FIRST RESULTS FROM THE NOVA EXPERIMENT

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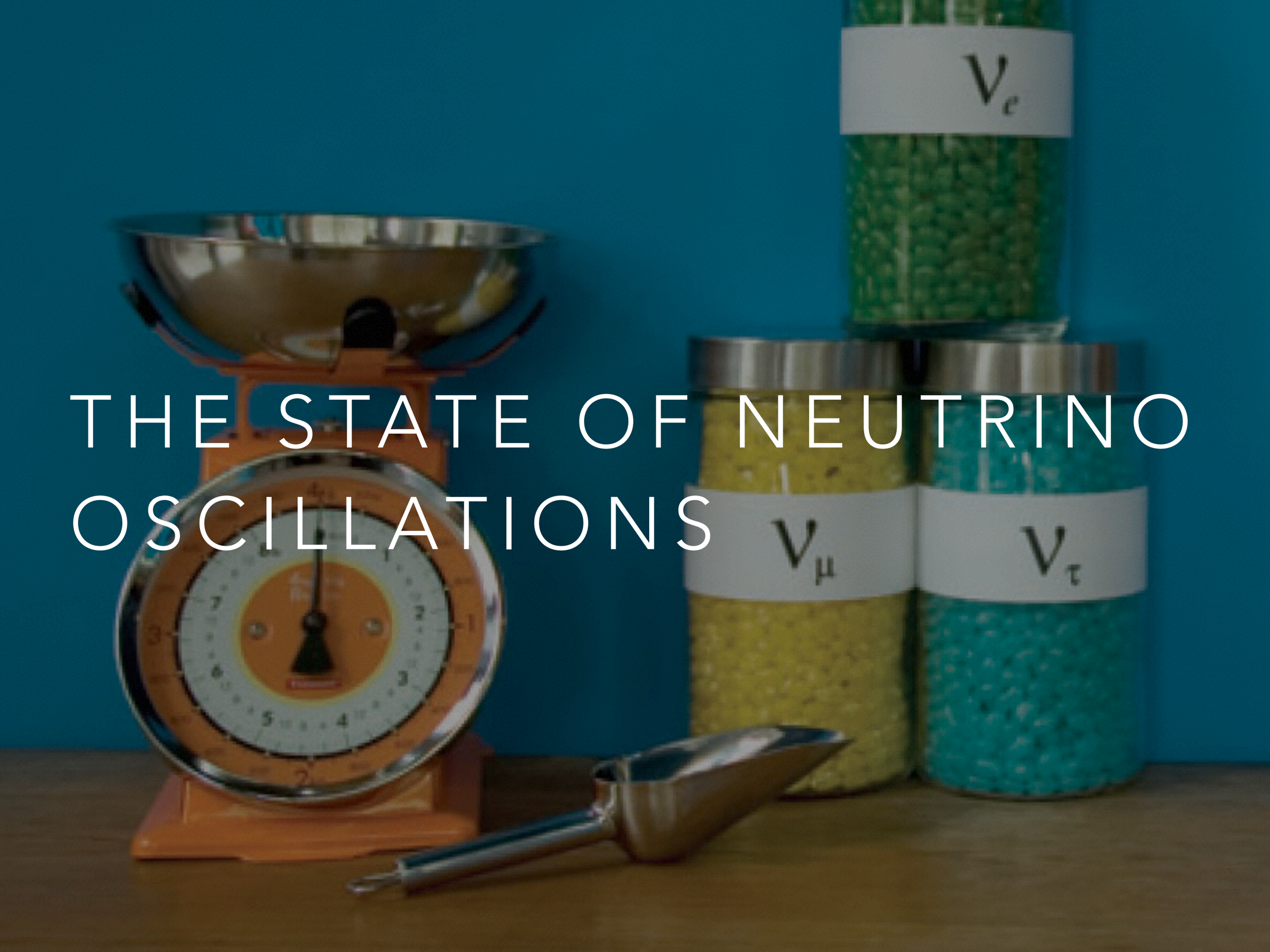
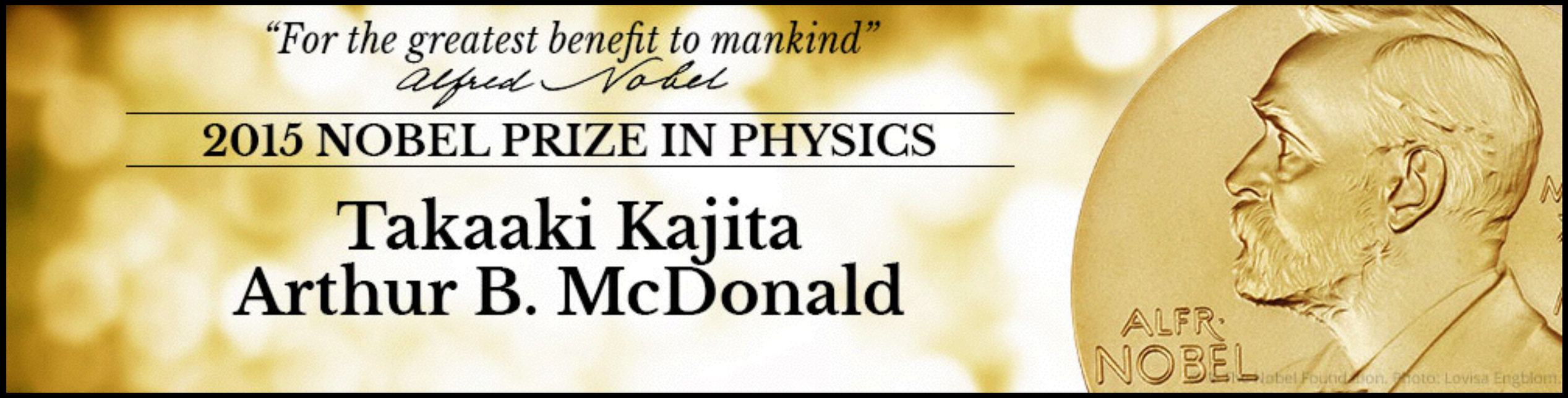
IOWA STATE UNIVERSITY

University of Chicago HEP Seminar — November 09, 2015

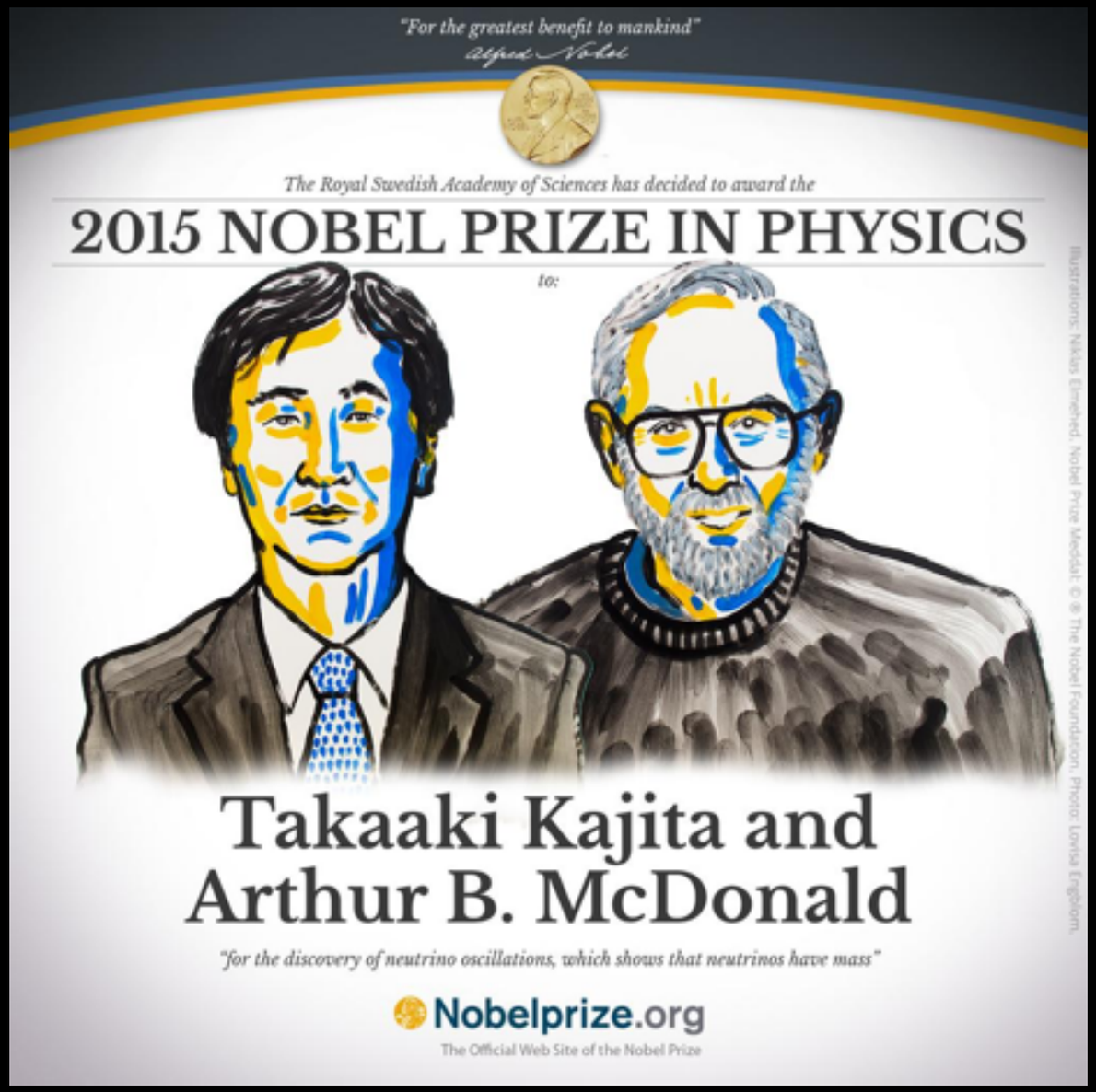
THE STATE OF NEUTRINO OSCILLATIONS





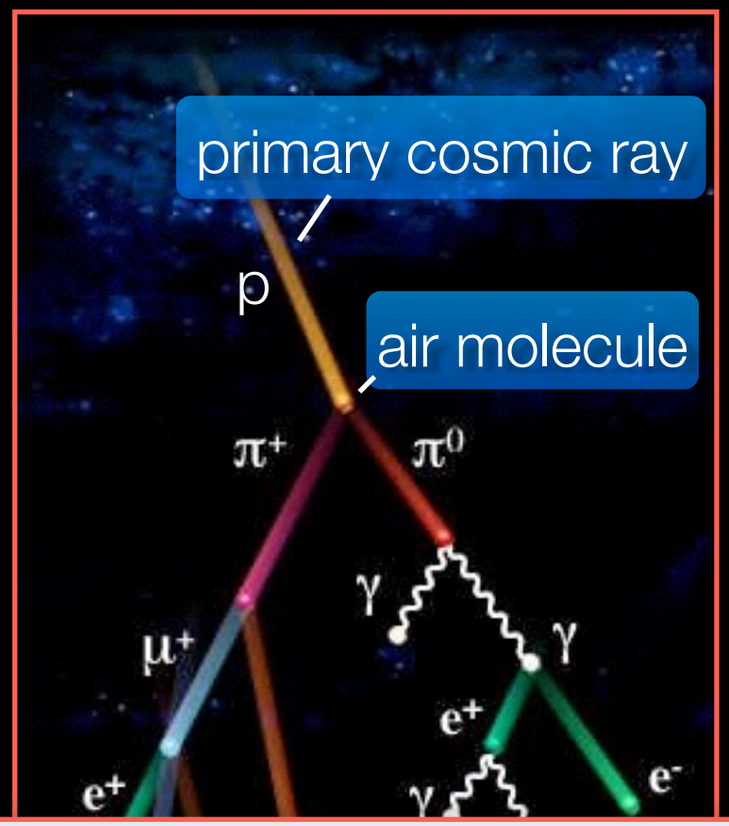
THIS YEAR'S NOBEL PRIZE

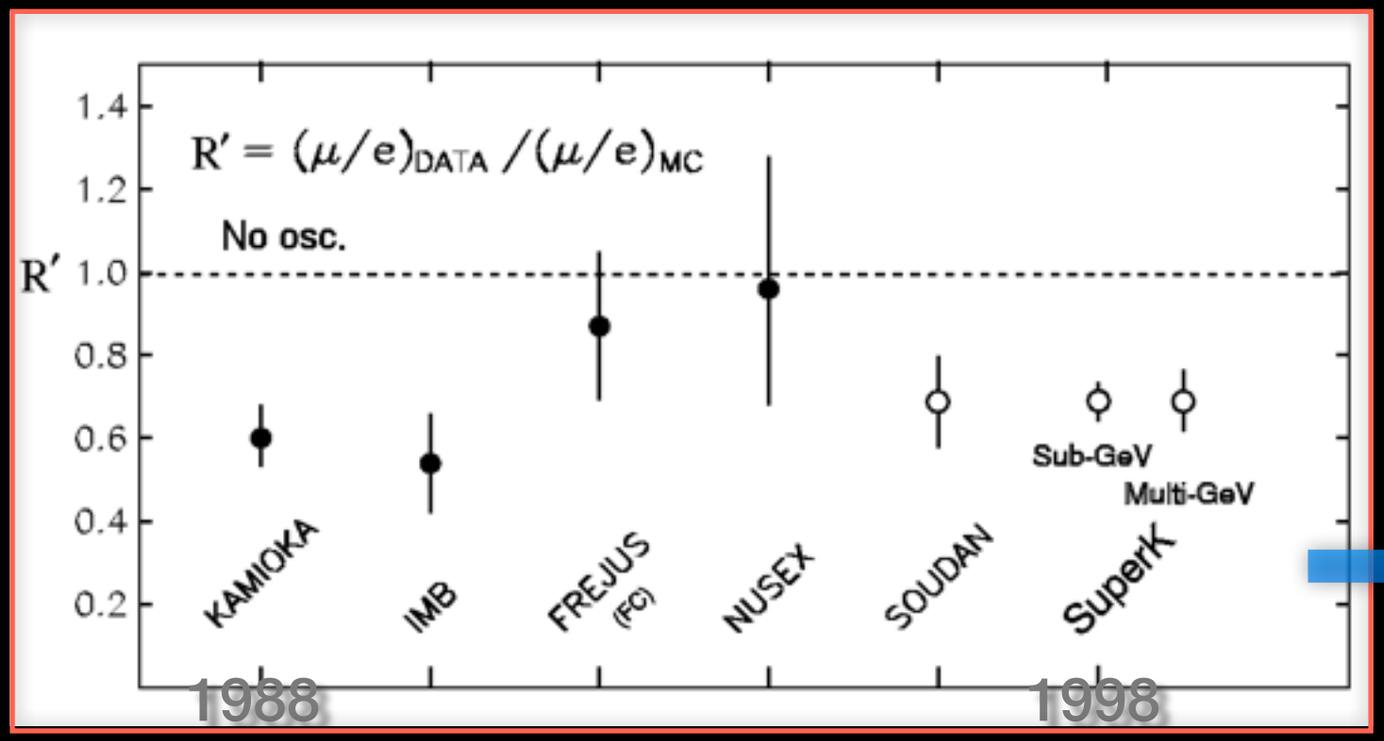
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

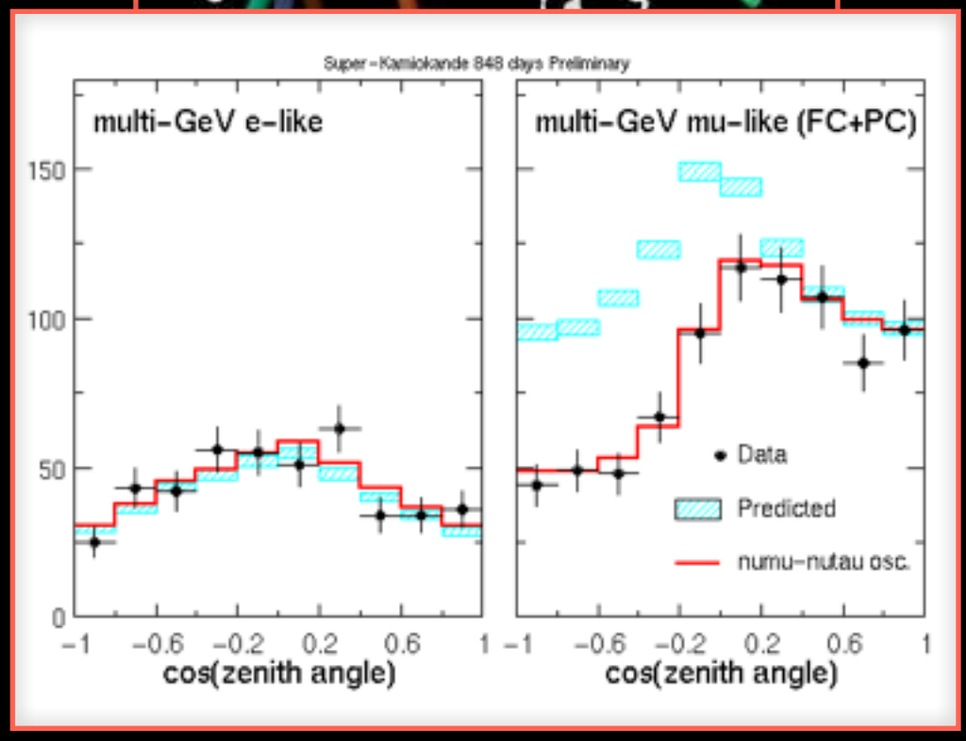


THE ATMOSPHERIC NEUTRINO ANOMALY

- Deficit first observed by IMB and Kamiokande, water based experiments. Experiments were designed for proton decay.
- A perfect example that having more than one experiment is very desirable.
- SuperK (lead by Kajita) observes the smoking gun for neutrino oscillations.

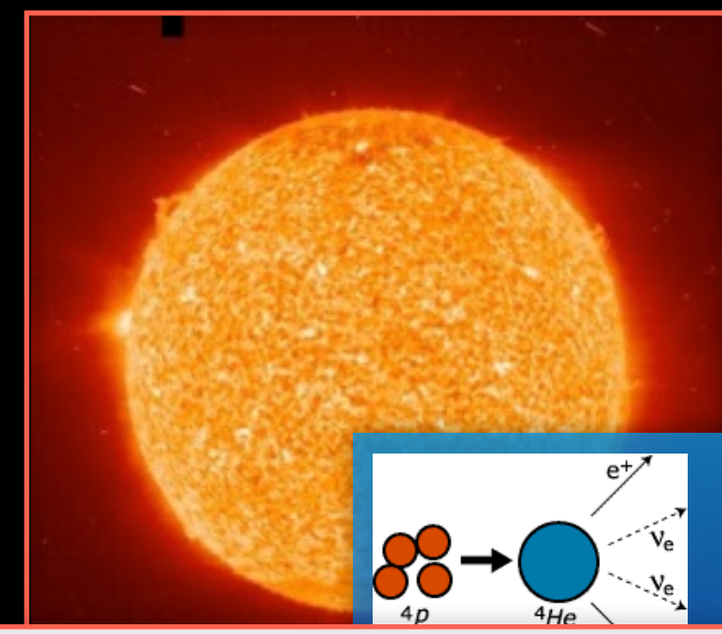




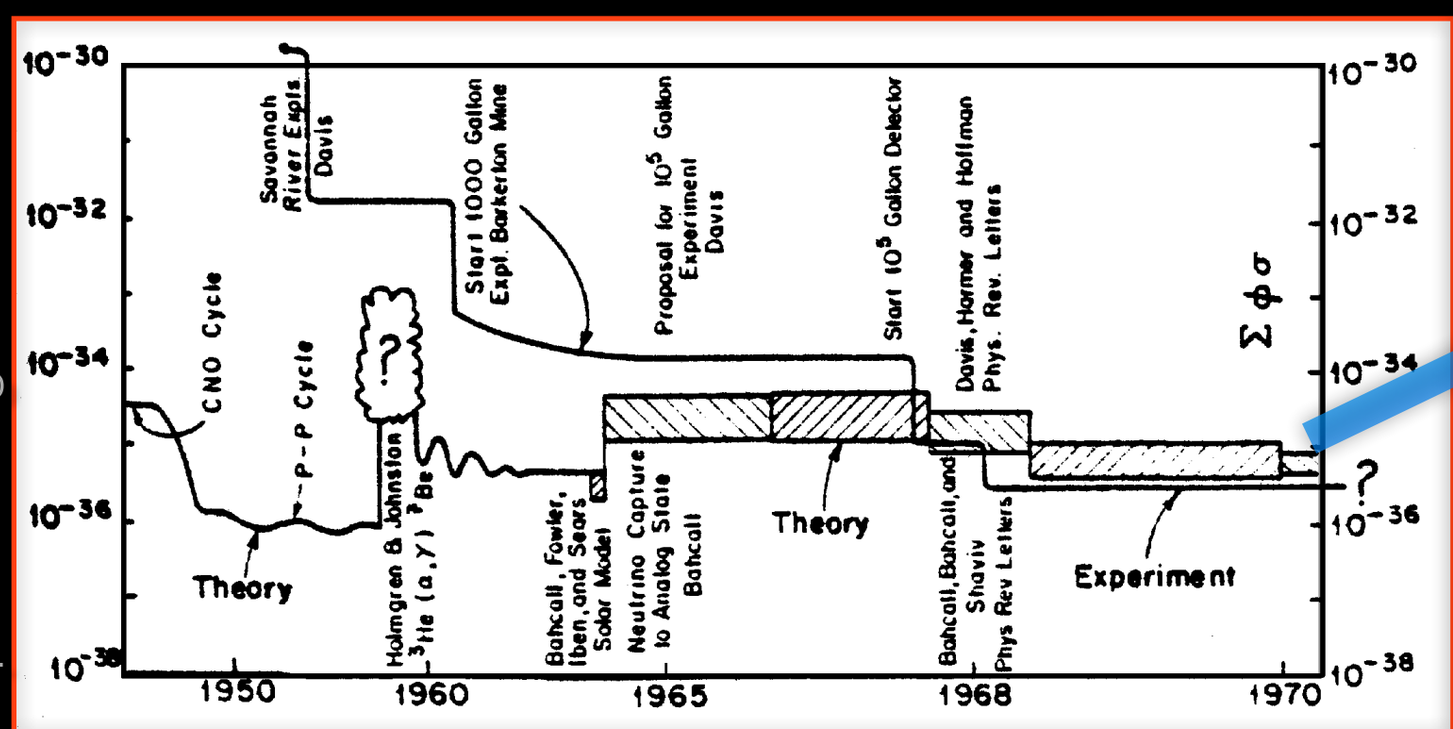


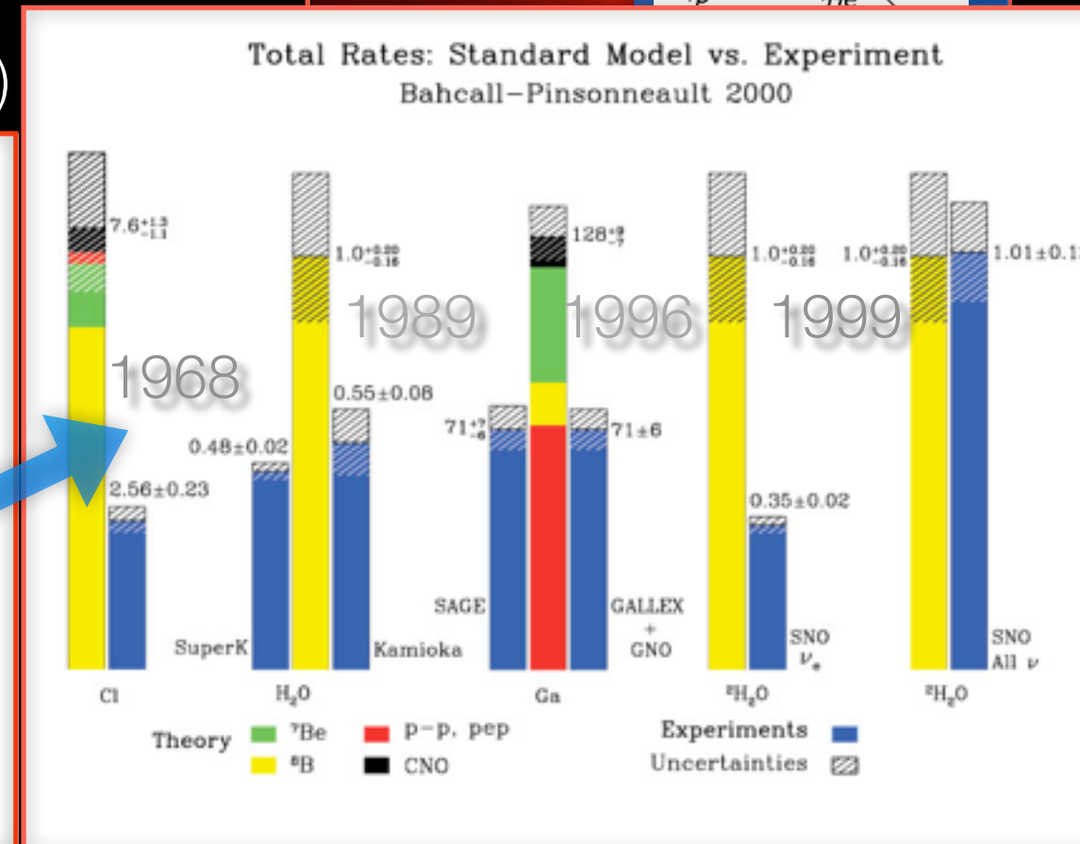
THE SOLAR NEUTRINO PROBLEM

- In the early 1960s Davis and Bahcall argued for a CL detector for solar neutrinos.
- In 1968 Davis (2002 Nobel Prize) publishes the first results indicating that only 1/3 of the neutrinos were observed, i.e. the solar neutrino problem.
- The SNO experiment (lead by McDonald) announces in 1999 that oscillations explains the solar neutrino problem.

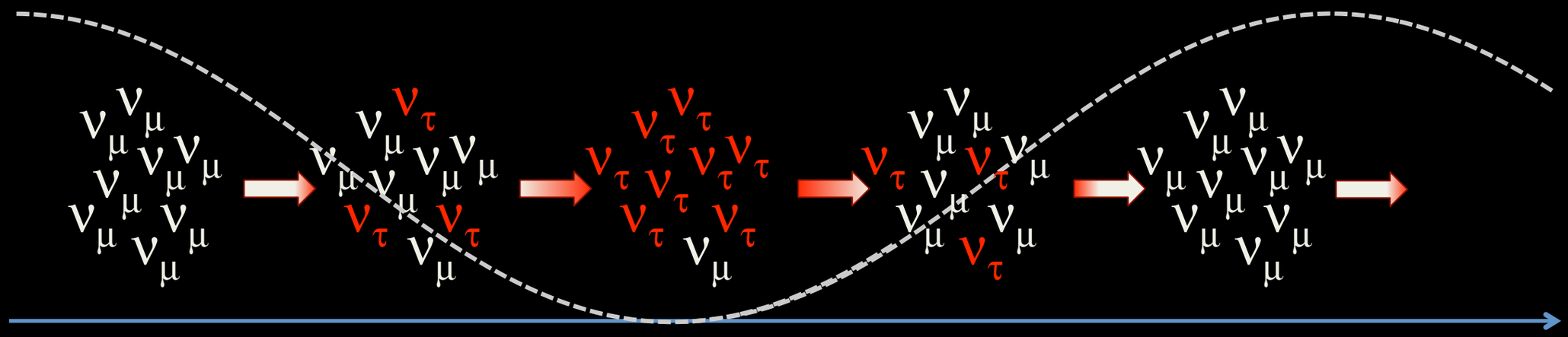


Ray Davis (1971)





NEUTRINO OSCILLATIONS



- Three flavor eigenstates are linear combinations of the mass eigenstates:

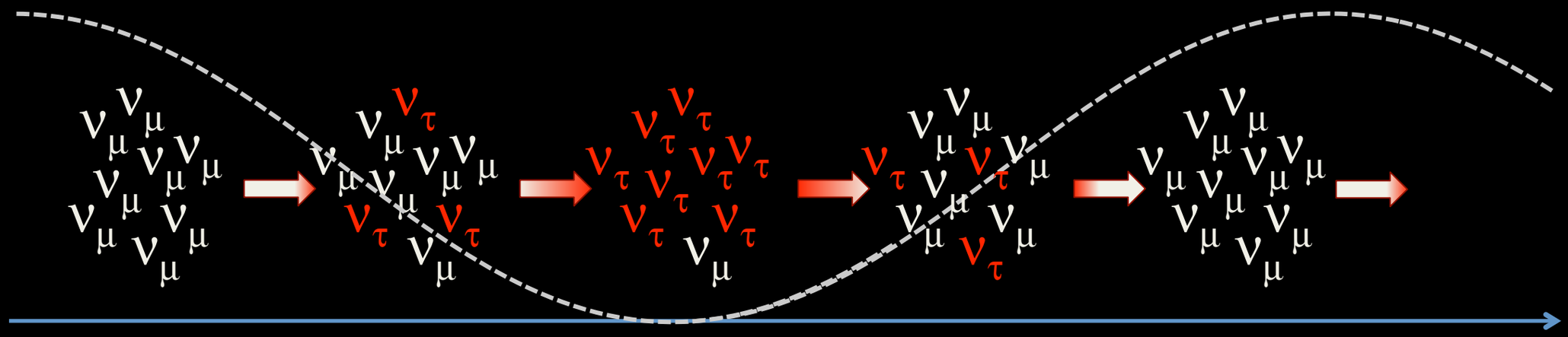
$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

- There is thus a non-zero probability of detecting a different neutrino flavor than that produced at the source:

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- The probability depends on the distance traveled and energy (experimental parameters) as well as the mixing amplitudes and the difference of the square of the masses (Nature's parameters).

NEUTRINO OSCILLATIONS



- Three flavor eigenstates are linear combinations of the mass eigenstates:

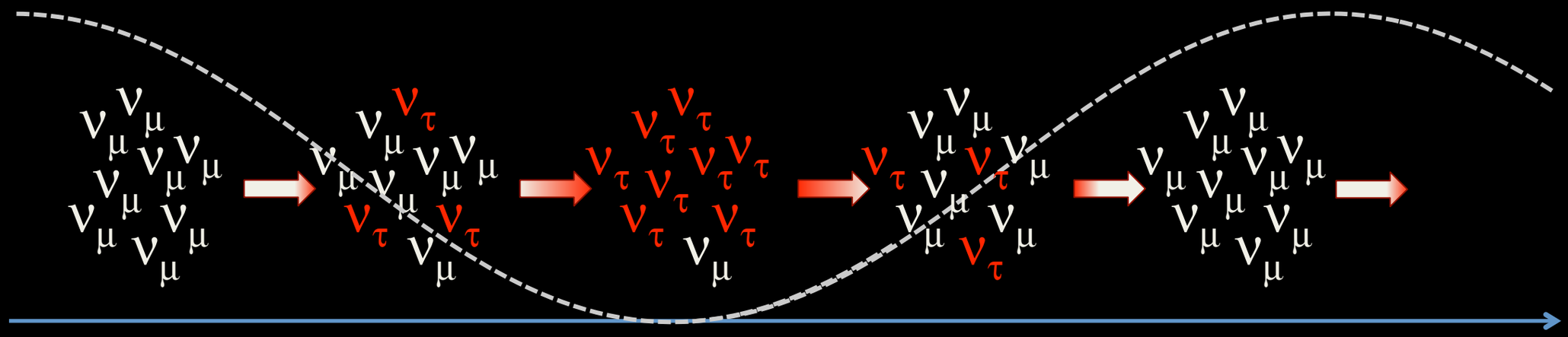
$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k}|\nu_k\rangle \quad (\alpha = e,\mu,\tau)$$

- Where the mixing matrix has 3 mixing angles and one phase (ignoring Majorana):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- The **(12)** sector: **Solar** + Reactor, L/E 15,000 km/GeV
- The **(23)** sector: **Atmospheric** and Accelerator, L/E 500 km/GeV
- The **(13)** sector: **Reactor** and Accelerator, L/E 500 km/GeV

NEUTRINO OSCILLATIONS



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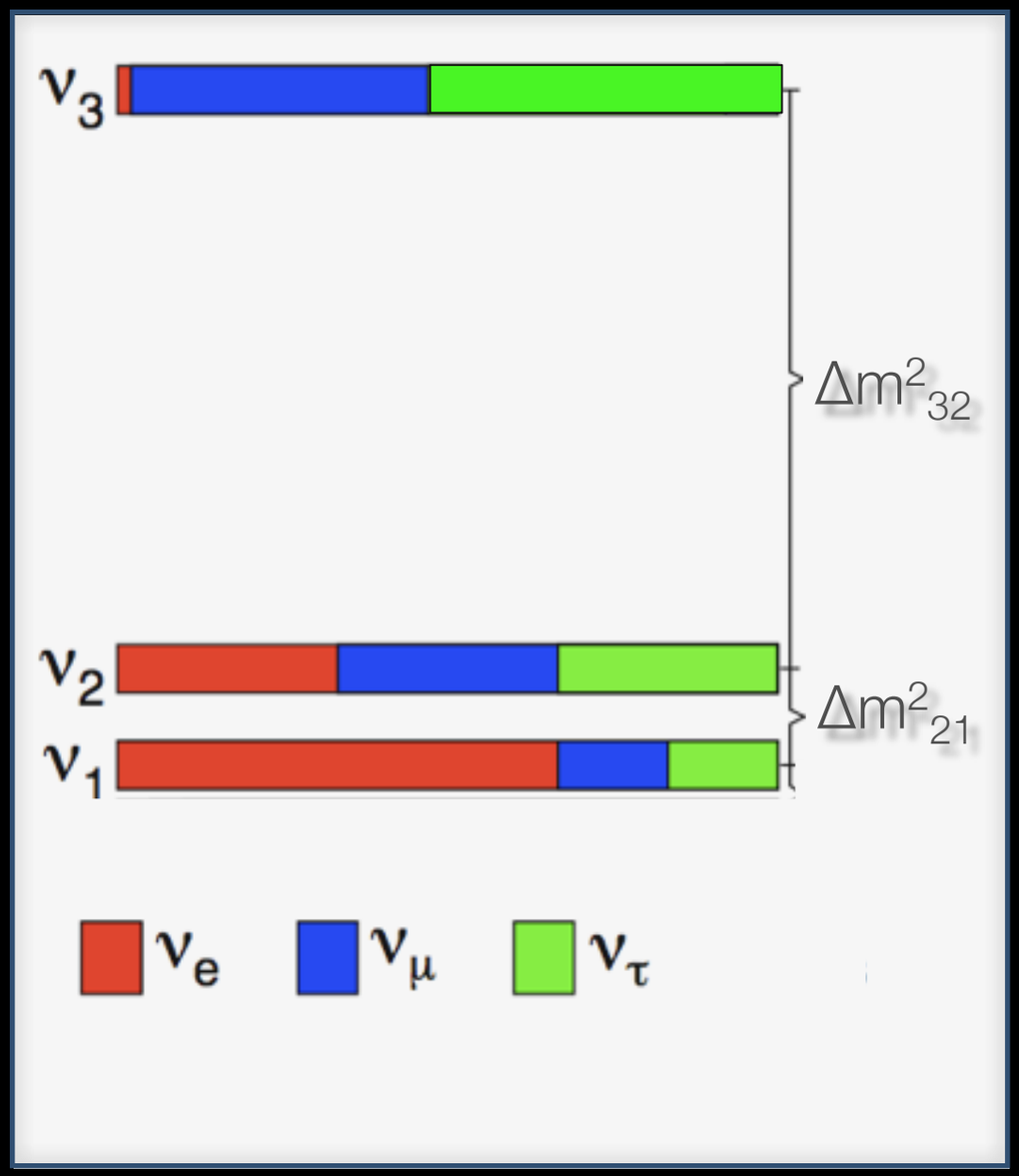
- For non-zero $\sin^2 2\theta_{13}$ we can access δ_{CP} which might be a key to the matter anti-matter asymmetry of the universe.
- Precision measurements of neutrino oscillations might reveal new physics.

NEUTRINOS MASSES AND MIXING

What do we know and what is left to know?

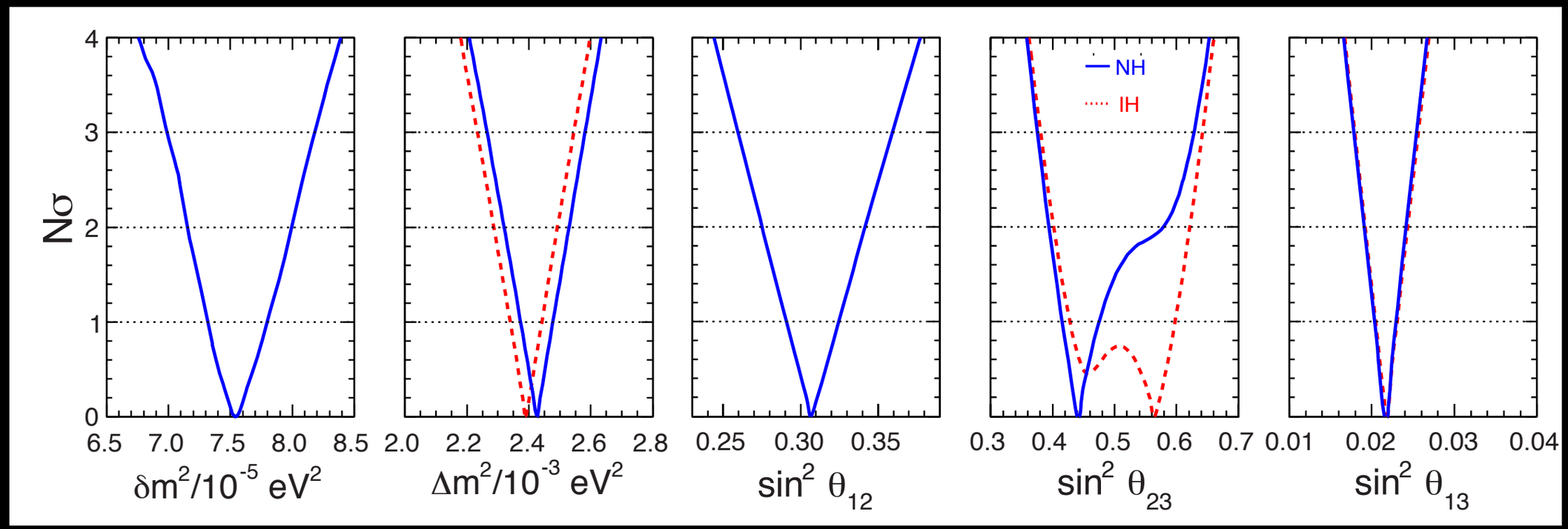


- Two mass scales:
  - The "atmospheric" mass scale: Δm^2_{32}
  - The "solar" mass scale: Δm^2_{21}
- Large mixing angle for atmospheric neutrino oscillations.
- Solar neutrino oscillations are subject to matter effects with a non-maximal mixing angle.
- Third mixing angle is small and has been measured.
- **CP violation in the lepton sector has NOT been measured.**
- **Mass ordering is NOT known for atmospheric neutrinos but known for the solar mass scale.**
- **The octant of the large mixing angle is NOT known!**

EXPERIMENTAL PICTURE EVOLVING QUICKLY!

NEUTRINOS MASSES AND MIXING

How well are these measured?



	Accuracy (2014):		
SOLAR	δm^2	2.6	%
ATMOSP.	Δm^2	2.6	%
SOLAR	$\sin^2\theta_{12}$	5.4	%
REACT.	$\sin^2\theta_{13}$	5.8	%
ATMOSP.	$\sin^2\theta_{23}$	~10	%

- Global analysis presented by A. Marrone at TAUP 2015 (before NOvA results).
- This analysis combines the World's data from solar, reactor, atmospheric and long baseline neutrinos.

EXPERIMENTAL PICTURE EVOLVING QUICKLY!

THE NOVA EXPERIMENT

THE NOVA COLLABORATION

Argonne National Laboratory · University of Athens · Banaras Hindu University · California Institute of Technology · Institute of Physics of the Academy of Sciences of the Czech Republic · Charles University, Prague · University of Cincinnati · Czech Technical University · University of Delhi · Fermilab · Indian Institute of Technology, Guwahati · Harvard University · Indian Institute of Technology · University of Hyderabad · Indiana University · **Iowa State University** · University of Jammu · Lebedev Physical Institute · Michigan State University · University of Minnesota, Crookston · University of Minnesota, Duluth · University of Minnesota, Twin Cities · Institute for Nuclear Research, Moscow · Panjab University · University of South Carolina · Southern Methodist University · Stanford University · University of Sussex · University of Tennessee · University of Texas at Austin · Tufts University · University of Virginia · Wichita State University · College of William and Mary

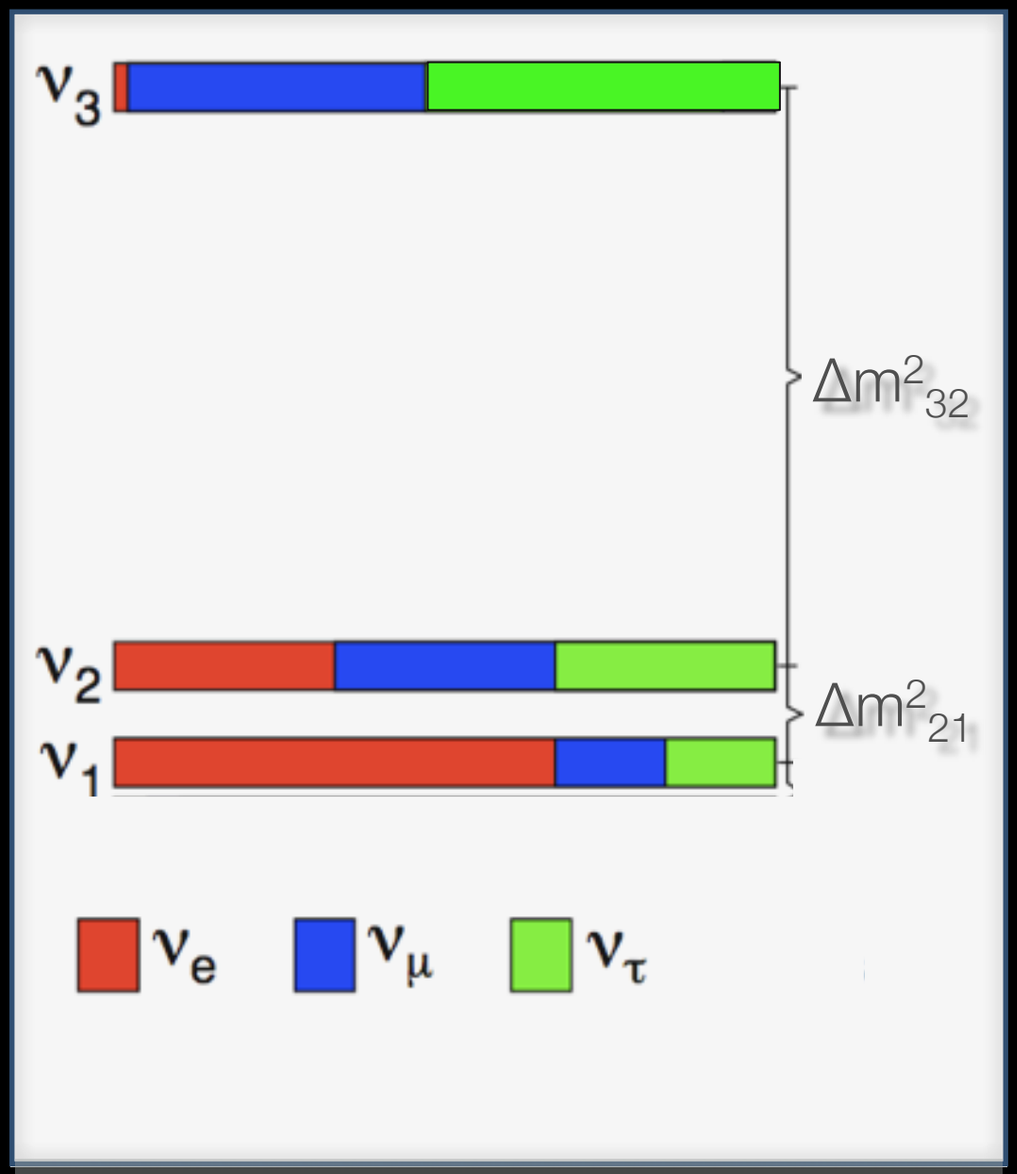
THE NOVA EXPERIMENT IN A NUTSHELL

- Upgrade existing high intensity NuMI **beam of muon neutrinos** at Fermilab from 350 to 700kW.
- Construct a highly active liquid scintillator **14-kton detector** off the main axis of the beam.
- If neutrinos oscillate, **muon neutrinos disappear** as they travel and **electron neutrinos appear** at the Far Detector in Ash River, 810 km away.

2nd generation
← long baseline →

L/E ~ 500 km

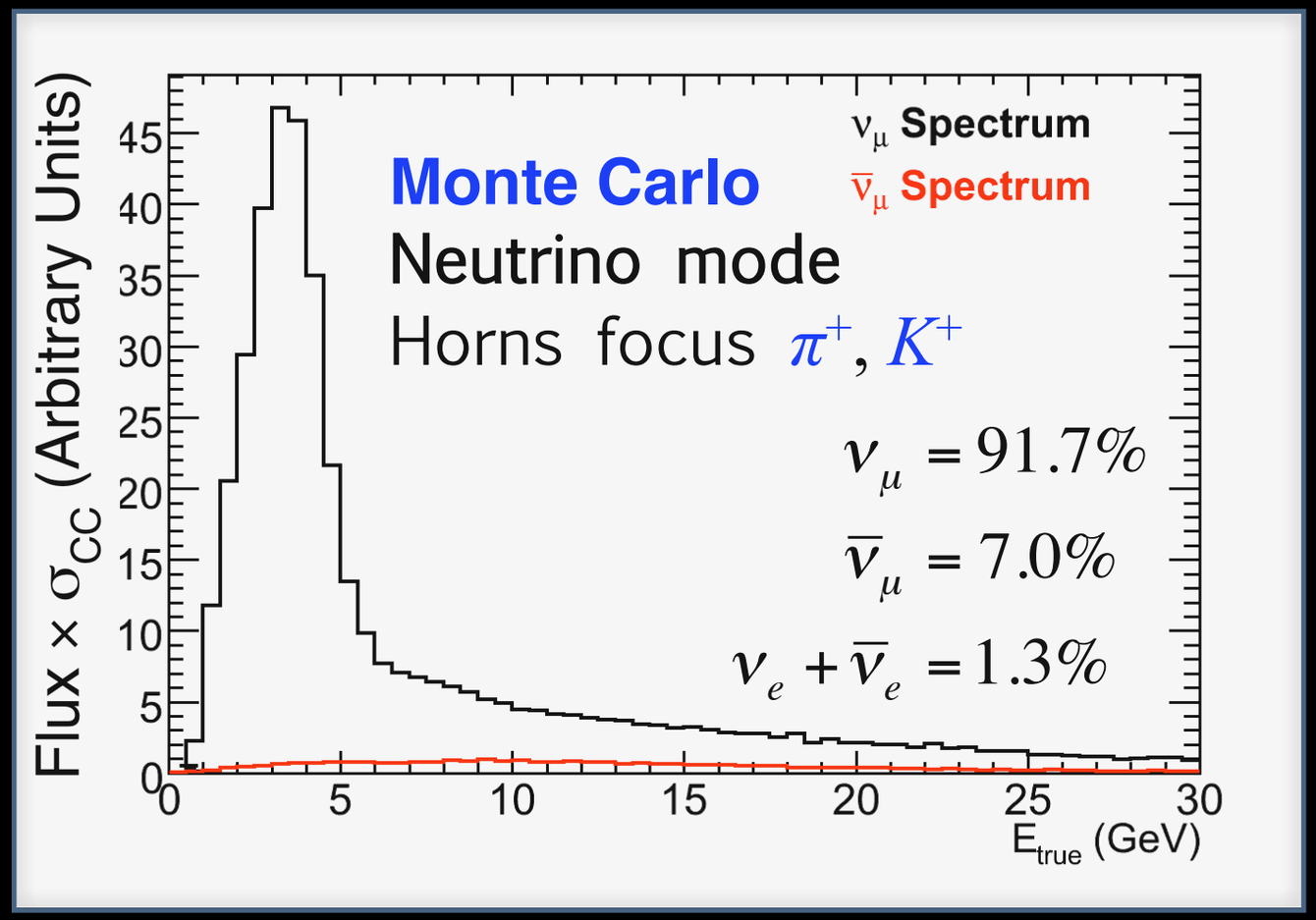
THE GOALS OF THE NOVA EXPERIMENT



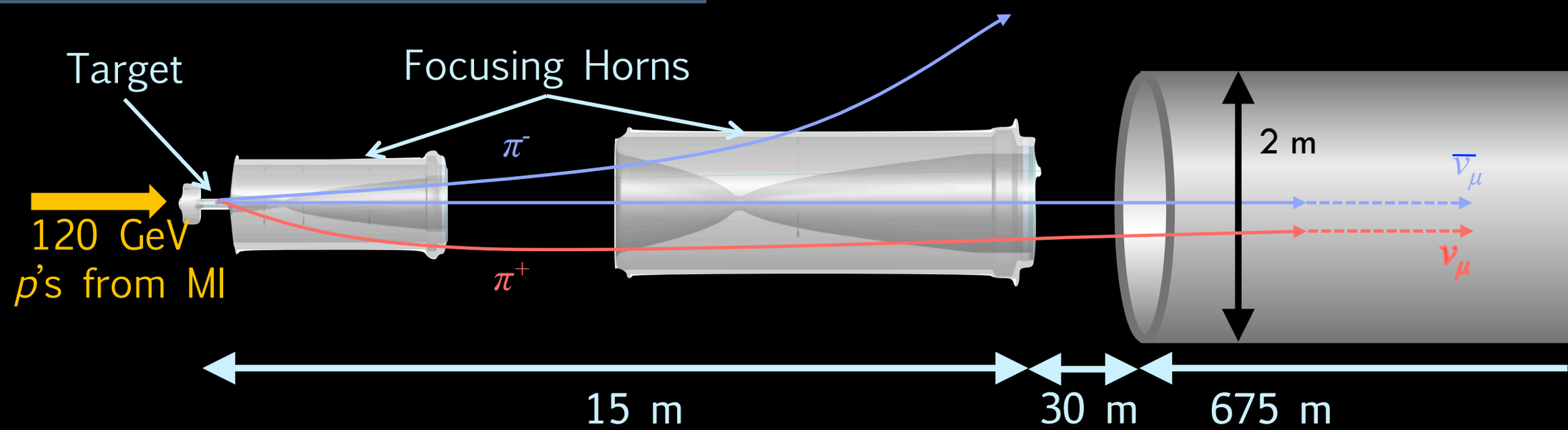
FIRST STEP OBSERVE DISAPPEARANCE AND APPEARANCE FOR NEUTRINOS

- Measure the oscillation probabilities of $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ as well as $\nu_\mu \rightarrow \nu_e$,$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.
  - Precision measurements of Δm^2_{32}, θ_{23}.
  - Determine neutrino mass hierarchy.
  - Study the phase parameter for CP violation δ_{CP}.
  - Resolution of the θ_{23} octant.
- As well as:
  - ν cross sections and interaction physics.
  - Sterile neutrinos.
  - Supernovae and monopoles!

PRODUCING NEUTRINOS: NUMI BEAM



- Produce protons in accelerator, shoot them at the target. Produce other particles.
- Horns focus positive pions and kaons which decay into neutrinos.
- Higher energy anti-neutrinos come from very forward negative pions.

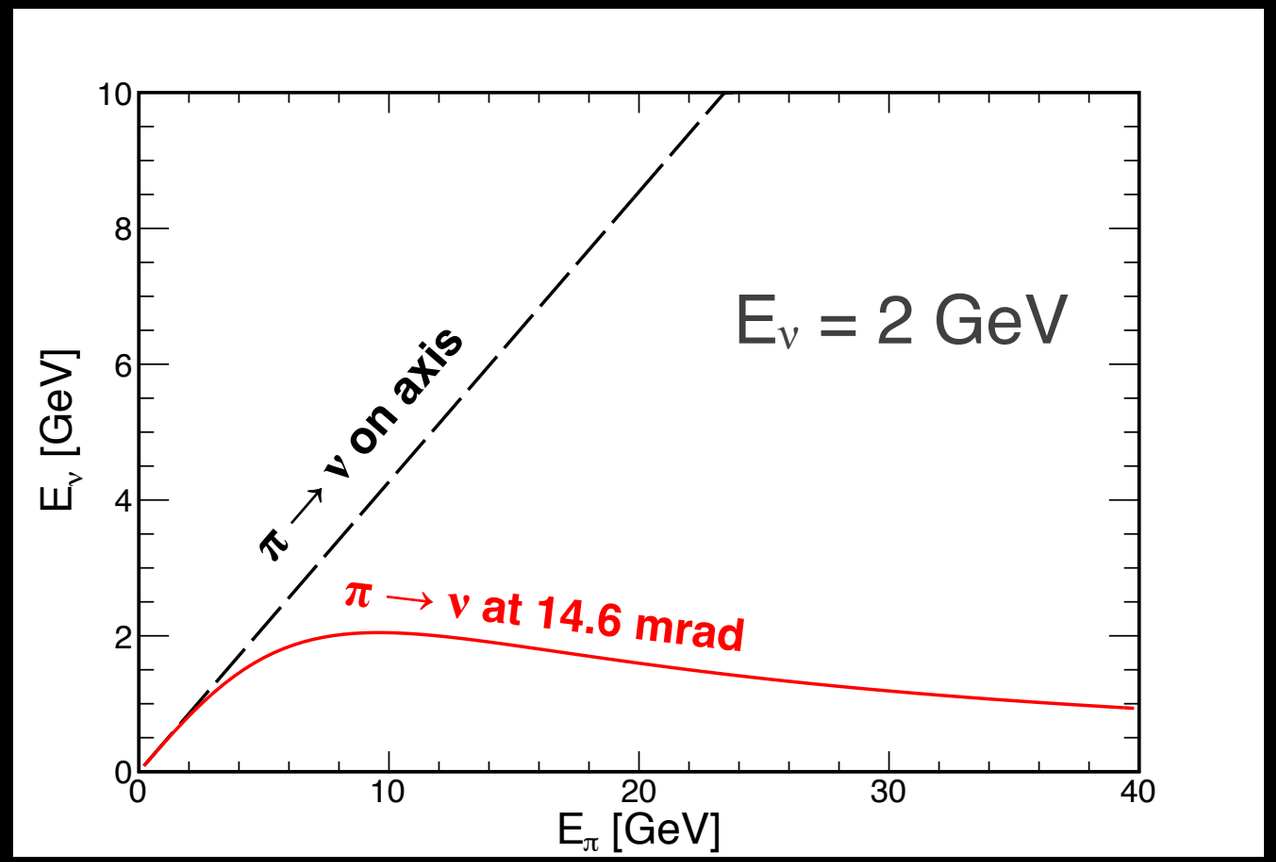


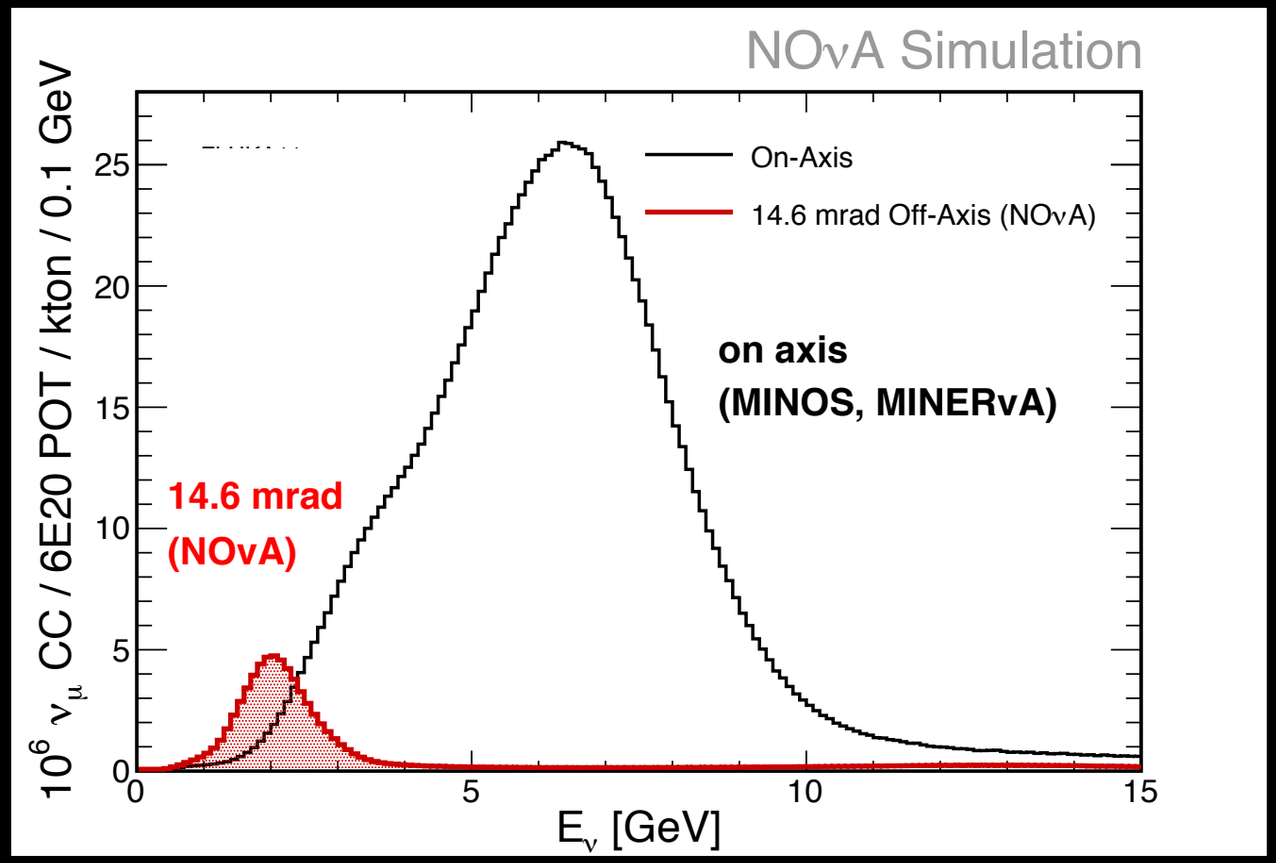
THE OFF-AXIS NUMI BEAM

- NOνA detectors are located **14 mrad** off the NuMI beam axis.
- With the **medium-energy NuMI** configuration, it yields a narrow 2-GeV spectrum at the NOνA detectors due to meson decay kinematics:

$$E_\nu = \frac{1-(m_\mu/m_\pi)^2}{1+\gamma^2\tan^2\theta}E_\pi$$

- Location reduces NC and νe CC backgrounds in the oscillation analyses while maintaining high ν_μ flux at 2 GeV.





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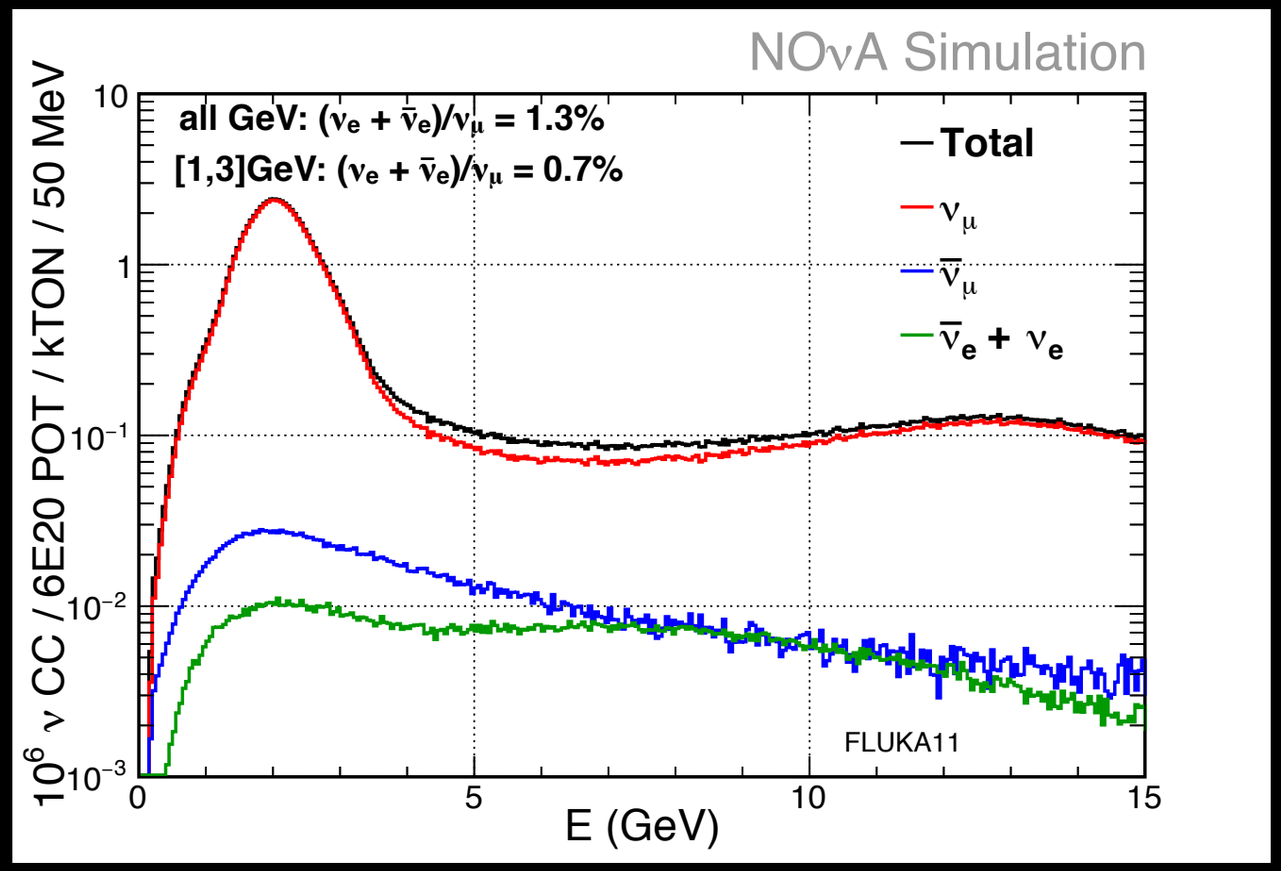
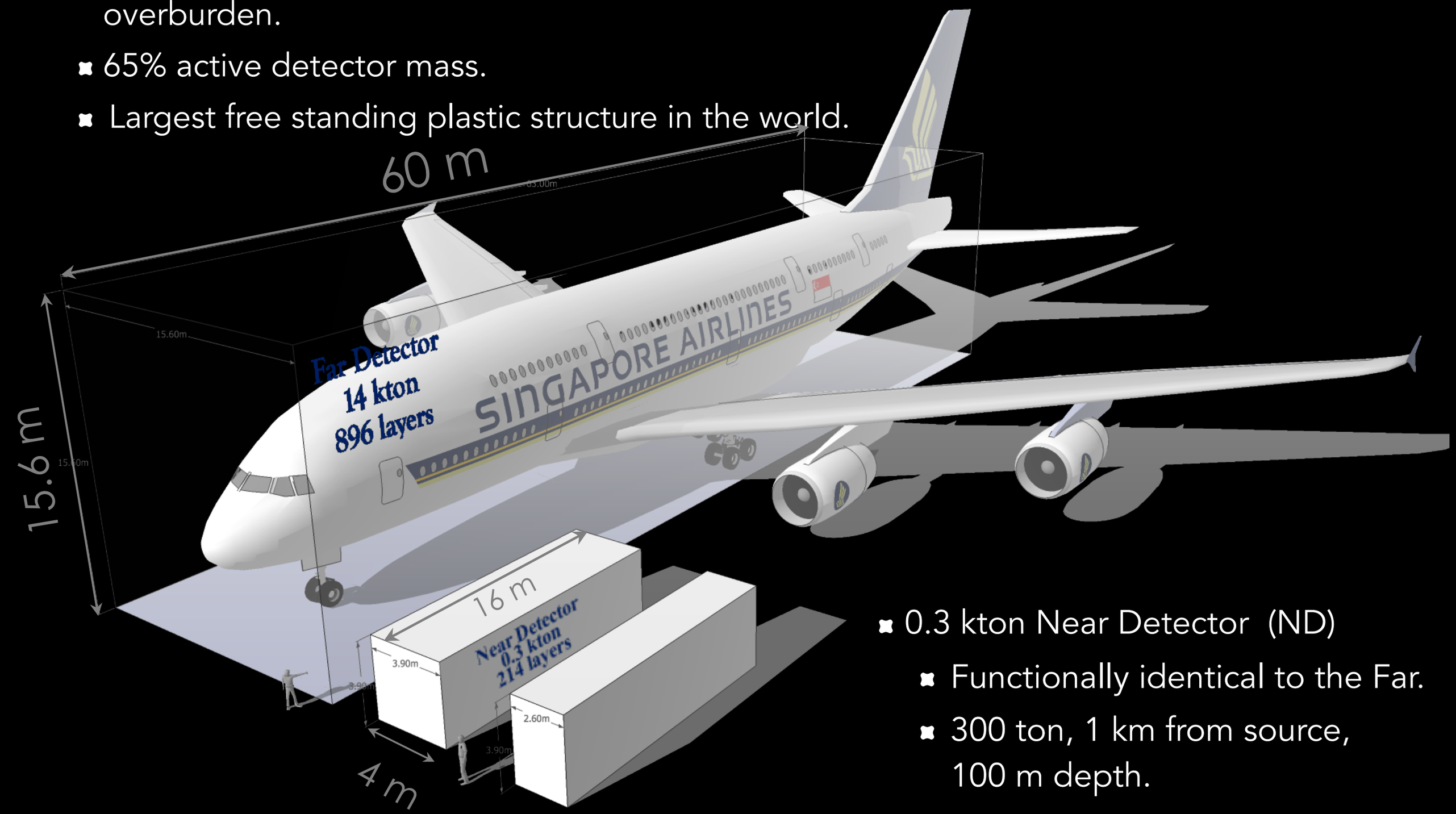


- In FY15 NuMI beam routinely operated at 400 kW for NOvA.
- Overall uptime: 85%. Peak intensity of 520 kW achieved.
- A total of 3.45 x 10^{20} POT delivered is used for these analyses equivalent to 2.74 x 10^{20} POT with full 14 kton detector.
- Data taken from February 6, 2014 and May 15, 2015 with detector still under construction.

THE NOVA DETECTORS

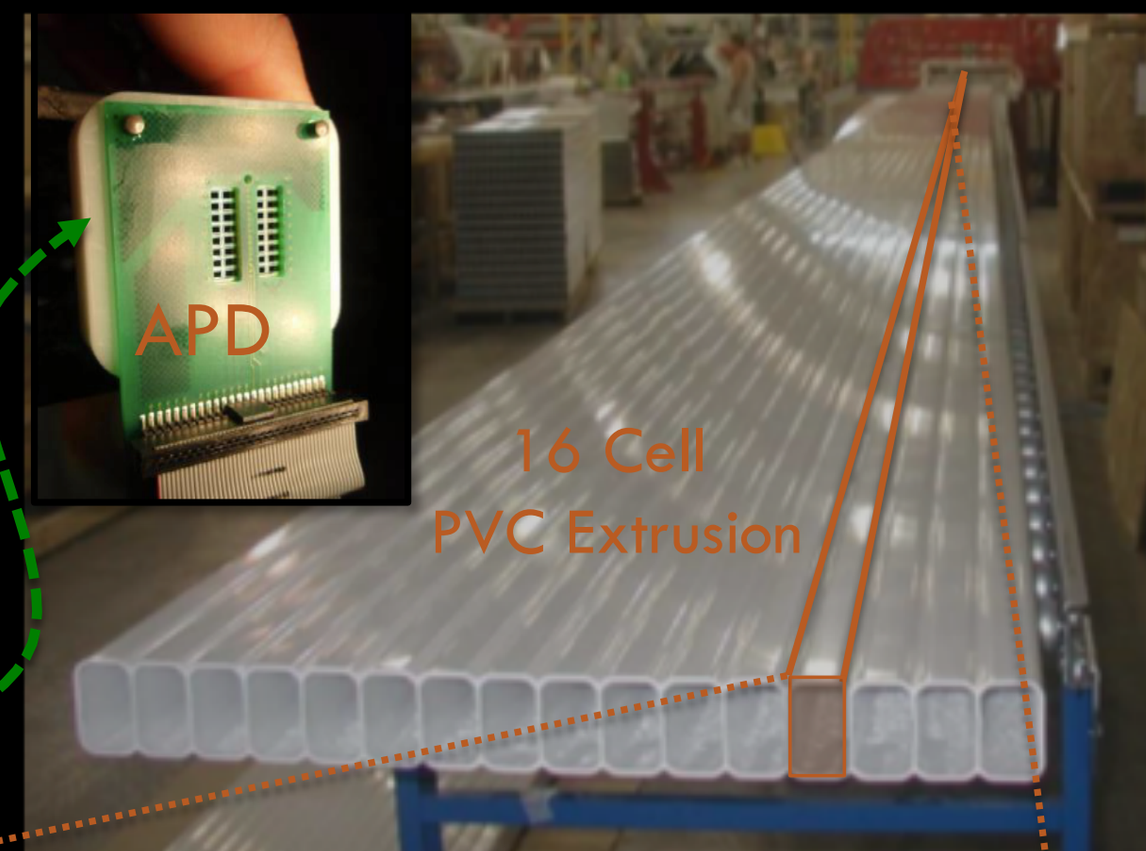
- 14 kton Far Detector (FD), low-Z, tracking calorimeter.
  - 810 km from source, on the surface, 3 m.w.e. overburden.
  - 65% active detector mass.
  - Largest free standing plastic structure in the world.

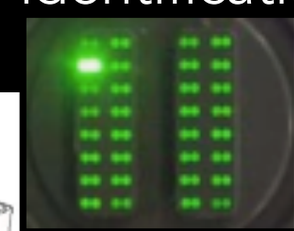


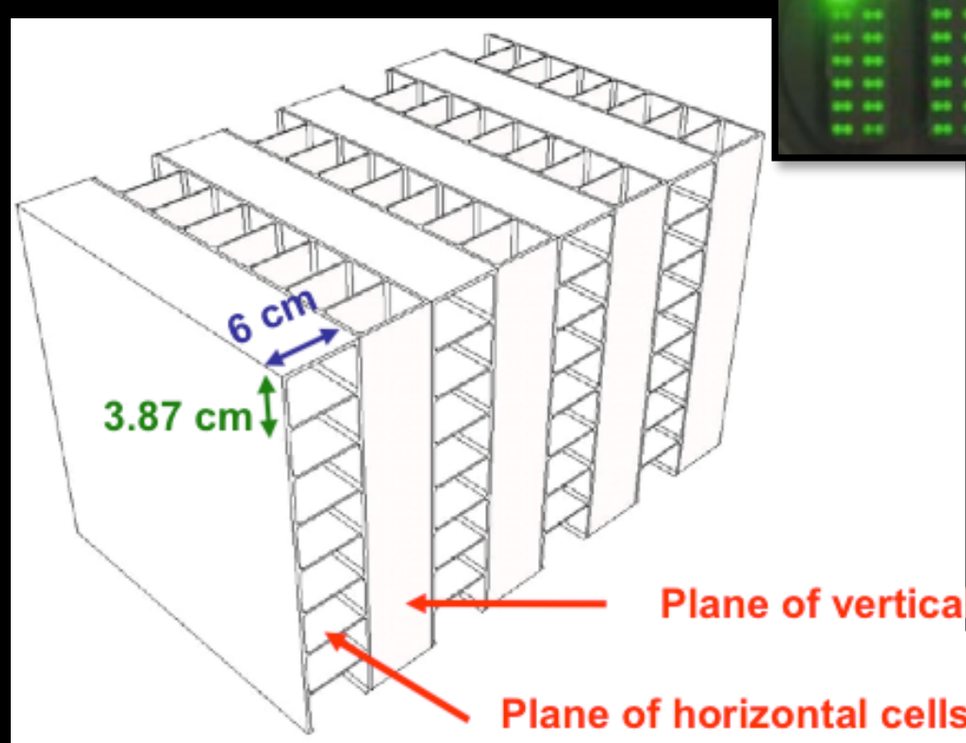
- 0.3 kton Near Detector (ND)
  - Functionally identical to the Far.
  - 300 ton, 1 km from source, 100 m depth.

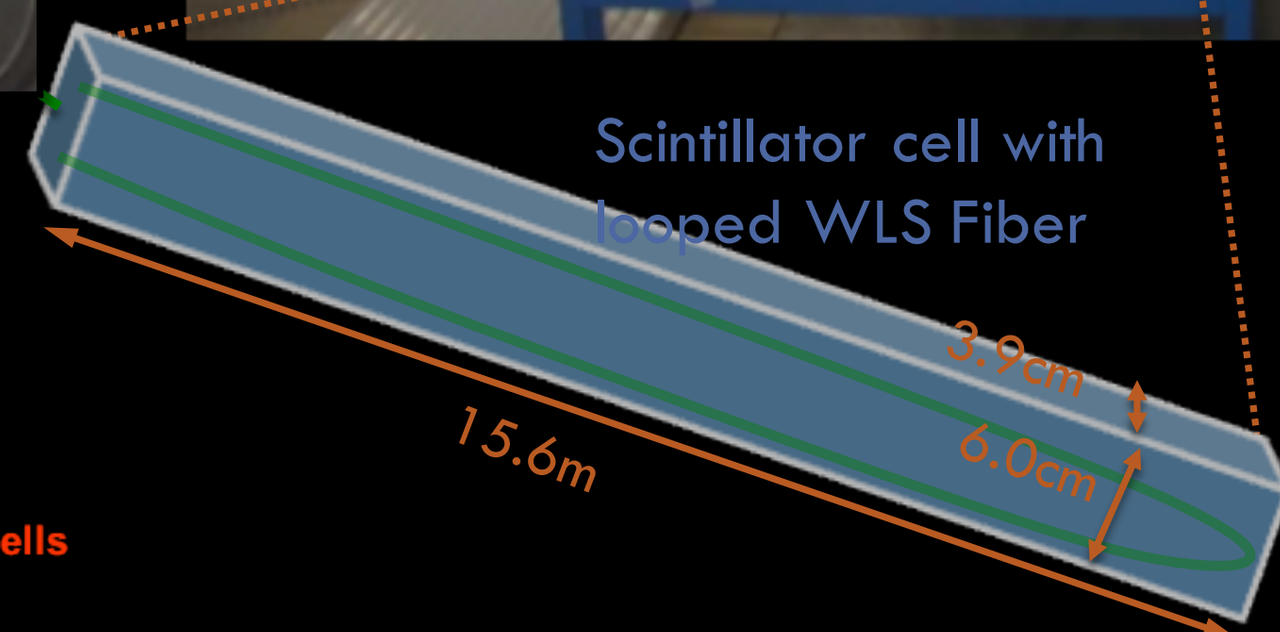
THE NOVA DETECTORS

- PVC extrusion + Liquid Scintillator
  - 11M liters of mineral oil + 5% pseudocumene
- Read out via WLS fiber to 32-pixel APD
  - FD has 344,064 channels
  - ND has 18,000 channels
  - muon crossing far end at FD~25 PE
- Layered planes of orthogonal views
- 0.15 X_0 per layer, excellent for e- identification.

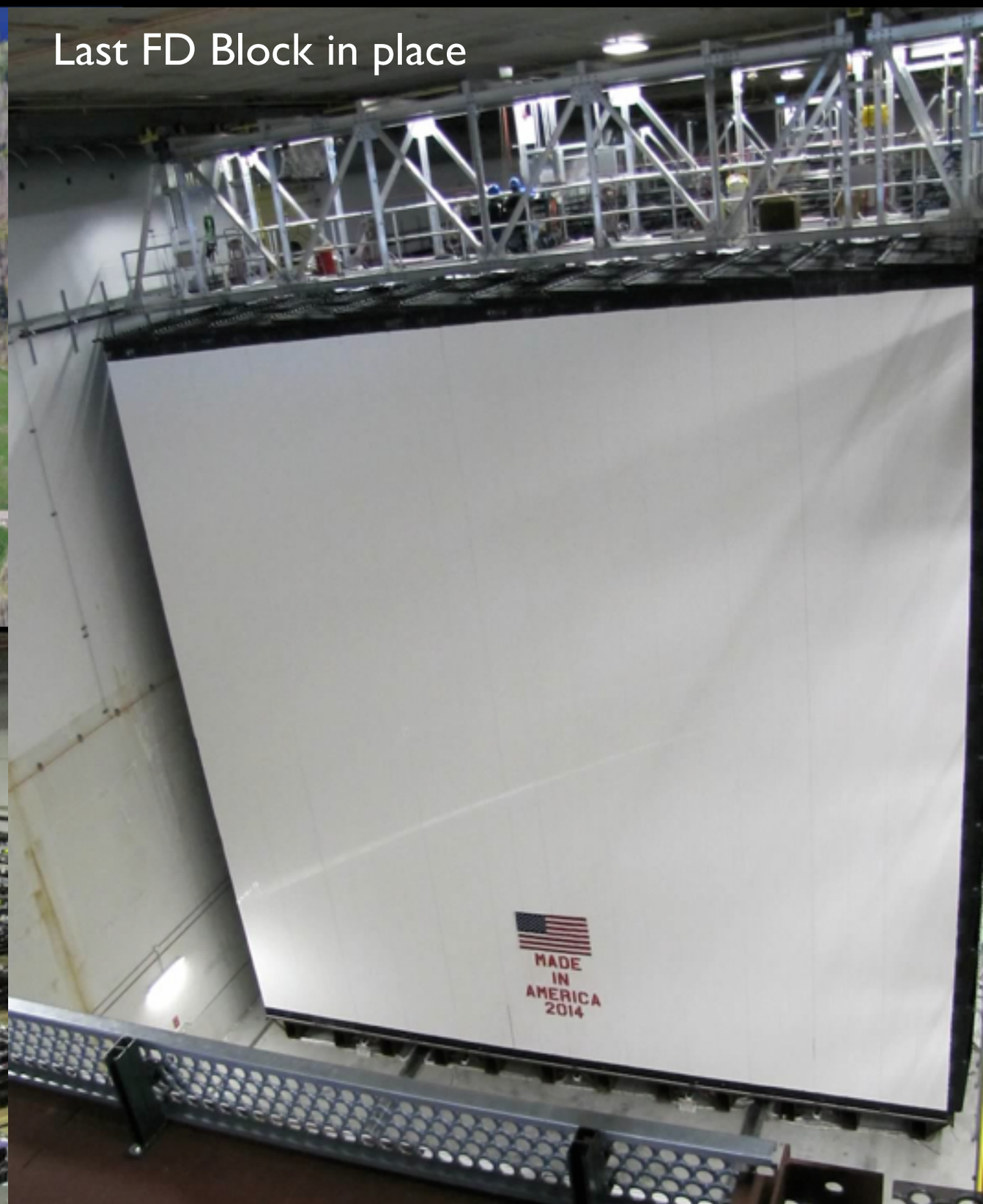








THE NOVA FAR DETECTOR



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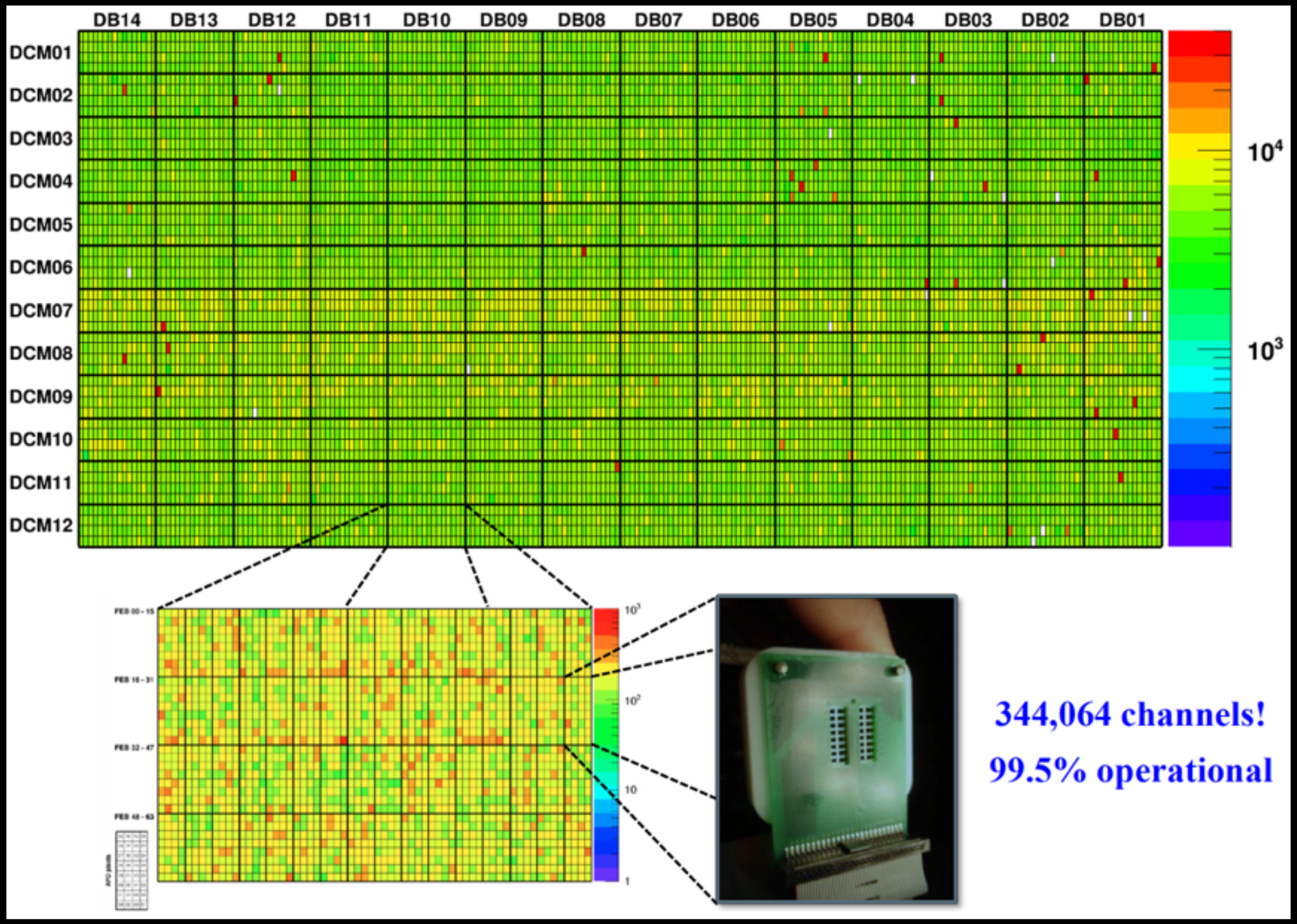
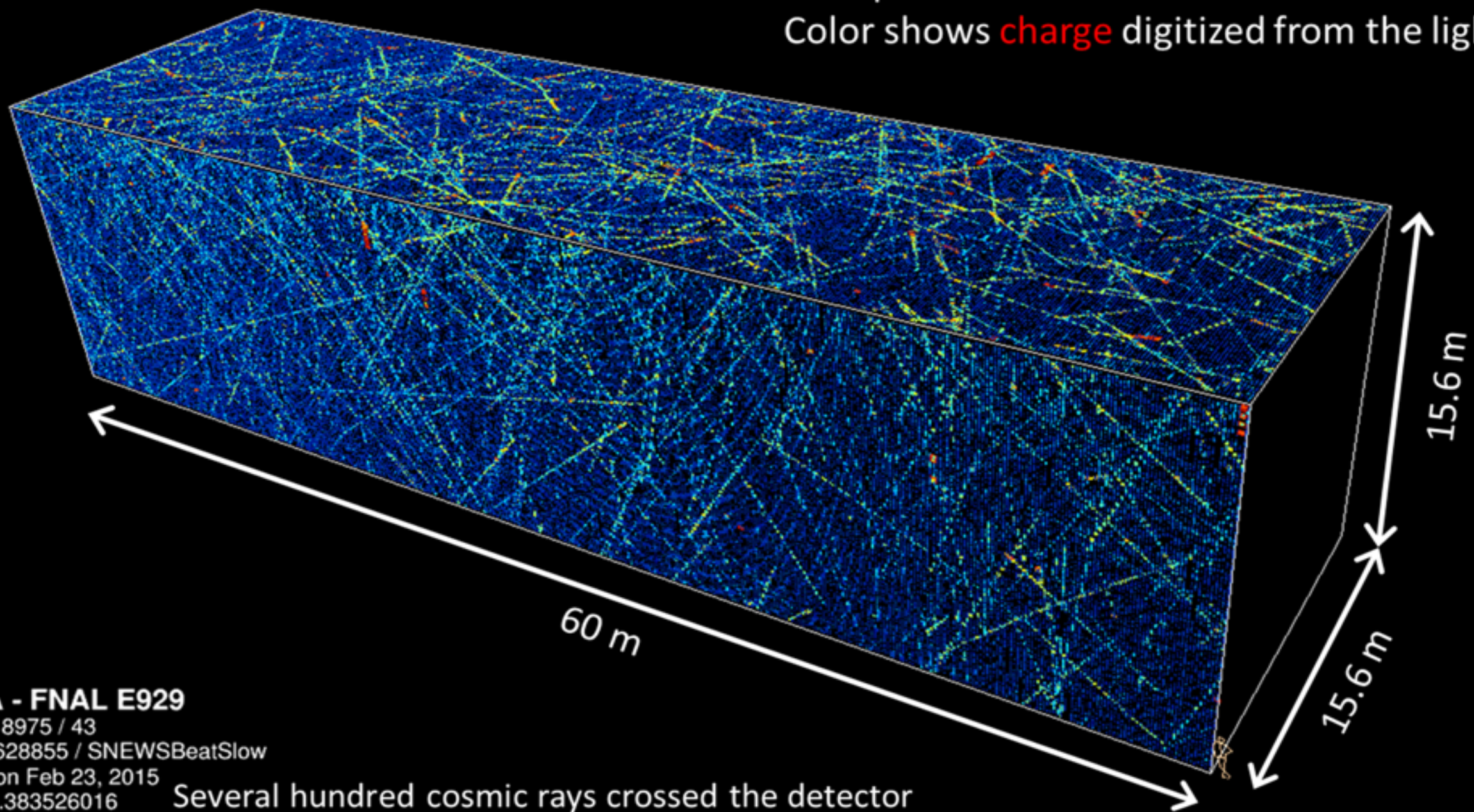


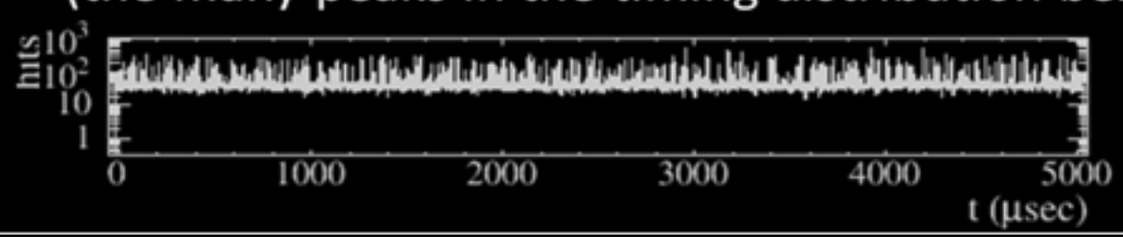
BUT WHERE ARE THE NEUTRINOS?

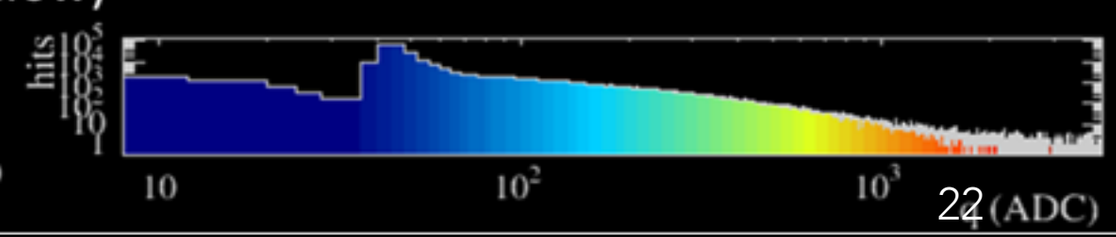
5ms of data at the NOνA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light



NOvA - FNAL E929
Run: 18975 / 43
Event: 628855 / SNEWSBeatSlow
UTC Mon Feb 23, 2015
14:30:1.383526016

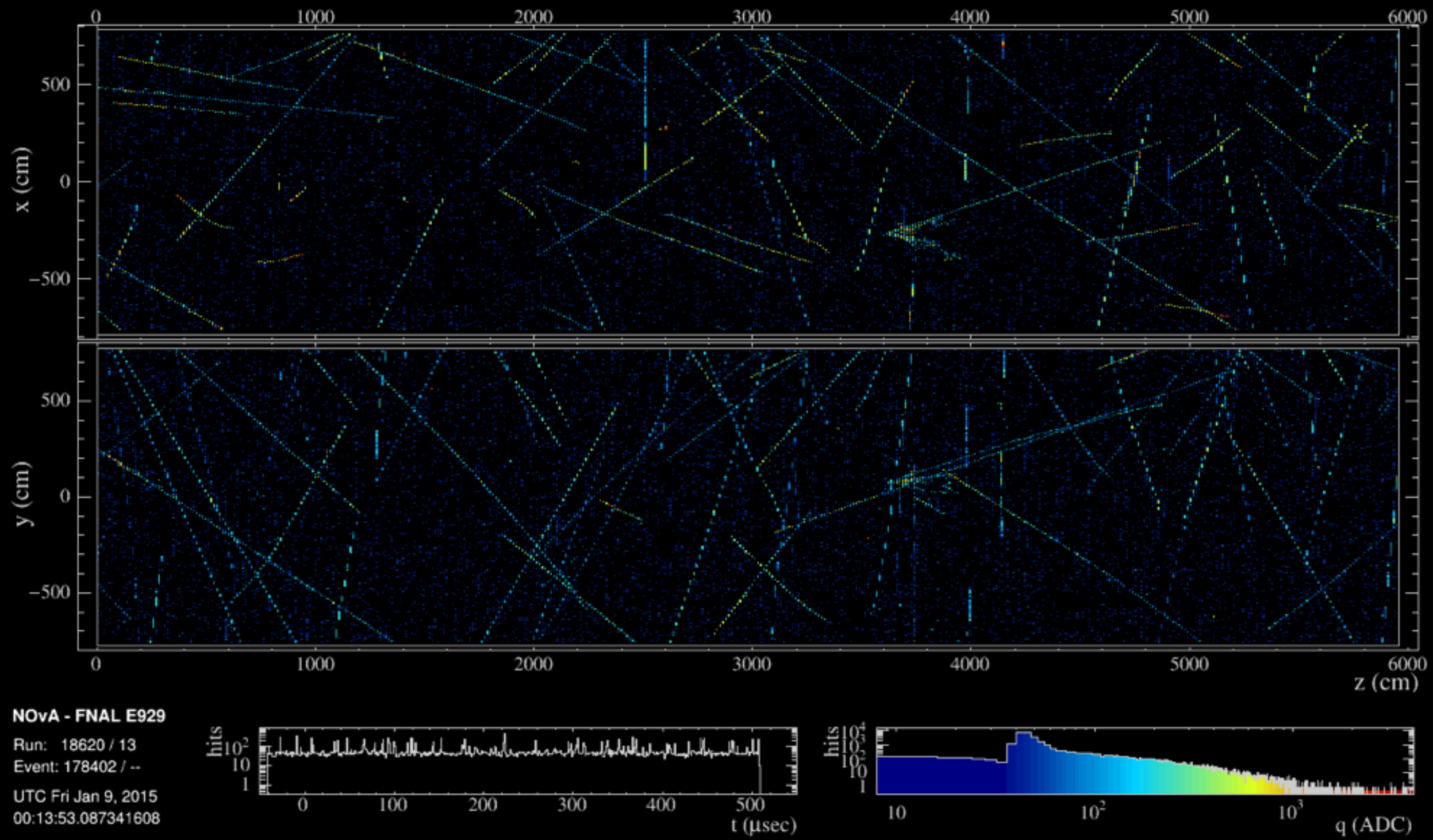
Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)





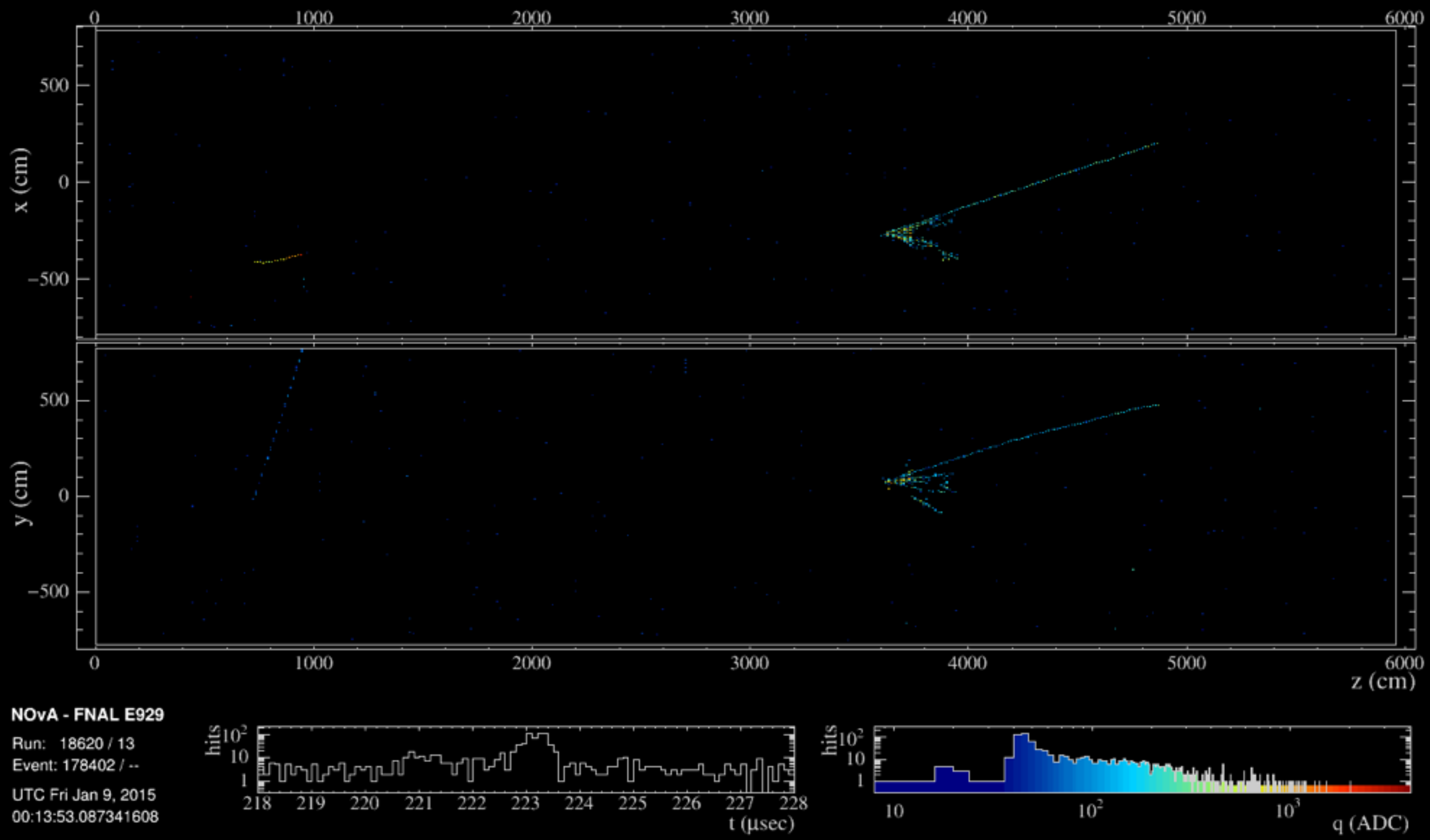
SEARCHING FOR NEUTRINOS IN FD

Beam spill trigger: 500 μsec



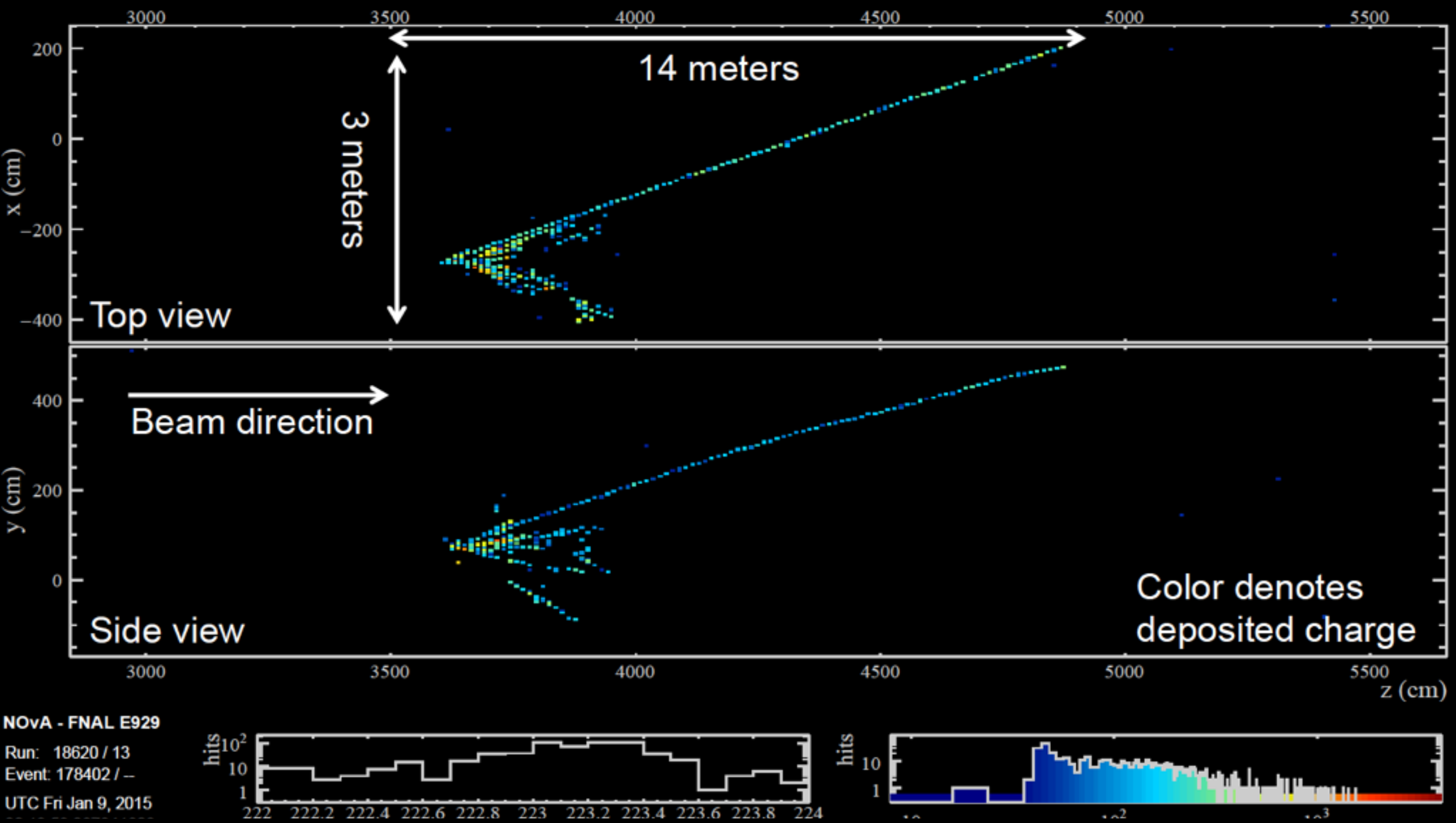
SEARCHING FOR NEUTRINOS IN FD

Beam spill trigger: zoom 10 μsec



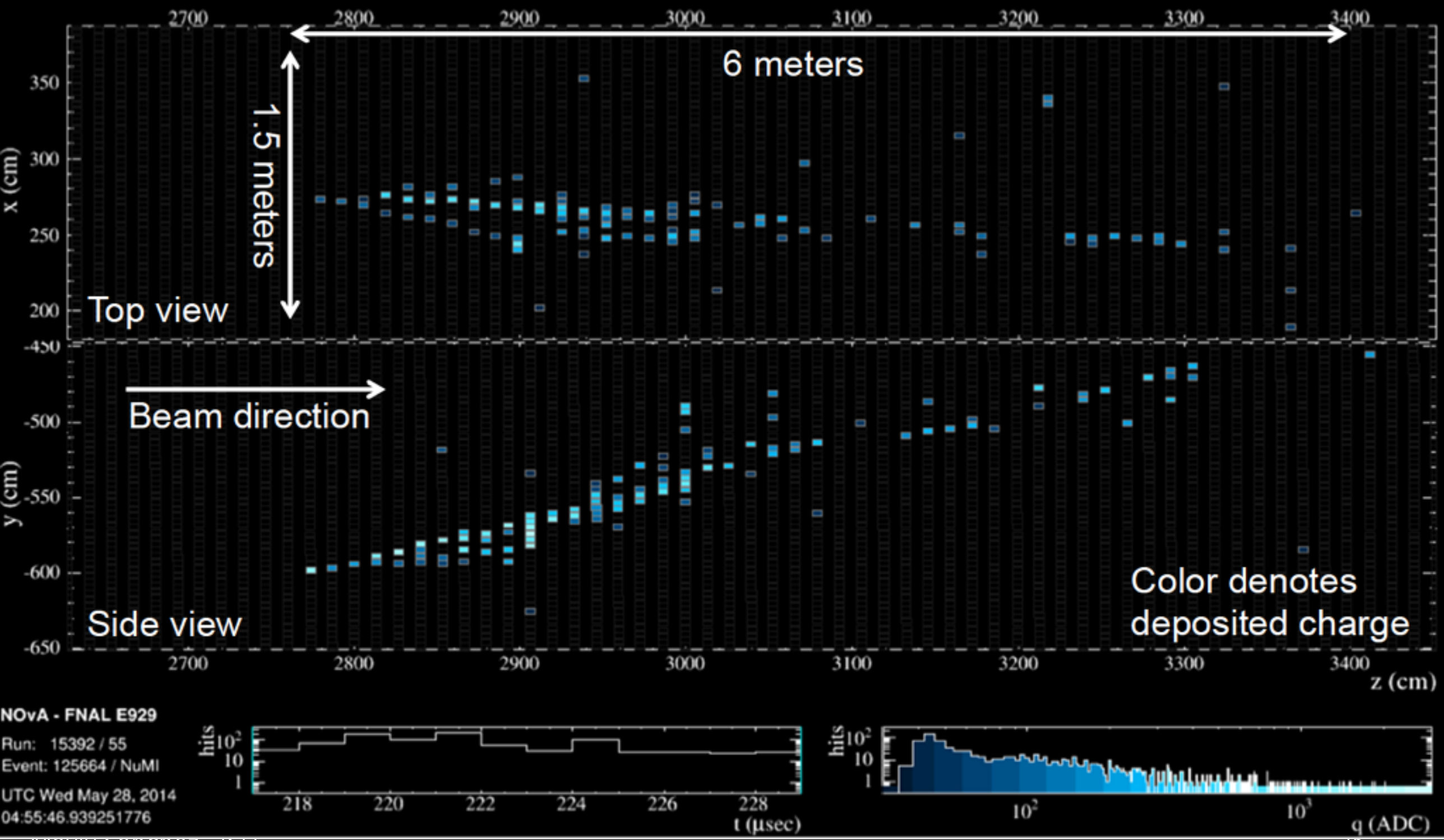
A MUON NEUTRINO CANDIDATE

Zoomed in spatially

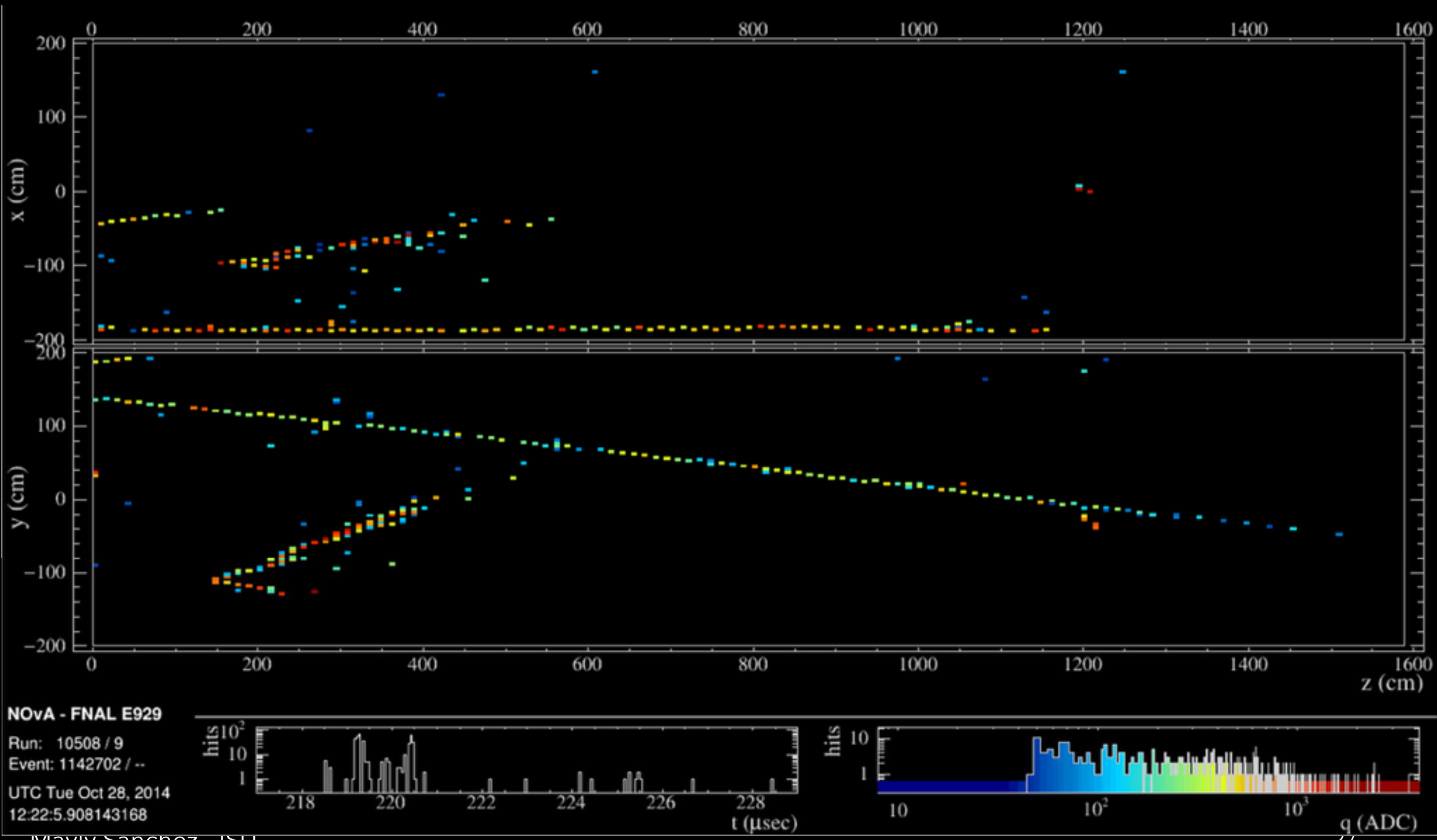


AN ELECTRON NEUTRINO CANDIDATE

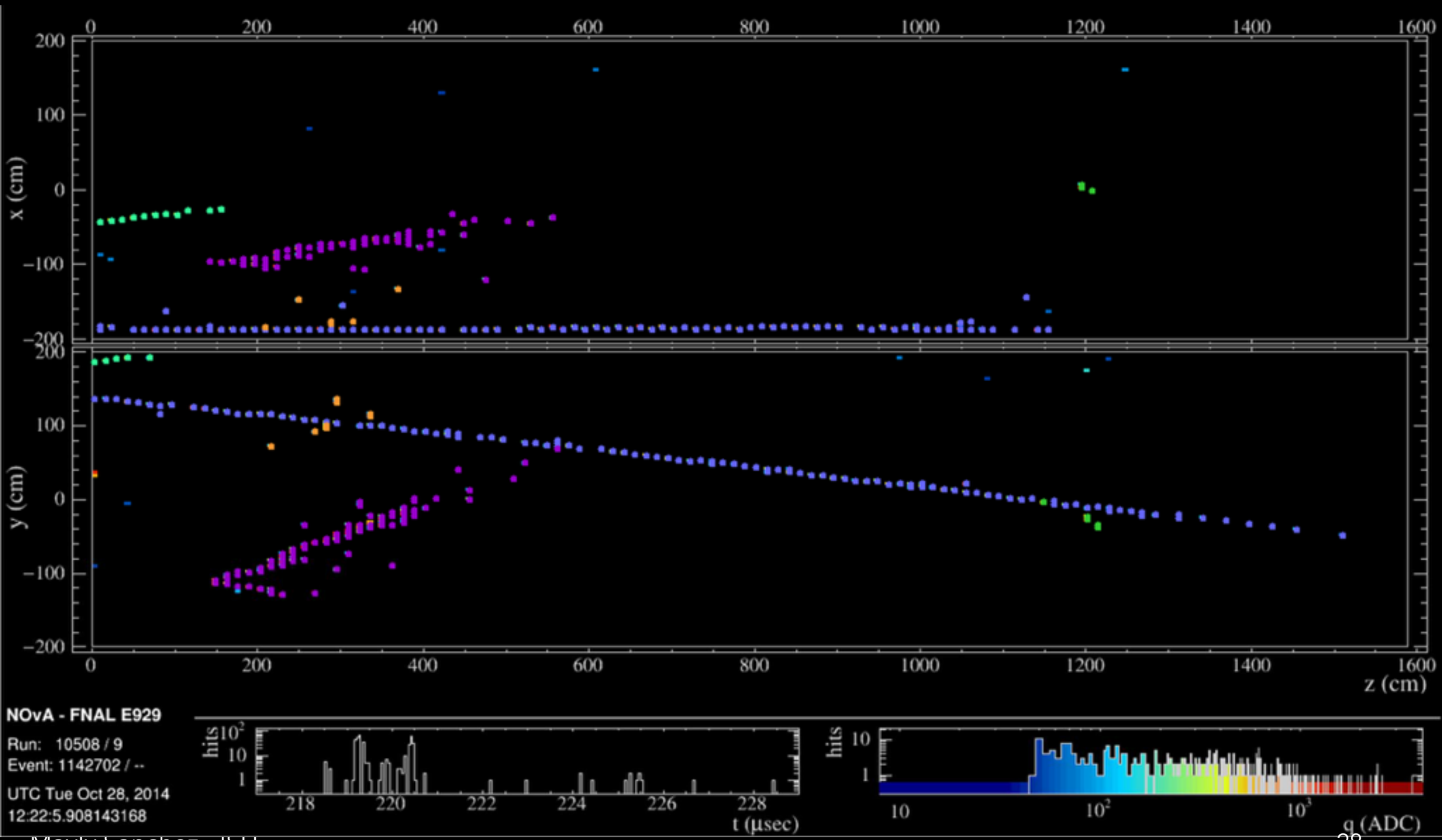
Zoomed in spatially



NEUTRINOS IN THE NEAR DETECTOR



NEUTRINOS IN THE NEAR DETECTOR



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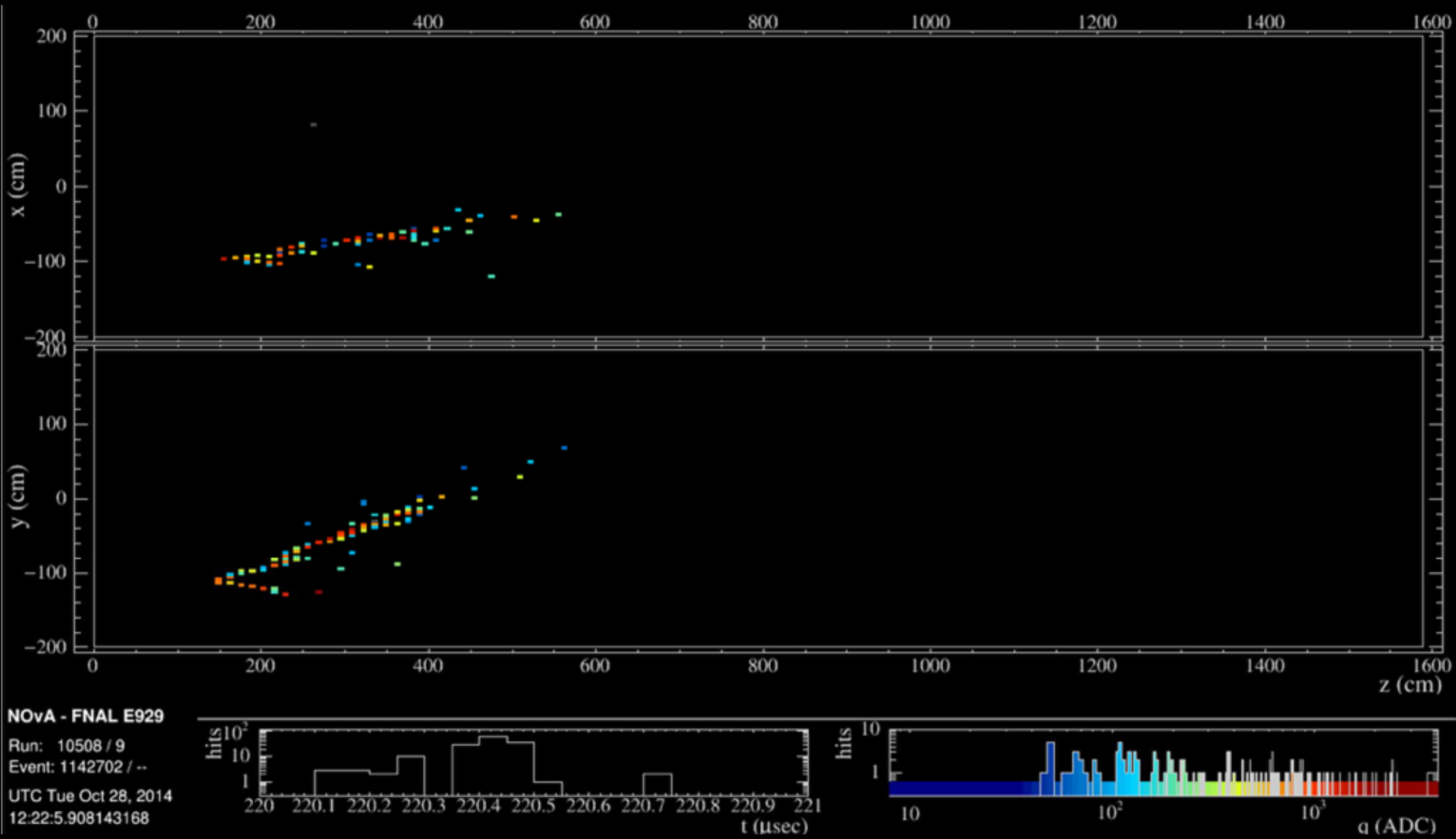

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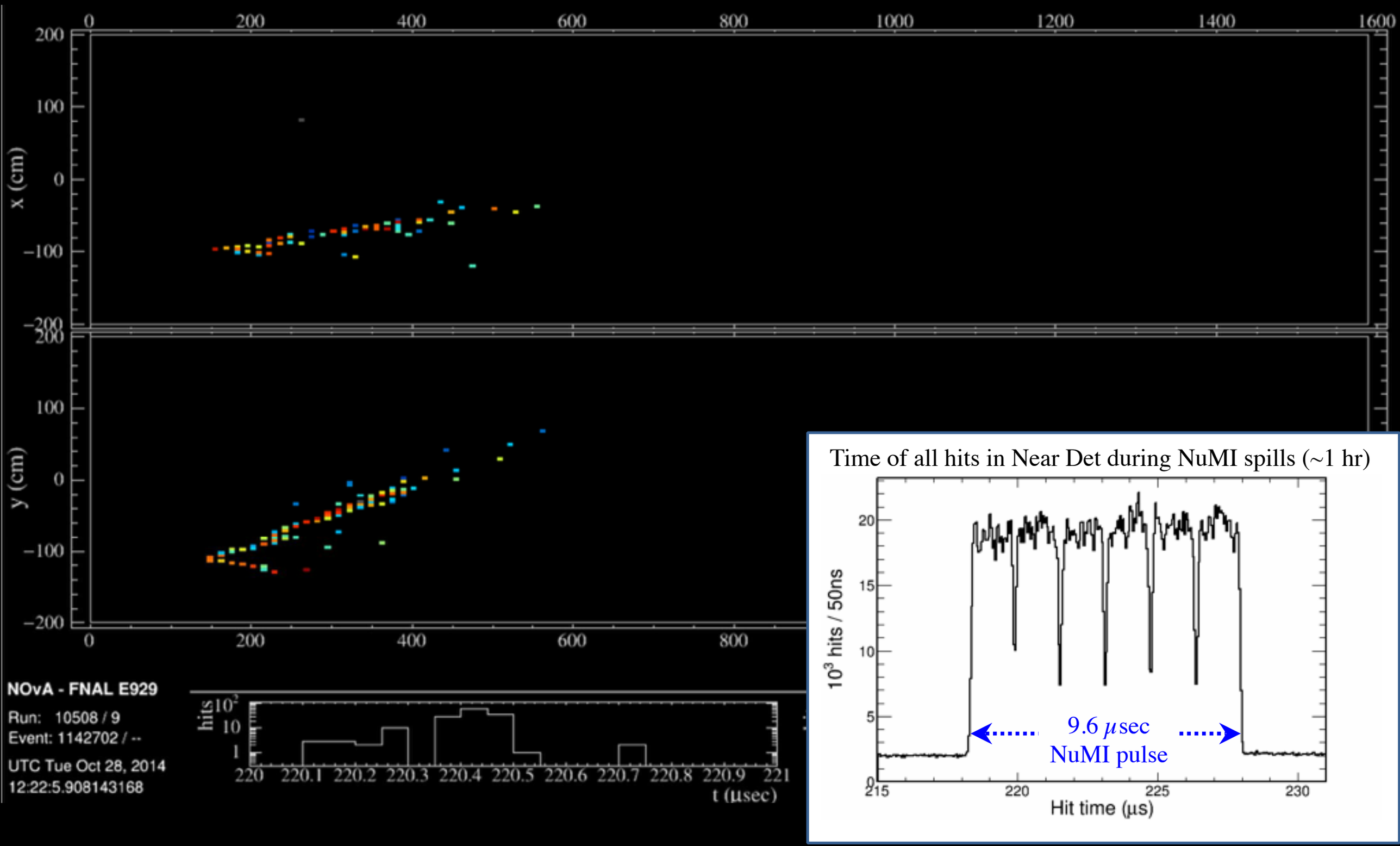
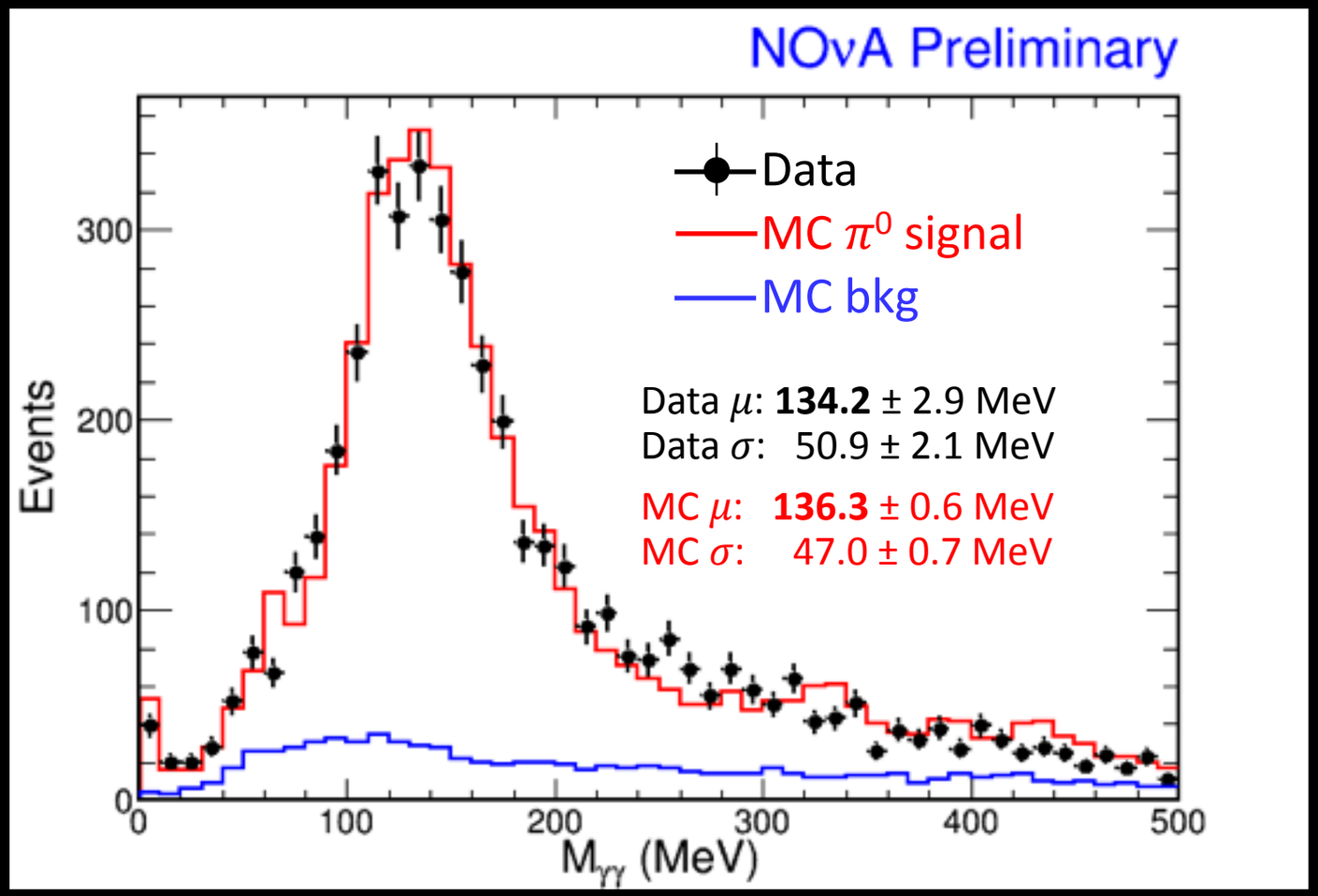
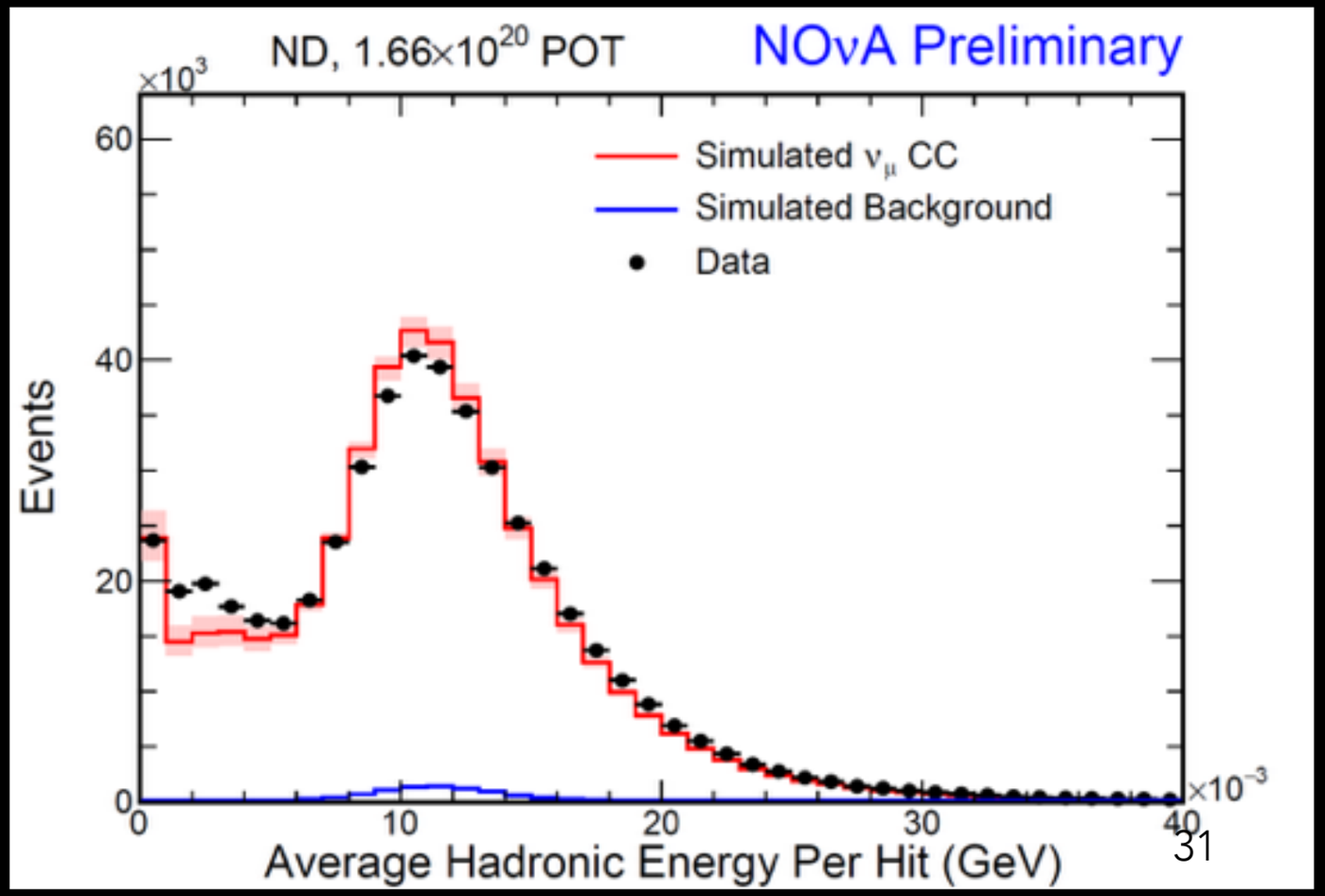


CALIBRATION AND THE ABSOLUTE ENERGY SCALE

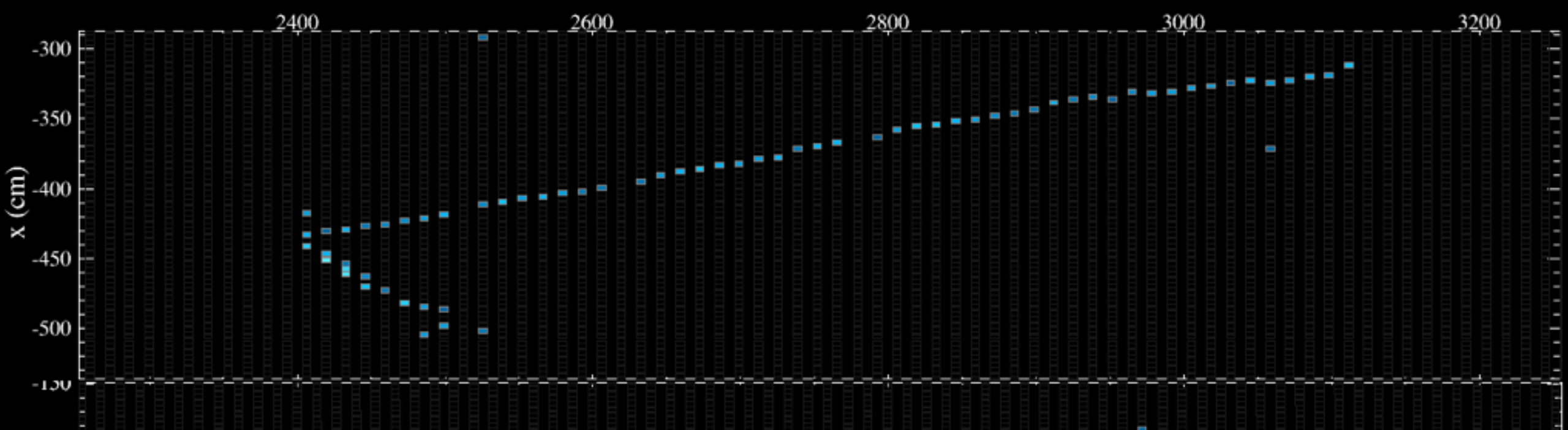
- Stopping muons provide a standard candle for setting absolute energy scale.
- Several samples demonstrate successful energy scale calibration:
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e- spectrum
  - π^0 **mass**
  - **hadronic shower energy/hit**

ALL SAMPLES AGREE WITHIN ±5%





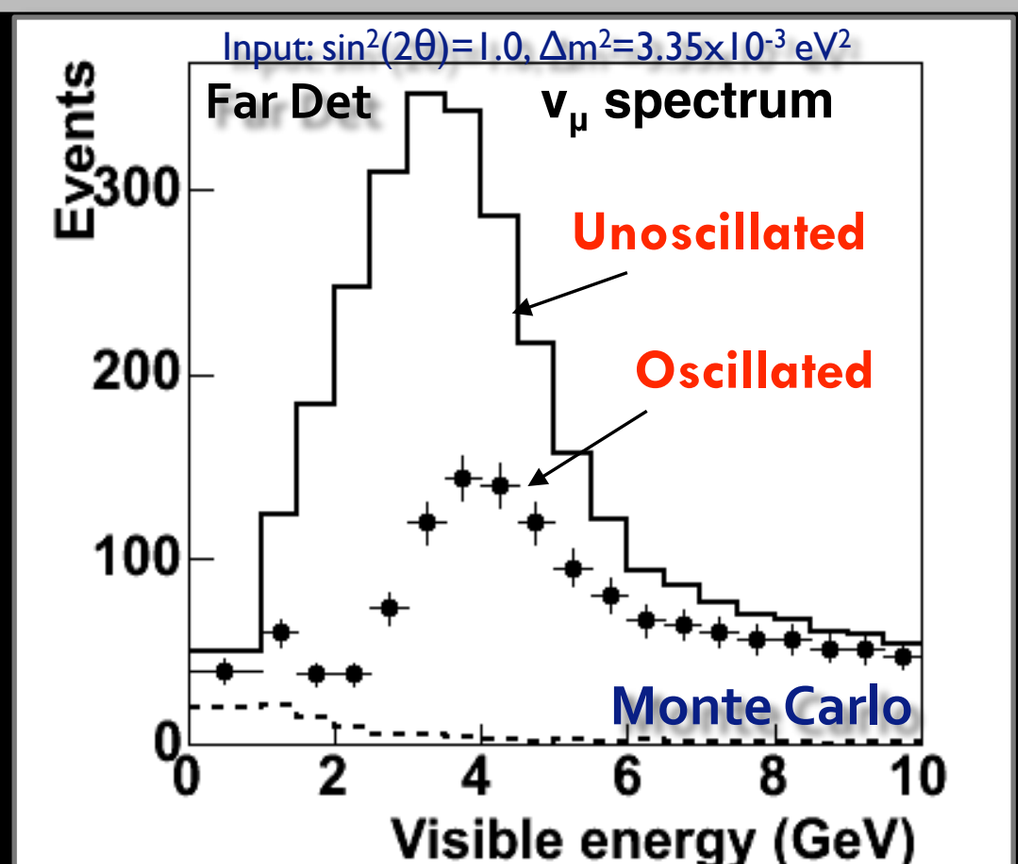
MUON NEUTRINO DISAPPEARANCE

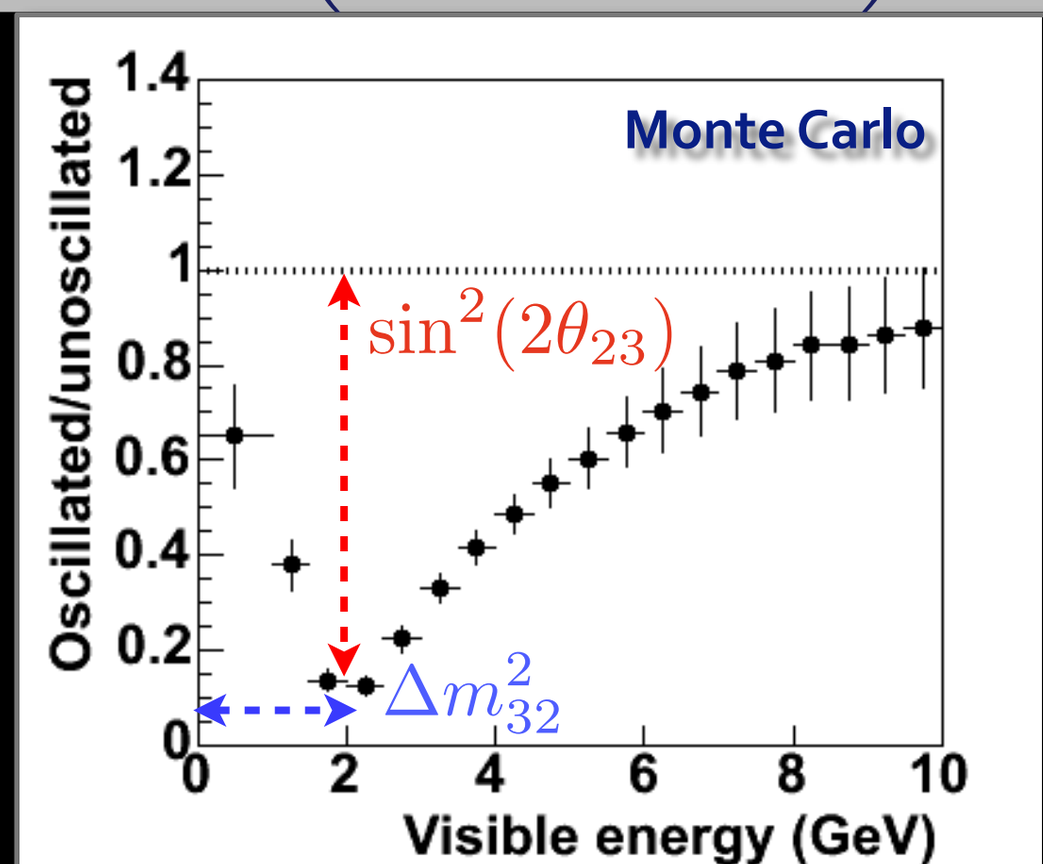


MUON NEUTRINO DISAPPEARANCE

- In long-baseline experiments, we compare a prediction of the muon neutrino spectrum obtained from Near Detector data with a Far Detector measurement. Neutrino oscillations deplete rate and distort the energy spectrum.

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267 \Delta m^2_{32} \frac{L}{E}\right)$$

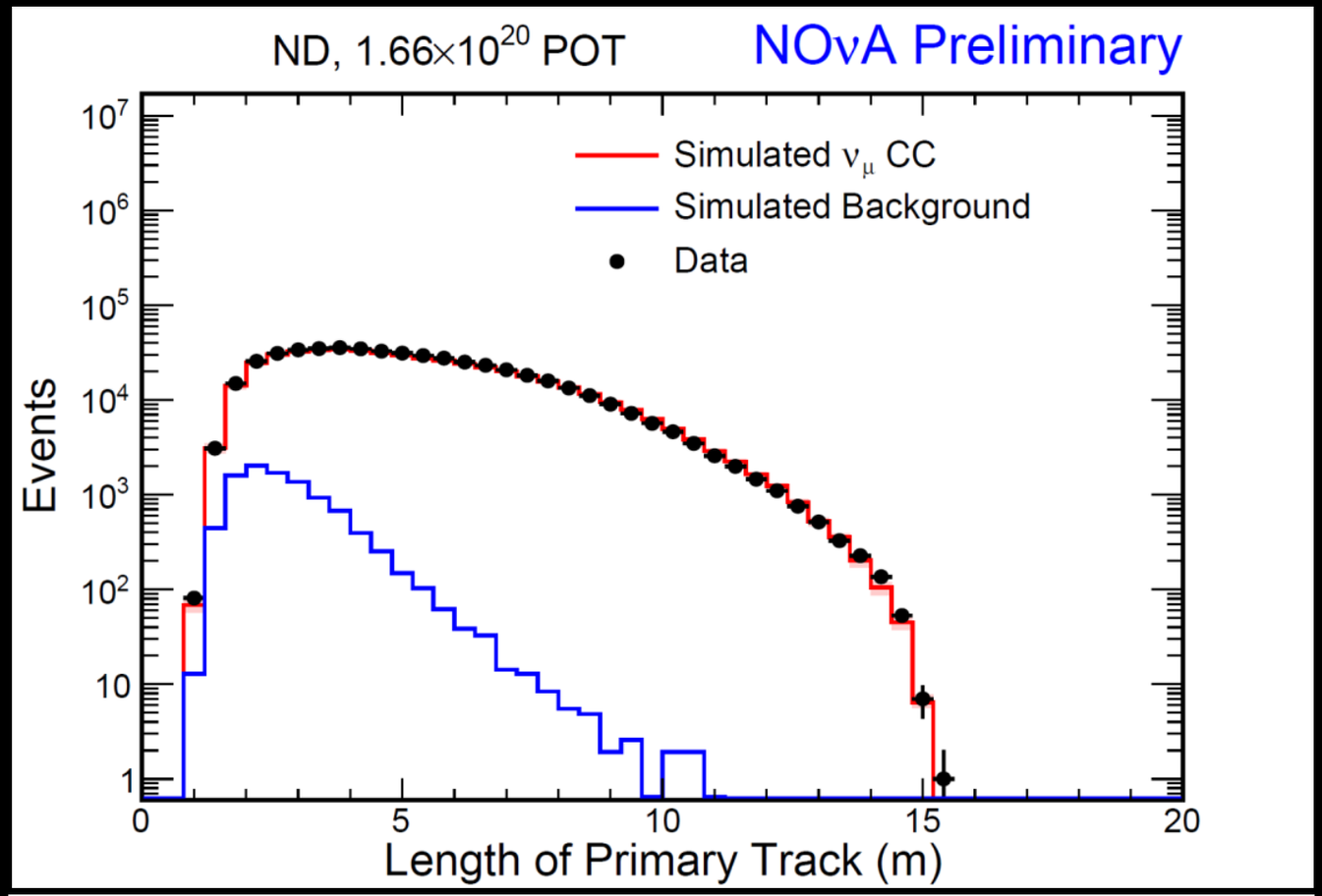


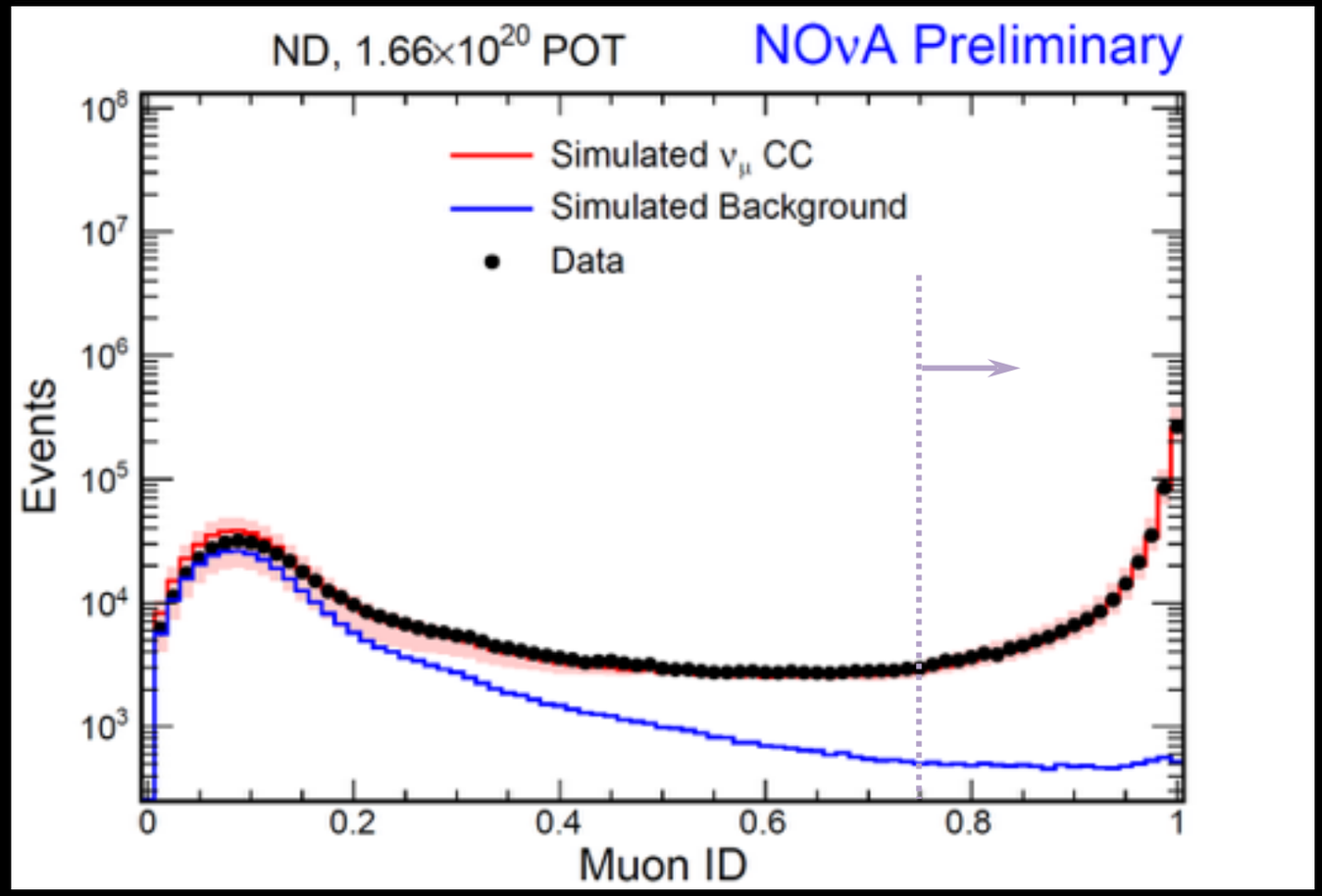


IN AN OFF-AXIS EXPERIMENT NEAR THE OSCILLATION MAXIMUM THE EFFECT IS **EVEN MORE DRAMATIC**

MUON NEUTRINO SELECTION

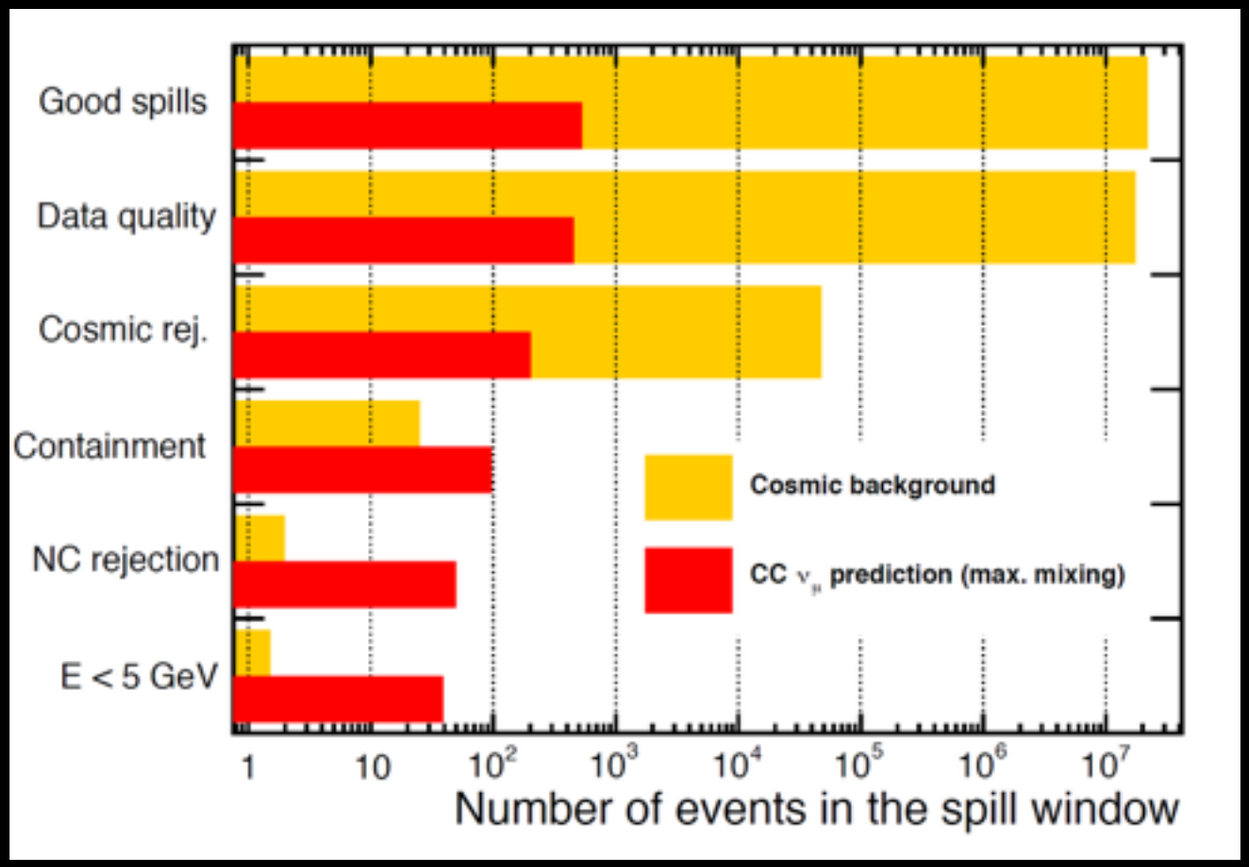
- We apply first basic containment cuts requiring no activity close to the wall of the detector.
- Excellent agreement of muon based data vs MC.
- We have developed a particle identification algorithm (k-nearest-neighbors) based on muon characteristics:
  - **track length**
  - dE/dx along the track
  - scattering along track
  - track-only plane fraction

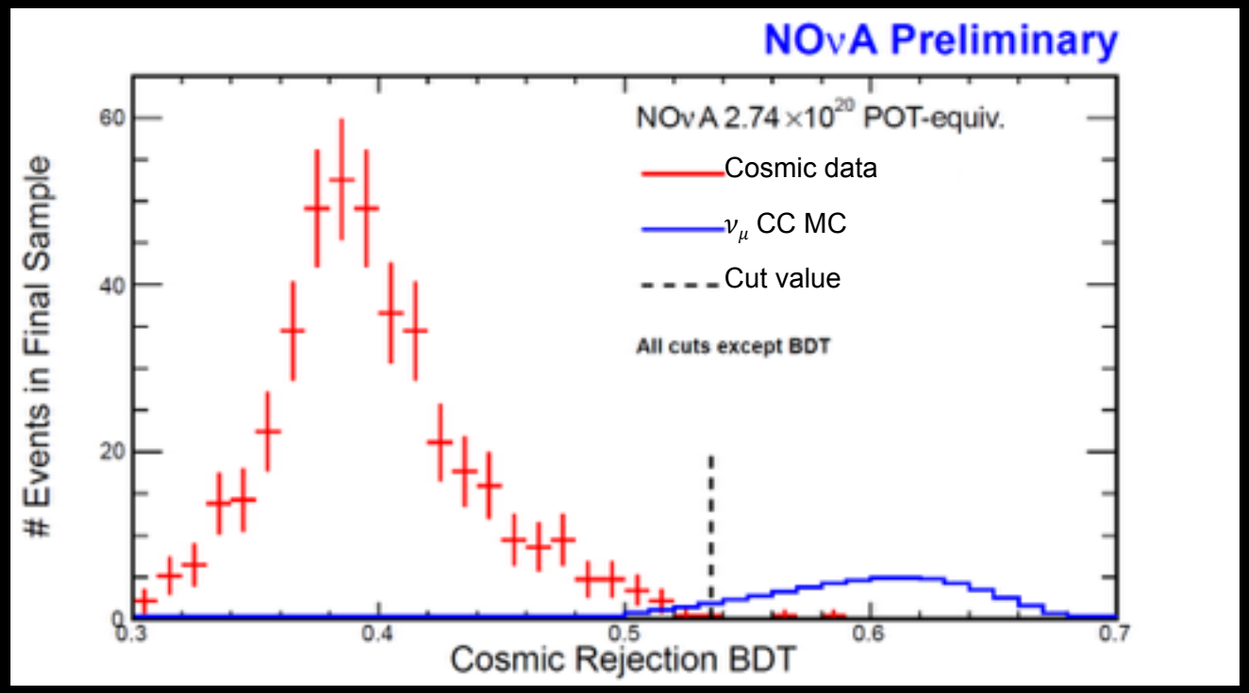




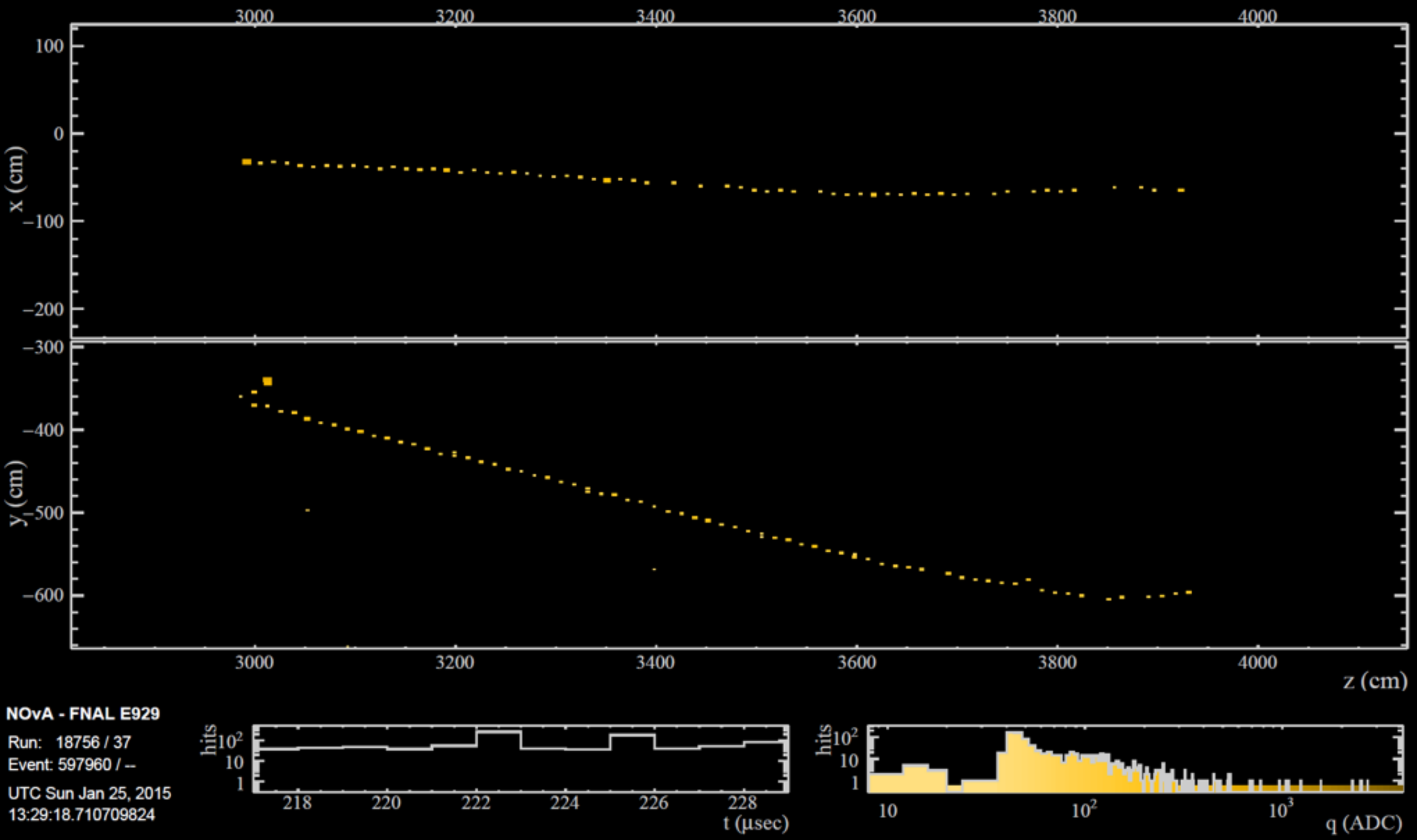
COSMIC REJECTION FOR MUON NEUTRINOS

- Final cosmic background rate is measured directly from data taken concurrently with beam spill by using the out-of-time window.
- Selecting a narrow window around the 9.6 μsec spill gives a rejection factor of 10^5.
- For the cosmic rejection of the muon neutrino disappearance analysis, we use a boosted decision tree algorithm based on:
  - Reconstructed track direction, position, and length; and energy and number of hits in event.
- Event topology gives an additional factor of 10^7 rejection.



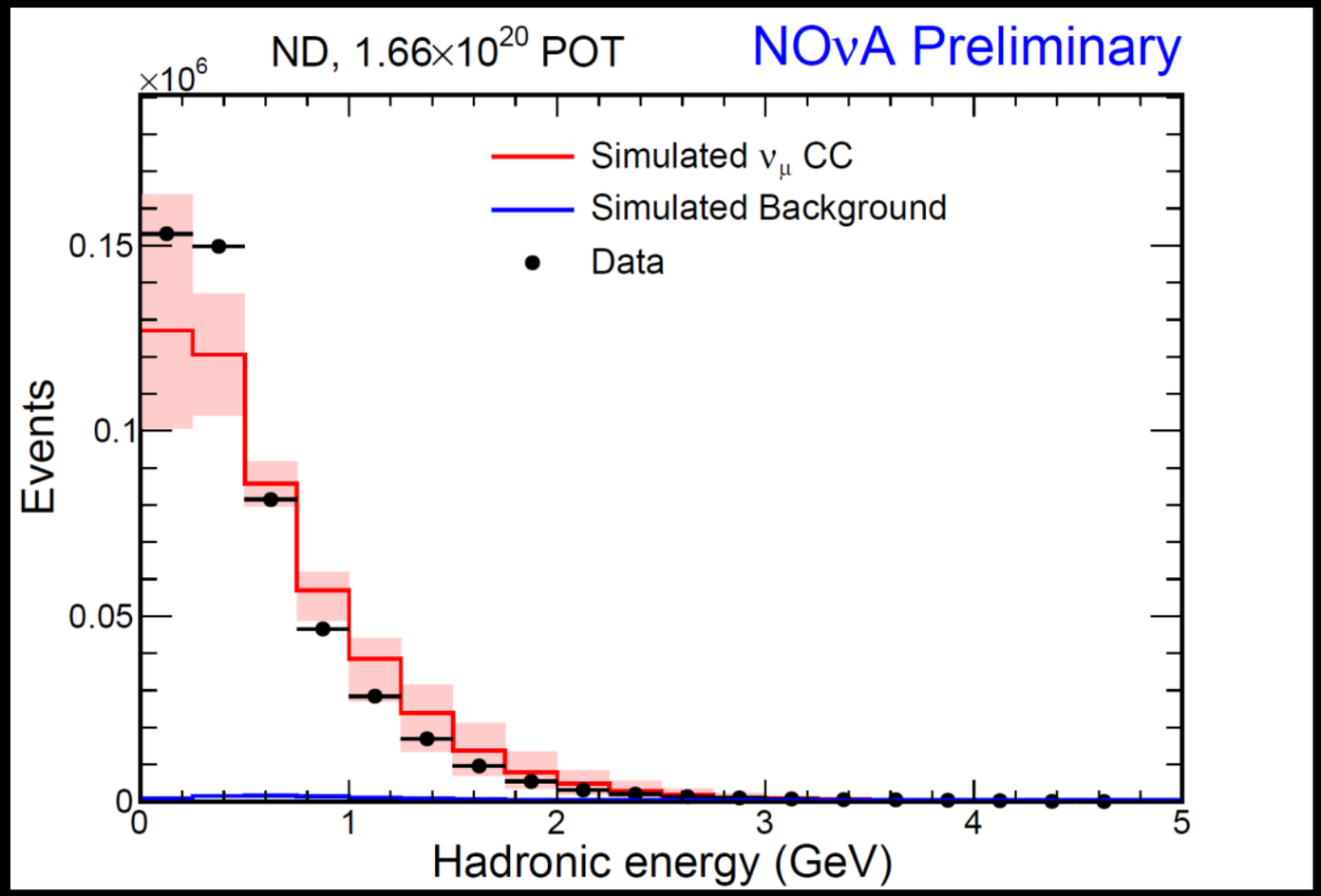


MUON NEUTRINO CANDIDATE



MUON NEUTRINO ENERGY

- Data vs MC show good agreement for muon neutrino selected events.
  - Muons are very well described by our MC.
- However, Monte Carlo has 21% more energy in the hadron system than seen in data.
- The hadron energy is thus recalibrated such that the total energy peak of the data matches the MC.
- This results in 6% overall neutrino energy scale uncertainty.



ND DATA IS USED TO PRODUCE A DATA DRIVEN PREDICTION IN THE FD

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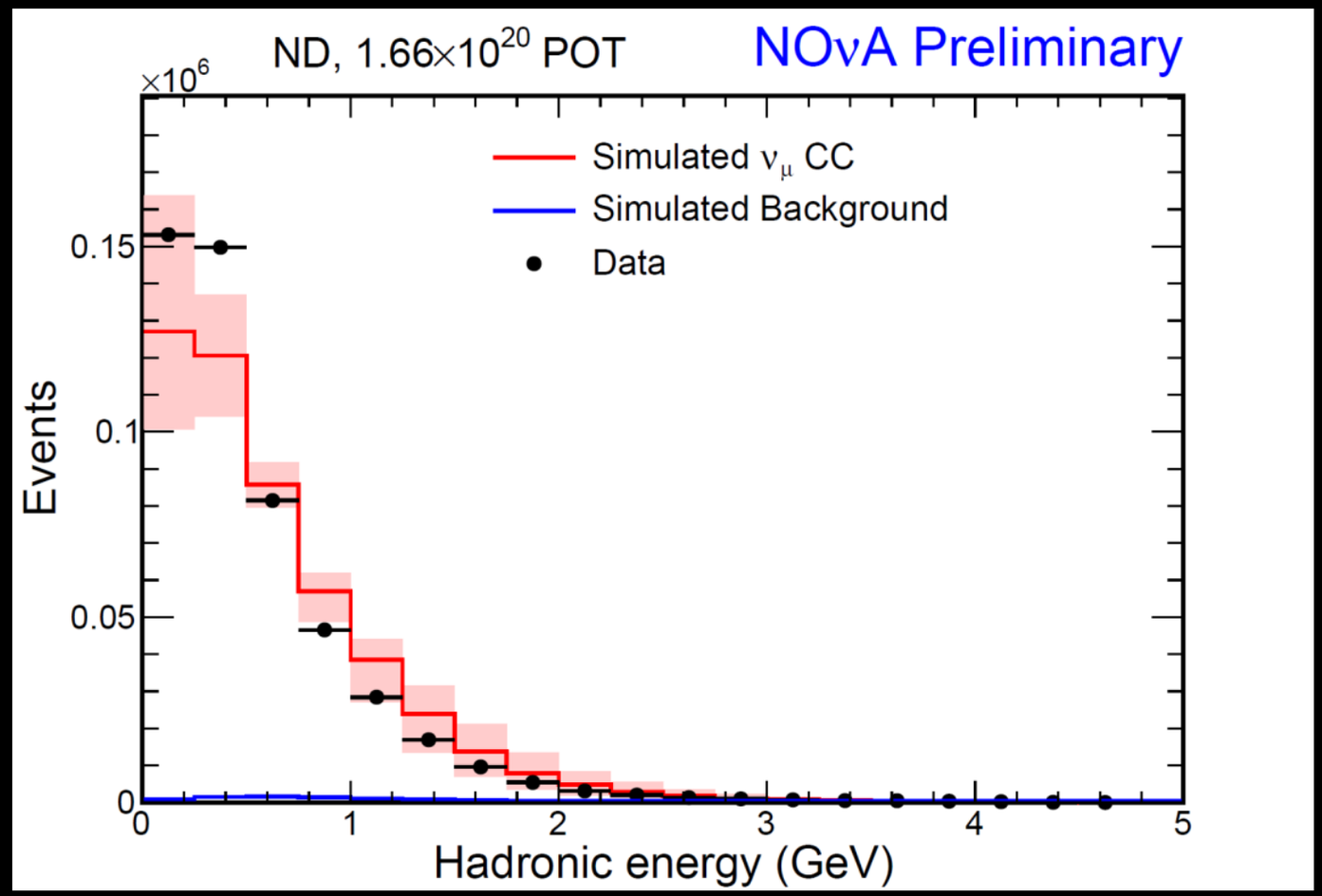
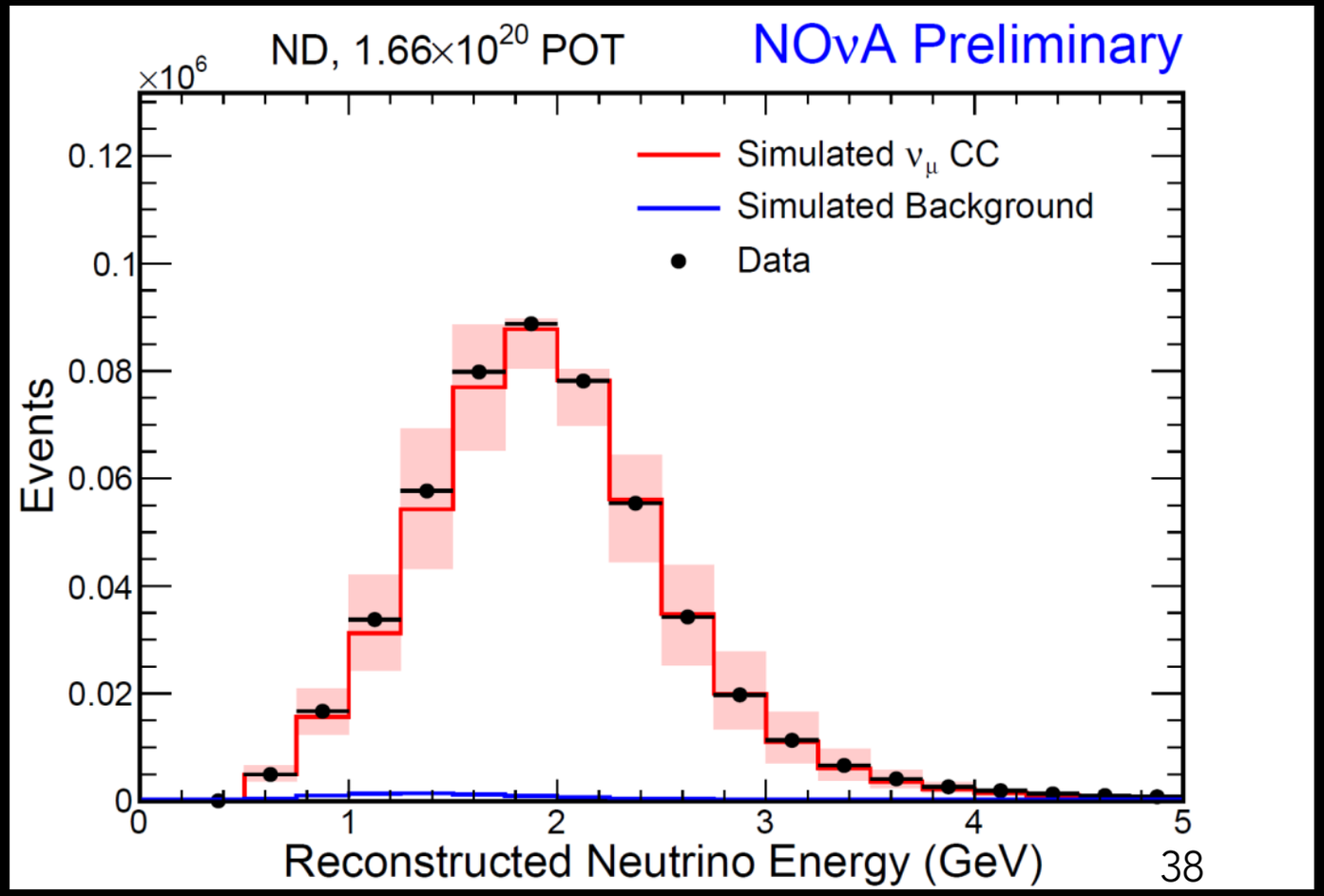
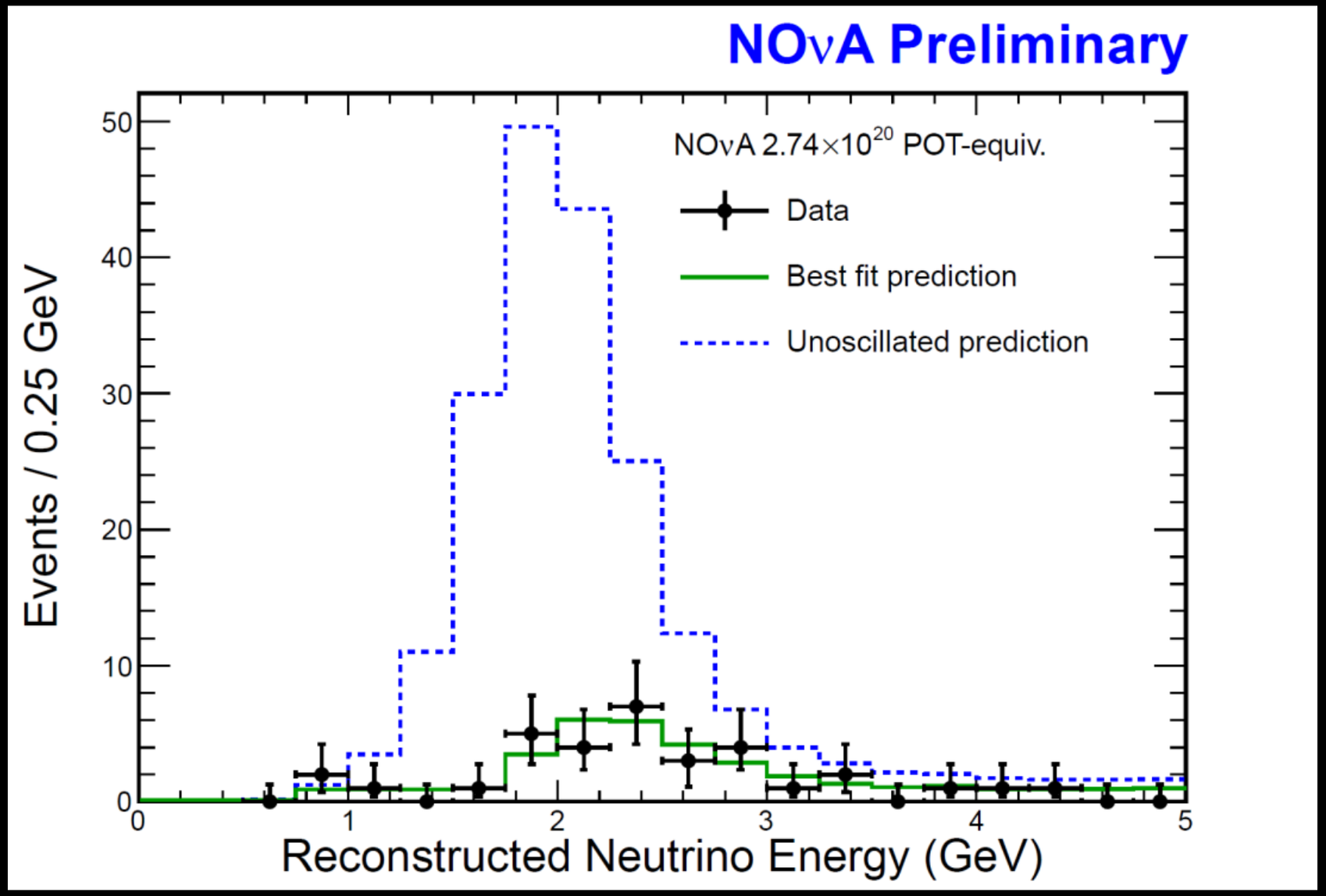




MUON NEUTRINO SELECTED SPECTRUM



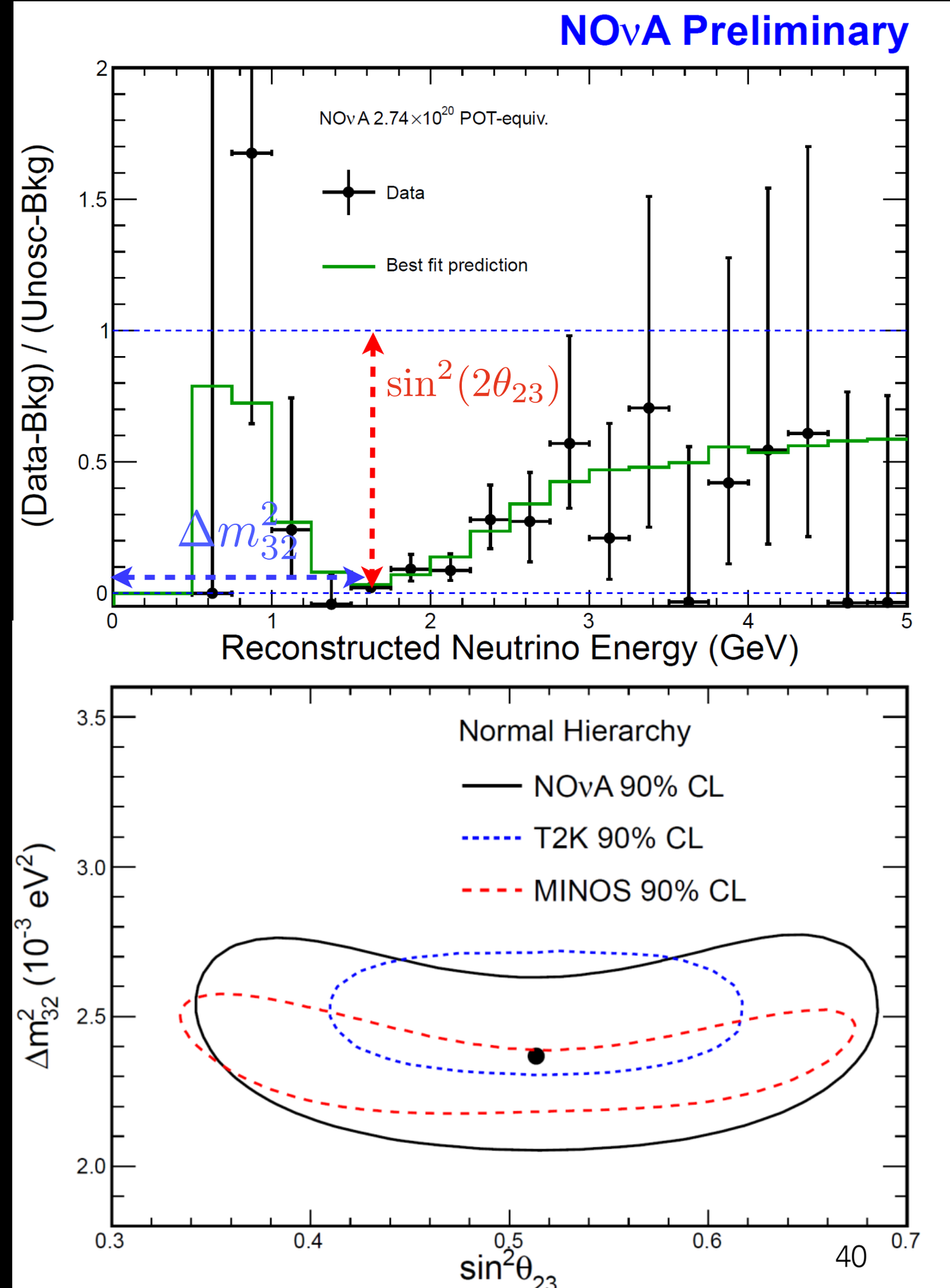
- We expect 201 events before oscillations.
- We observe 33 events.

MUON NEUTRINO DISAPPEARANCE RESULTS

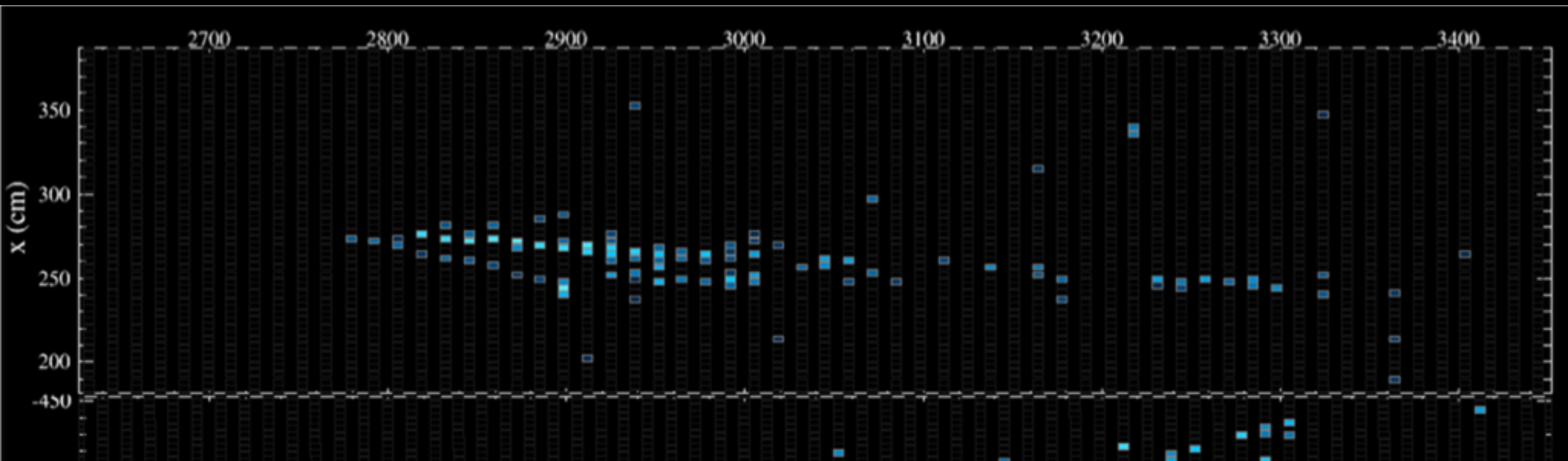
- The spectrum is matched **beautifully** by the oscillation fit.
- Largest systematic is hadronic neutrino energy.
- Parameter measurements:

$$\Delta m^2_{32} = +\,2.37^{+0.16}_{-0.15}\ \text{[normal ordering]}$$
$$\Delta m^2_{32} = -\,2.40^{+0.14}_{-0.17}\ \text{[inverted ordering]}$$
$$\sin^2\theta_{23} = 0.51 \pm 0.10$$

COMPELLING MEASUREMENT WITH 7.6% OF NOMINAL EXPOSURE



ELECTRON NEUTRINO APPEARANCE



ELECTRON NEUTRINO APPEARANCE

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

- The probability of ν_e appearance in a ν_μ beam:

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

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

- Searching for ν_e events in NOvA, we can access **$\sin^2(2\theta_{13})$**.
- Probability depends not only on **θ_{13} but also on δ_{CP}** which might be the key to matter anti-matter asymmetry of the universe.
- Probability is enhanced or suppressed due to **matter effects** which depend on the mass hierarchy i.e. the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs anti-neutrino running.

NOVA PROBES THE MASS HIERARCHY AND CP VIOLATION SPACE

ELECTRON NEUTRINO APPEARANCE IN NOVA

- The probability of ν_e appearance in a ν_μ beam:

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

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
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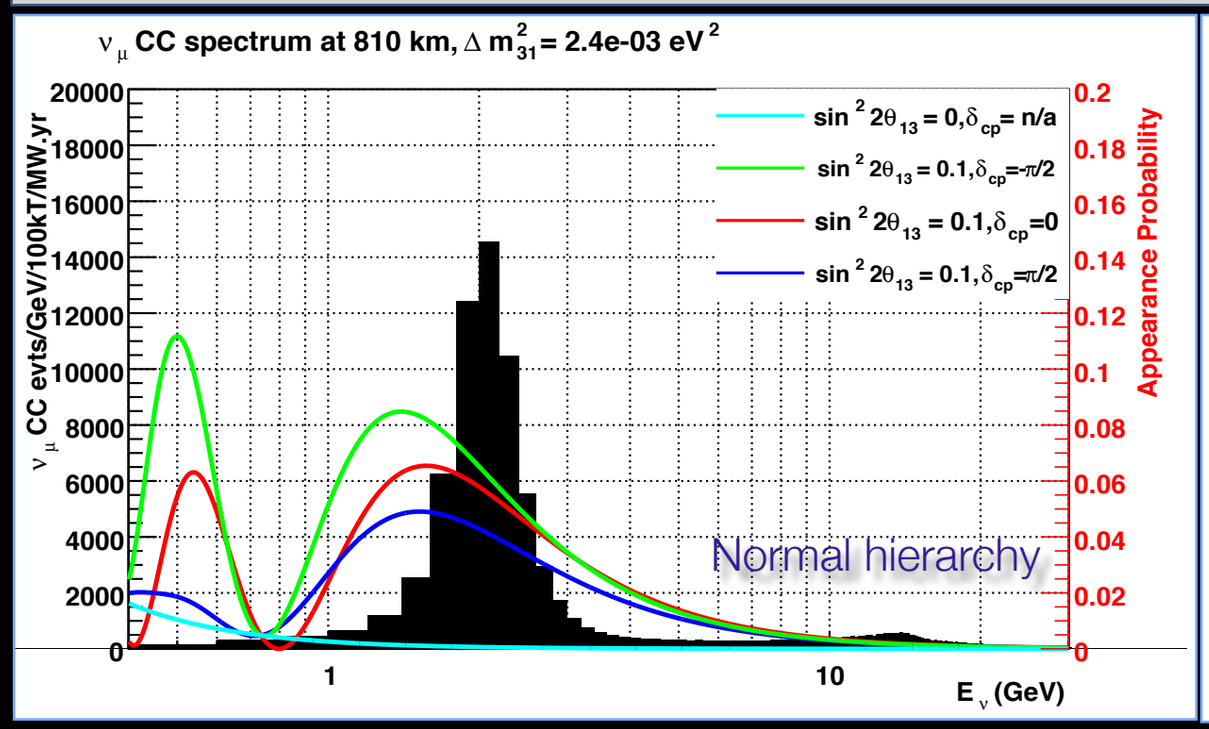
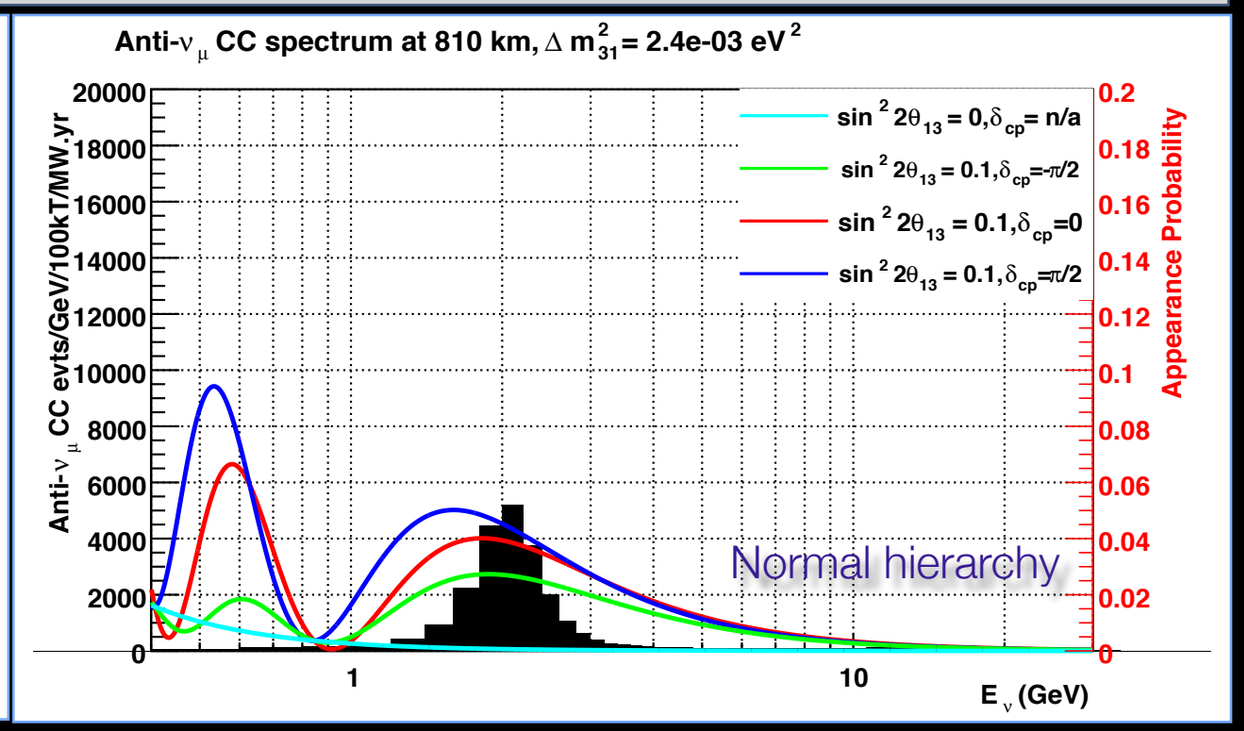
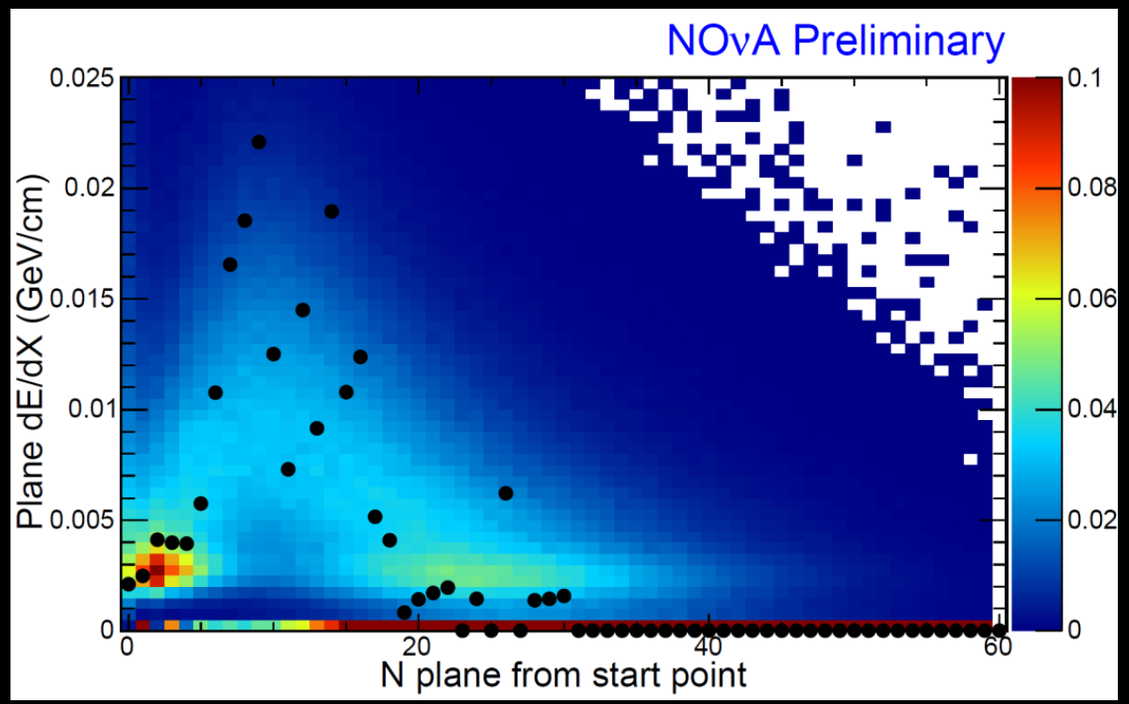
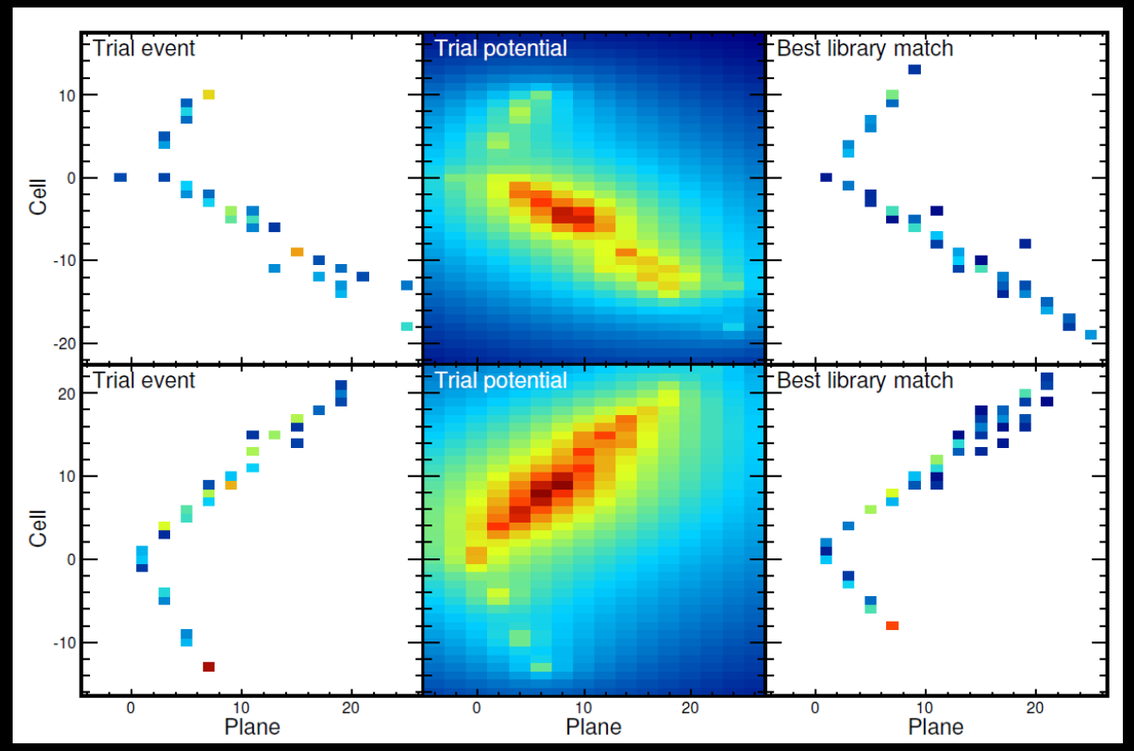




ELECTRON NEUTRINO SELECTION

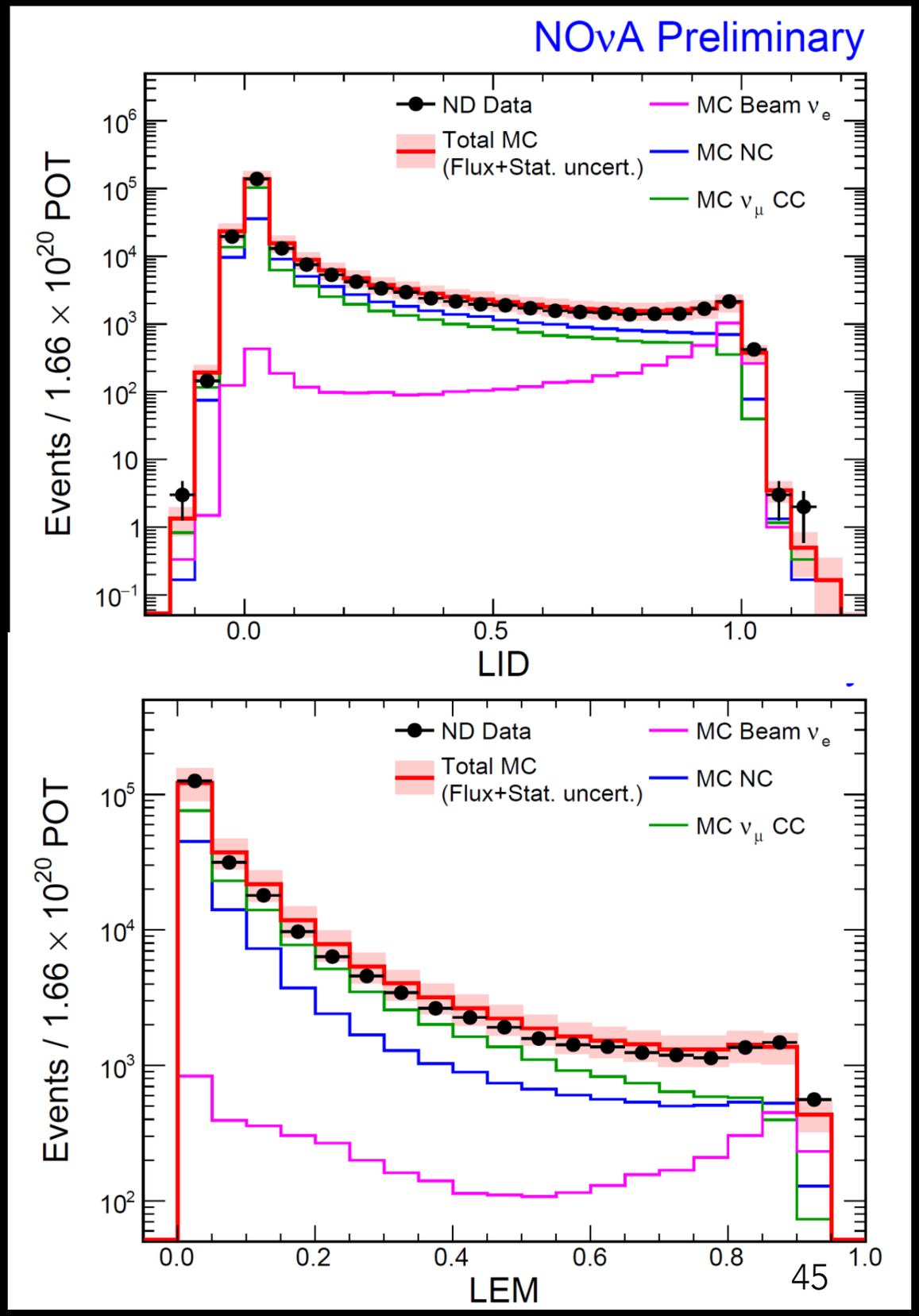
- Two particle ID algorithms based on pattern recognition techniques have been developed:
  - **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for e/μ/π/p particles hypotheses. Uses a neural net.
  - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns identification to trial event according to top matches in library.
- Good separation of electron neutrino signal from background including cosmic background.





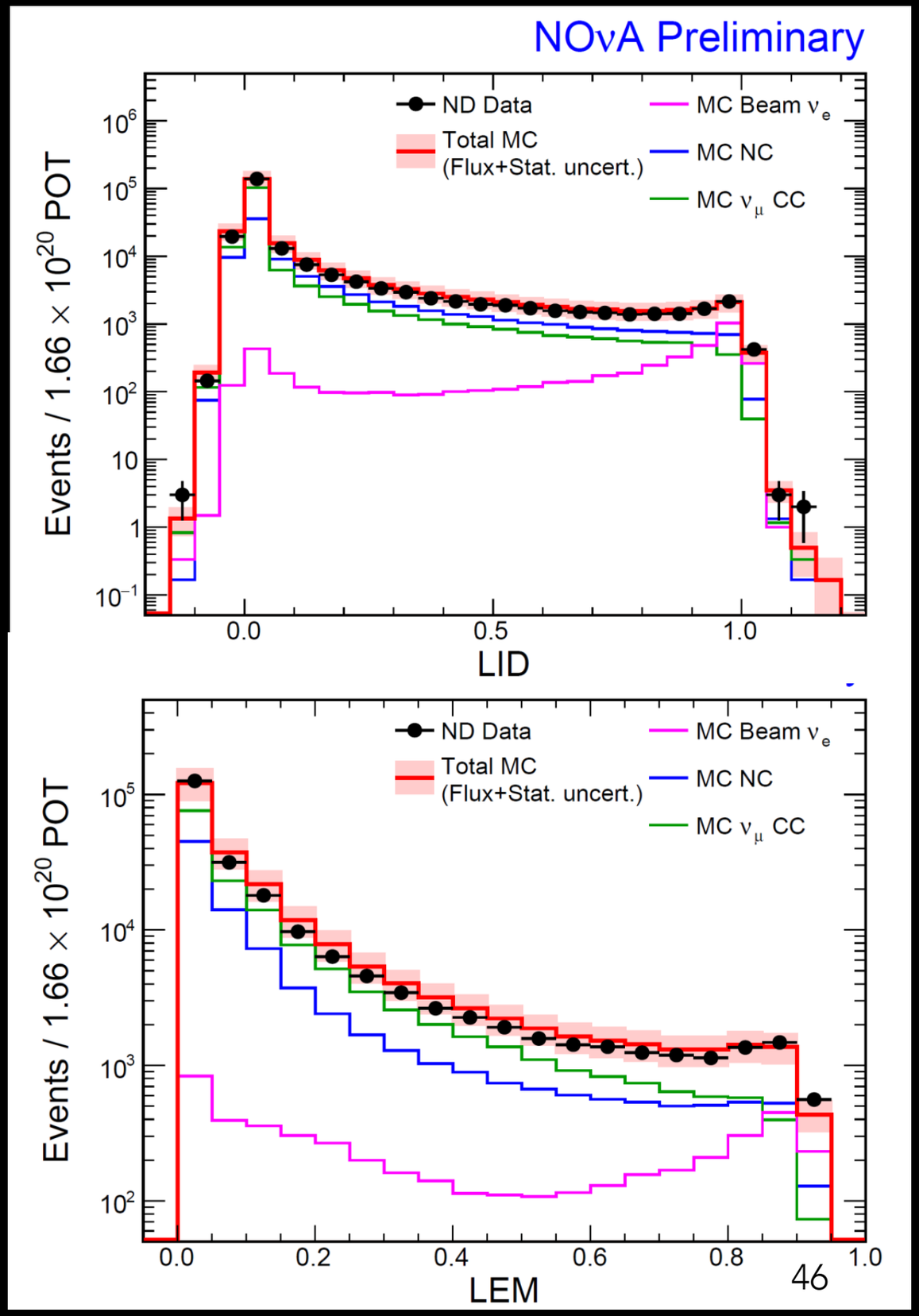
ELECTRON NEUTRINO SELECTION

- Two particle ID algorithms based on pattern recognition techniques have been developed:
  - **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for various particles hypothesis. Uses a neural net.
  - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns characteristics according to top matches.
- Identical performance. Signal efficiency relative to containment cuts: 35%. After all selection, 0.7% of NC events remain, relative to those after containment. Expected overlap in LID and LEM signal samples: 62%.



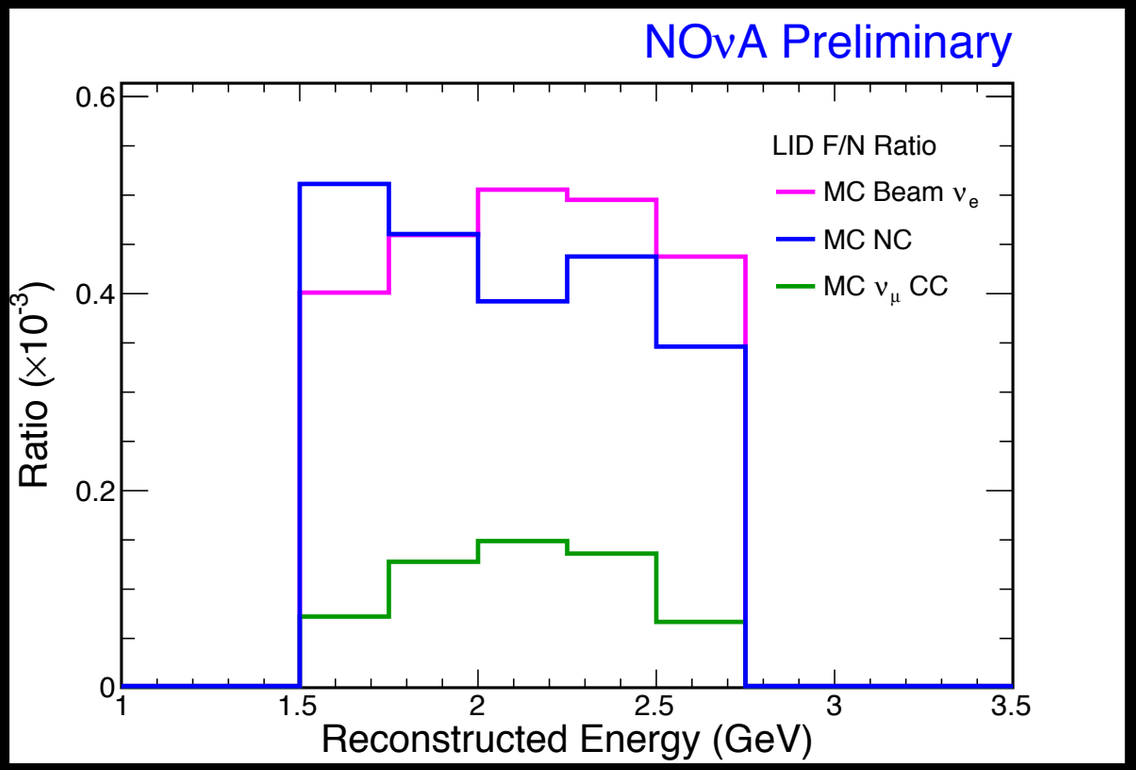
ELECTRON NEUTRINO SELECTION

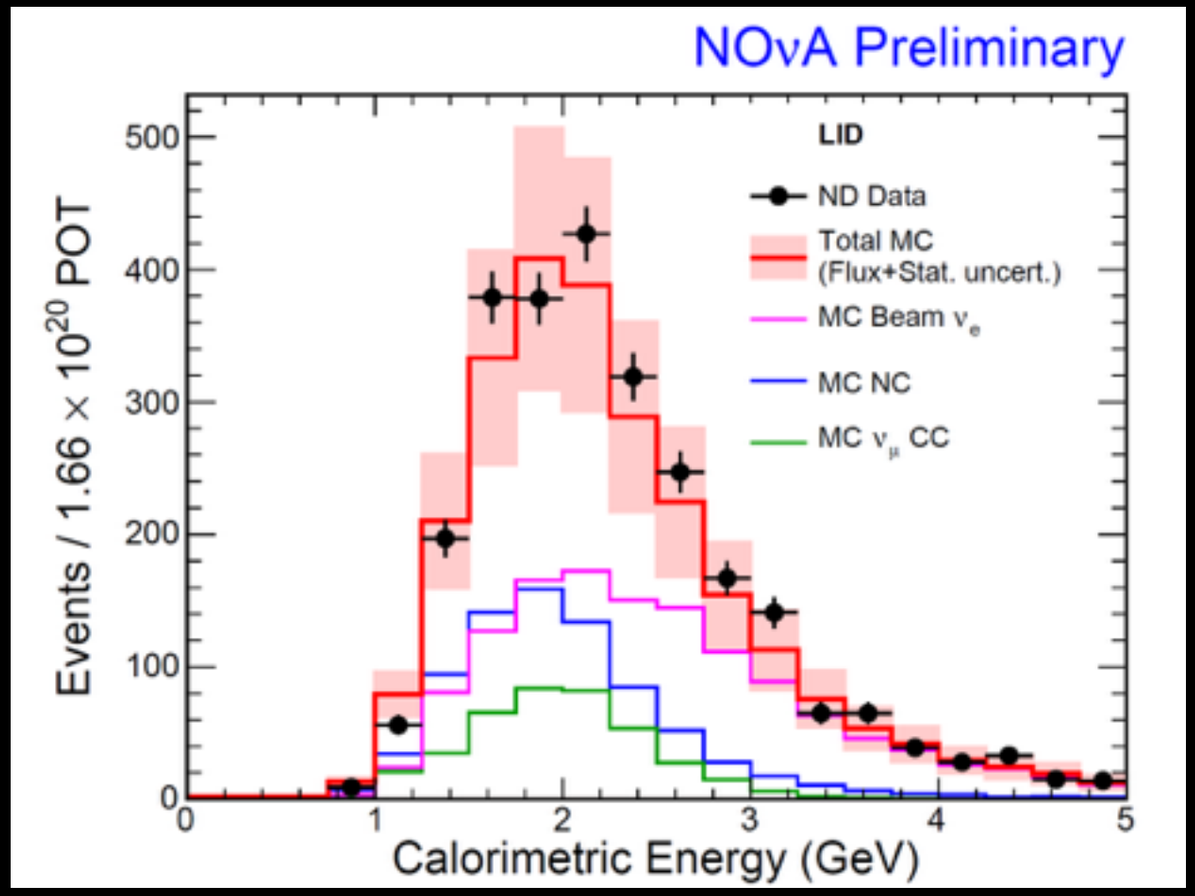
- Two particle ID algorithms based on pattern recognition techniques have been developed:
  - **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for various particles hypothesis. Uses a neural net.
  - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns characteristics according to top matches.
- PRIOR TO UNBLINDING DECIDED TO SHOW BOTH RESULTS AND USE **LID** AS PRIMARY SELECTOR



PREDICTING THE BACKGROUND IN THE FD

- Calorimetric energy after electron neutrino selection (shown for LID) shows good agreement.

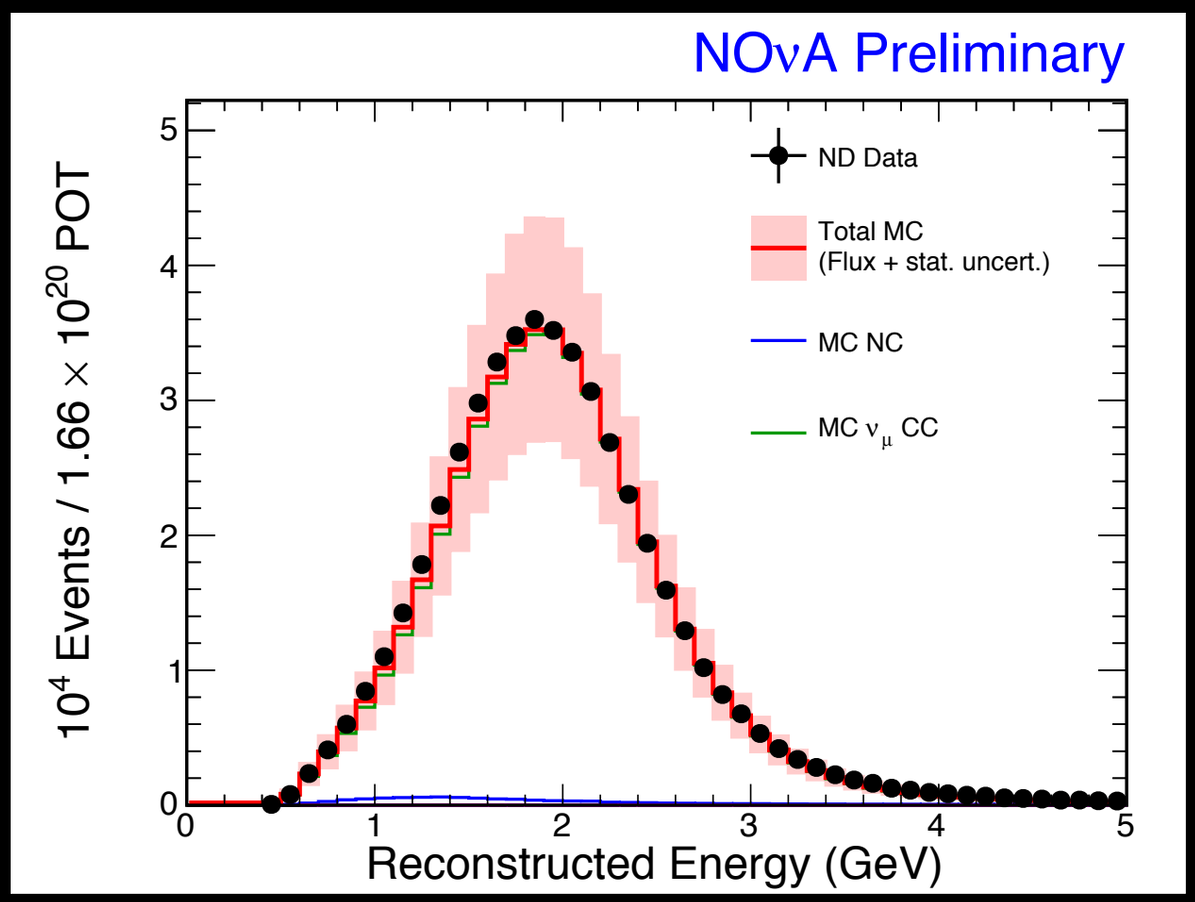


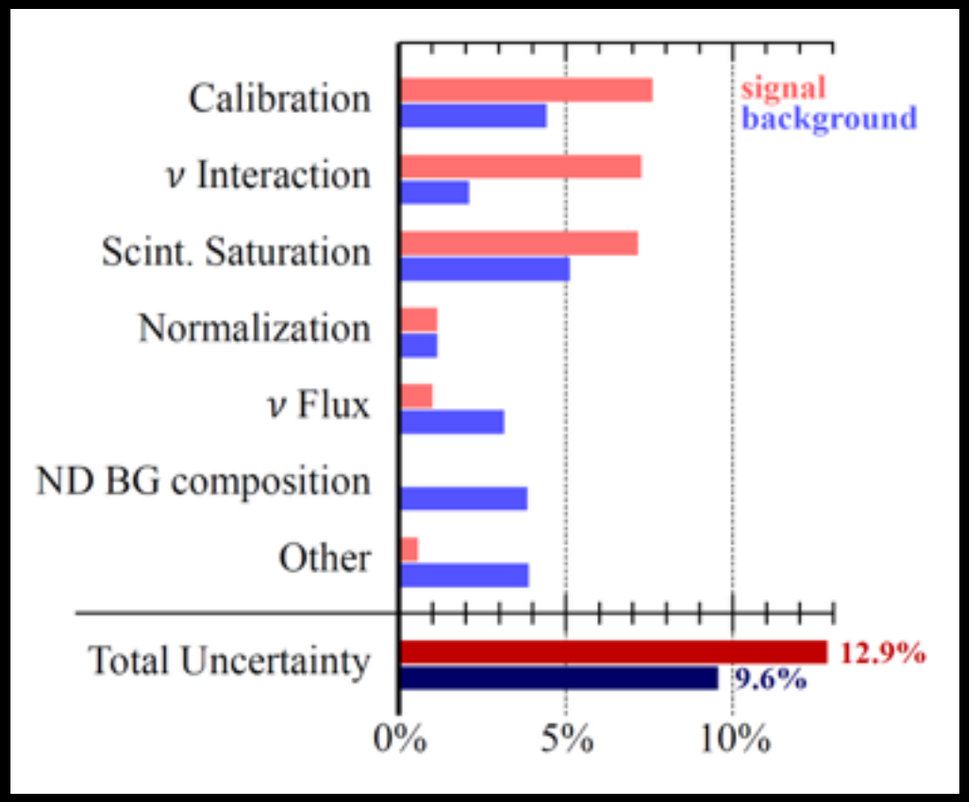


- ND data is translated to FD background expectation in each energy bin, using Far/Near ratios from simulation.
- A small 5% excess in data is observed in the ND which is used as a correction to the FD background prediction.

PREDICTING THE SIGNAL IN THE FD

- FD signal expectation is predicted using the ND-selected ν_μ CC spectrum using same technique as for muon neutrino disappearance.





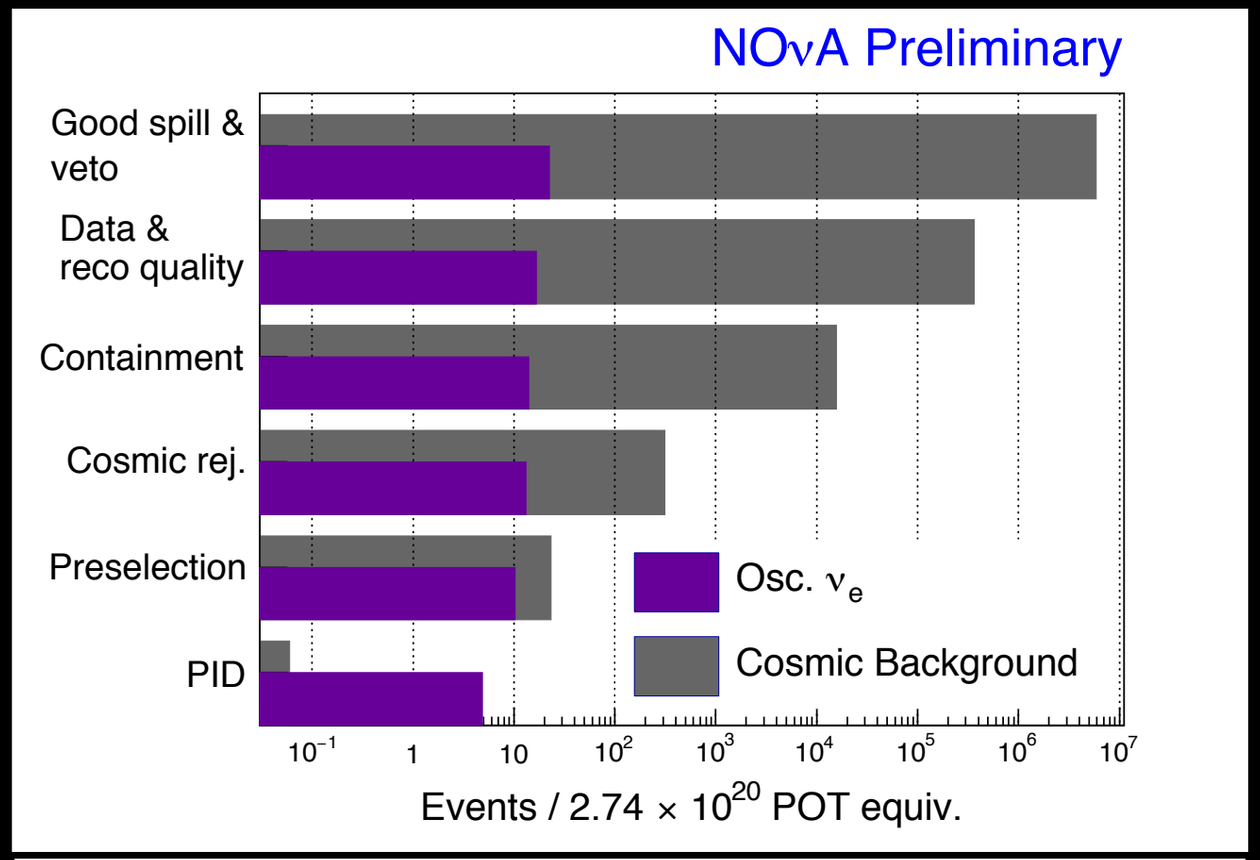
- Most systematics are assessed by modifying the Far/Near simulated ratios and calculating the variation in the prediction both for signal and background.

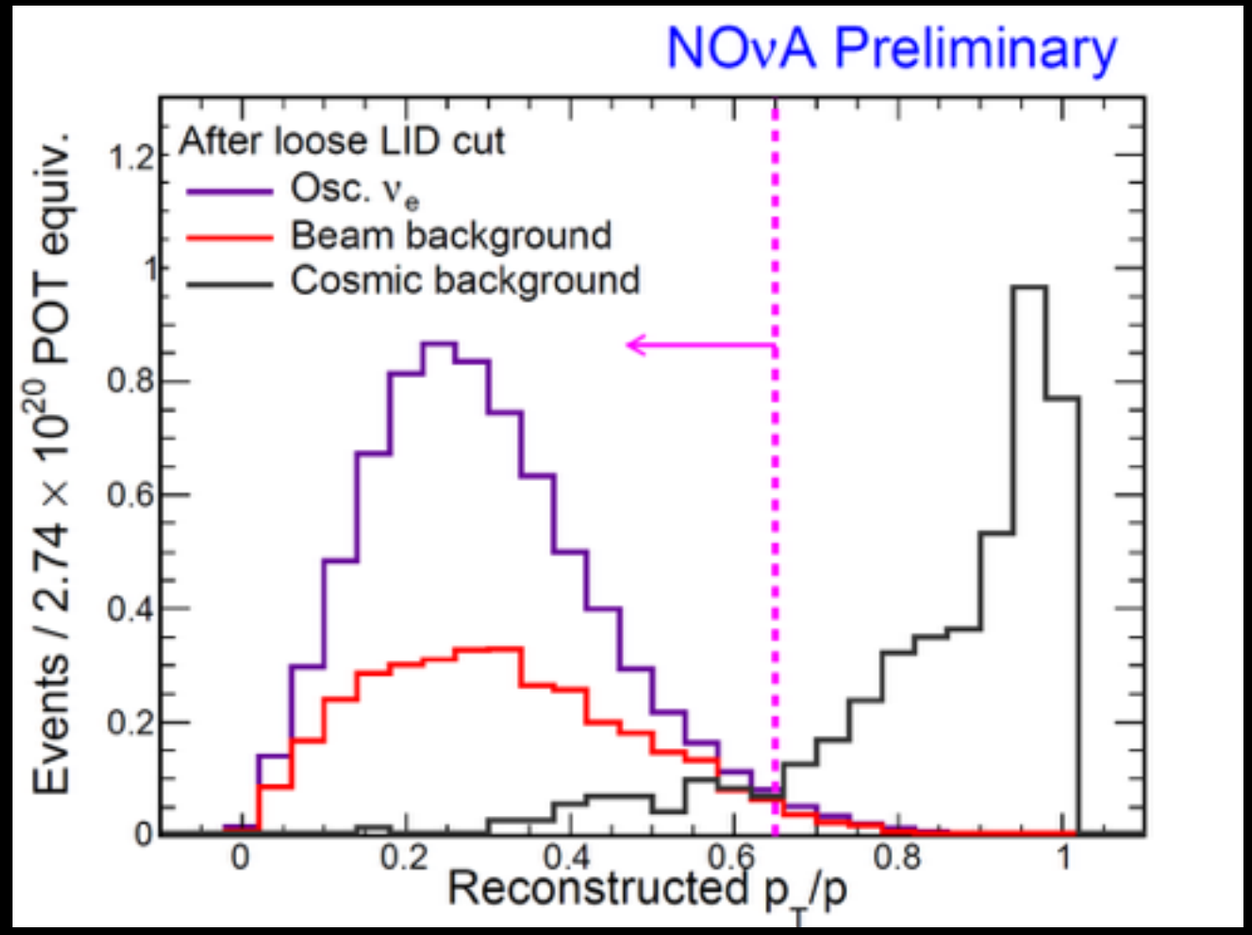
SEVERAL INDEPENDENT EM SAMPLES SHOW GOOD DATA/MC AGREEMENT

COSMIC REJECTION FOR ELECTRON NEUTRINOS

- Containment and topological cuts such as removing events with large p_T/p remove significant factors of this background.
- The electron neutrino selectors themselves provide the remaining level of rejection to achieve 10^8 removal of cosmic ray interactions.
- Measurement of background on out-of-time spill data.

EXPECTED COSMIC BACKGROUND: 0.06 EVENTS





THE PREDICTION

- Background predictions are about 1 count each, 10% error. Few percent dependence on other oscillation parameters.
- Dominated by beam electron neutrinos and neutral current interactions.
- Cosmic background comparable to smallest beam backgrounds.

PID	**total bkg**	ν_e CC bkg	NC bkg	ν_μ CC bkg	ν_μ CC bkg	cosmic bkg
LID	**0.94±0.09**	0.46	0.35	0.05	0.02	0.06
LEM	**1.00±0.11**	0.46	0.40	0.06	0.02	0.06

- Signal prediction depends on oscillation parameters, the extremes are:

2 ± 0.3 (IH $\delta_{CP}=\pi/2$) ⟷ **6 ± 0.7 (NH $\delta_{CP}=3\pi/2$)**

THE ANSWER

- Background predictions for both selectors are about 1 count each, 10% systematic. Few percent dependence on oscillation parameters.
- Dominated by beam electron neutrinos and NC.
- Cosmic background comparable to smallest beam backgrounds.

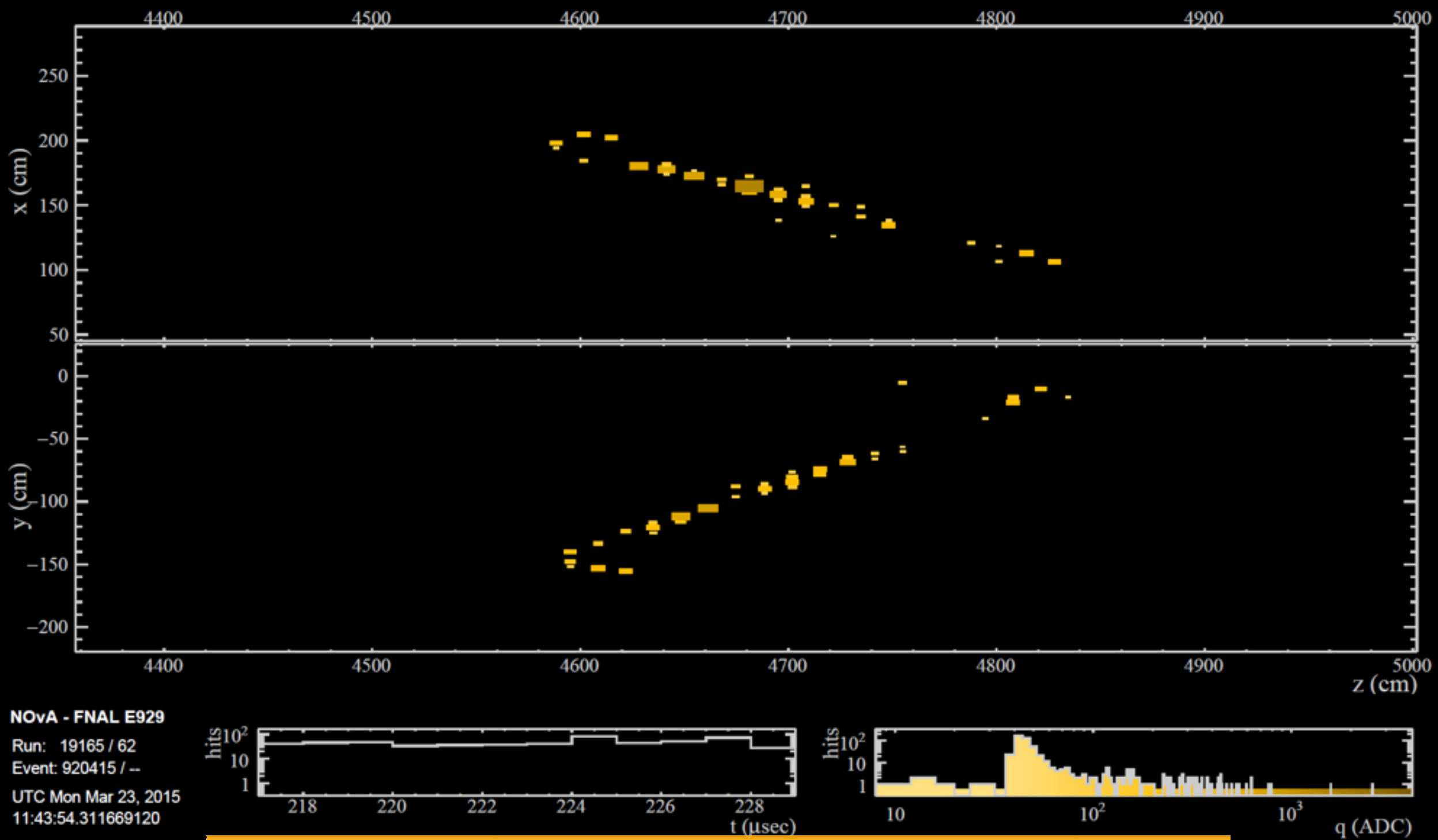
PID	**total bkg**	ν_e CC bkg	NC bkg	ν_μ CC bkg	ν_μ CC bkg	cosmic bkg
LID	**0.94±0.09**	0.46	0.35	0.05	0.02	0.06
LEM	**1.00±0.11**	0.46	0.40	0.06	0.02	0.06

- We observe:

6 ELECTRON NEUTRINOS

(11 WITH LEM)

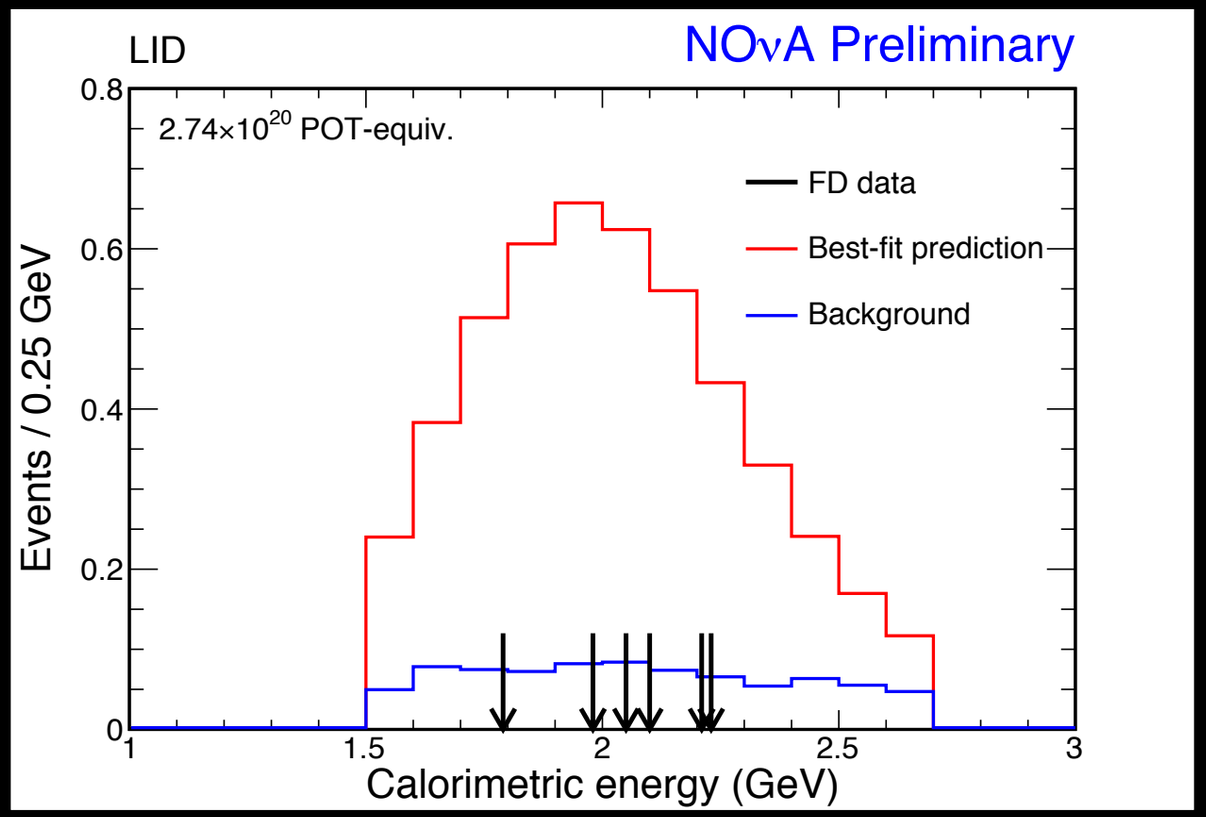
ELECTRON NEUTRINO CANDIDATE

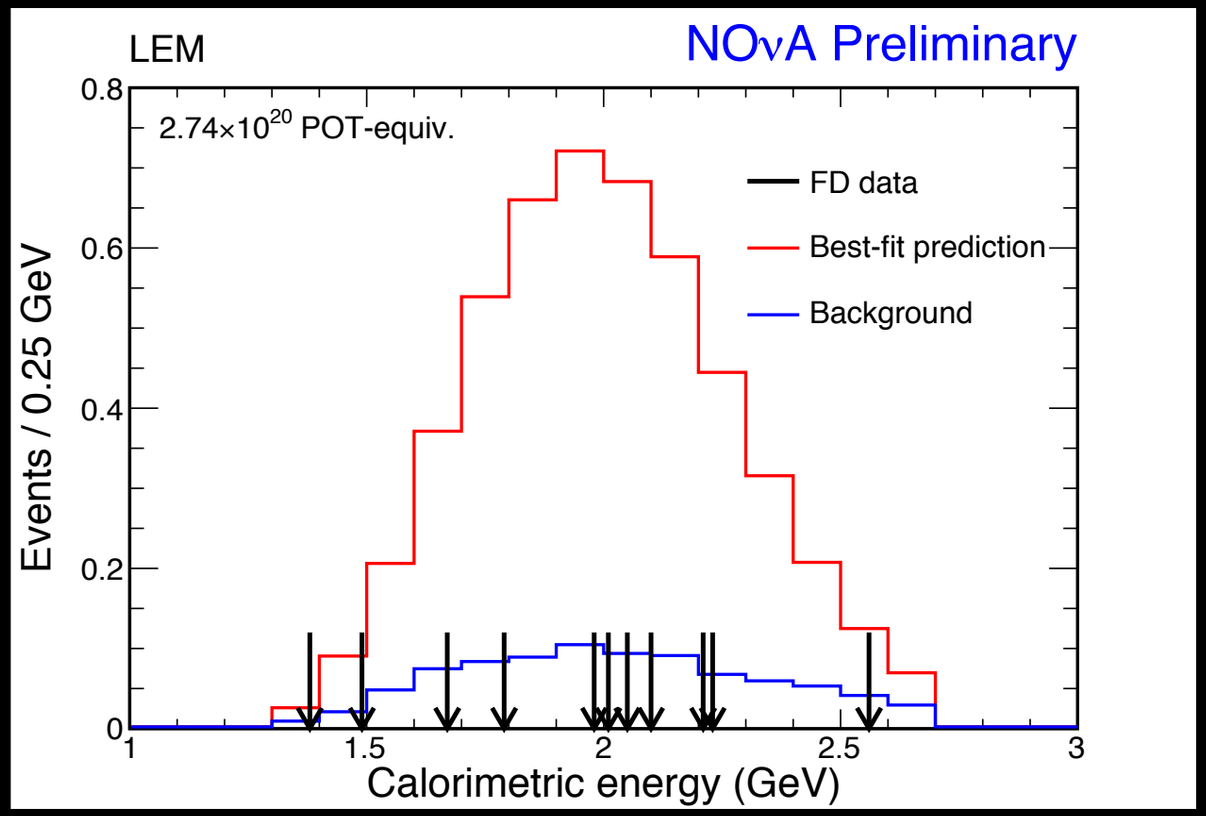


ALL 11 OF THEM ARE ABSOLUTELY GORGEOUS!

ELECTRON NEUTRINO SELECTED EVENTS

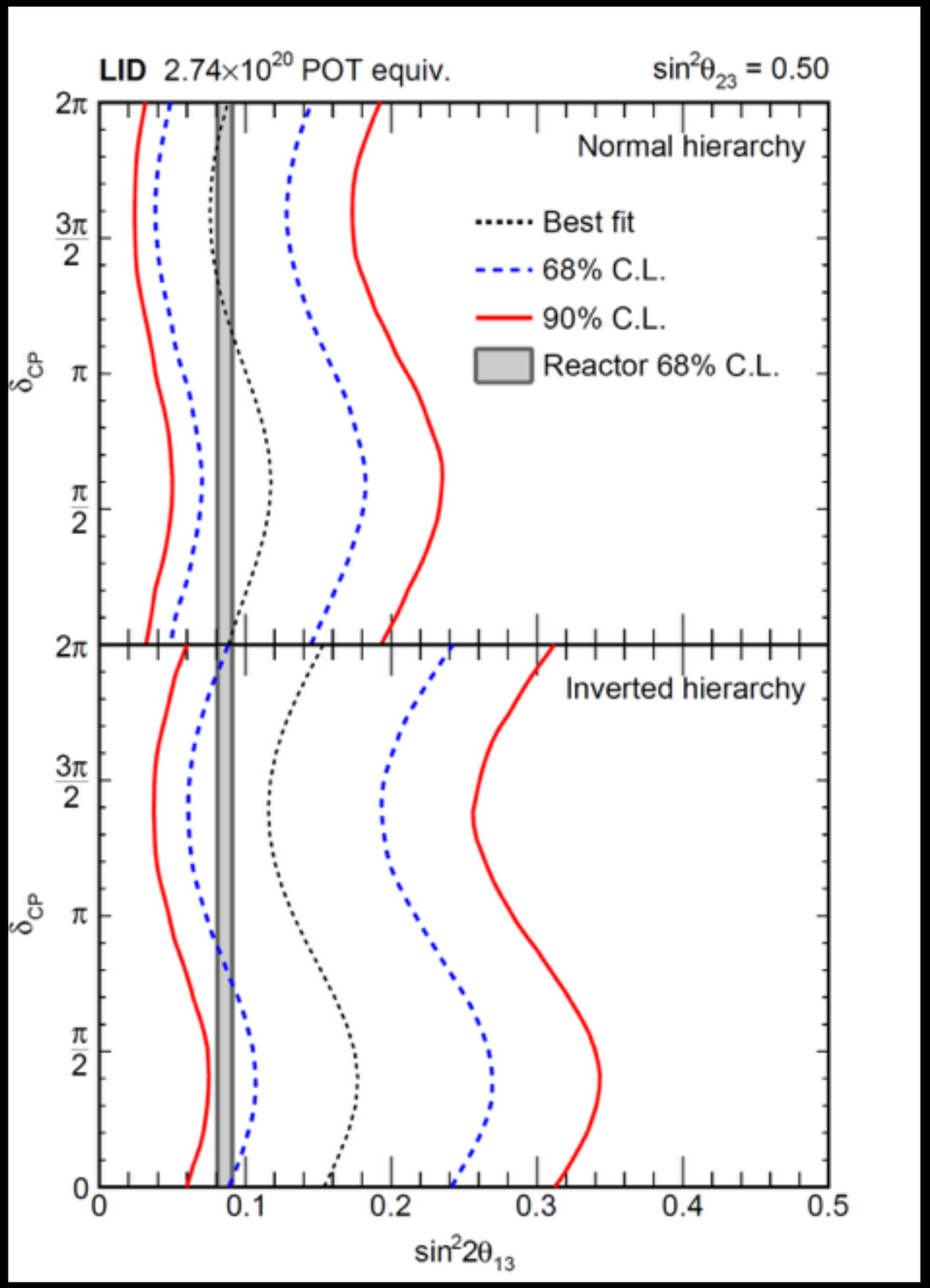
- **LID selects 6 events. The significance of appearance is 3.3σ**
- **LEM selects 11. The significance of appearance is 5.5σ**
- The expected background in each case is 1 event.
- All 6 of LID events are also selected by LEM. The P-value for selecting the combination (11:6/5/0) is 9.2%.
  - Note that LID and LEM have a difference in energy cuts in the low end.
- Other reassuring distributions include time, spatial and angular distributions.





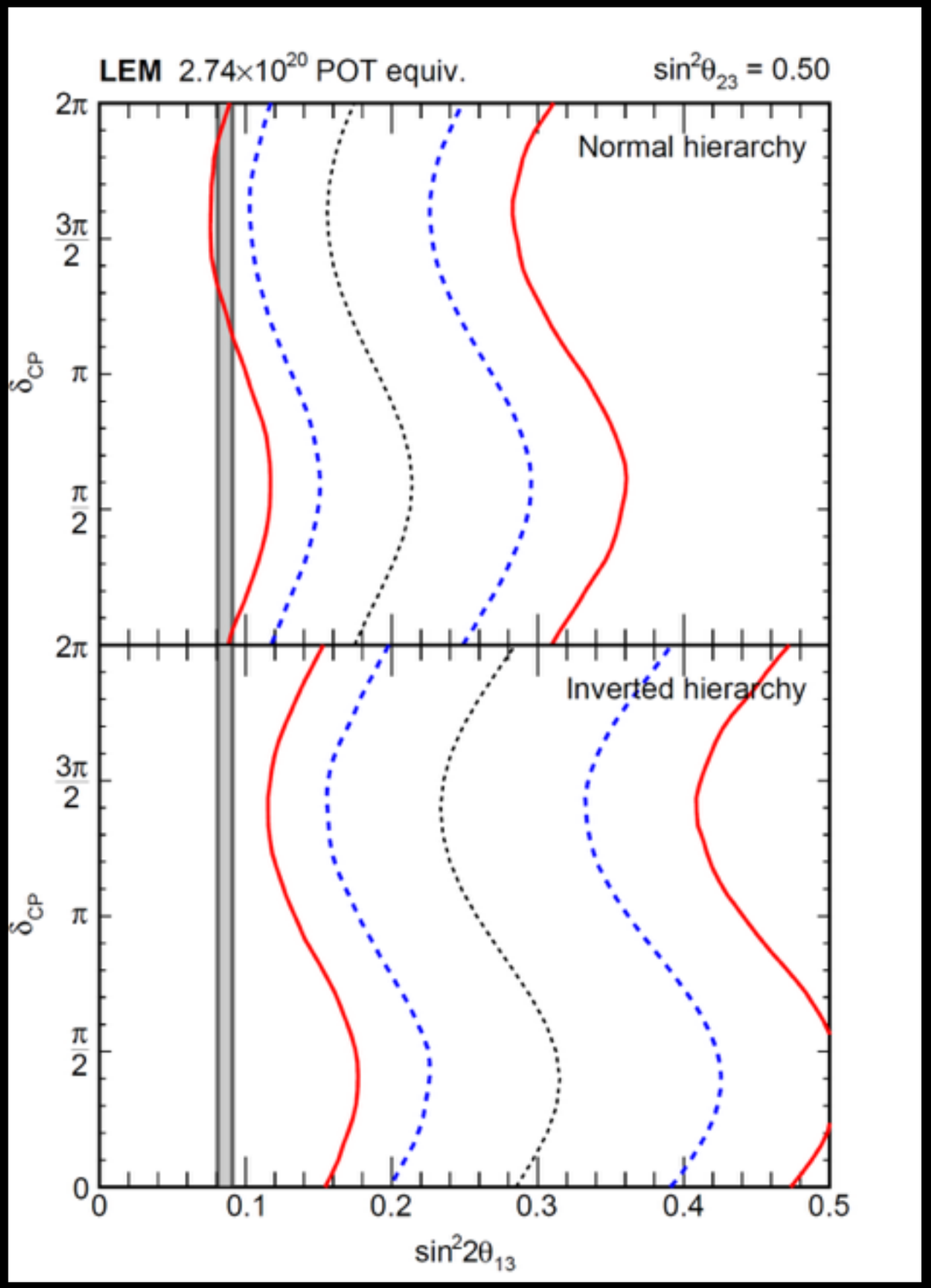
ELECTRON NEUTRINO APPEARANCE RESULTS

- Results show good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is ~1σ better for the normal ordering.
- This plot is for LID selector (n=6).



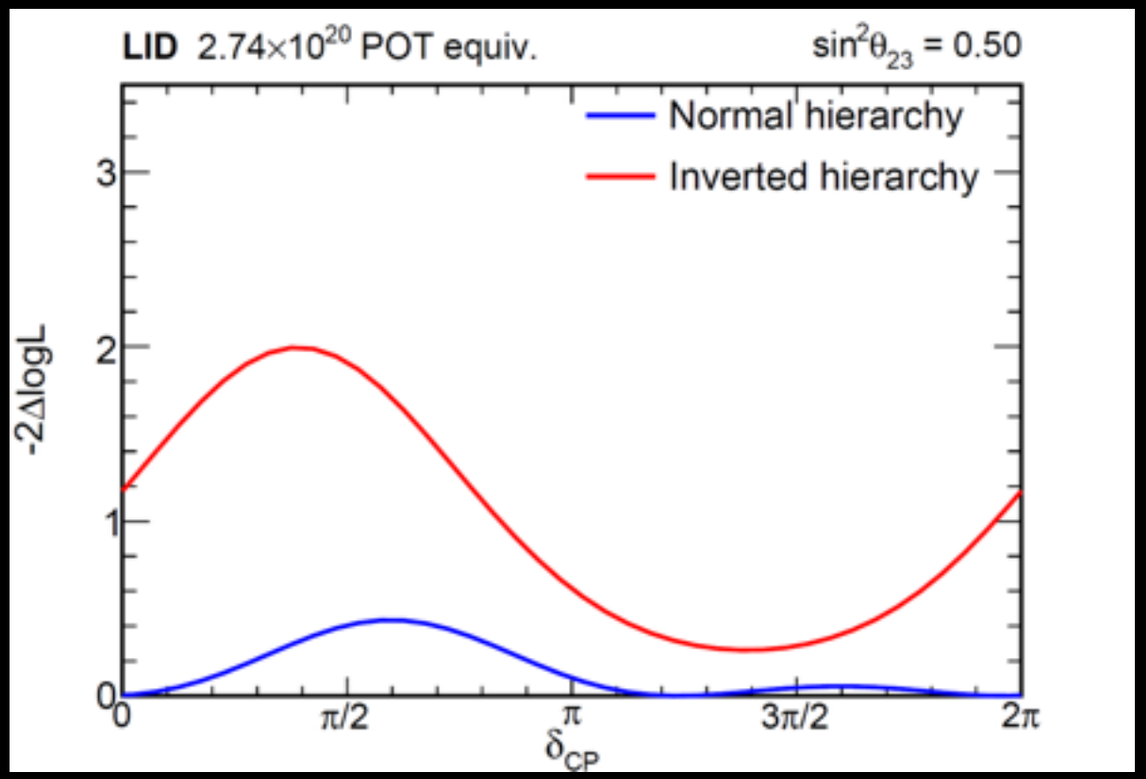
ELECTRON NEUTRINO APPEARANCE RESULTS

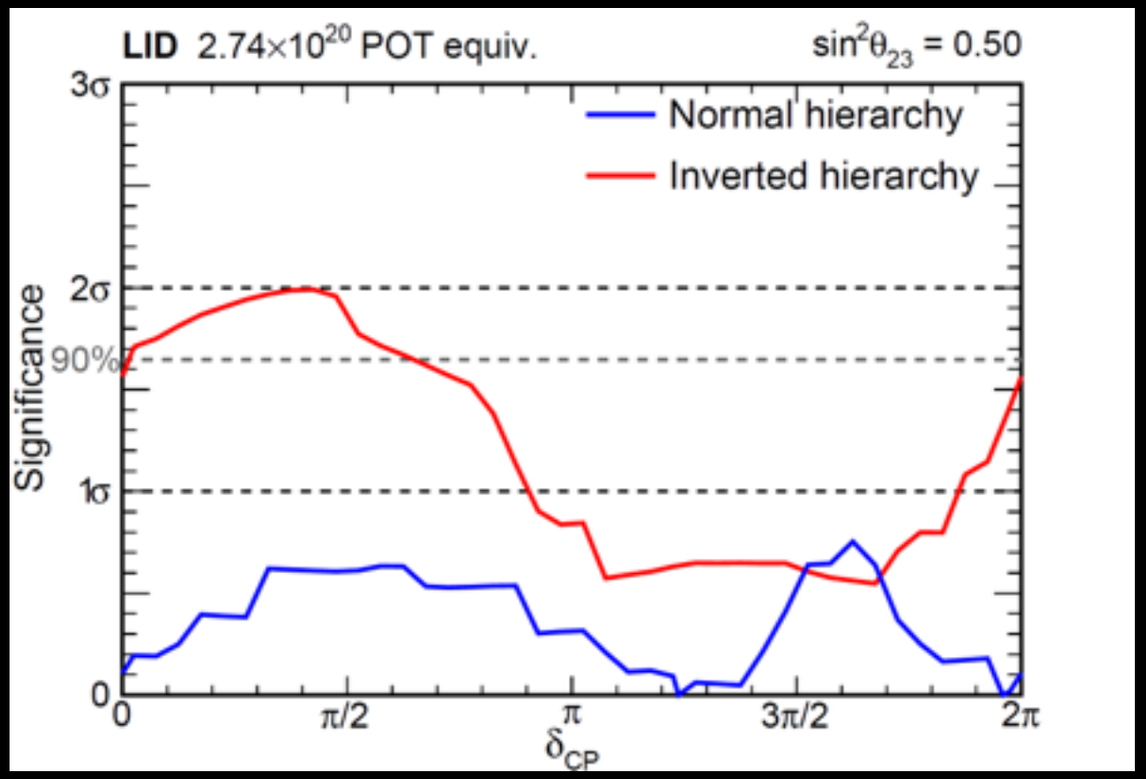
- Results show good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is ~1σ better for the normal ordering.
- For LEM (n=11) the s-curves shift by a factor of 2 to the right increasing tension for the inverted mass ordering.



ELECTRON NEUTRINO APPEARANCE RESULTS

- Taking the reactor measurement of θ_{13} as an input, we can explore compatibility with the mass hierarchy and and δ_{CP} using Feldman-Cousins.
- There is a significant deviation from gaussian limits in this case. Also non-smooth shape due to discreet nature of counting experiment.
- Resulting significances show that at maximal mixing, we disfavor the IH for $\delta \in [\,0, 0.6\pi\,]$ at 90% C.L. with primary selector.





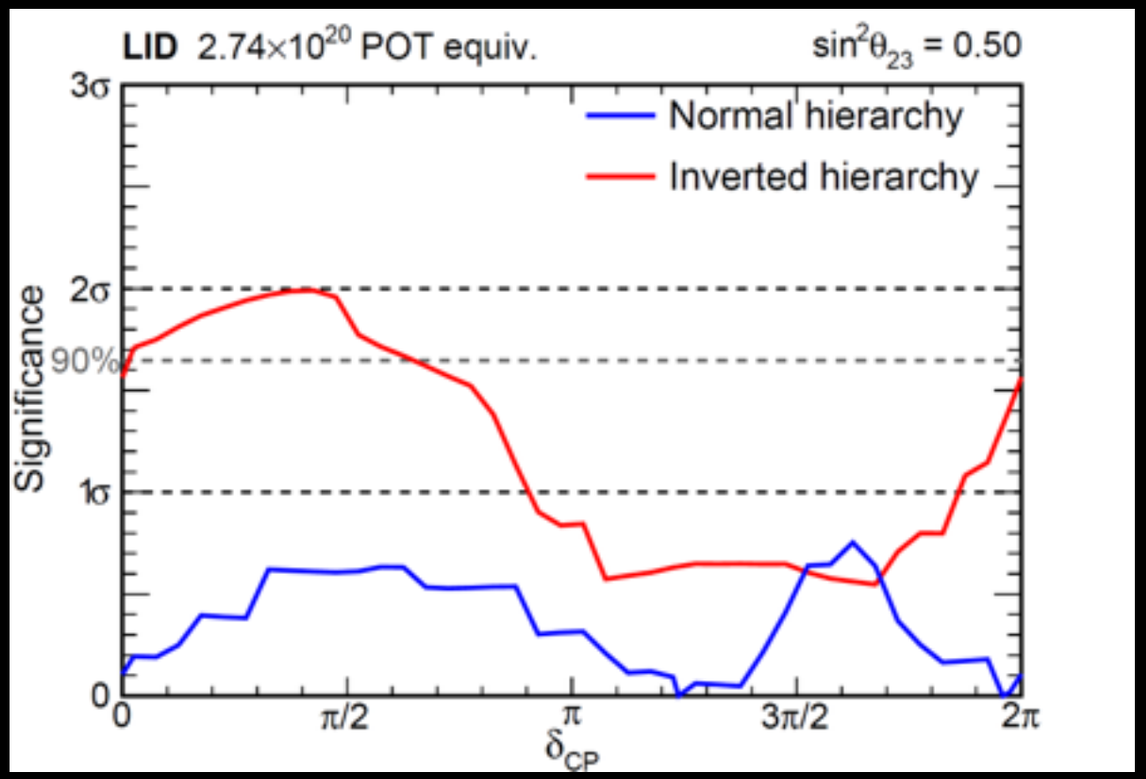
with $\sin^2 2\theta_{13} = 0.086 \pm 0.005$

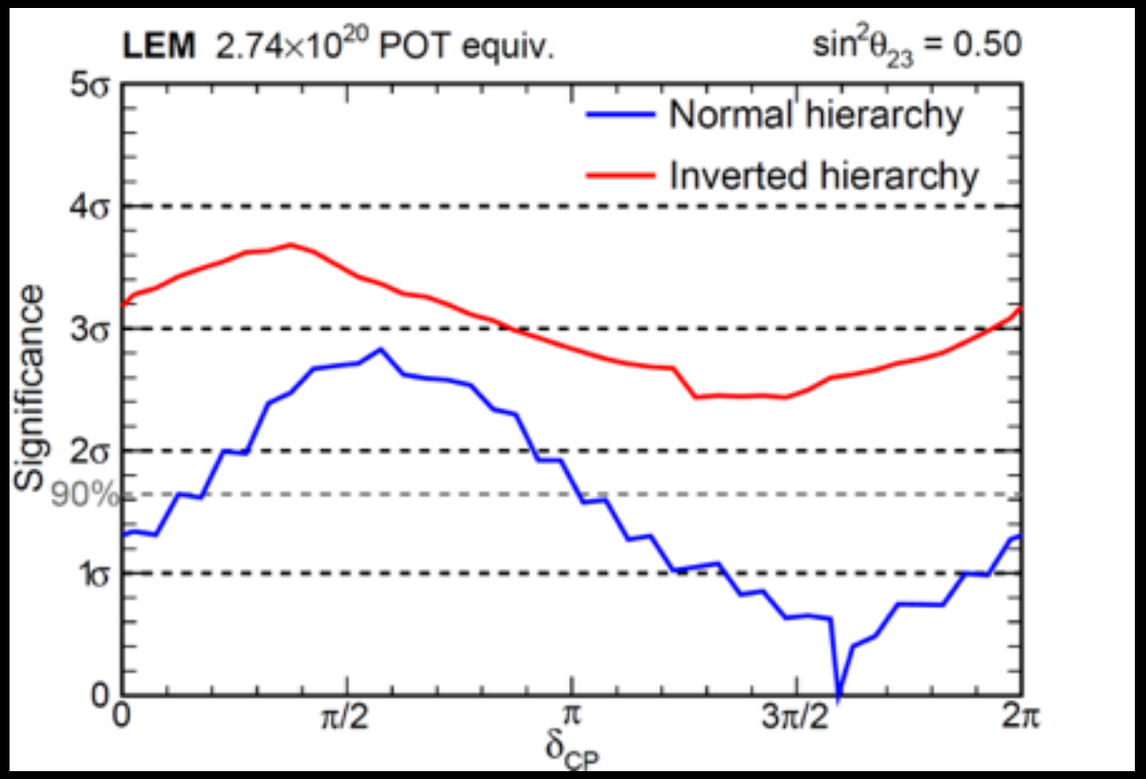
ELECTRON NEUTRINO APPEARANCE RESULTS

- Both selectors prefer normal hierarchy.
- Both selectors prefer δ near $3\pi/2$.
- Given expected correlations, the observed event counts yield a reasonable mutual p-value of 9.2%.
- The specific point IH, $\delta=\pi/2$ is disfavored at 1.6σ (LID) and 3.2σ (LEM)* for $\sin\theta_{23} = 0.4$-0.6.

CONSISTENT HINTS!

Beware of trials factor of choosing LEM over LID after seeing results.

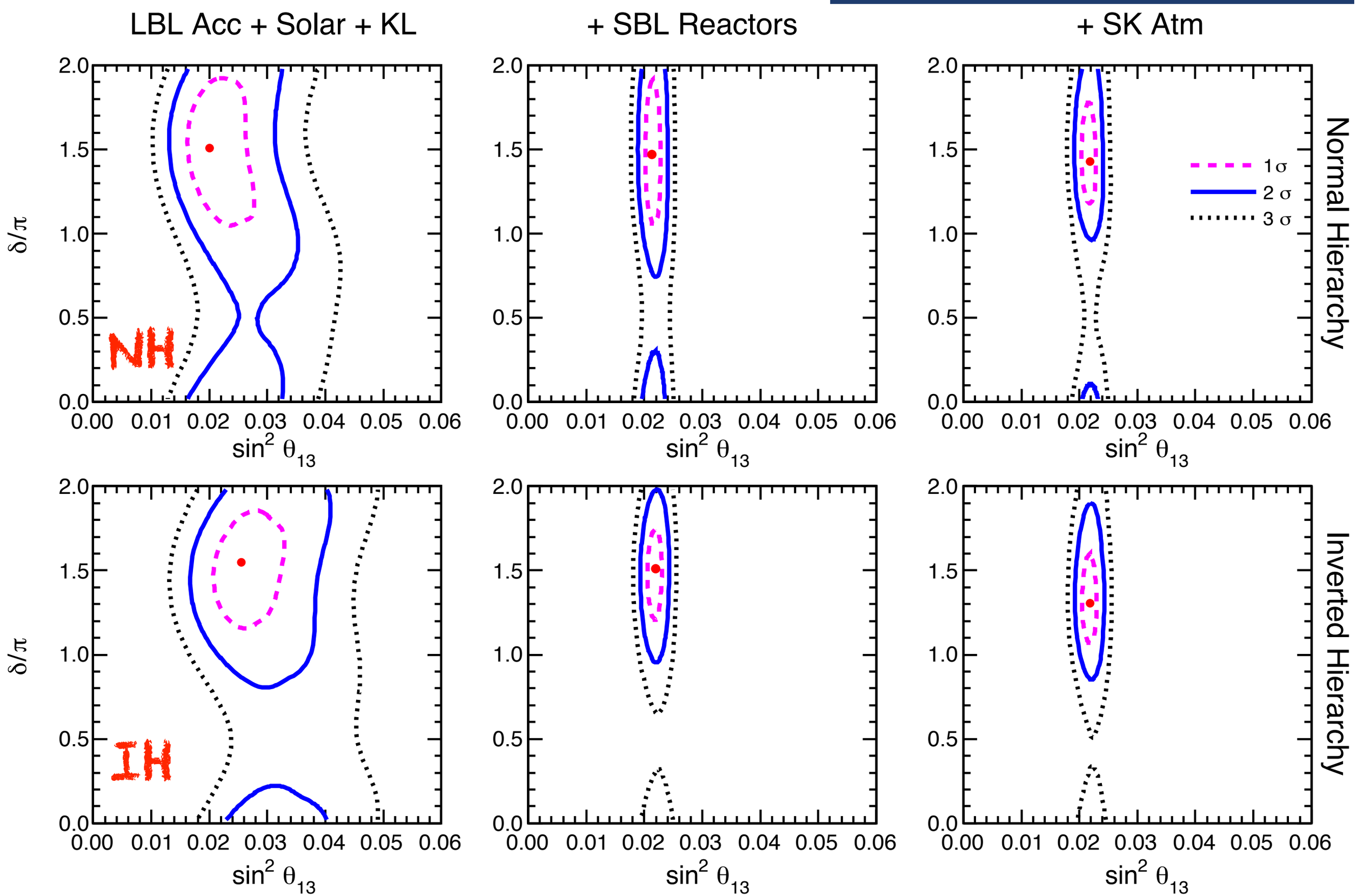




with $\sin^2 2\theta_{13} = 0.086 \pm 0.005$

GLOBAL ANALYSIS FOR CP VIOLATION

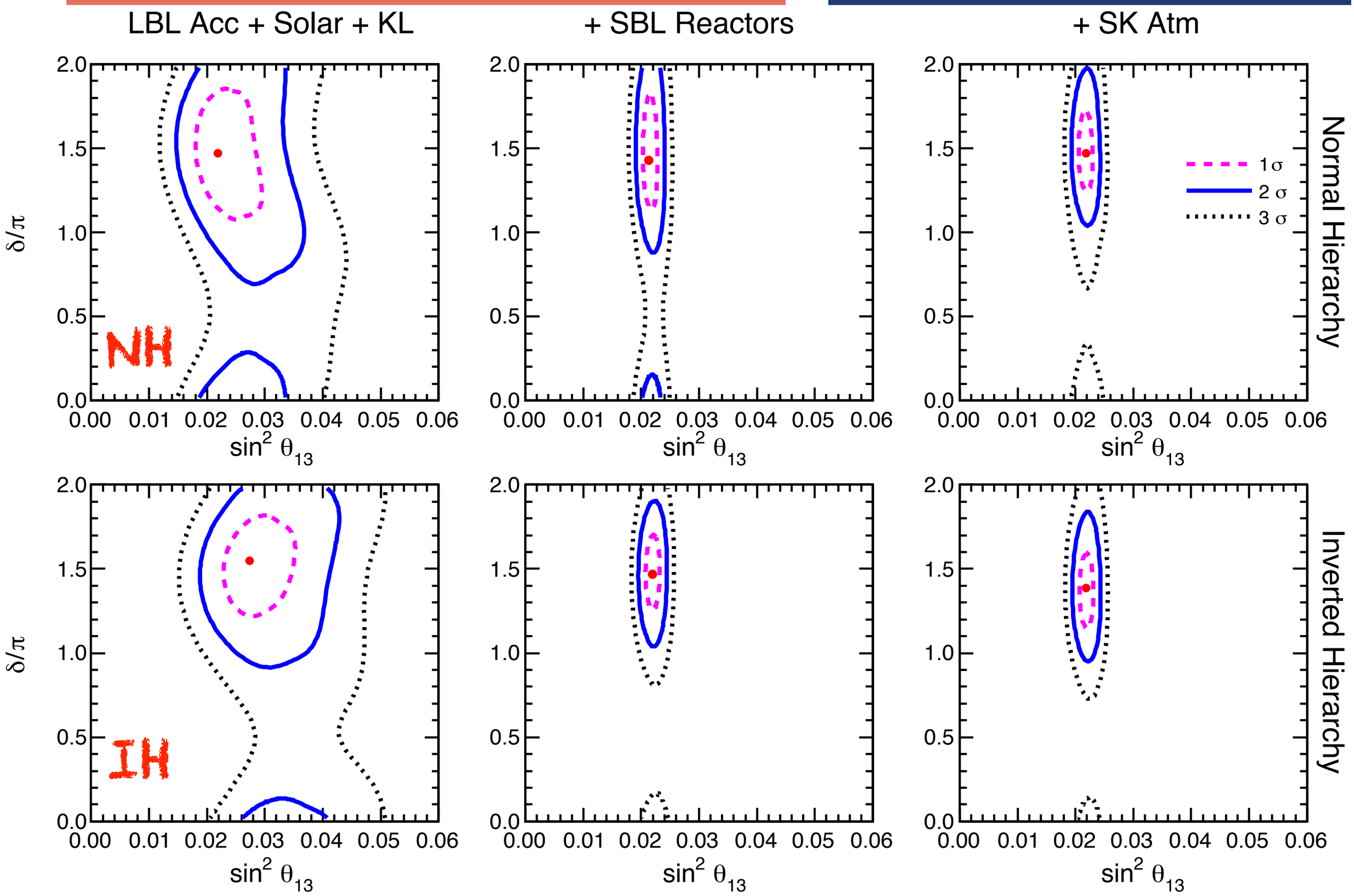
A. MARRONE (TAUP 2015)



GLOBAL ANALYSIS FOR CP VIOLATION

INCLUDES NOVA'S LATEST RESULTS

A. MARRONE (TAUP 2015)



SUMMARY

- NOvA has observed muon neutrino disappearance and electron neutrino appearance with 1/13th of baseline exposure:
  - Obtains 6.5% measurement of atmospheric mass splitting, and θ_{23} measurement consistent with maximal mixing.
  - Observes electron neutrino appearance signal at 3.3σ for primary ν_e selector, 5.5σ for secondary selector.
    - Consistent with hints of a preference for $\pi<\delta_{CP}<2\pi$ normal mass ordering.
    - In global analysis the preference for $\pi<\delta_{CP}<2\pi$ is clear.
- Stay tuned for doubling of the data set by next summer!