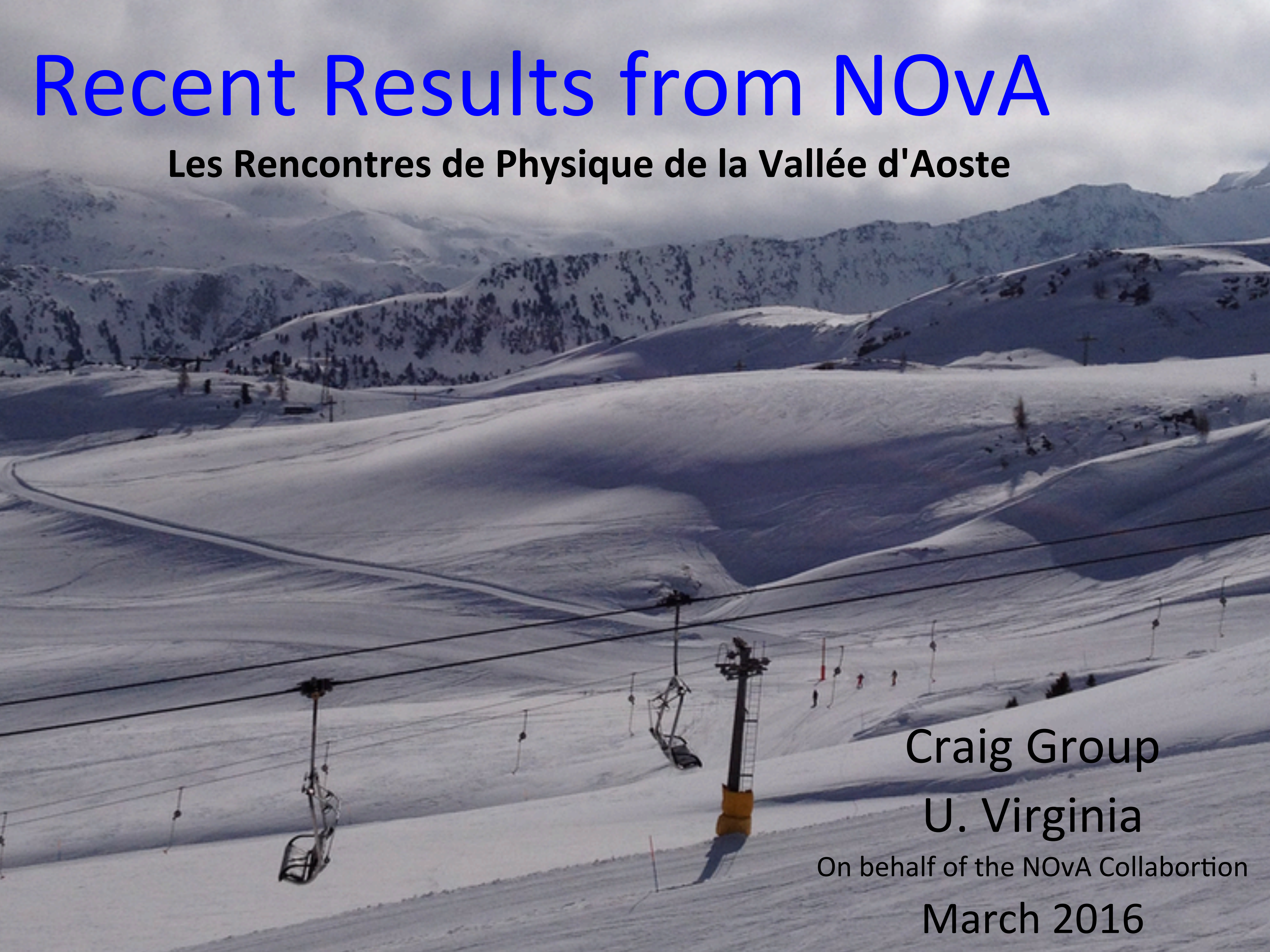
Recent Results from NOvA

Les Rencontres de Physique de la Vallée d'Aoste



Craig Group

U. Virginia

On behalf of the NOvA Collabortion

March 2016

Introduction

Neutrino Oscillation (2-flavor case)

If the neutrino mass eigenstate isn't equal to its flavor (weak interaction) eigenstate then ν_e and ν_μ can be written as linear combinations of ν_1 and ν_2:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

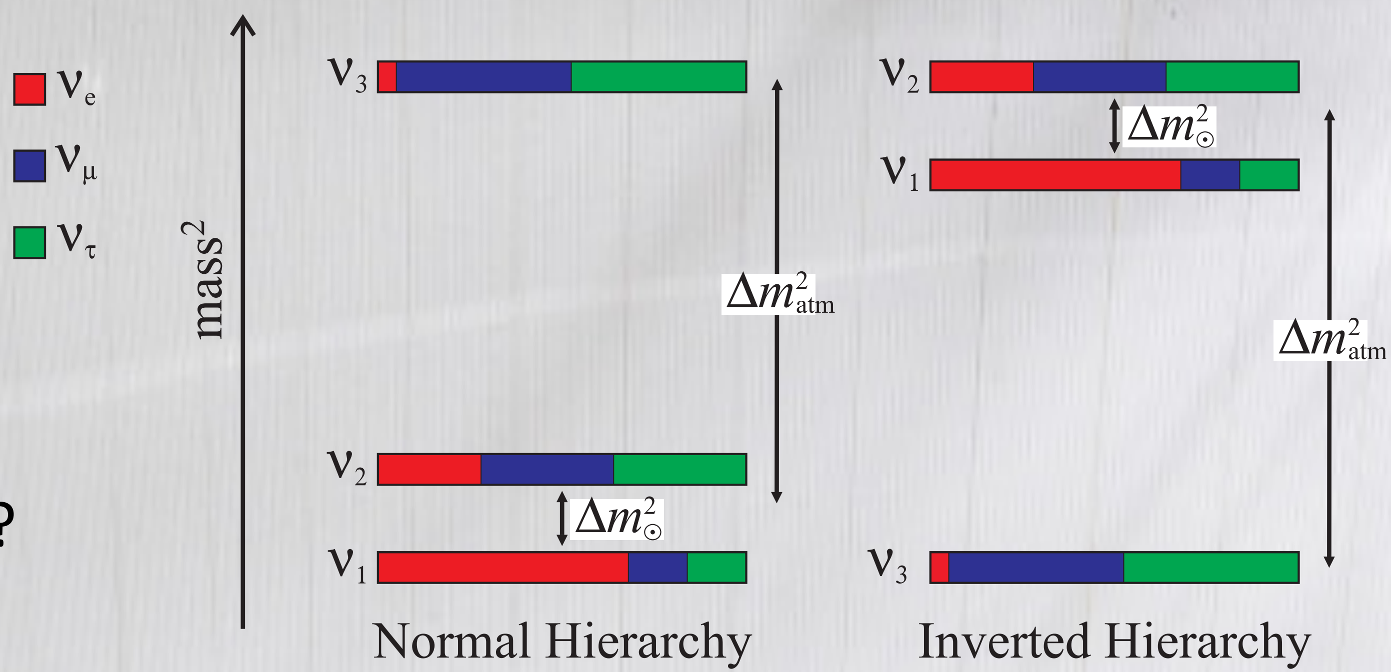
By applying the time-dependent Schrödinger equation and assuming relativistic neutrinos the transition probability is:

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2(2\theta)\sin^2(\frac{\Delta m^2 L}{4E})$$

So, neutrino oscillation probabilities depend on the mixing angle, and oscillate as a function of L/E. Note that we know neutrinos have mass based on oscillation measurements!

Current Questions In Neutrino Physics

- Mass hierarchy
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



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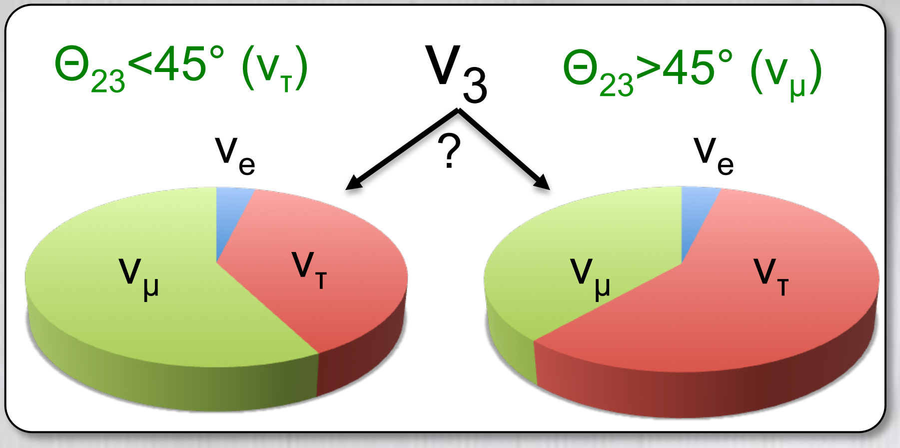

Current Questions In Neutrino Physics

- Mass hierarchy
- Nature of ν_3 - θ_{23} octant
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- Is there more to this picture?

Are neutrino and antineutrino oscillation parameters the same?

If neutrino interactions violate CP, then neutrinos could have played an important role in Leptogenesis.

Current Questions In Neutrino Physics

- Mass hierarchy
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?

Maybe the simple 3-flavor model is incomplete.

Oscillation (3 flavors)

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

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

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

± neutrino mode

± anti-neutrino mode

- The **NOvA baseline** (L = 810 km) and **neutrino beam energy** (E = 2 GeV) place our detector at the first $\nu_\mu \to \nu_e$ 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 get information about the ϑ_{23} octant from the leading term.
- **δ_{CP}**: we have sensitivity to the CP-violating phase angle.
- **mass hierarchy**: depending on the sign of Δm^2_{31} (~ Δm^2_{32}), the oscillation probability is either enhanced or suppressed.

Extracting Oscillation Parameters

Bottom line:

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

Oscillation rates can tell us about the properties of neutrinos.

- 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.

Principle of NOνA measurements

By counting events of each flavor at the near and far detector, NOνA measures oscillations probabilities in four channels:

$$\nu_\mu \rightarrow \nu_e \quad \& \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$ → ν_e appearance

$$\nu_\mu \rightarrow \nu_\mu \quad \& \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$ → ν_μ disappearance

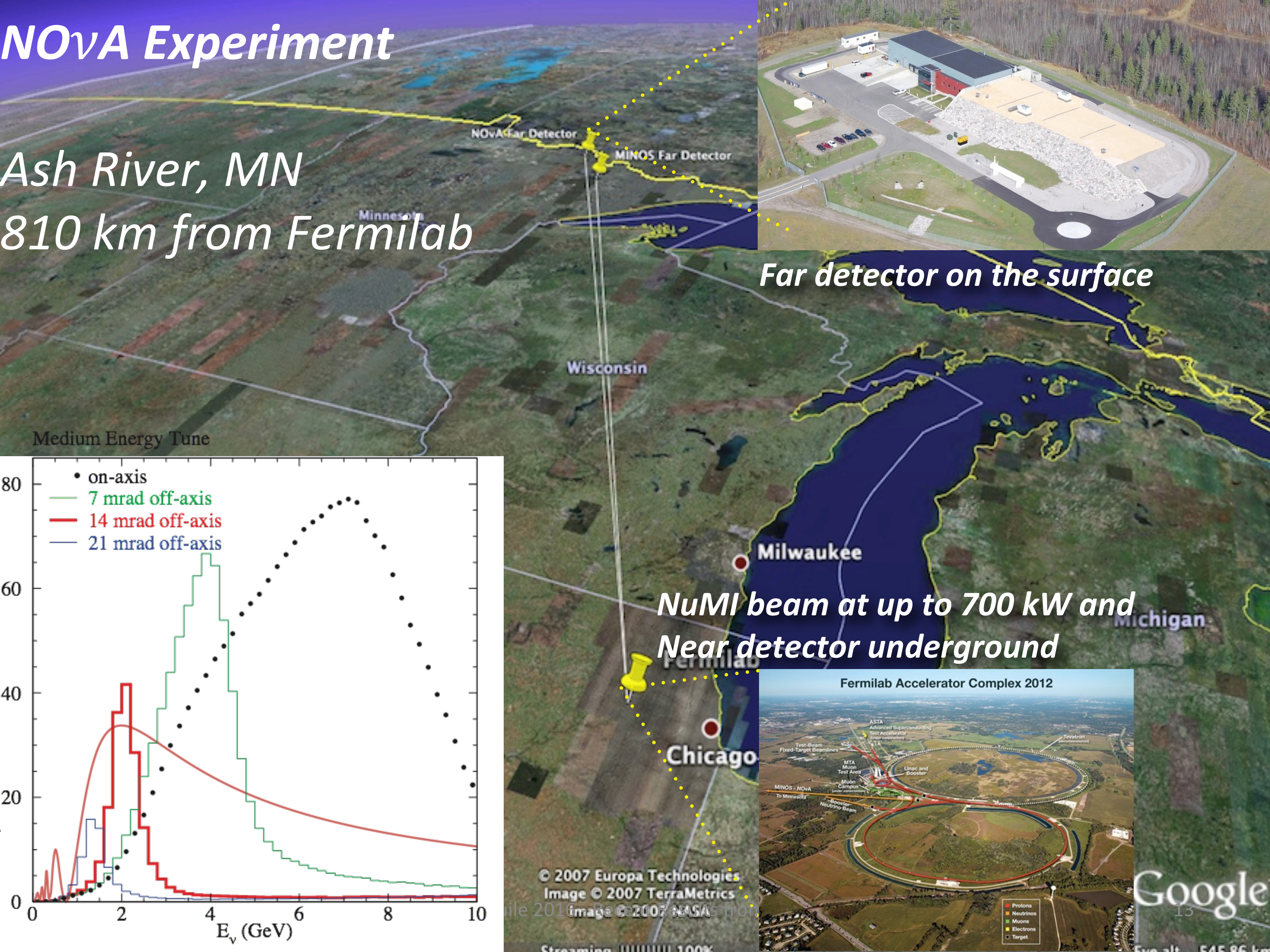
(Note; Precision ν_μ disappearance measurements constrain θ_{23})

Apparatus


Liner
Tongue
Grab loop
Spoiler
Power Strap
Upper Cuff
3rd Buckle
Cuff Adjustment
Buckle
Heel Cup
Toe Box
Heel Lug
Toe Lug
Foot Bed

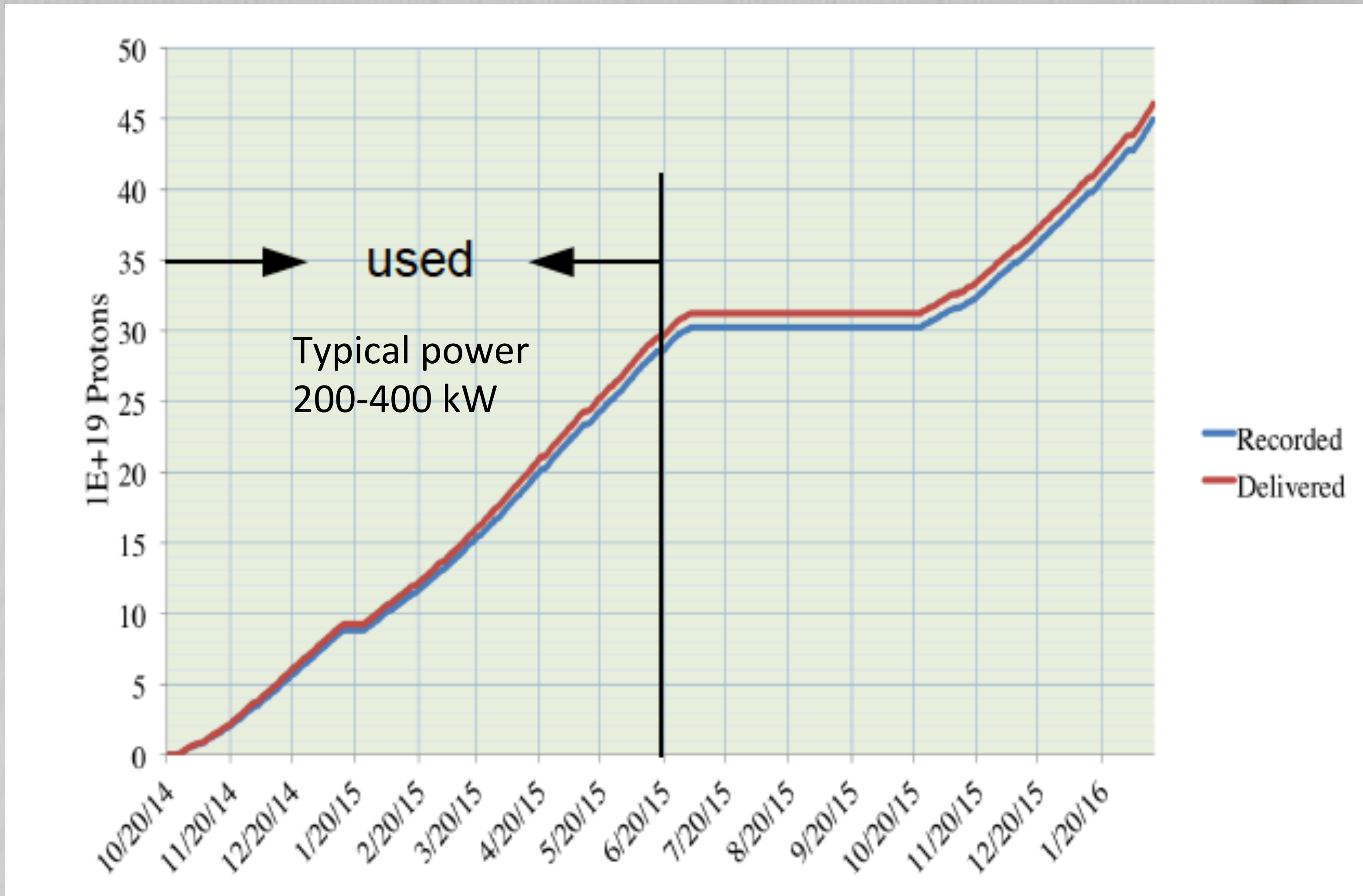
The NOνA Experiment

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



NOνA Experiment
Ash River, MN
810 km from Fermilab
Far detector on the surface
NuMI beam at up to 700 kW and
Near detector underground
NOvA Far Detector
MINOS Far Detector
Minnesota
Wisconsin
Milwaukee
Michigan
Fermilab
Chicago
Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
E_ν (GeV)
Fermilab Accelerator Complex 2012
MINOS - NOvA
To Minnesota
Tevatron
Linac and Booster
© 2007 Europa Technologies
Image © 2007 TerraMetrics
Image © 2007 NASA
Google

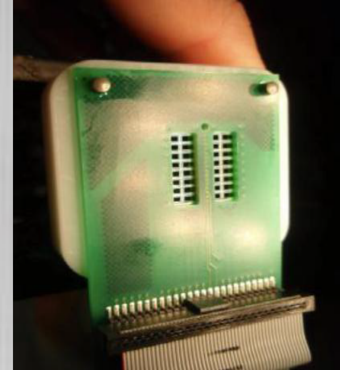
NuMI Beam



Beam is currently operating at ~500 kW with record of 570 kW
Scaling to full 14 kton-equivalent exposure, 2.74×10^{20} POT.

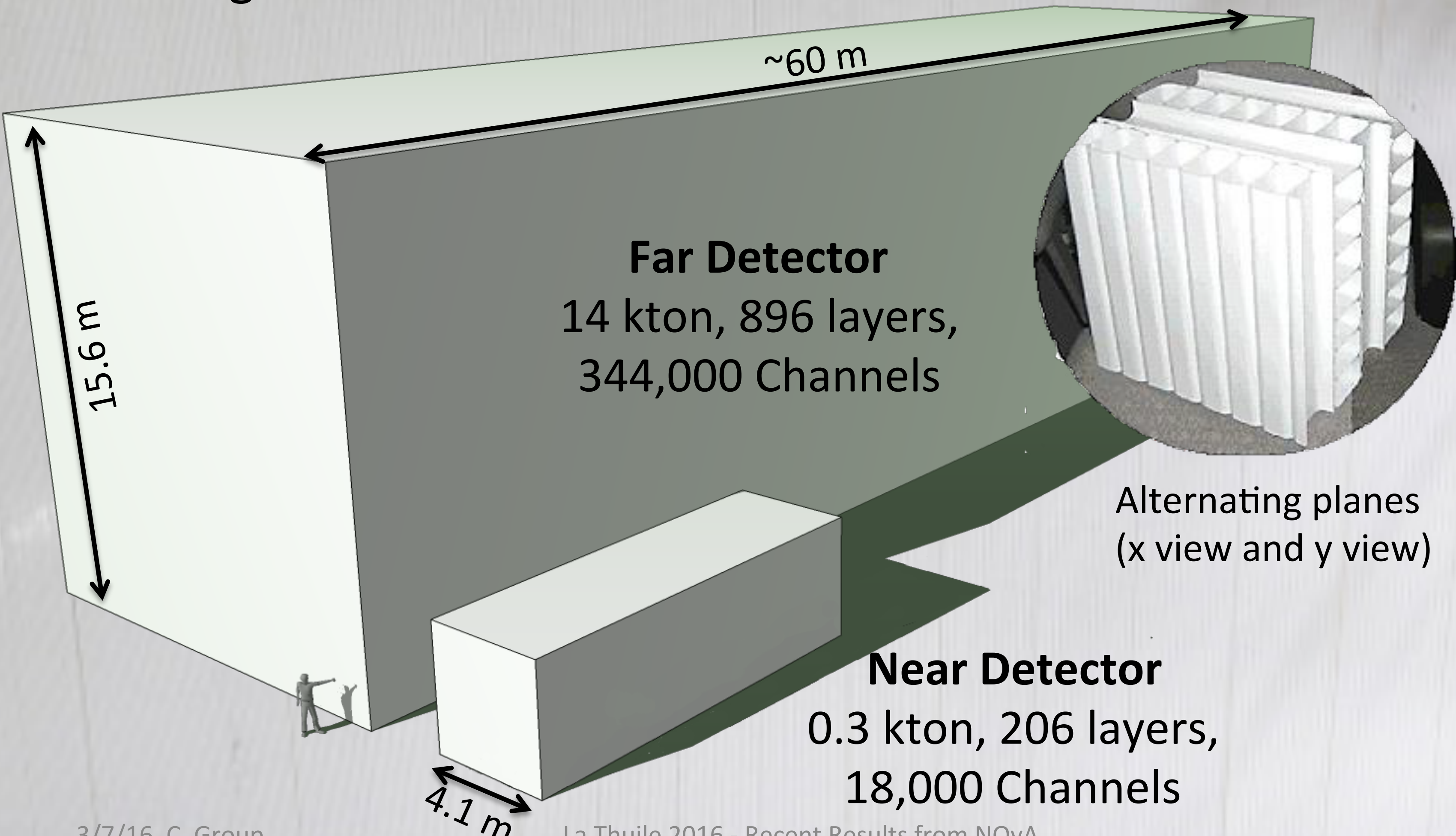
NOνA Detectors:

- Fine-grained, low-*Z*, highly-active tracking calorimeters
- 11 M liters of scintillator
- λ-shifting fiber and APDs



32-pixel APD

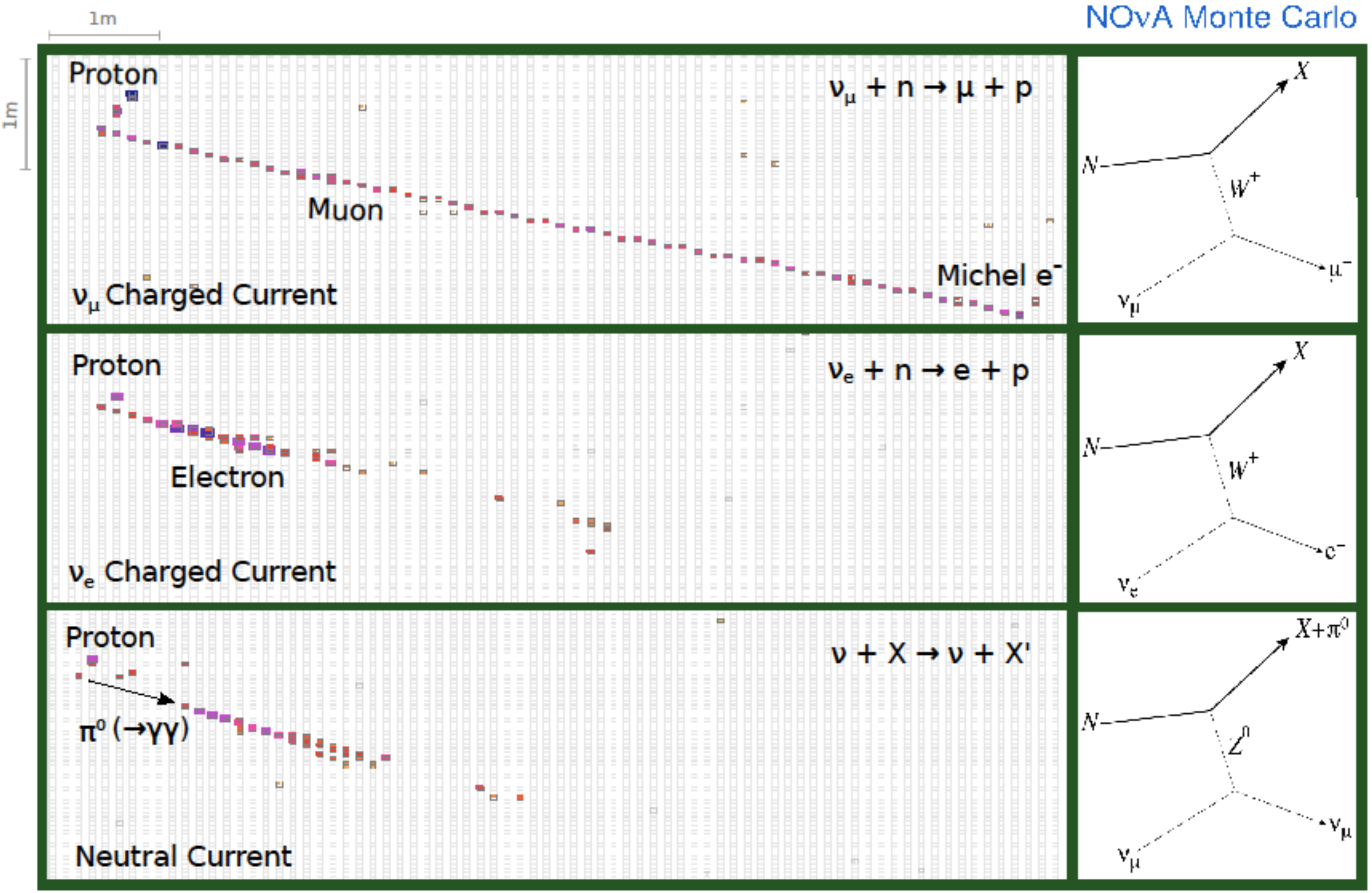
Fiber pairs from 32 cells



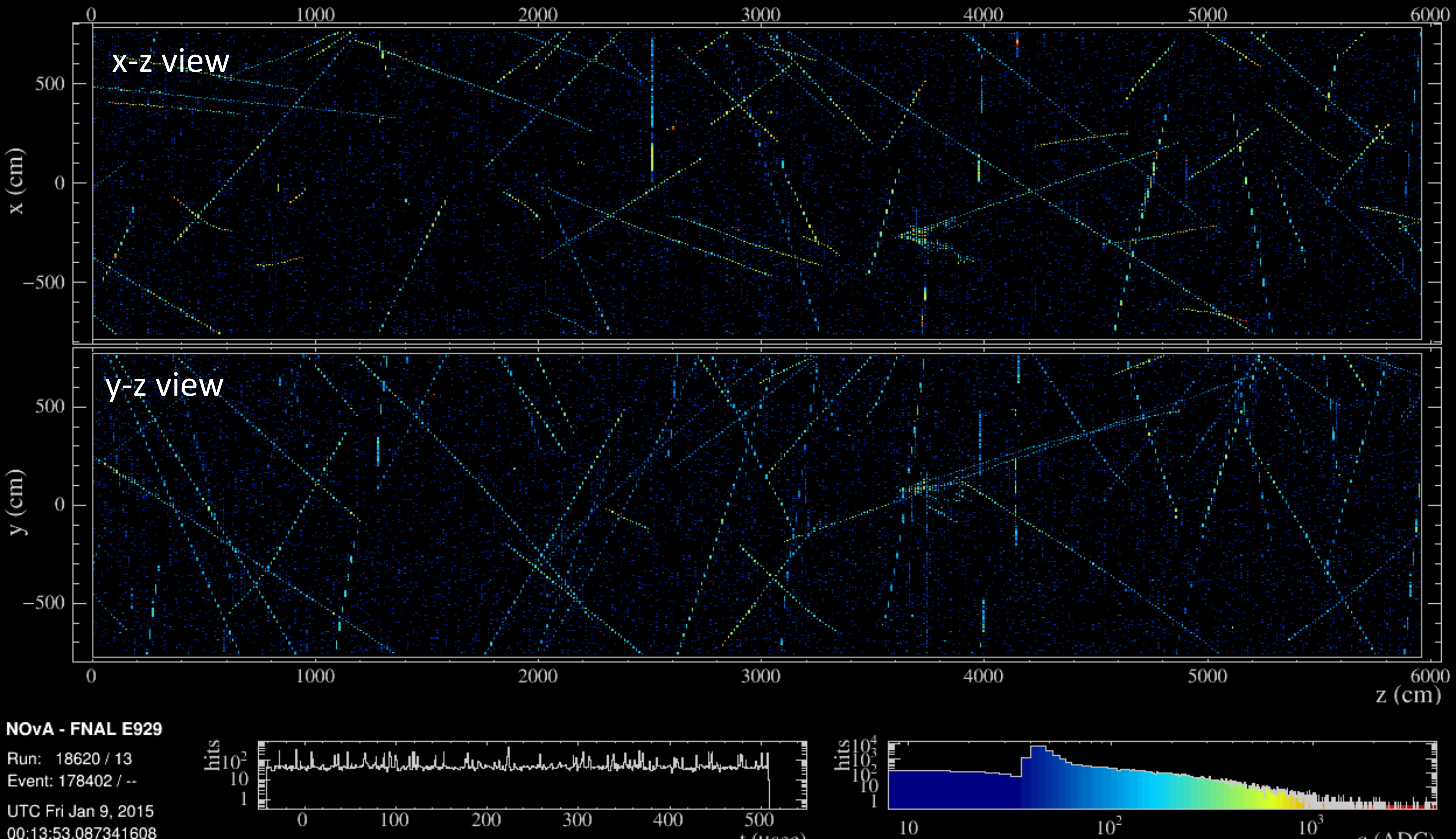
Alternating planes
(x view and y view)

Reconstruction and Calibration

Event Topologies

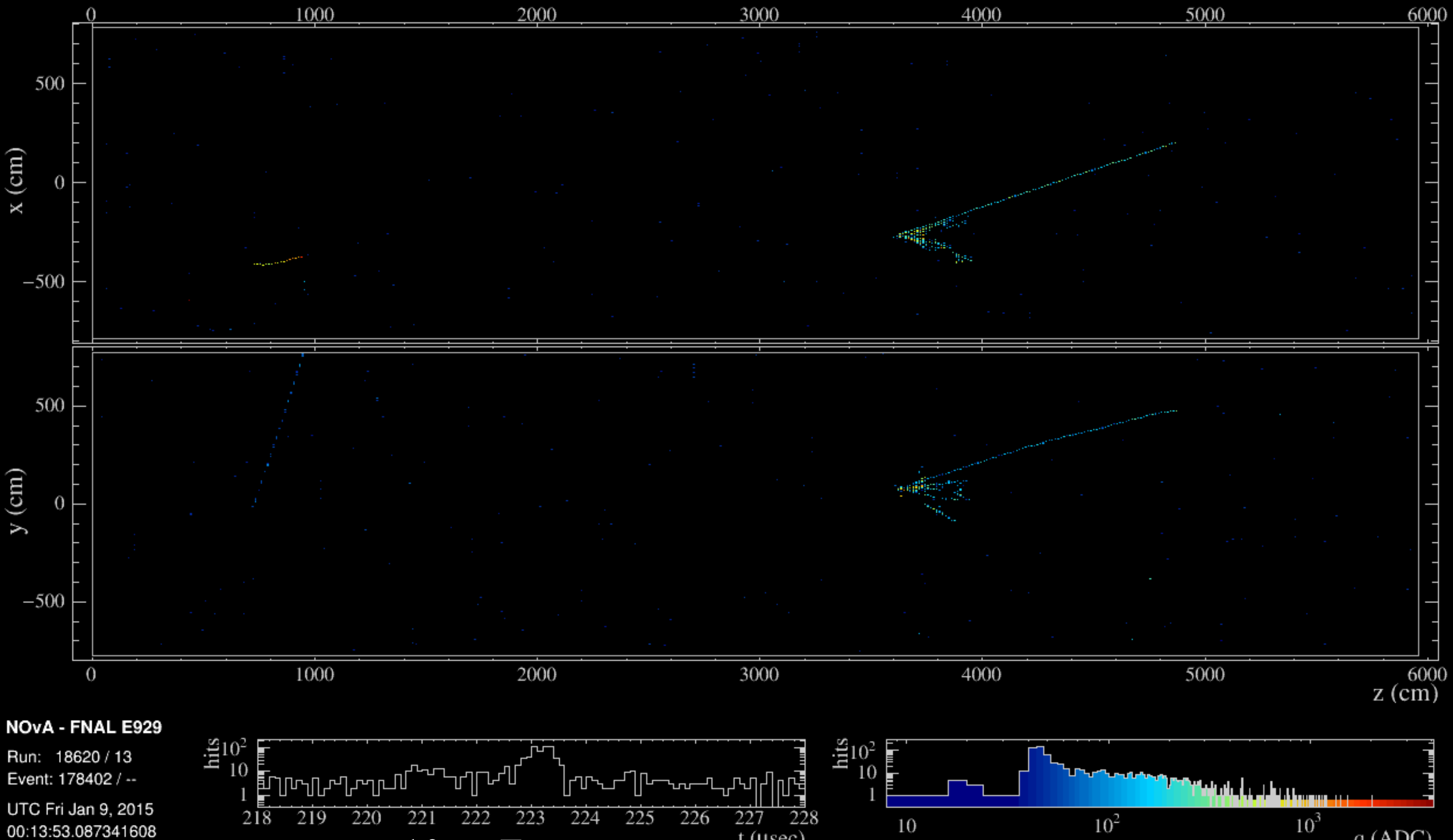


Data Event Display of Far Detector



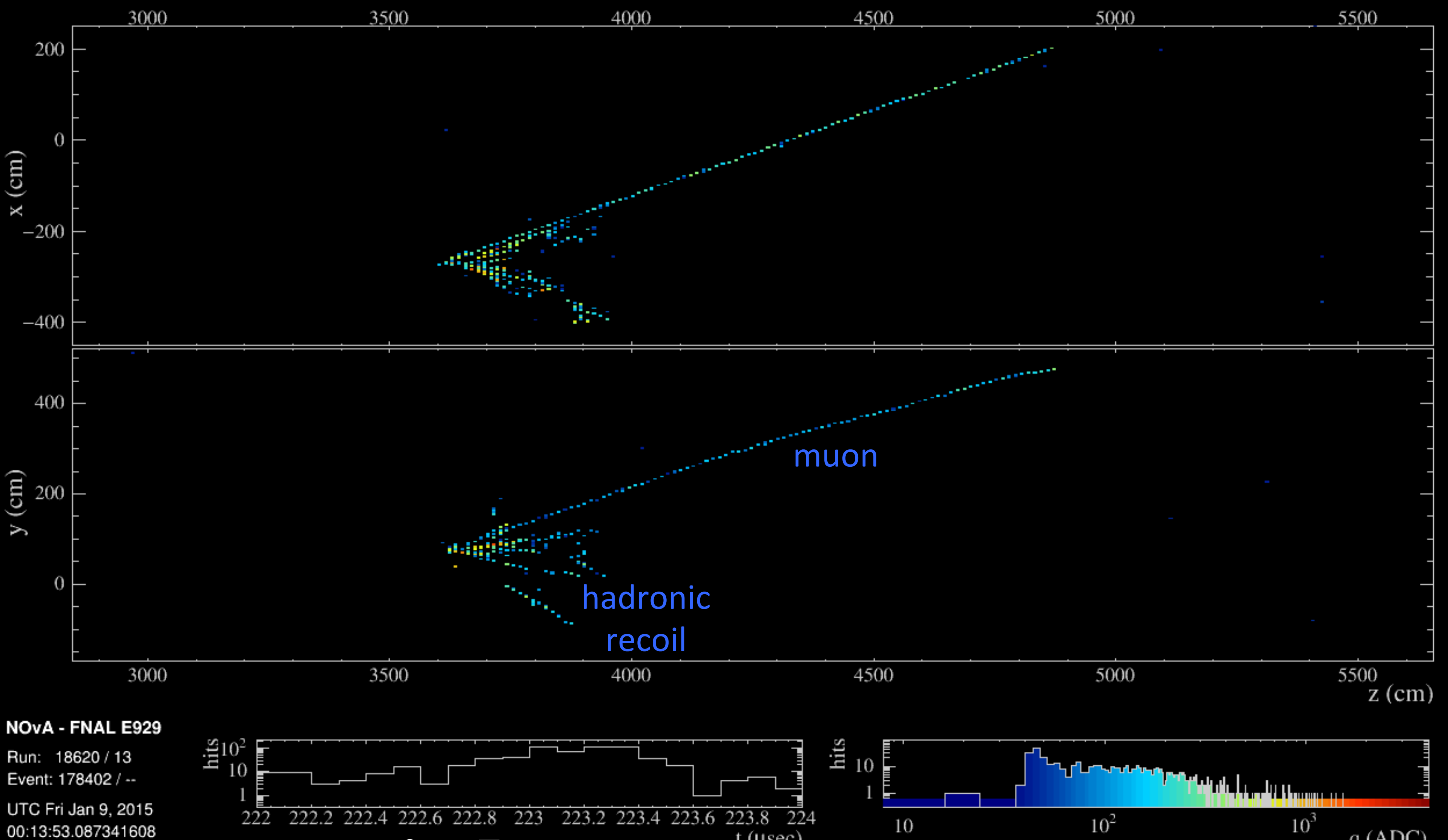
550 μs Exposure

Time Zoom on NuMI Beam Pulse



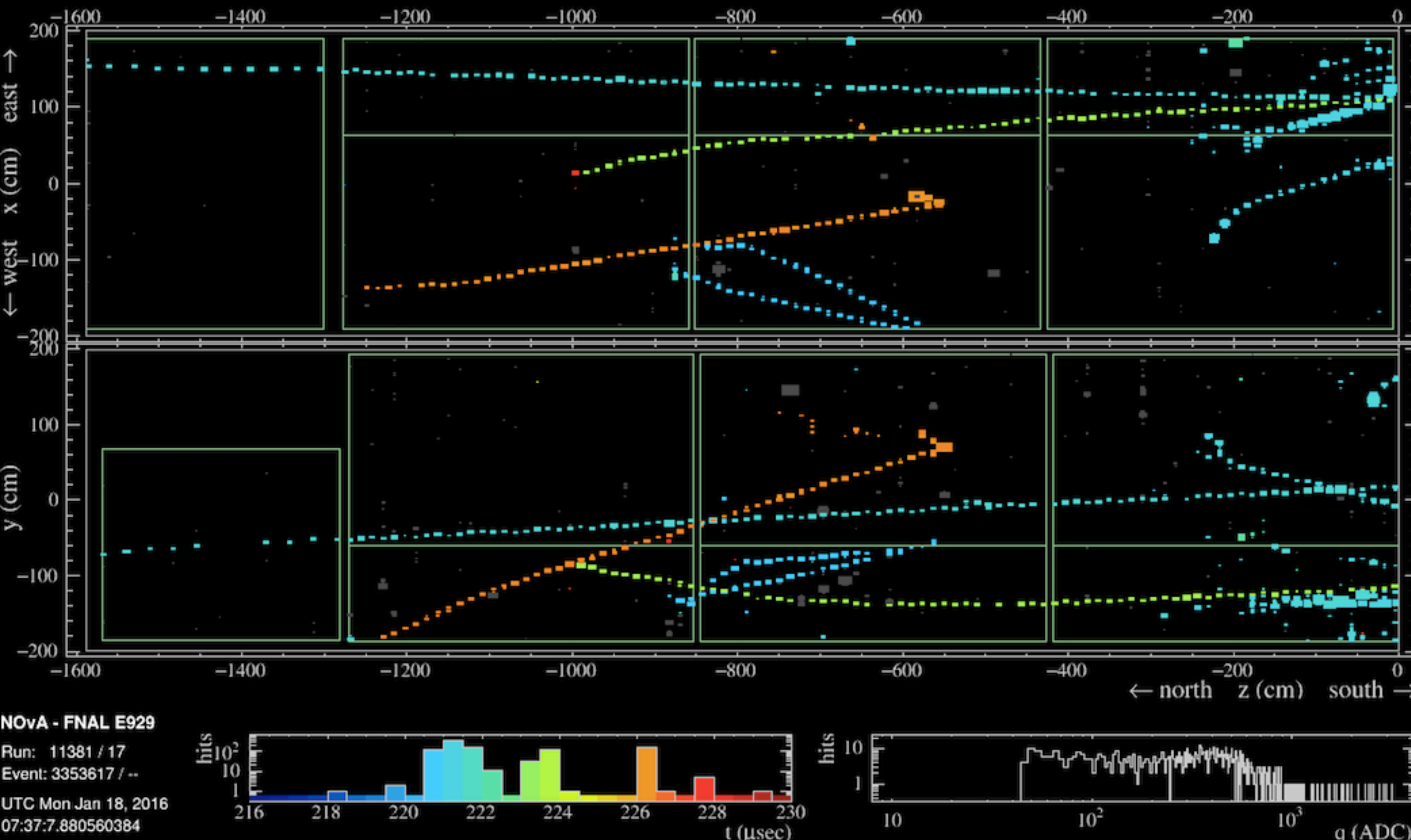
10 μs Exposure

Close-Up of Neutrino Interaction



2 μs Exposure

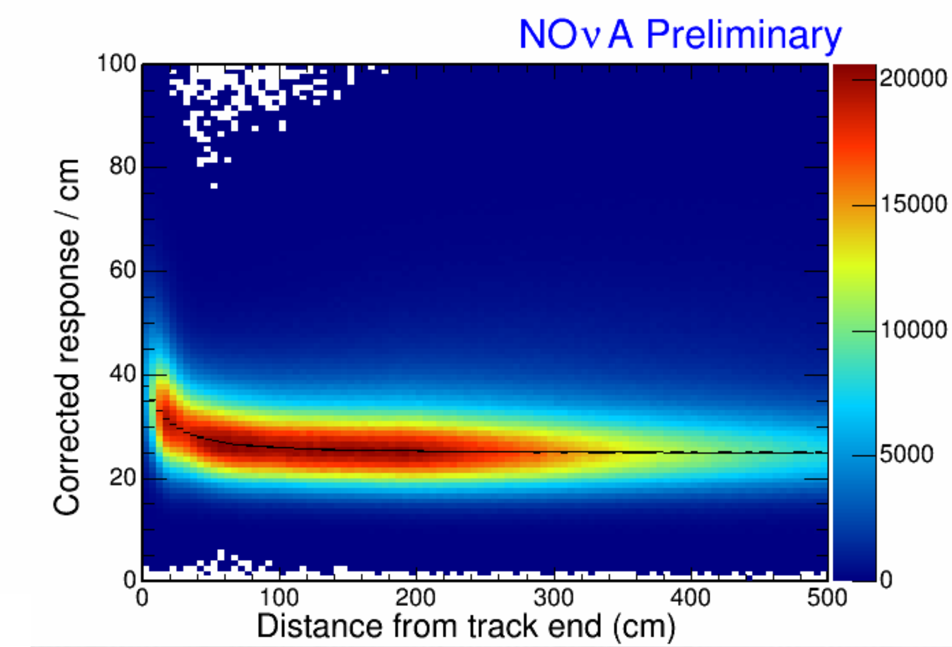
Neutrinos "pile up" in the Near Detector!

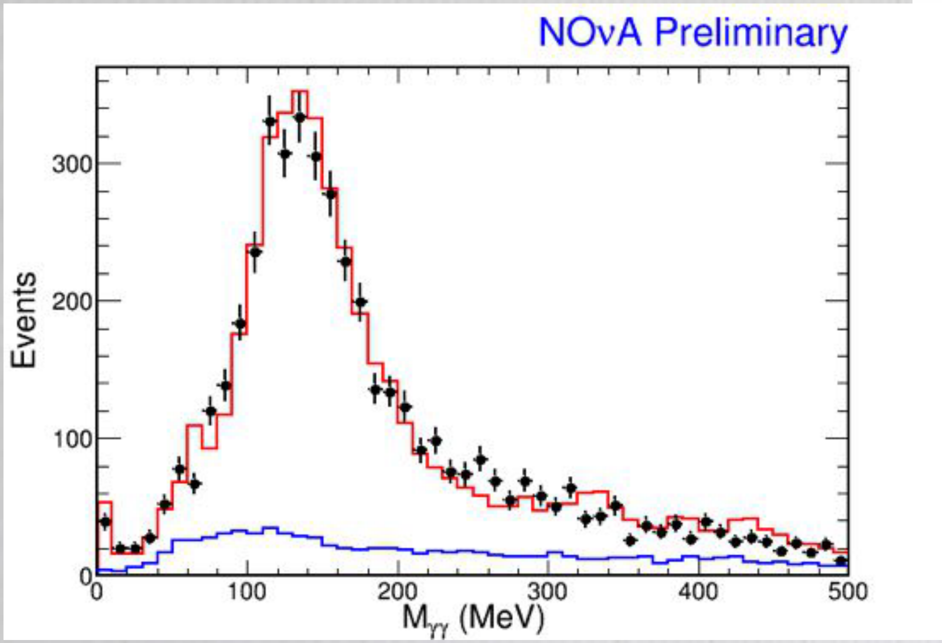


Pulled from live event stream: http://nusoft.fnal.gov/nova/public/

Calibration

- Use cosmic muons to determine channel-to-channel and attenuation calibrations.
- Use stopping muons as a standard candle for setting the absolute energy





Multiple cross-checks:

- cosmic muon dE/dx
- beam muon dE/dx
- Michel e- spectrum
- **π_0 mass**
- hadronic shower energy per hit

All samples agree within 5%.

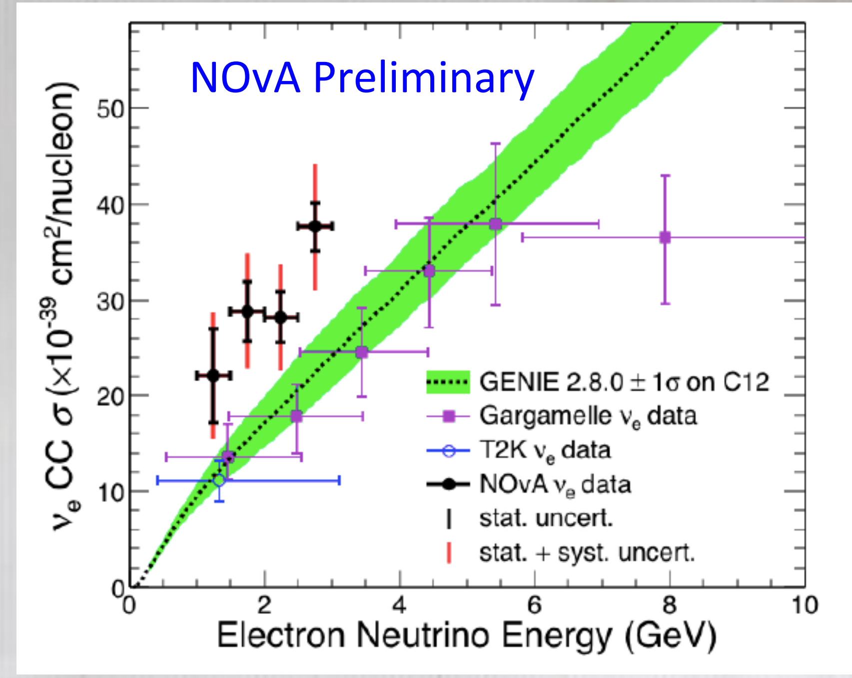
Results

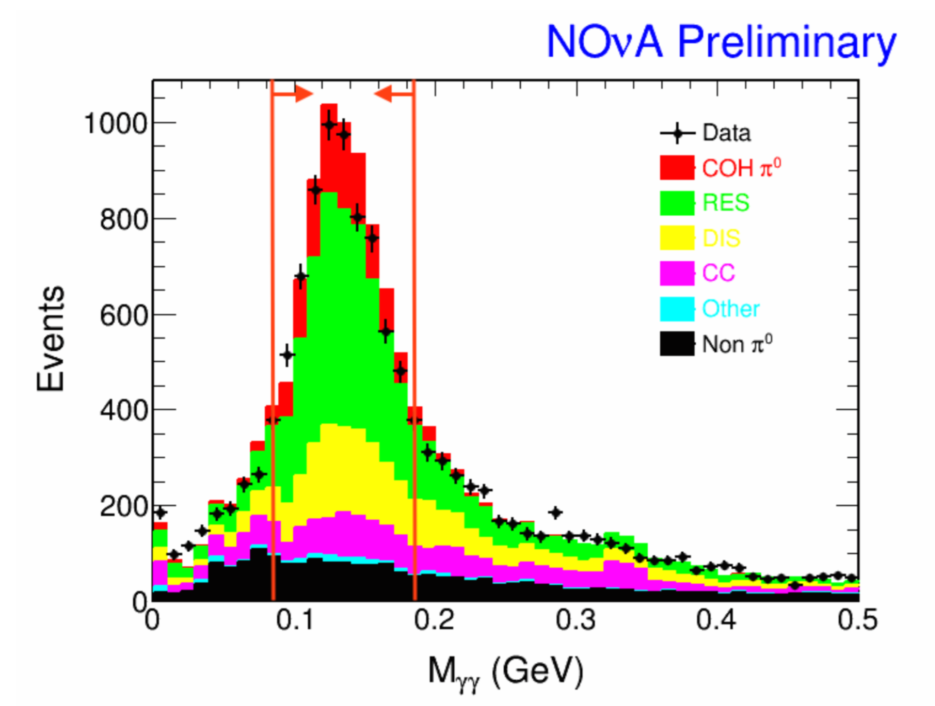

ALMATY
FIS SKI JUMPING WORLD CUP
VIESSMANN
LIQUI MOLY
SKI JUMPING WORLD CUP
Audi
48
49
ALMATY
FISCHER

Near Detector Cross Sections

Electron-neutrino inclusive cross-section

- Important for understanding electron neutrino interactions in current and future long-baseline experiments
- ~ 50% higher than the GENIE prediction, but agree to about 1.5 sigma
- Note that data points are highly correlated.
- Presented at Fermilab Wine and Cheese last week.





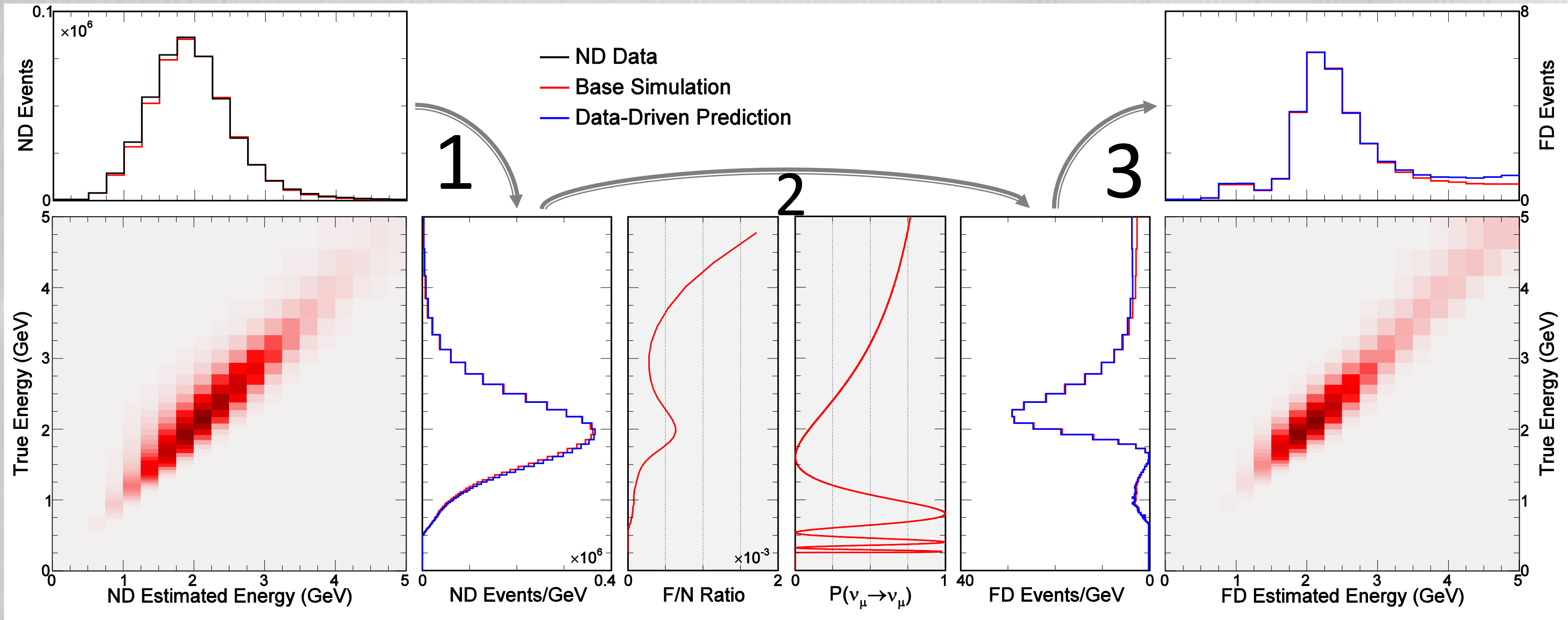
Coherent π^0 production.

- Single forward-going pion in the final state, no vertex activity.
- Background to ν_e analyses

Both results in process of publication.
Many other Near Detector analyses in process.

Far Detector Neutrino Prediction

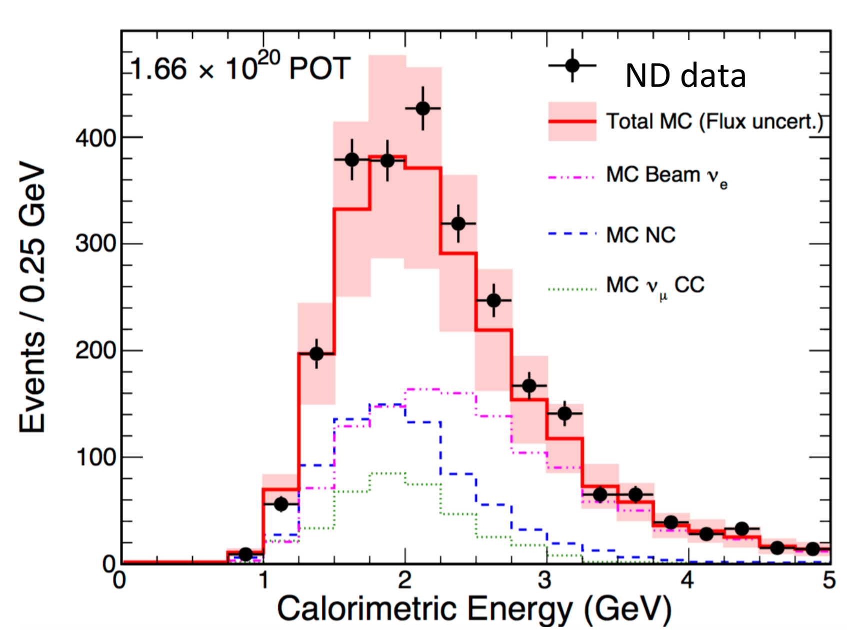
- We use a data-driven technique to extrapolate the neutrino events in the near detector to the far detector:
  1. Estimate true energy distribution of near detector events.
  2. Multiply by expected far/near event ratio and oscillation probability.
  3. Convert far detector true energy into reconstructed energy.

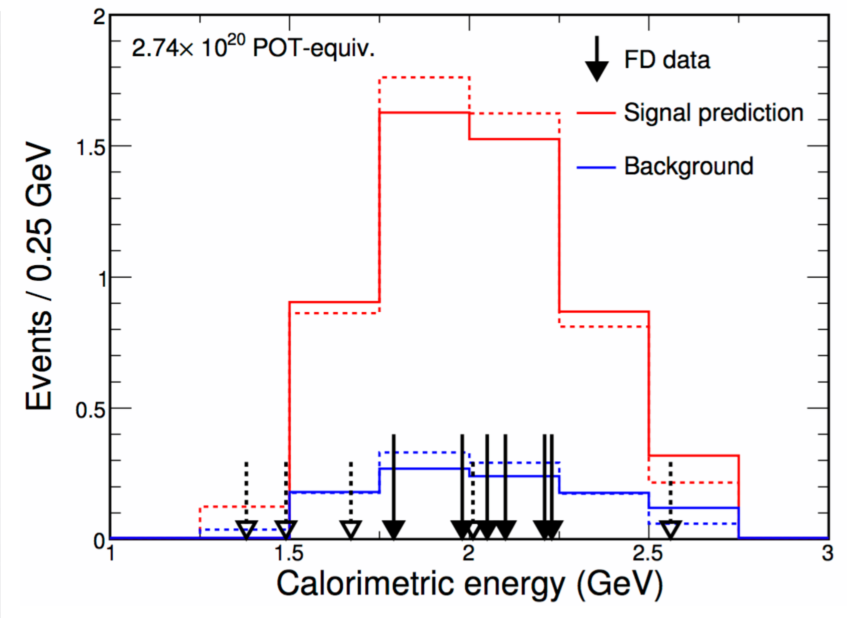


First results: $\nu_\mu \to \nu_e$ Appearance

arXiv:1601.05022

- Decided to implement two independent particle IDs: "LID" and "LEM". LID is the primary. "Cut and count" between 1.5 and 2.7 GeV.
- These select **6 (LID)** and **11 (LEM)** events. All 6 of the LID events are selected by LEM. Expected **background is 1 event** for each.
- LID and LEM have 62% overlap, determined from simulation and checked in NOvA near detector. The P-value for selecting the combination (11:6/5/0) is 7.8%.
- Top plot shows the ND energy spectrum of e-like candidates. Bottom plot shows the energy spectrum of the 11 events. LID are in black, LEM in dashed.

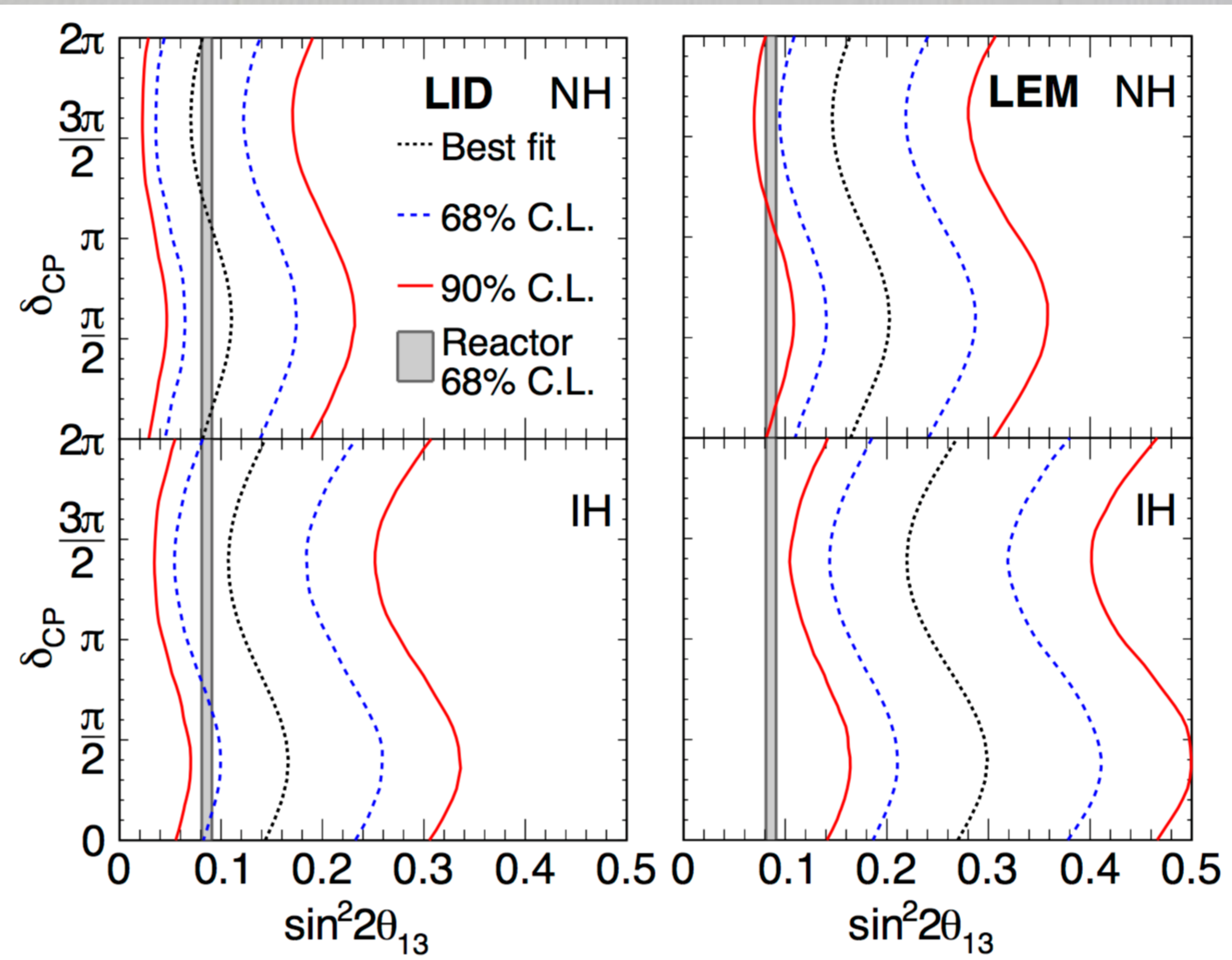




6 LID ν_e candidates
(3.3 σ signal of ν_e appearance)

11 LEM ν_e candidates
(5.5 σ signal of ν_e appearance)

First results: $\nu_\mu \rightarrow \nu_e$ Appearance



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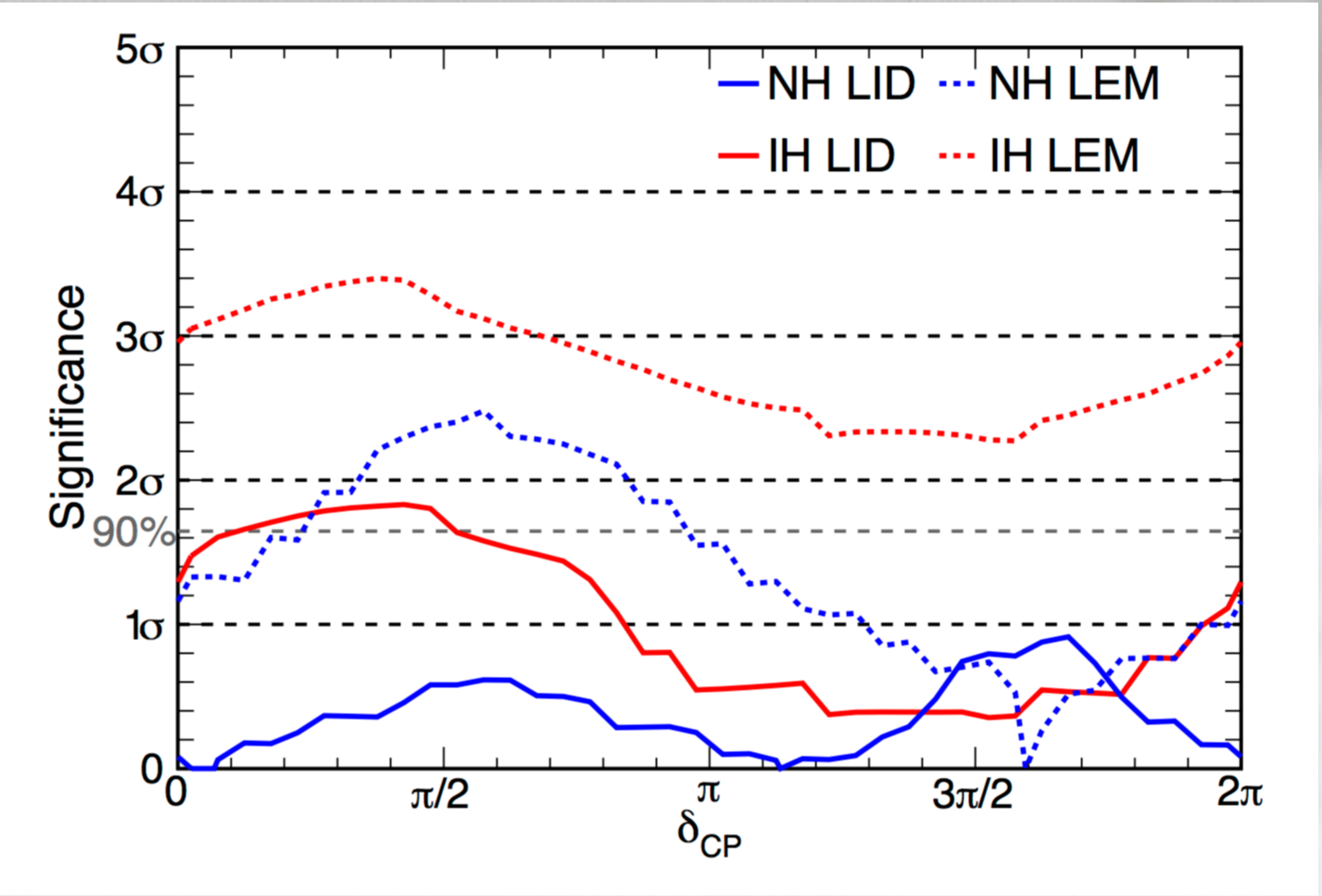
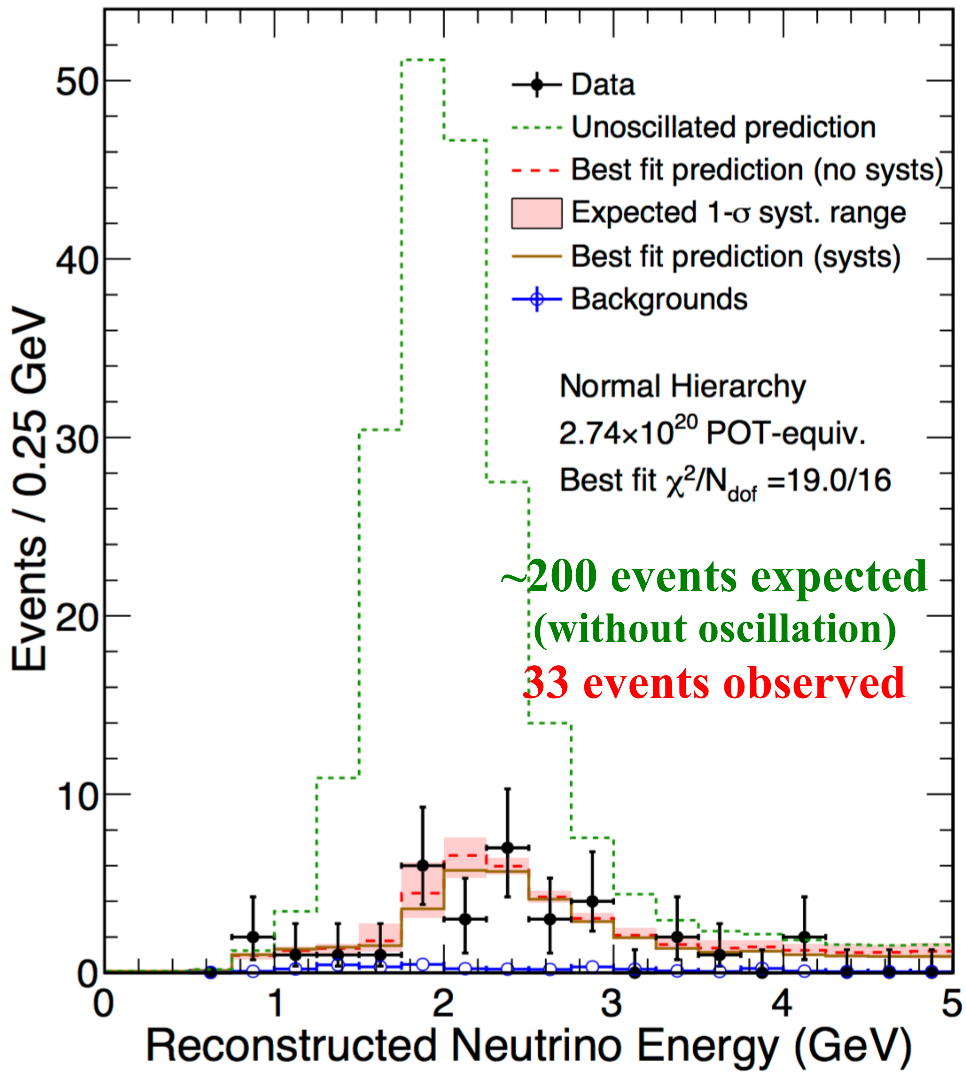
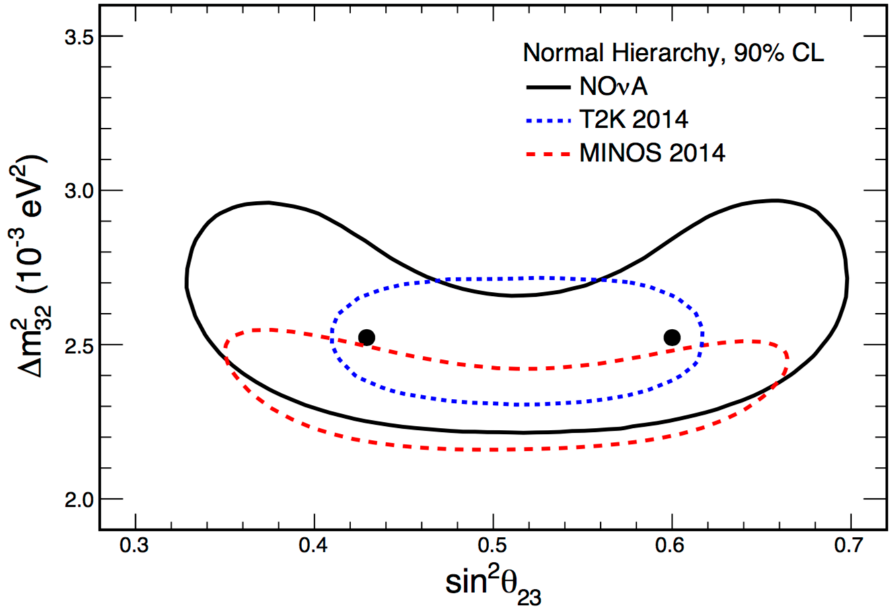


Muon Neutrino Disappearance - Results





$$0.38 < \sin^2\theta_{23} < 0.65$$
$$\Delta m^2 = 2.52^{+0.20}_{-0.18}\ \mathrm{meV}^2 \quad (68\%\ \mathrm{C.L.})$$

arXiv:1601.05037

Accepted by Physical Review D, RC

Exotics

Exotic Triggers at NOνA

- Upward-going muon – Atmospheric physics and search for neutrinos produced from dark matter annihilation.
- High-energy (large dE/dx) – Highly-ionizing particles, monopoles, ..
- Slow tracks (beta<<1) – slow monopoles, other slow particles
- High-energy trigger – cosmic ray air showers, high-energy cosmic rays
- SNEWS – Super Nova Early Warning System

Outlook and Conclusions

NOνA Outlook

- New oscillation results expected for Neutrino 2016 (July'16) with twice as much data.
- Both near and far detector are running well.
- Recent raised gain on the far detector -- tracking efficiency up from 85% to 92% at far end of 15.5 m long cells.
- Should see some 700 kW running this year. Sustained running at 700 kW depends on work to be done during summer'16 shutdown.
- Plan to run in neutrino mode until at least this summer.

NOνA Summary

- **NOνA will help answer important questions in neutrino physics**
  (Mass hierarchy / θ_{23} and its octant / CP violation / BSM)

- **With less than 8% of NOνA's design exposure:**

  - We see the unambiguous ν_μ disappearance signature with competitive oscillation measurements.

  - We see ν_e appearance signal at >3σ.

- **First analyses:**

  - $\nu_\mu \rightarrow \nu_\mu$: arXiv:1601.05037. Coming soon to PRDRC

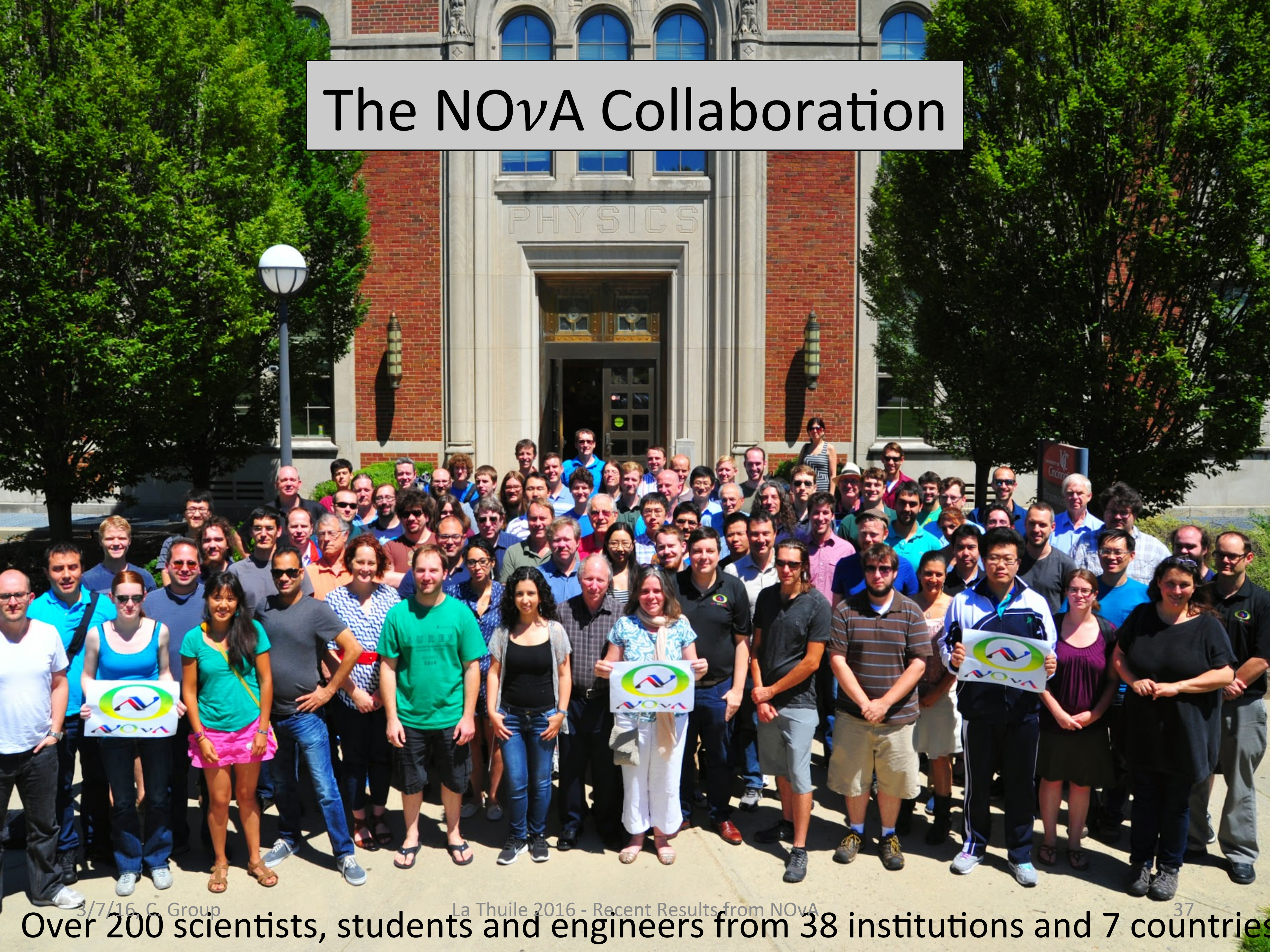
  - $\nu_\mu \rightarrow \nu_e$: arXiv:1601.05022. Coming soon to PRL

  - Cross-section program underway

- **Expect an update in July at Neutrino 2016 with twice the data sample**

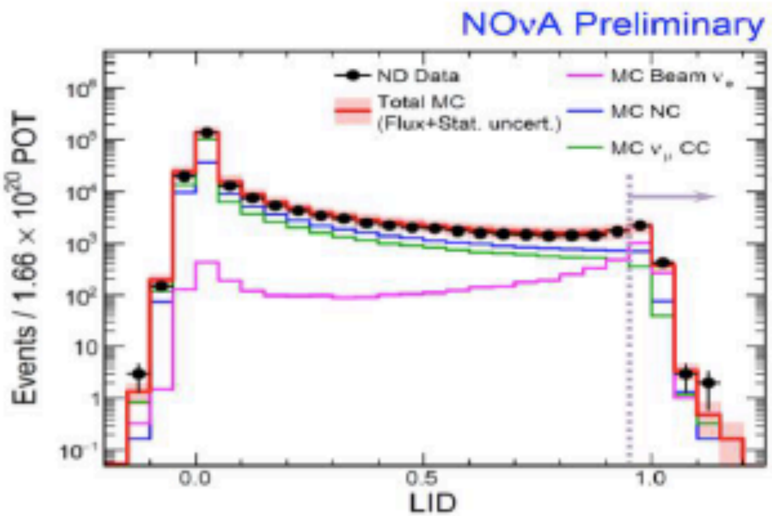

Thank you to the organizers!

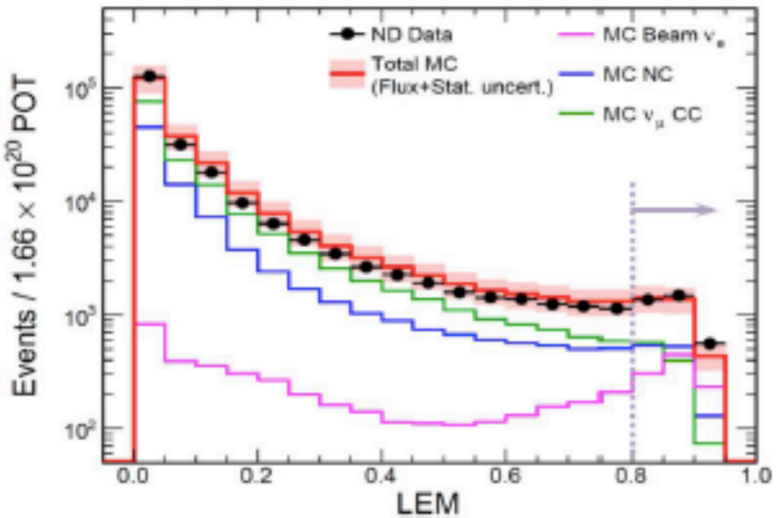
The NOνA Collaboration



Over 200 scientists, students and engineers from 38 institutions and 7 countries

LID and LEM





- LID
  - Calculates transverse and longitudinal dE/dx likelihoods for various particle hypotheses.
  - These, plus topological features, are fed into a standard neural network
- LEM
  - Finds best matches to a library of simulated events.
  - Properties of the best matches are fed into a decision tree.

Good data/MC agreement over the full PID range for both selectors.

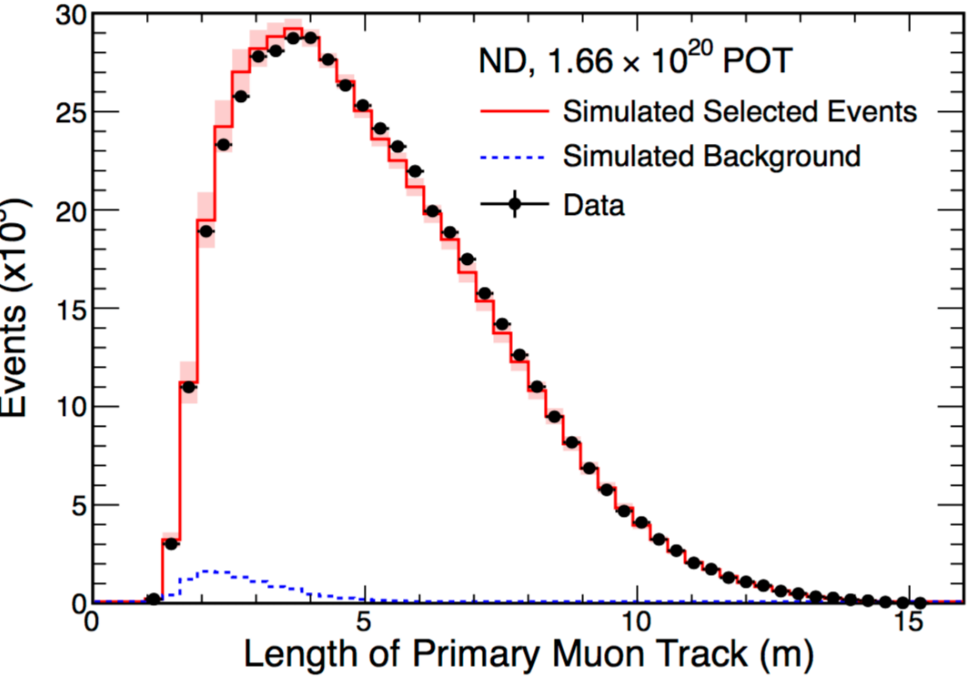
Signal and Background Predictions

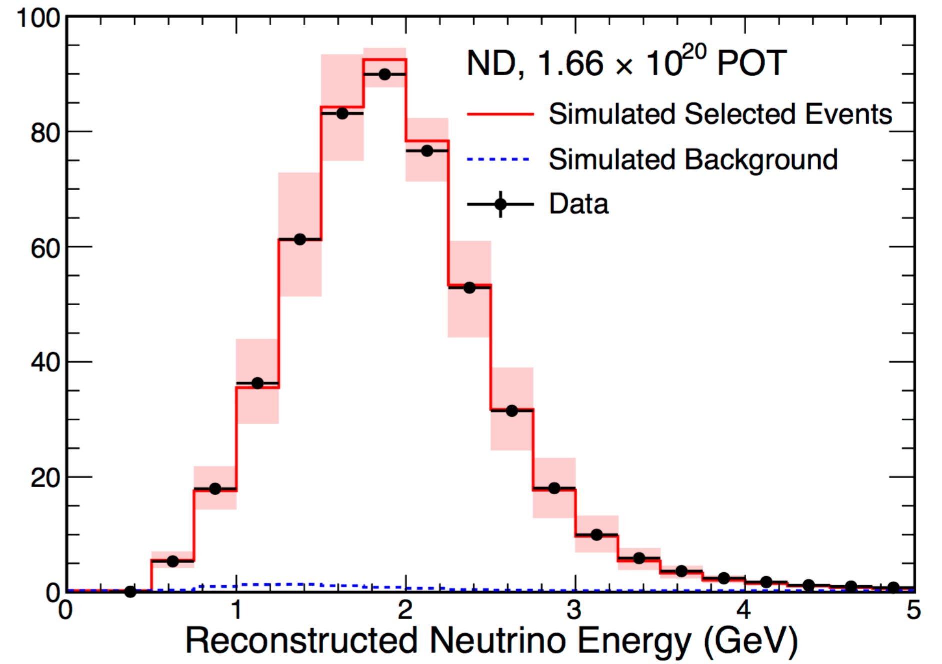
- Background prediction for both selectors is ~1 event with 10% systematic uncertainty.
- Selected backgrounds are dominated by beam ν_e and neutral current events.
  - Beam ν_e events are irreducible – can only be exclude if they are outside our chosen energy window.
  - Most selected neutral current events contain an energetic π^0.
- Signal prediction depends on chosen oscillation parameters.
- Both selectors have ~same performance. Prior to unblinding, decided to show results using both selectors, but use the more traditional LID as our primary selector.

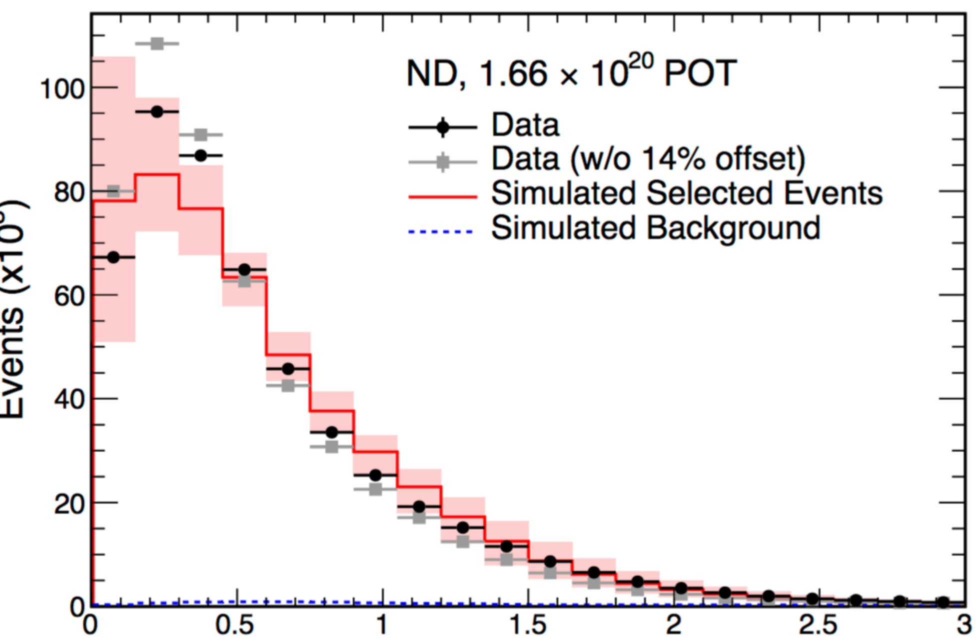
	Total Bkg	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic
LID	0.94 ± 0.09	0.47	0.36	0.05	0.02	0.06
LEM	1.00 ± 0.11	0.46	0.40	0.07	0.02	0.06

Signal prediction: →
Chosen parameters reflect the outer range of possible results.

	NH, $\delta_{CP} = 3\pi/2$	IH, $\delta_{CP} = \pi/2$
LID	5.62 ± 0.72	2.24 ± 0.29
LEM	5.91 ± 0.59	2.34 ± 0.23







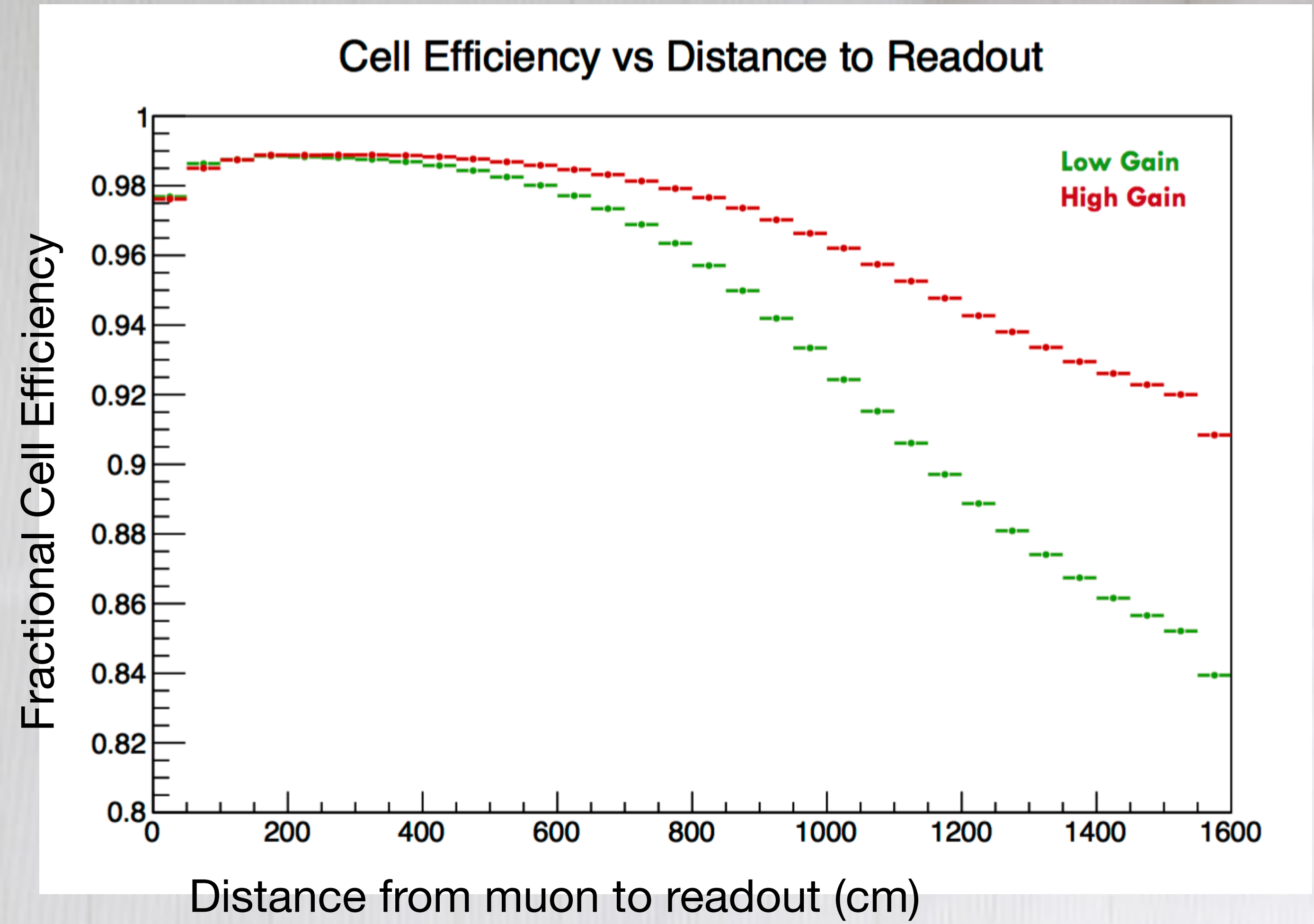
$\nu_\mu \rightarrow \nu_\mu$ Disappearance ND modelling

- top left: Muon path length in ND
- bottom left: Hadronic energy in ν_μ-CC events in ND
- top right: ν_μ-CC neutrino energy spectrum in ND

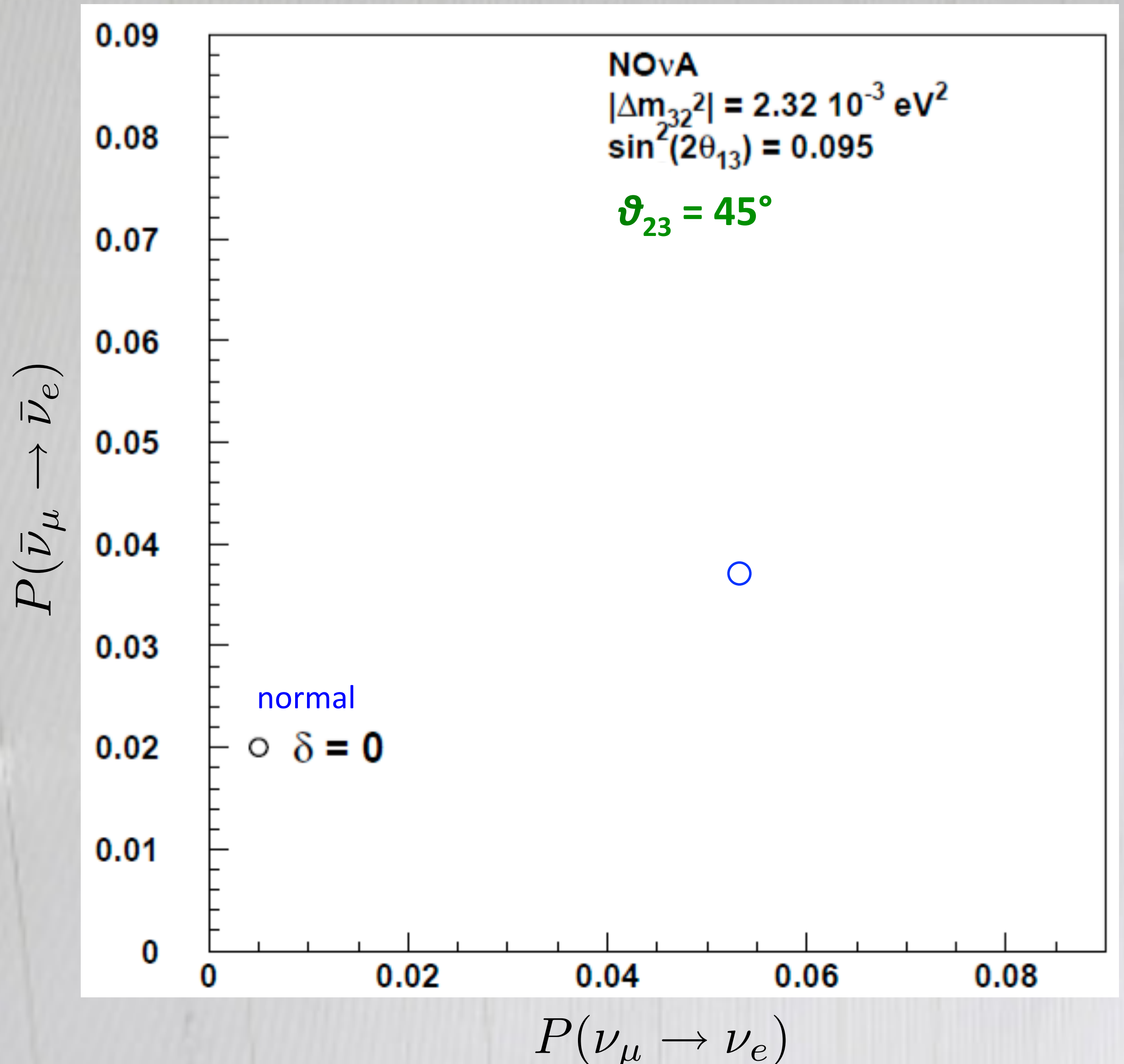
arXiv:1601.05037

Far Detector Status

- Took advantage of lower-than-spec APD noise to run far detector at higher gain (100→150)
- Tracking efficiency up from 85% to 92% at far end of 15.5 m long cells

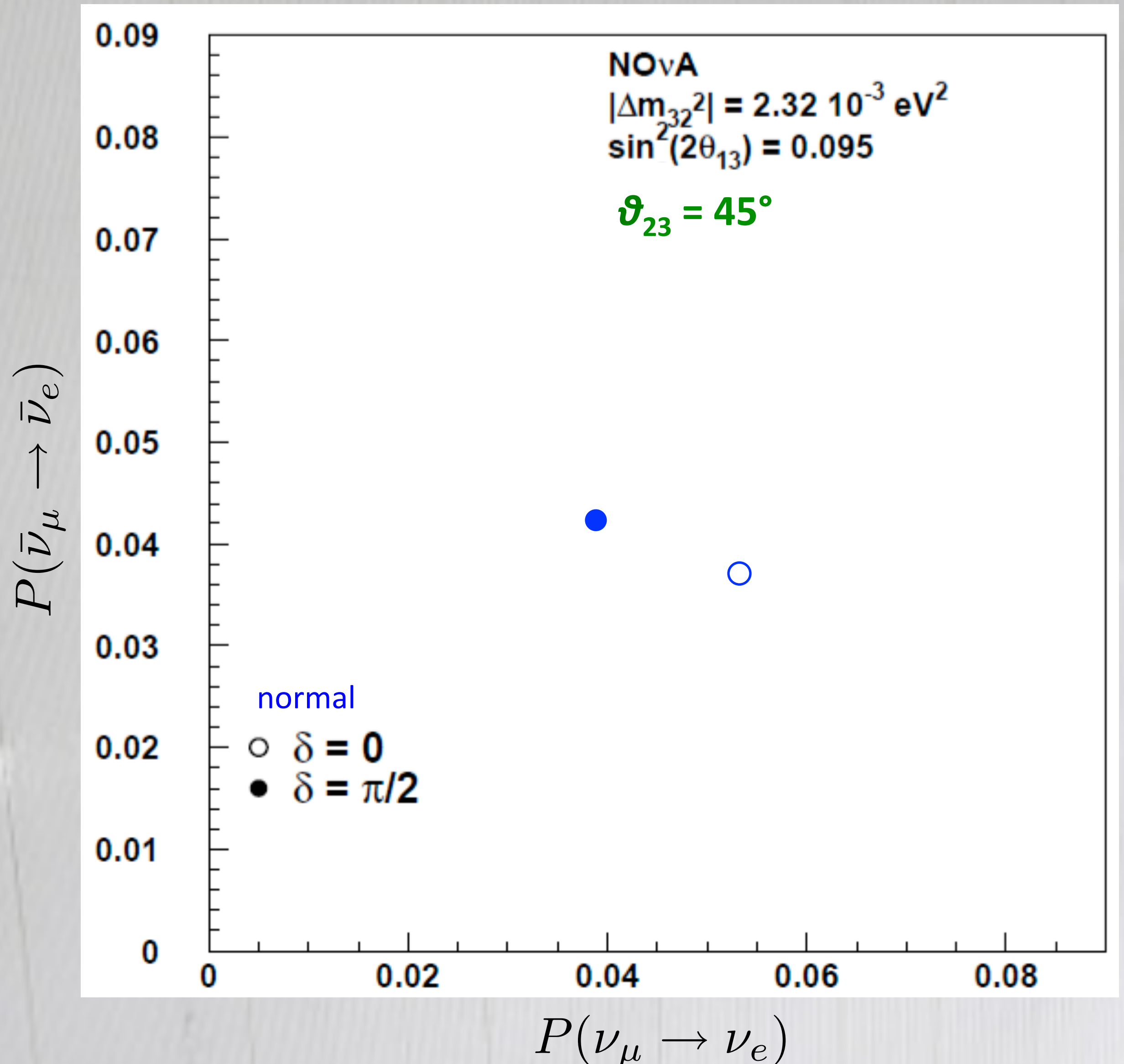


Principle of NOνA measurements



- Using the previous equations, we can calculate the neutrino and anti-neutrino appearance probabilities.

Principle of NOνA measurements



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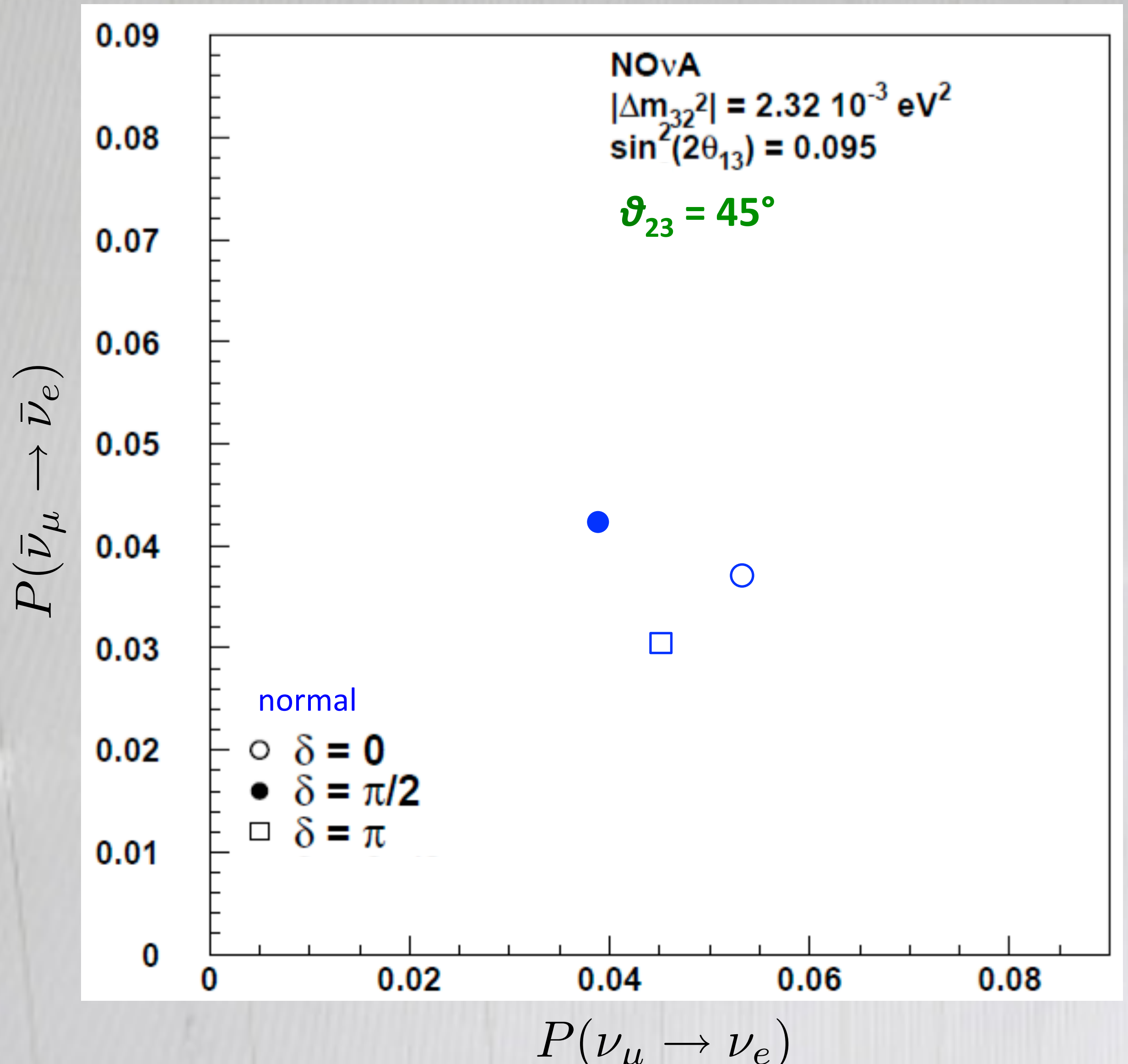

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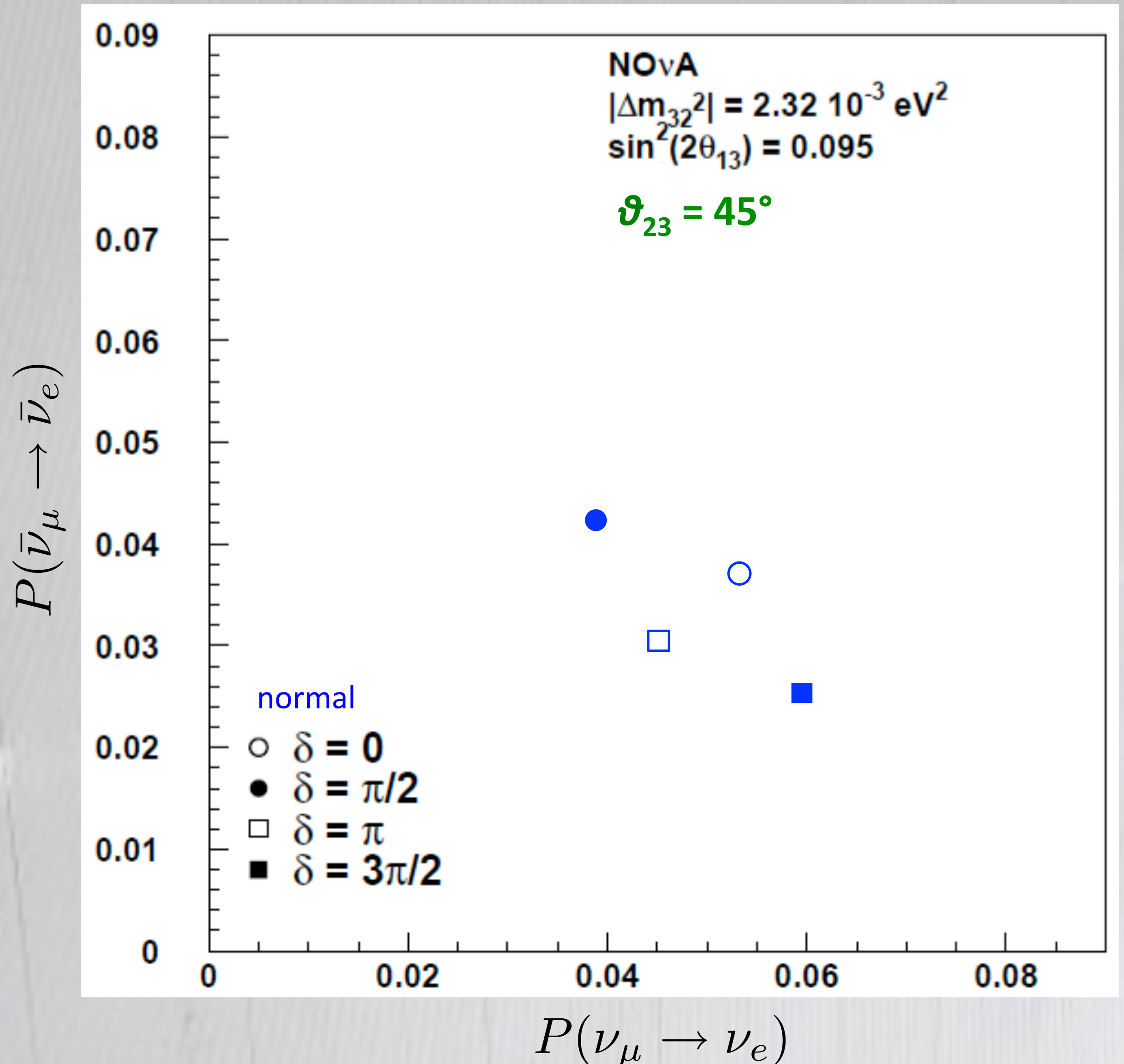

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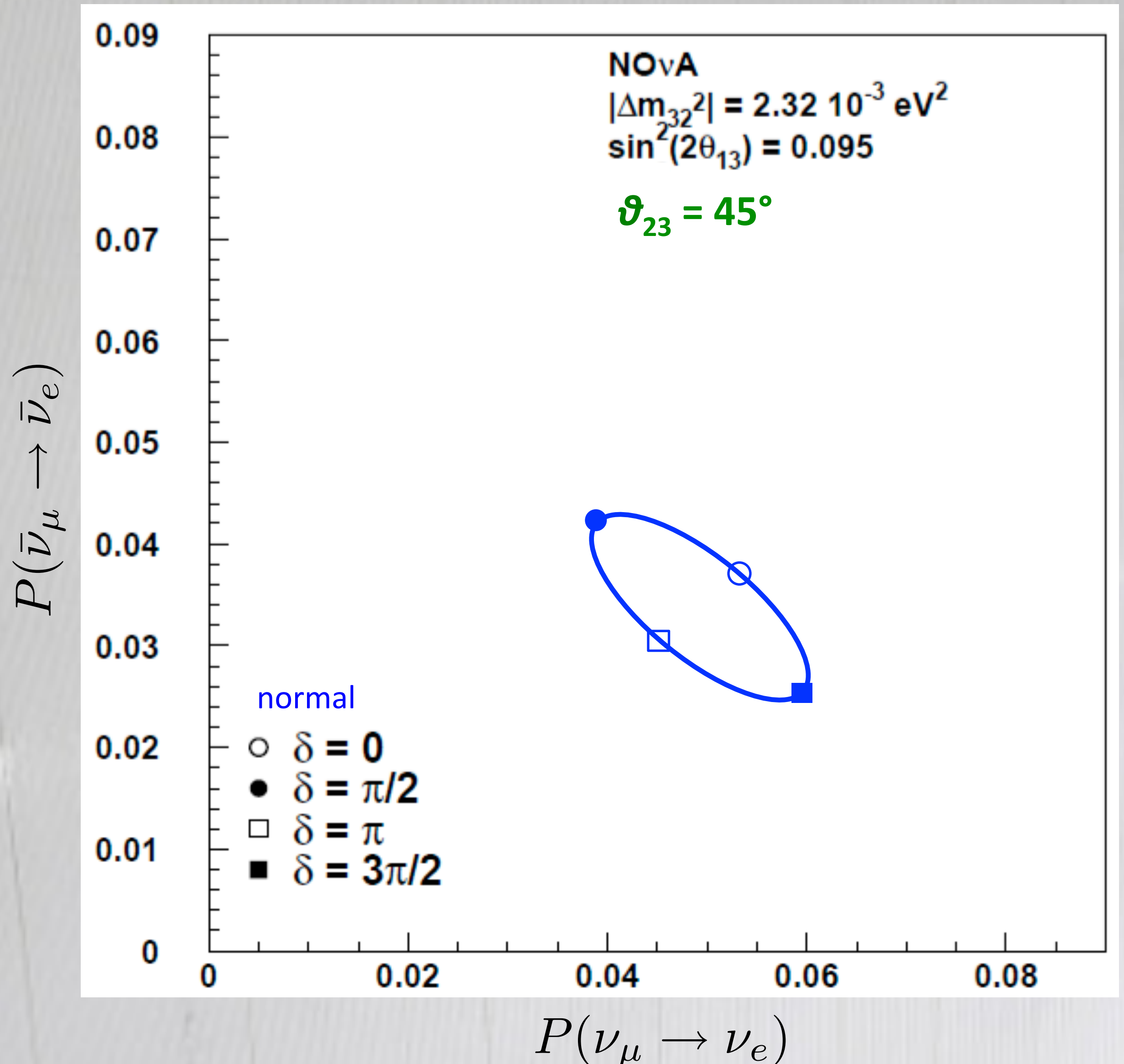

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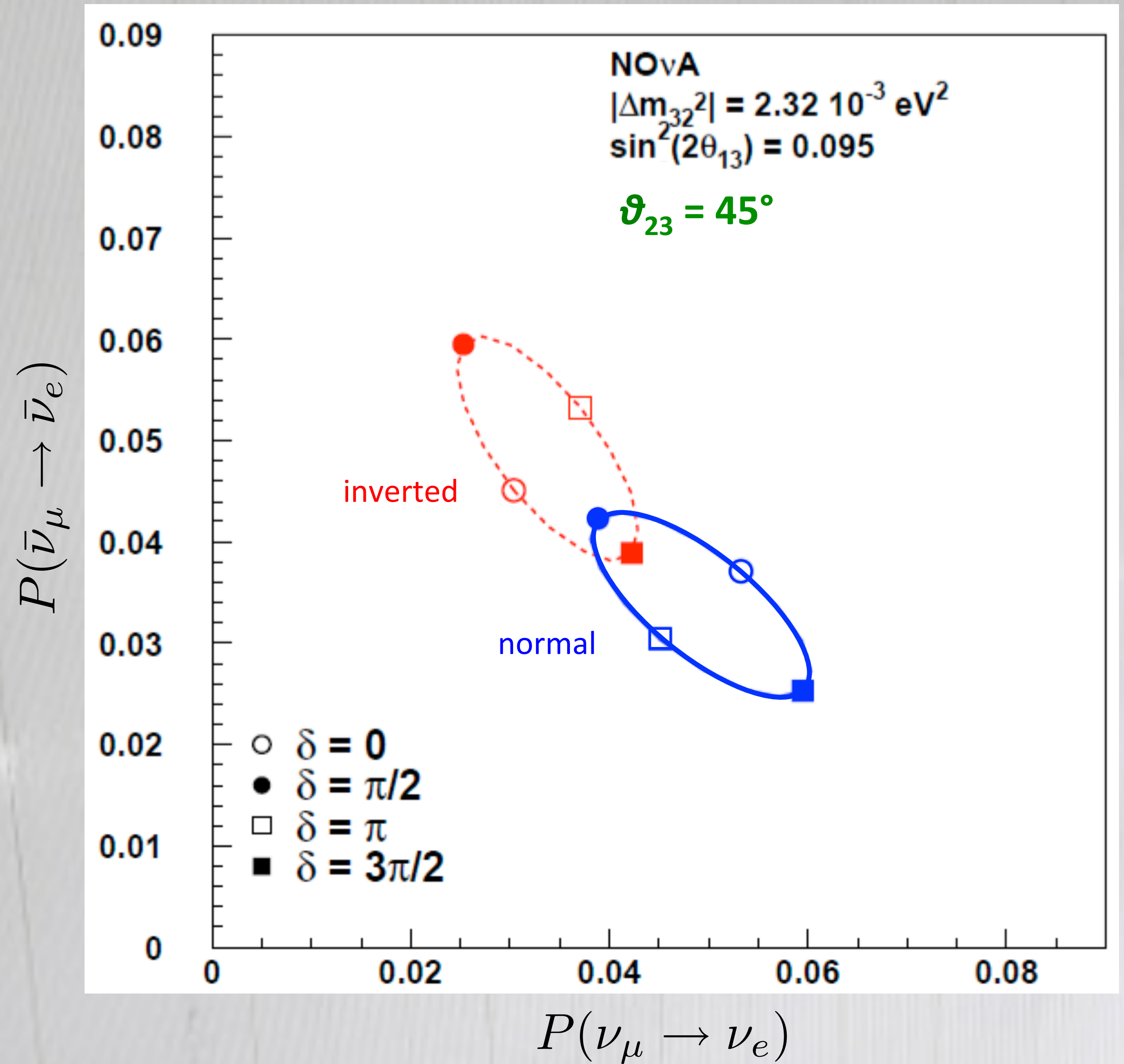
Principle of NOνA measurements



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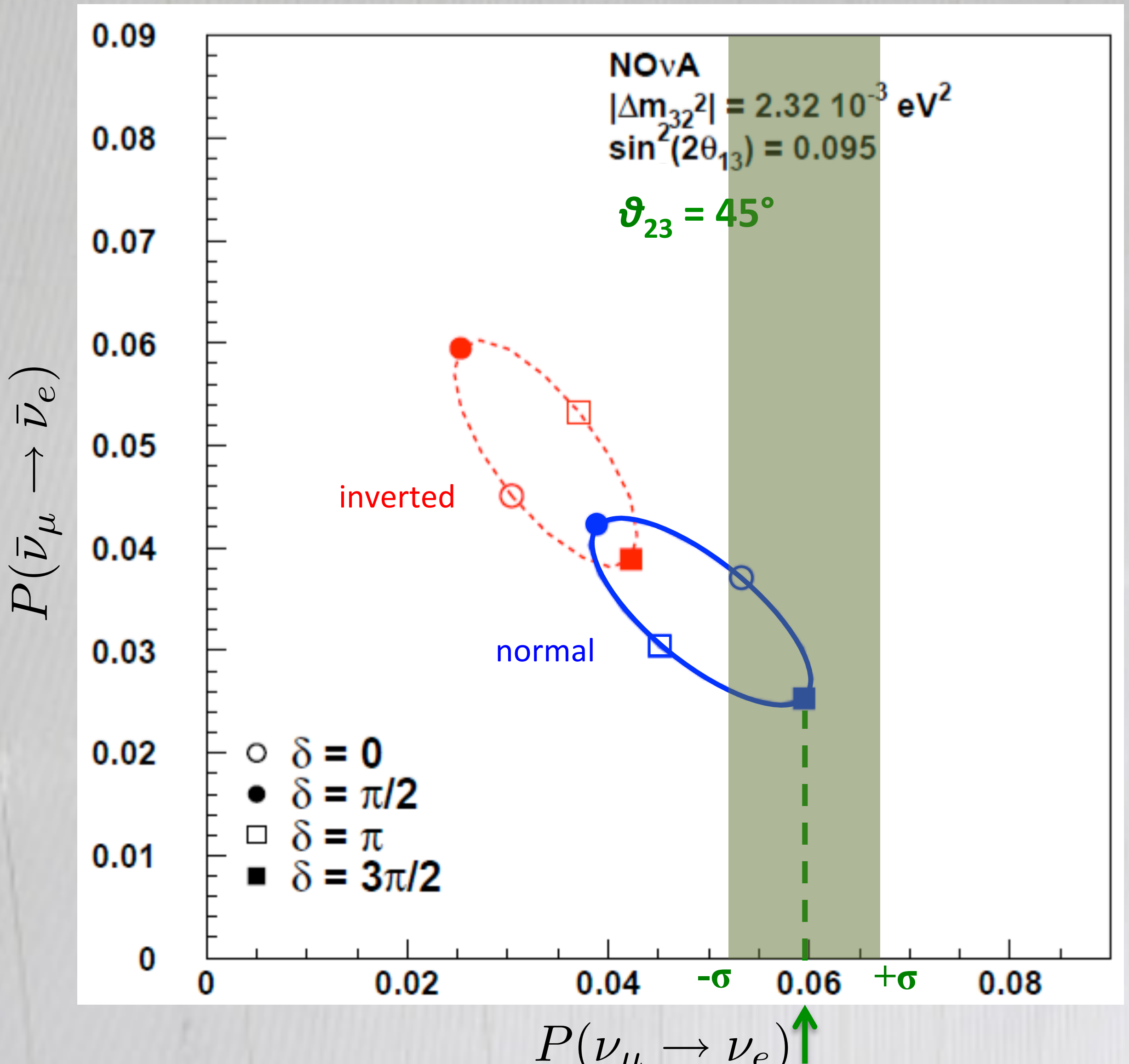
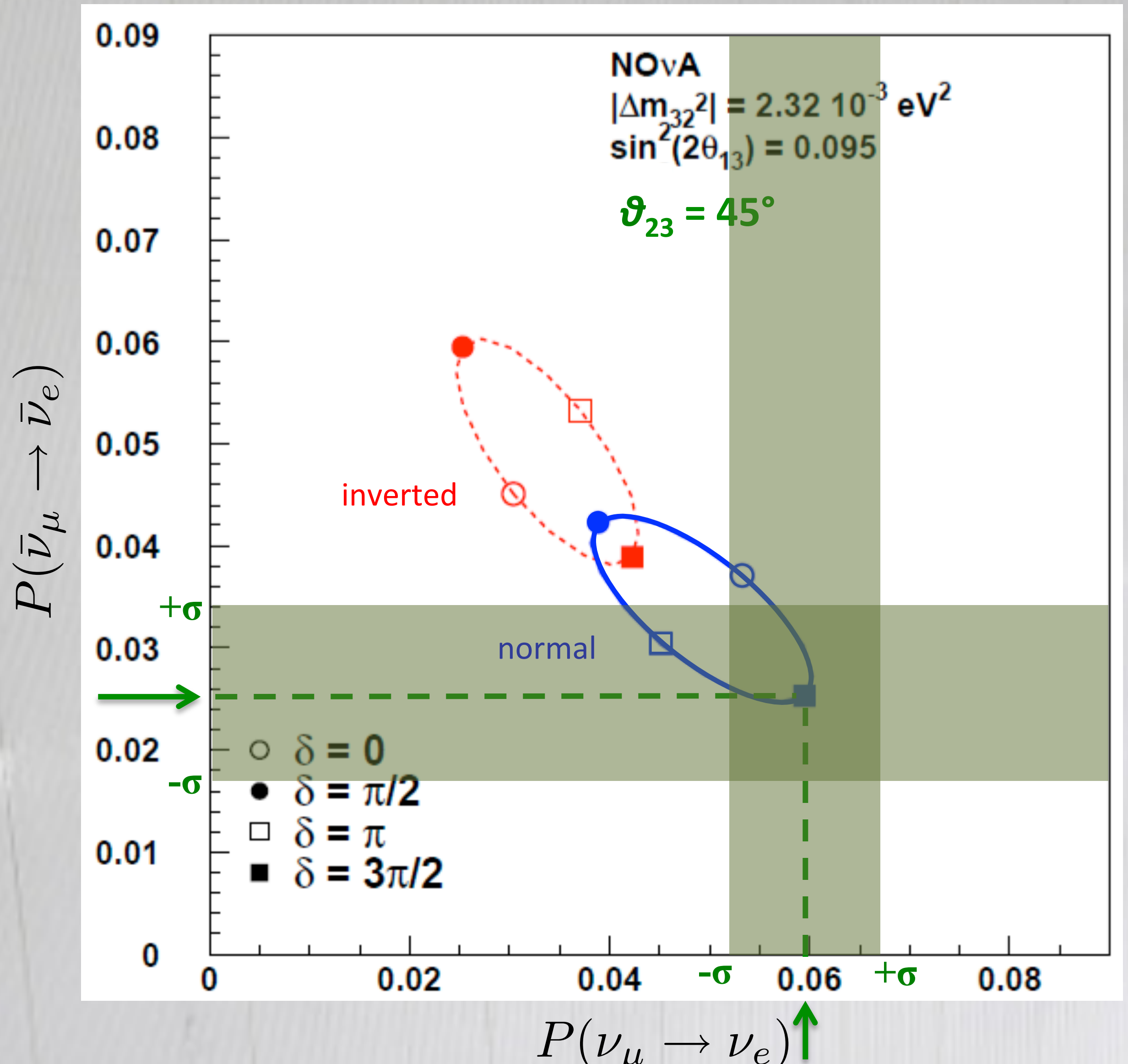
Principle of NOνA measurements



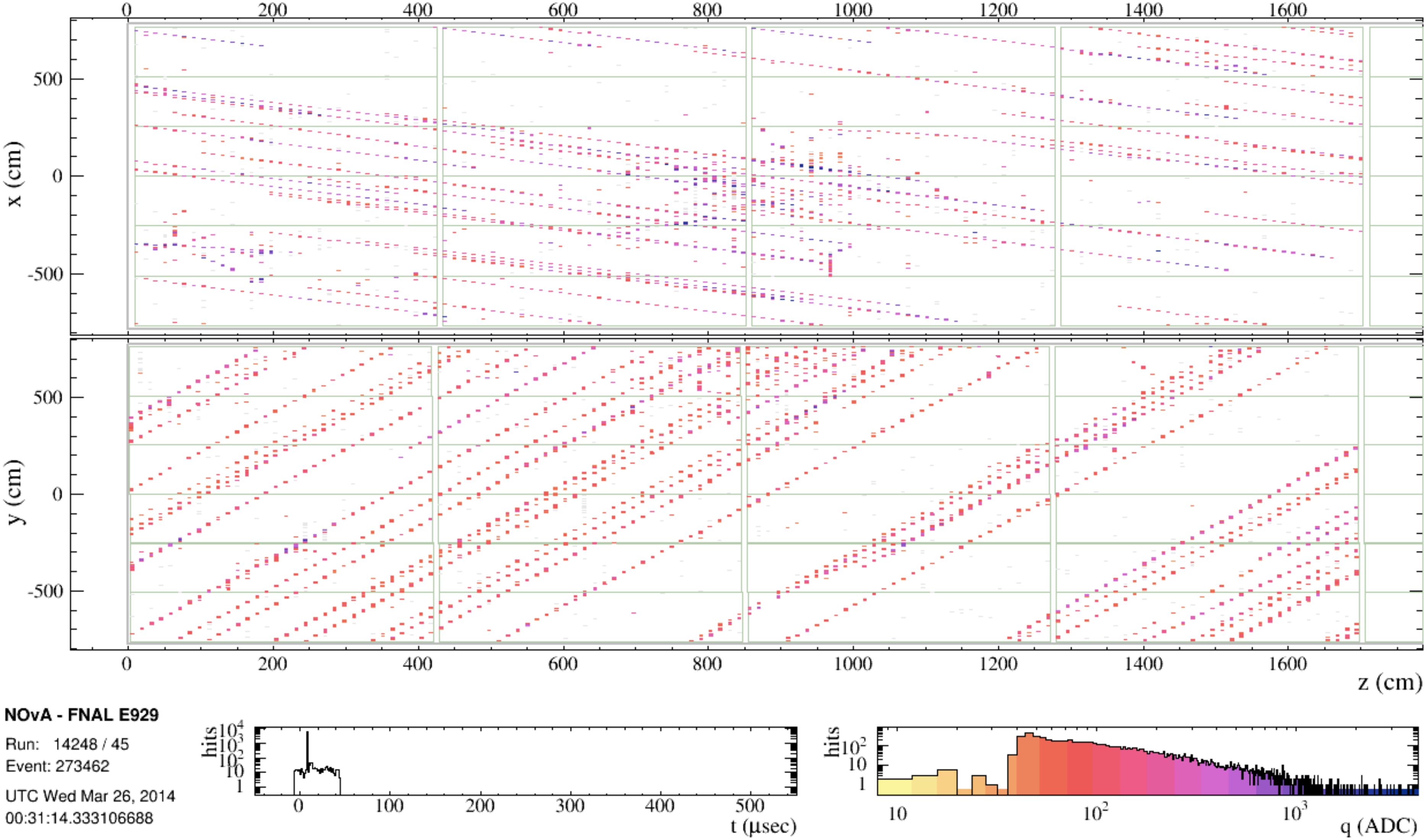
- Using the previous equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Here is an example measurement NOνA might make.

Principle of NOνA measurements



- Using the previous equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Here is an example measurement NOνA might make.
- Ambiguities exist for some regions of parameter space

Cosmic Ray Air Showers (triggered)



High Energy (triggered)