensitivity

- Given the bi-probability plots, we can calculate how sensitive we will be to the θ_{23} octant:
  - $\theta_{23} > 45°$ (upper octant)
  - $\theta_{23} < 45°$ (lower octant)





Precision Measurements



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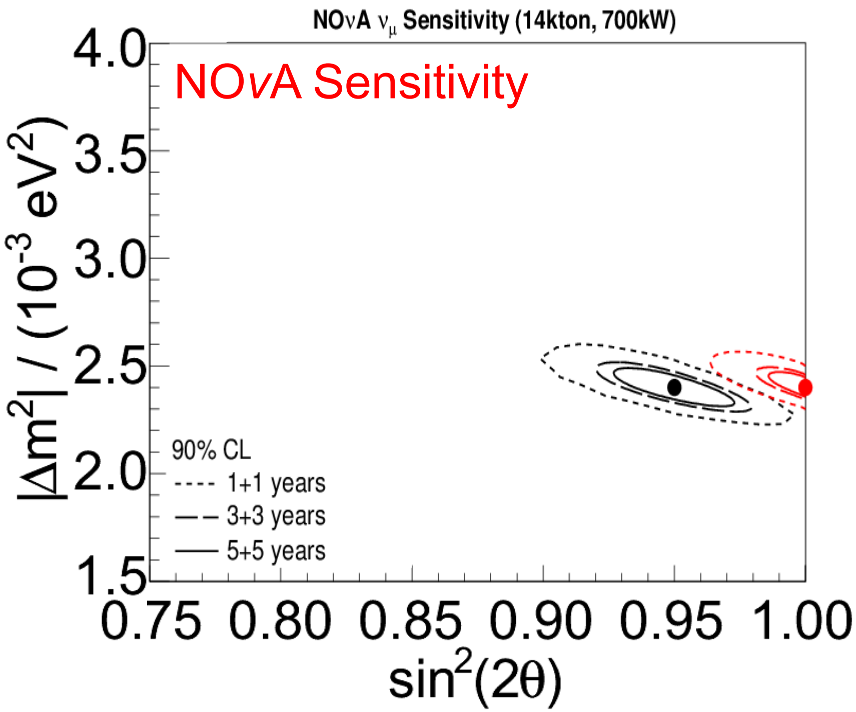

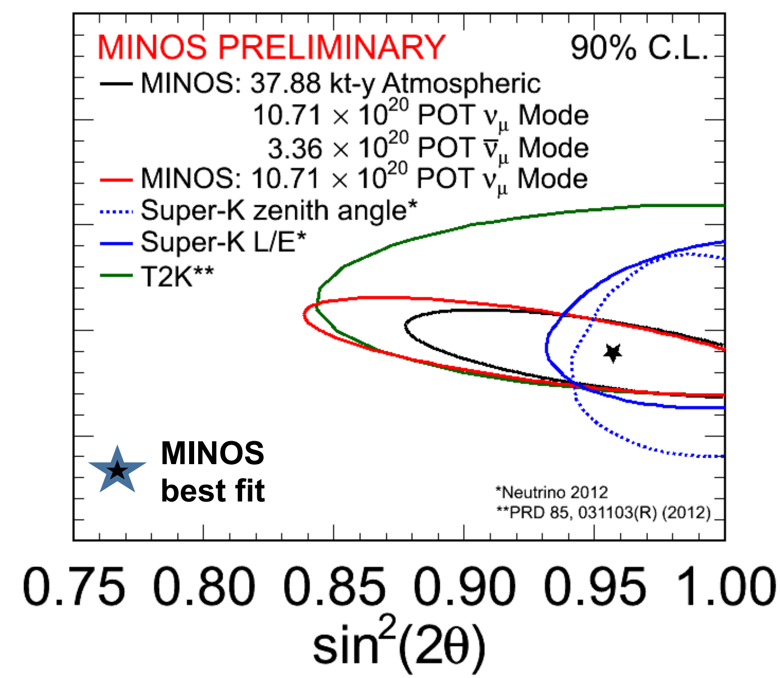

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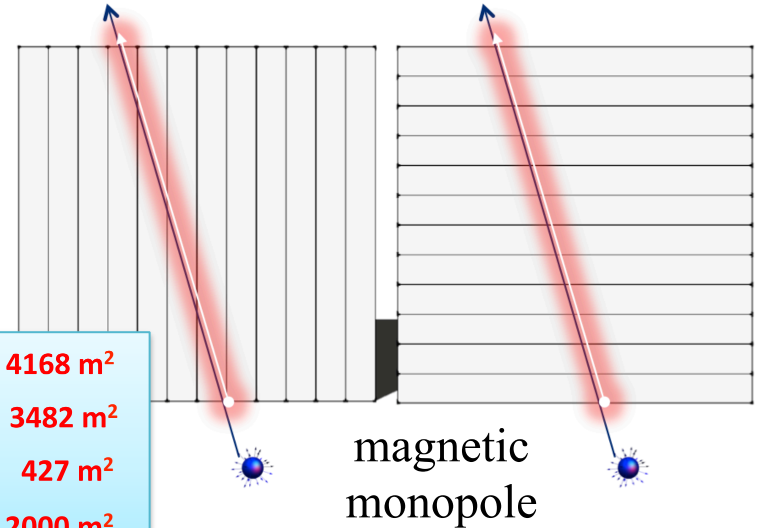
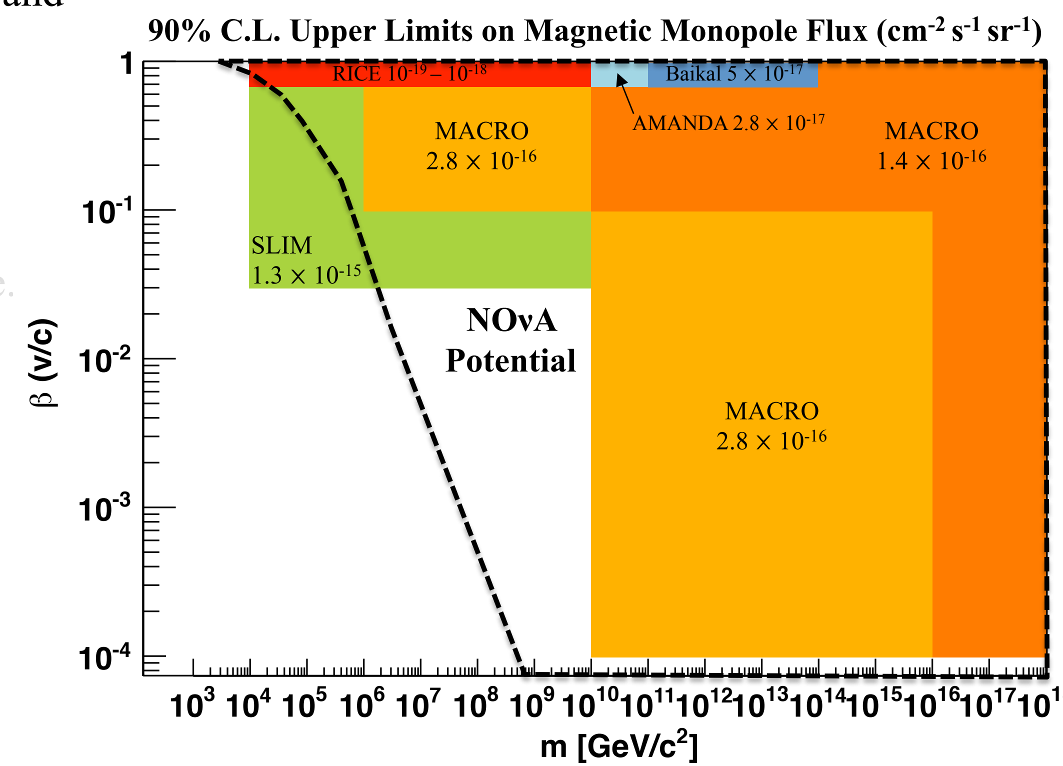
Exotic Searches

- Because the NOνA detector is so large and highly-segmented, it lends itself to exotic searches:
- Magnetic Monopoles
  - would be highly ionizing or slow moving particles.
  - The NOνA detector is favorable because of its large surface area and its surface location.
  - The plot on the right shows the monopole phase space we have access to.
- Supernovae
  - have a large neutrino shockwave.
- WIMP
  - highly energetic neutrinos coming from the sun
- Using the Near Detector:
  - Neutrino Magnetic Moment
  - Dark Sector

NOνA:	4168 m^2
MACRO:	3482 m^2
SLIM:	427 m^2
OHYA:	2000 m^2





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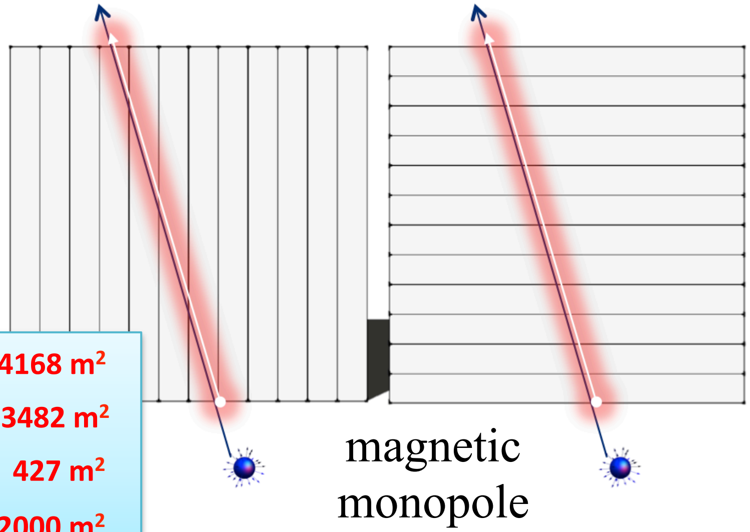

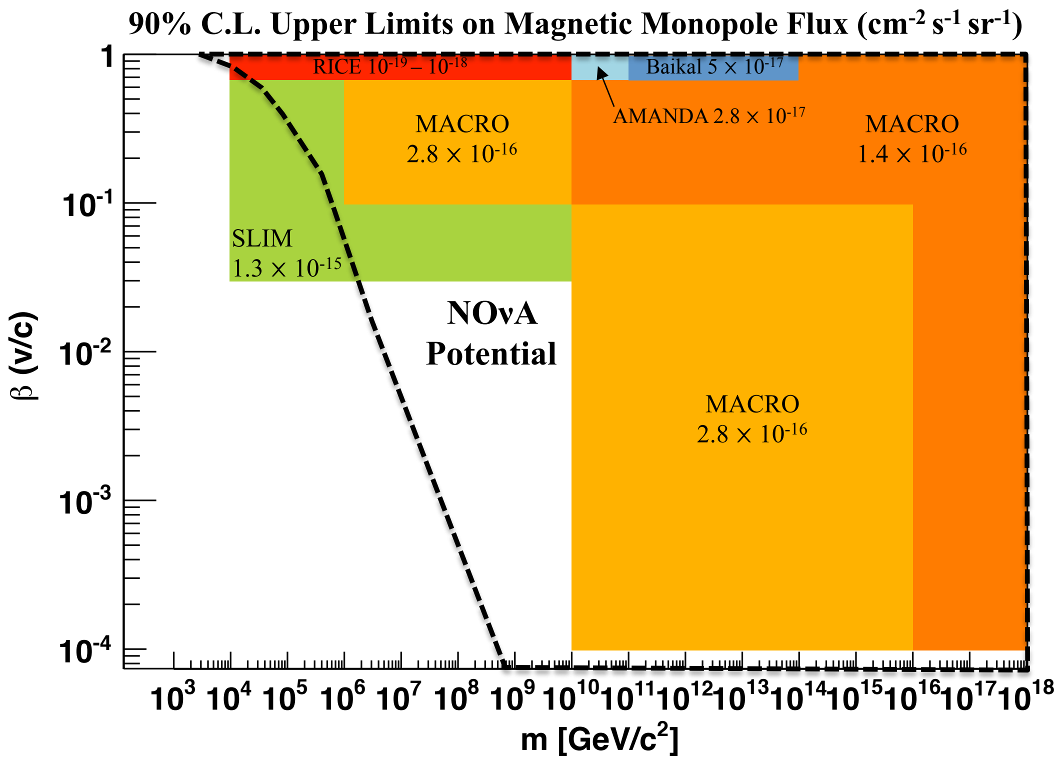

SUMMARY

- Far Detector construction half way complete with first kiloton fully instrumented and construction progressing quickly.
- NuMI beam return is imminent!
- Our analysis framework is ready to try to pin down the mass hierarchy and the θ_{23} octant, and have the first glimpse at δ_{CP}.
- We will use our detector as an eye to the universe and are excited about what we might learn.
- Please see the 5 NOνA posters this evening for more detail.
- We do not only have a massive detector, but also a massive collaboration of dedicated people!

180+ scientists and engineers from 35 institutions from 7 countries

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