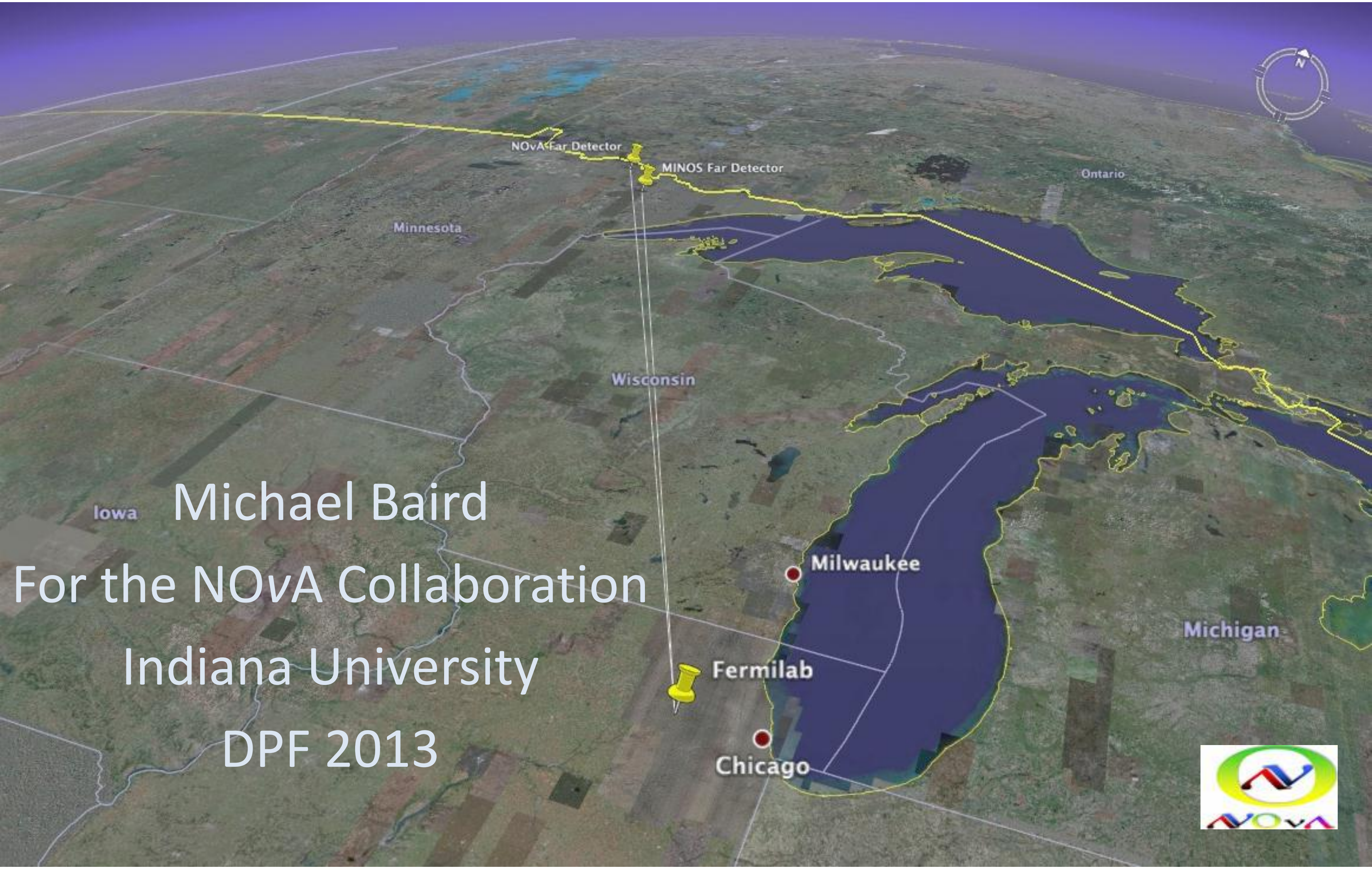
Expected Sensitivities from the ν_μ Disappearance Analysis Using the NOvA Detector



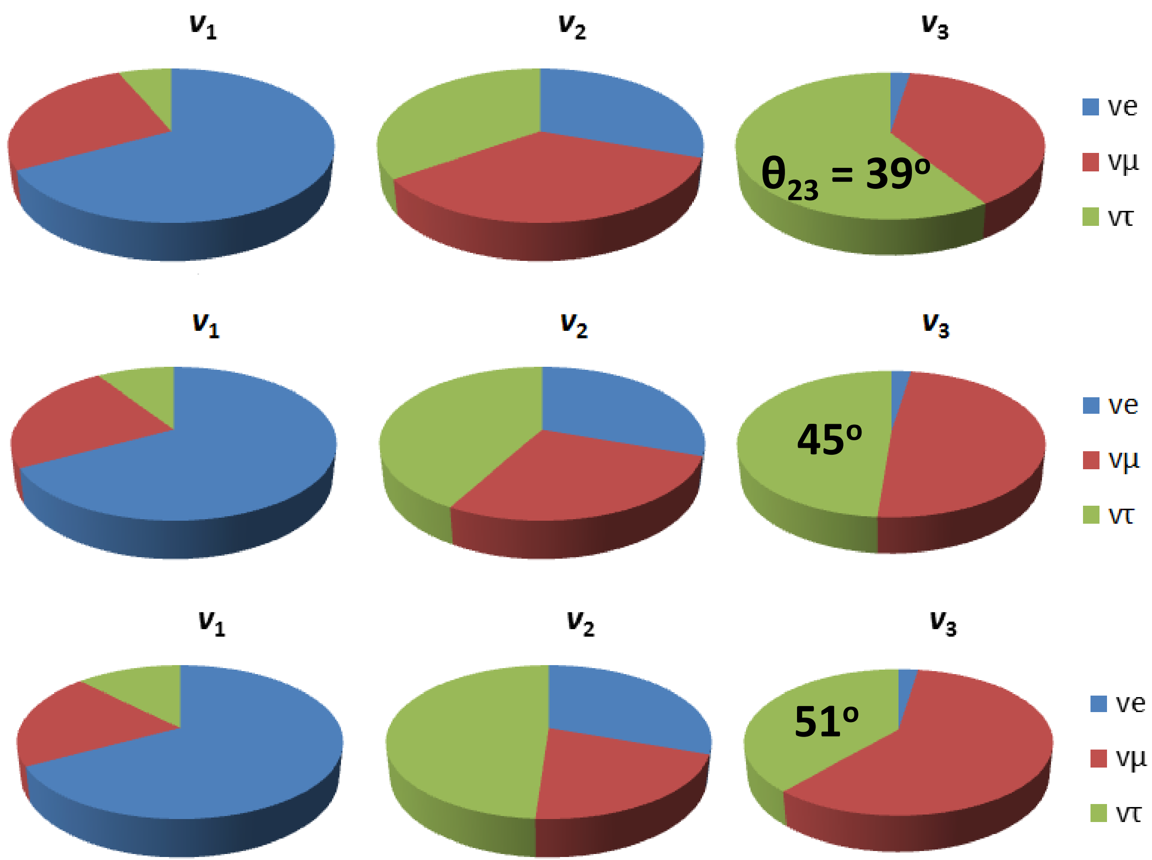
Michael Baird
For the NOvA Collaboration
Indiana University
DPF 2013

Motivation for Measuring θ_{23}

It tells us the relative proportions of ν_μ and ν_τ in each of the mass states.

Of the three mixing angles, it is the one currently known to the least precision.

If θ_{23} is maximal, it may hint at a new symmetry and expose previously unknown underlying structure.



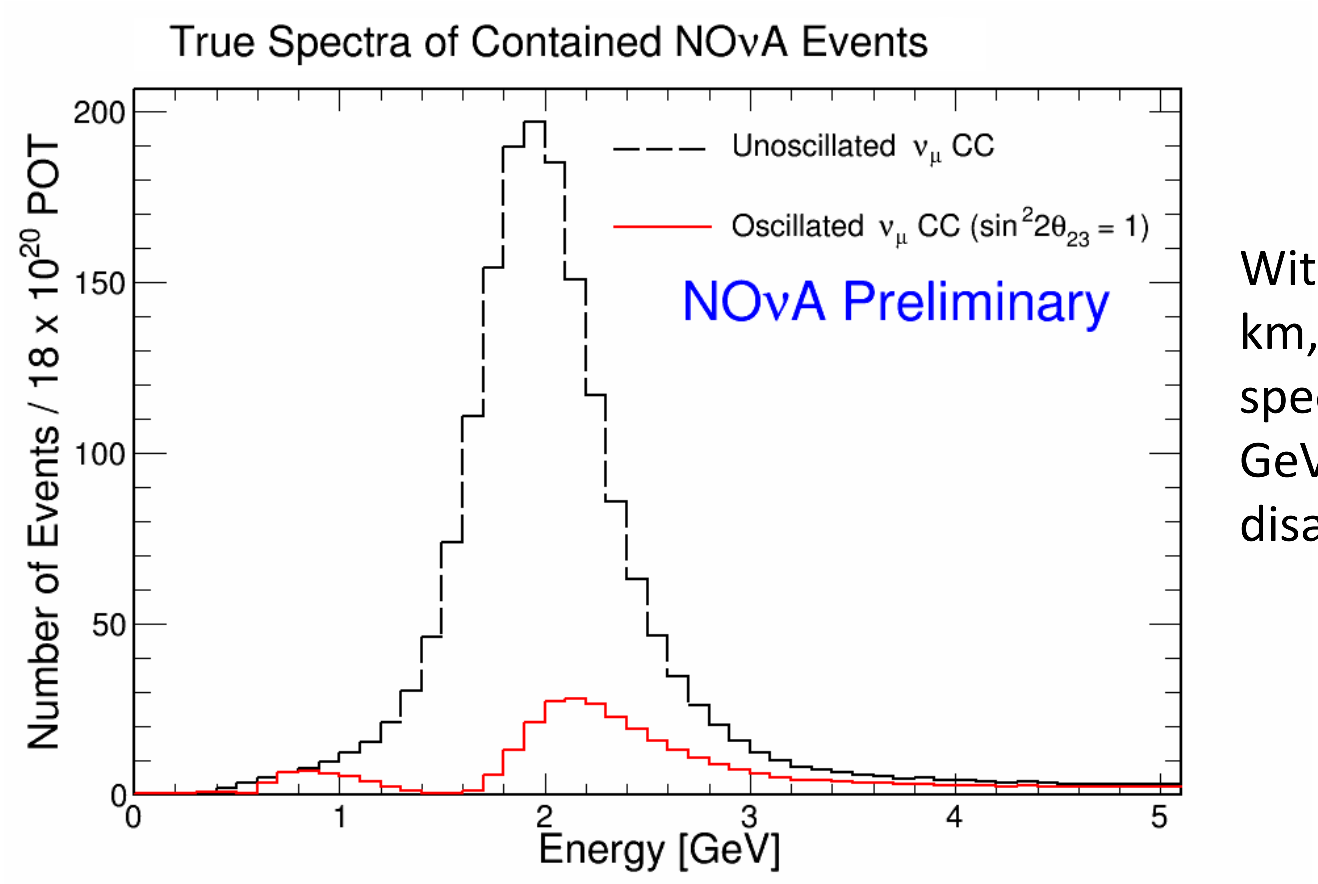
Current Range: $38^o < \theta_{23} < 52^o$

By combining our ν_μ disappearance and our ν_e appearance measurements of θ_{23} we can improve the science reach of NO*v*A.

How NOνA is Sensitive to θ_{23}

Basic disappearance probability:

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



With a baseline of L = 810 km, and a neutrino energy spectrum peaked at E = 2 GeV, NOνA is optimal for ν_μ disappearance.

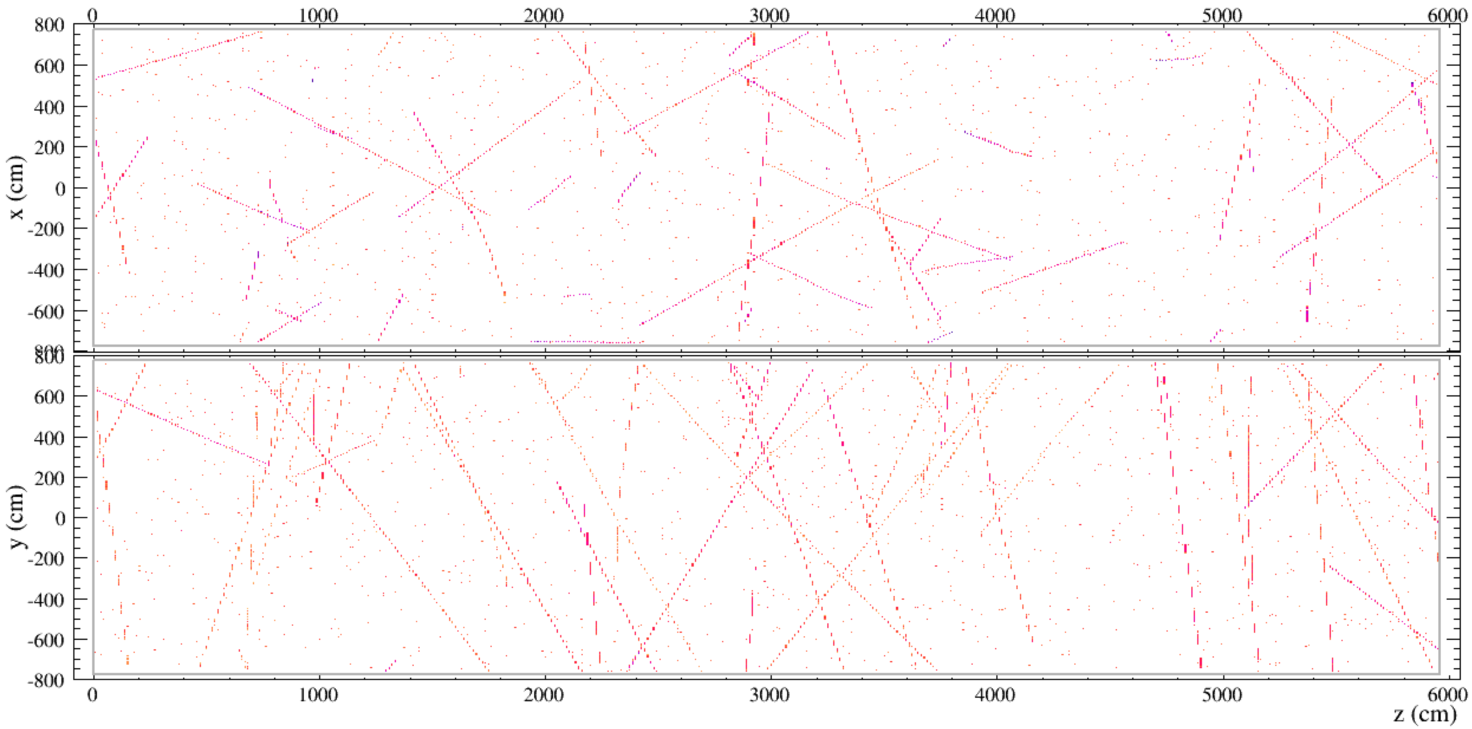
Goals of our ν_μ CC Analysis:

1. Deal with the fact that our far detector is on the surface (rejecting cosmic rays.)

2. Use every ν_μ CC possible (including uncontained events) by identifying events with well reconstructed muon tracks.

3. Isolate events with high energy resolution (contained ν_μ CC quasi-elastic events) to maximize our sensitivity.

Rejection of Cosmic Rays

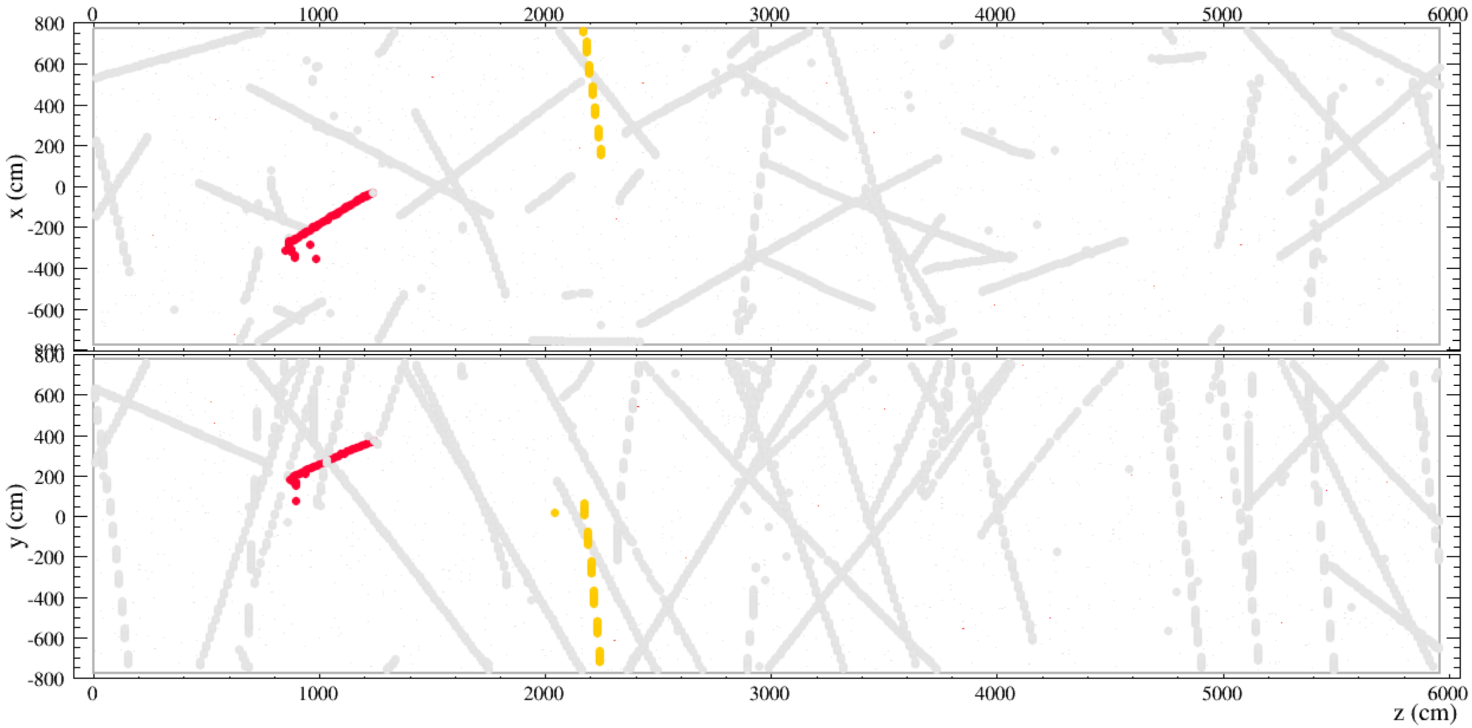


500 μs of simulated cosmic rays overlaid on a ν_μ CC event.

- We expect roughly 1 cosmic ray per 10 μs beam spill window. At one beam spill per 1.3 seconds, this leads to **~66,000 cosmics per day (in time with the beam)**.

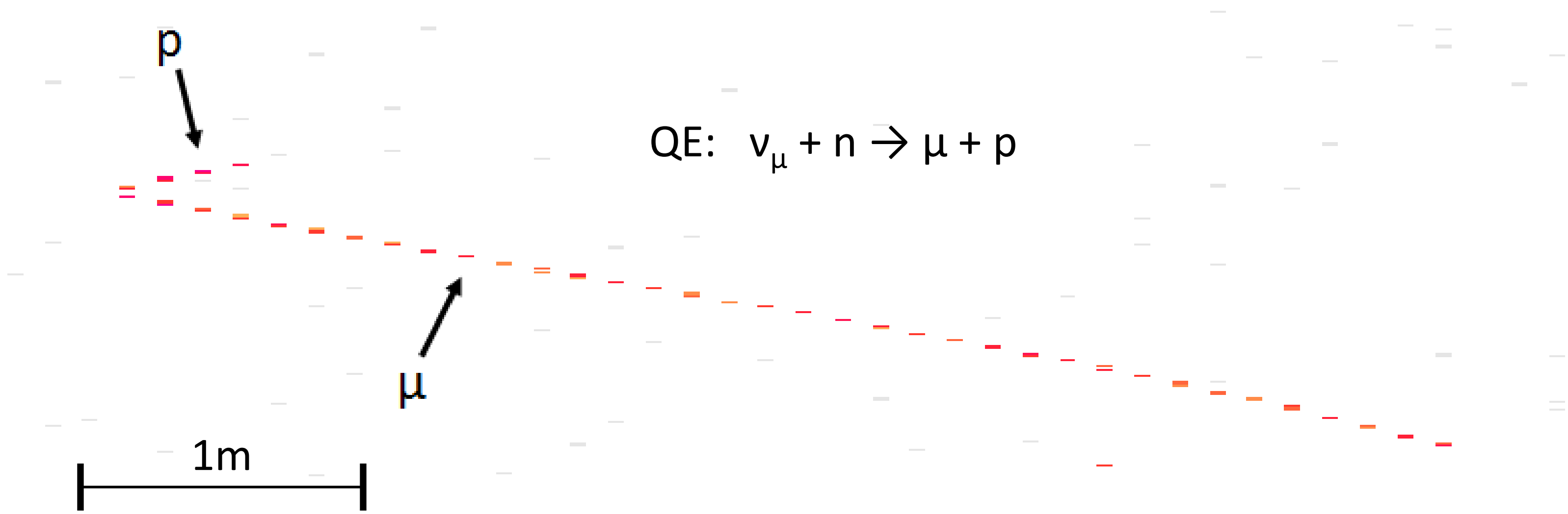
- With **~2-3 ν_μ CC events per day**, rejecting 99.999% of the cosmics will still leave us with 1 cosmic per day (we must do better than this…)

Rejection of Cosmic Rays



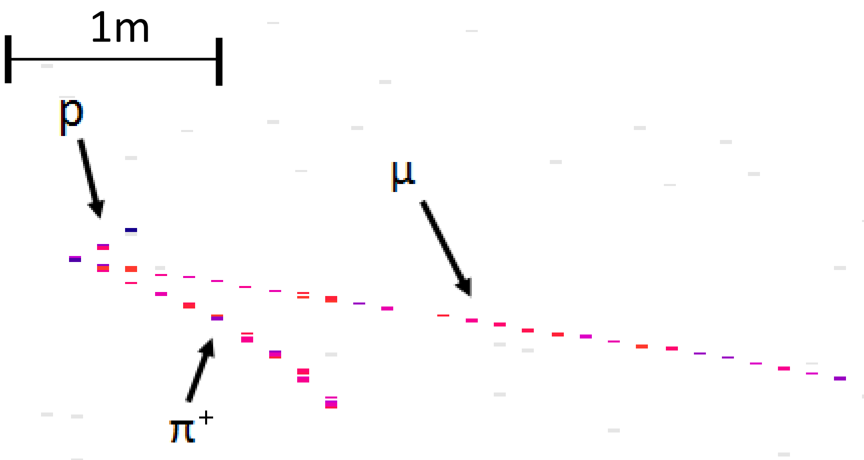
- By rejecting clusters of hits that occur outside our beam spill window, **we can isolate potential neutrino events**.
- For our contained sample, we can apply a series of cuts and a simple cosmic PID, and **reject > 99.9999% of cosmics while maintaining > 95% of our signal events**.
- Cosmic rejection for our uncontained events is still under development.

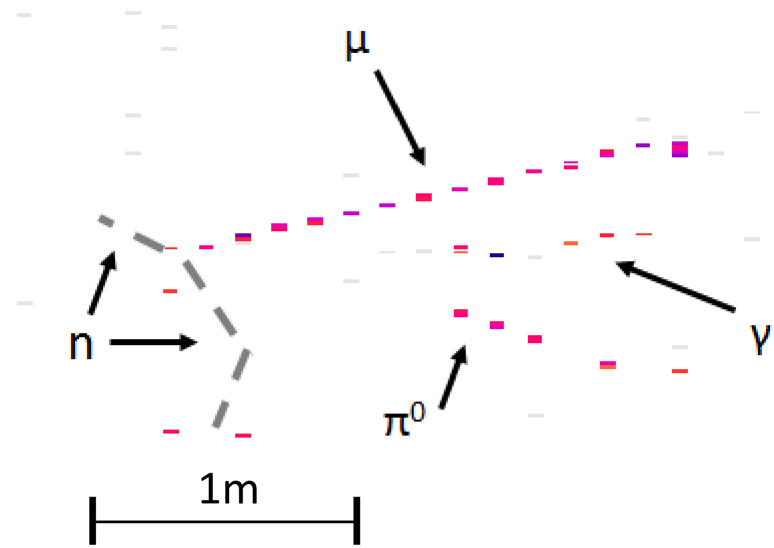
Event Types in NOvA: ν_μ CC QE



- QE events are **identified by a nice long muon track** with at most one other proton-like track.
- The simplicity of these events will provide **good energy resolution**.
- To improve our sensitivity, we **want to try to isolate as many of these as we can**.

Event Types in NOvA: ν_μ CC non-QE





Non-QE: RES

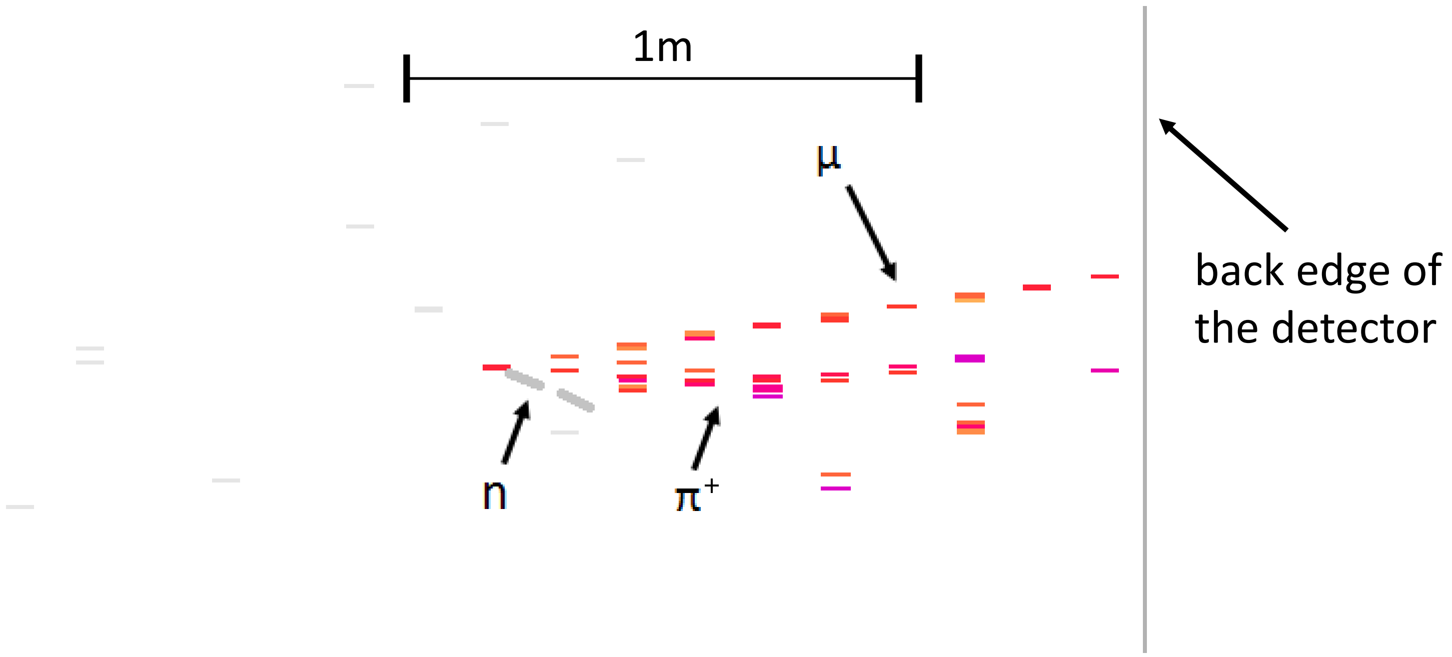
ν_μ + nuc. → μ + nuc. + X

Non-QE: DIS

ν_μ + nuc. → μ + $c_1$nuc. + $c_2\pi$

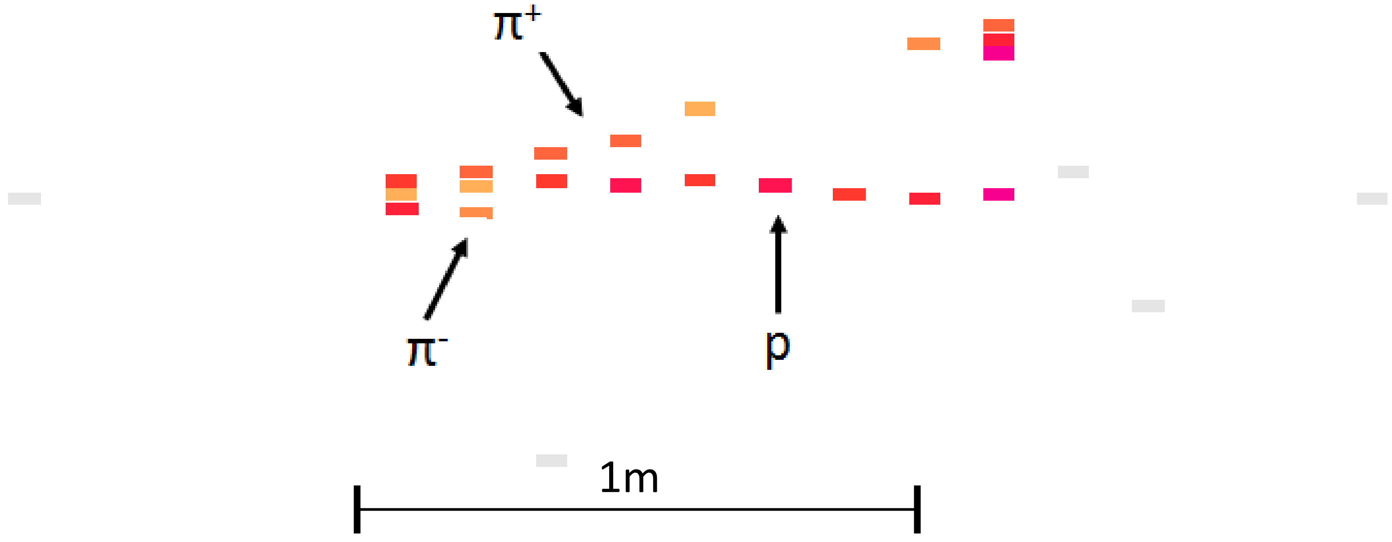
- Non-QE events are still **identified with clear muon track**.
- The **energy resolution for this sample is lower** (due to **missing energy** from neutral particles) but the **statistics will be higher**.

Event Types in NOvA: uncontained ν_μ CC



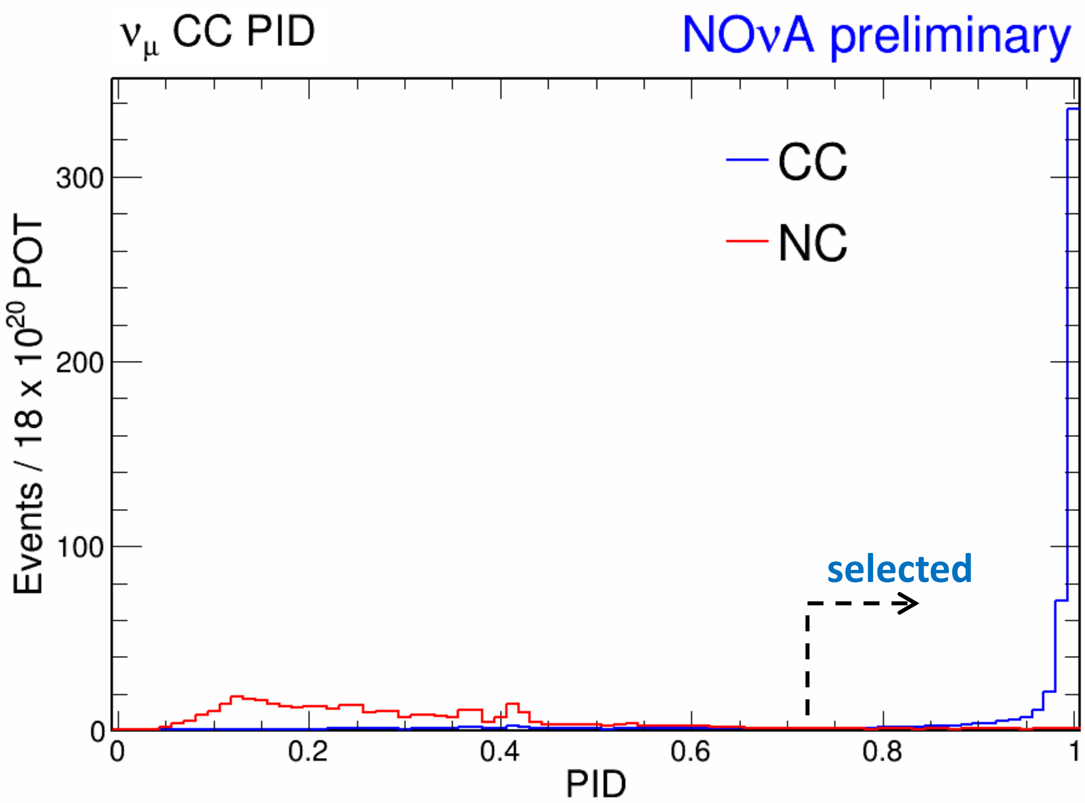
- Uncontained events **can still be labeled as ν_μ CC** given an identifiable muon track. We make no attempt to separate the uncontained into QE and non-QE.
- These events will have the **lowest energy resolution (due to escaping energy)** but they can still contribute to our overall sensitivity.

Background Events: NC



- NC events can be rejected from the ν_μ CC analysis due to the **absence of a reconstructed muon track**.

Removing NC from the ν_μ CC Event Sample



- Currently, we select events with a PID > 0.725 as ν_μ CC events.

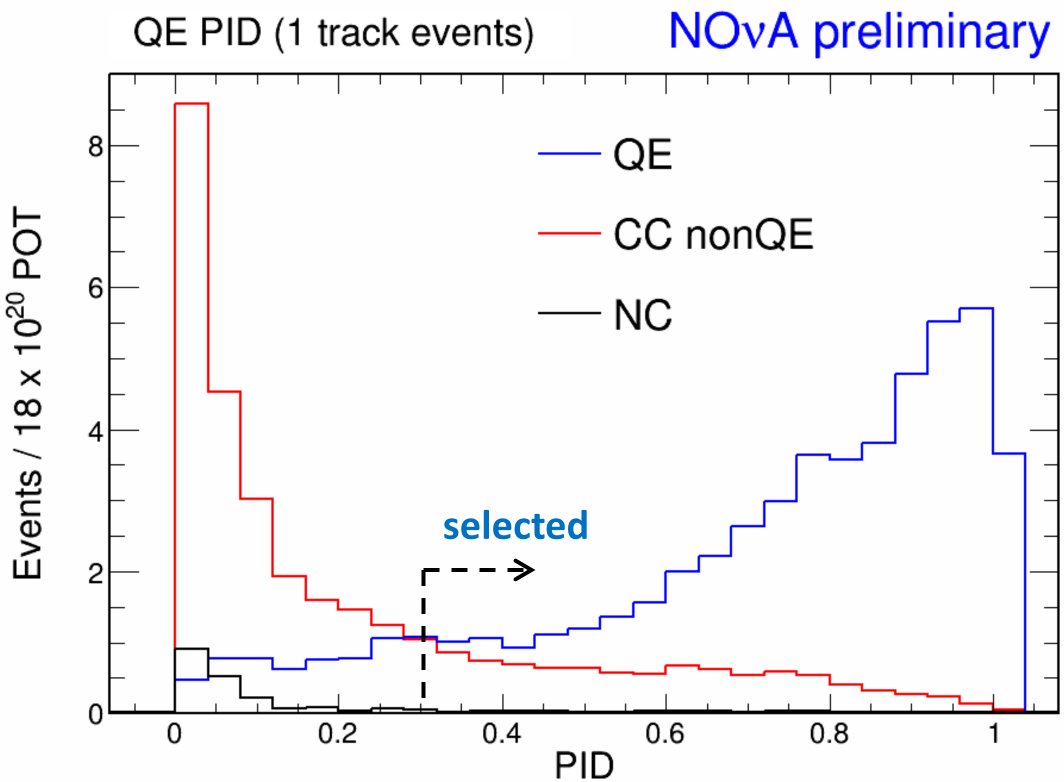
- Efficiency = 88.3%
- Purity = 94.3%
- 93.1% of NC events are rejected

Note: 18e20 POT ≈ 3 years assuming ~65% beam up time.

- We use a multivariate analysis based on quantities such as dE/dx and track length for the **most muon like track**, to **generate a ν_μ CC PID**.

- This allows us to **separate out NC events** from our ν_μ CC sample.

QE/non-QE Event Separation



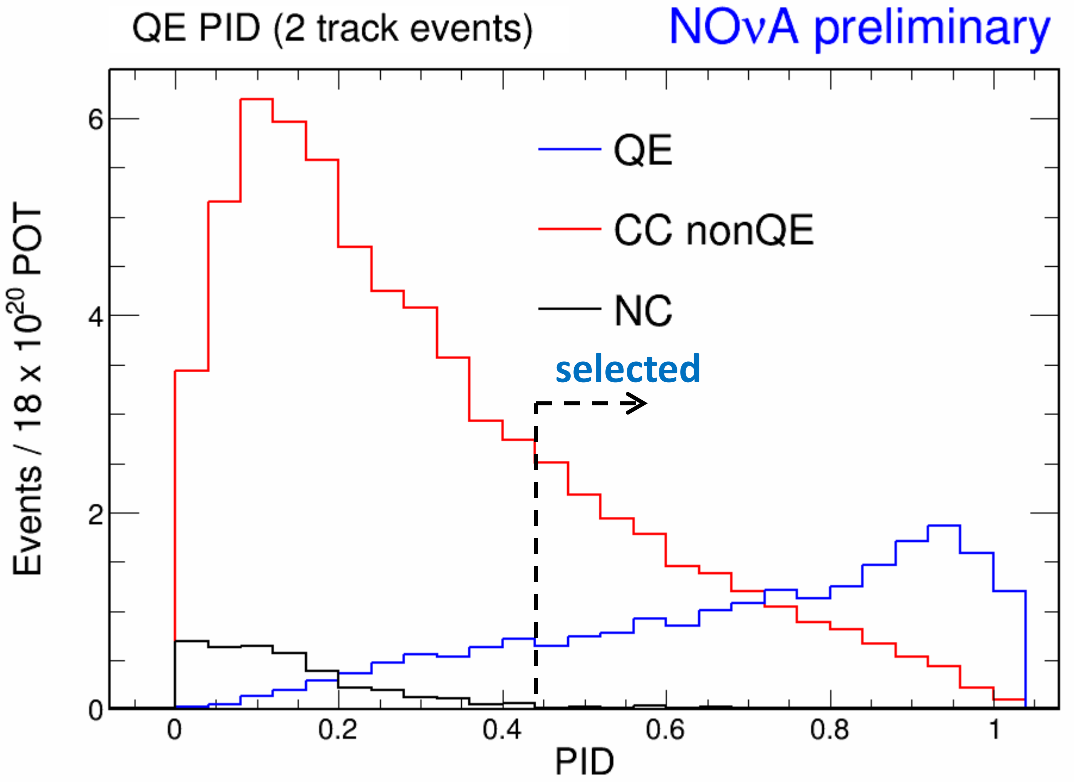
- For one track events, we select events with a PID > 0.3 as QE.

- Efficiency = 90.5%
- Purity = 82.3%

- In the contained sample, we will **distinguish QE from non-QE events** in order to improve our sensitivity.

- For this we use another **multivariate analysis to generate a QE PID** for events with one or two tracks based on things such as the amount of energy NOT on the main track and the difference between two different energy estimators.

QE/non-QE Event Separation



- For two track events, we select events with a PID > 0.45 as QE.

- Efficiency = 81.3%
- Purity = 50.1%

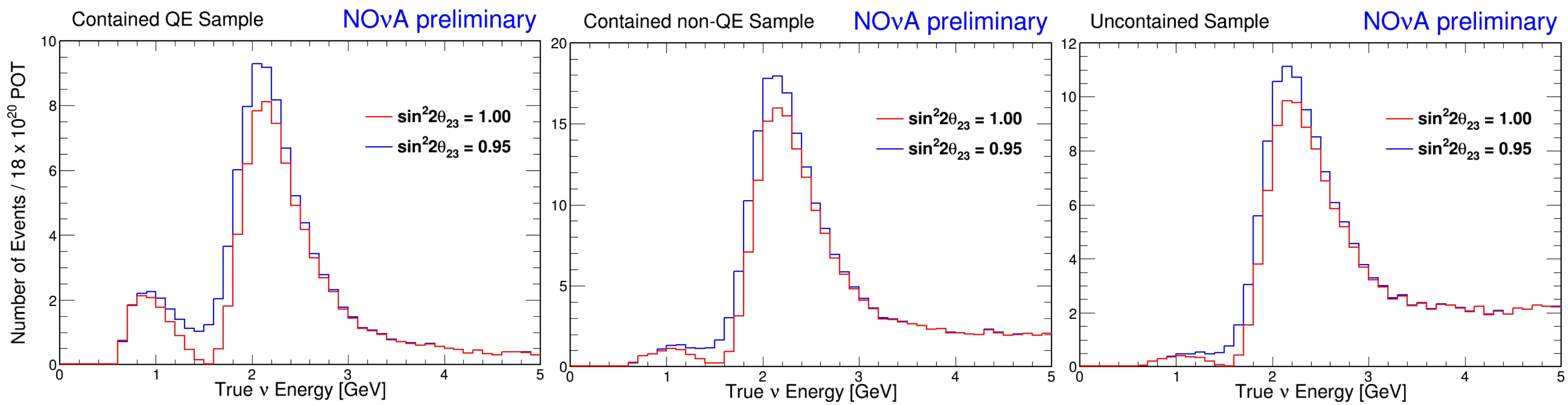
1 & 2 track samples combined:

- Total QE Efficiency = 87.9%
- Total QE Purity = 70.6%

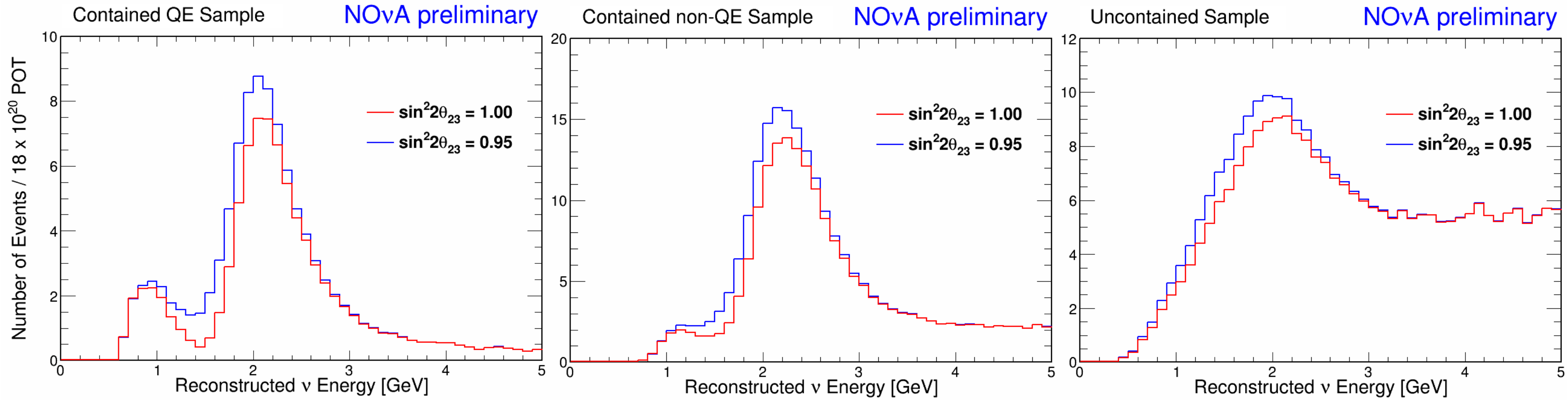
- For the 2 track sample, we **use the same PID** used for the 1 track samples but we **apply a different cut**.

Energy Spectra by Event Sample

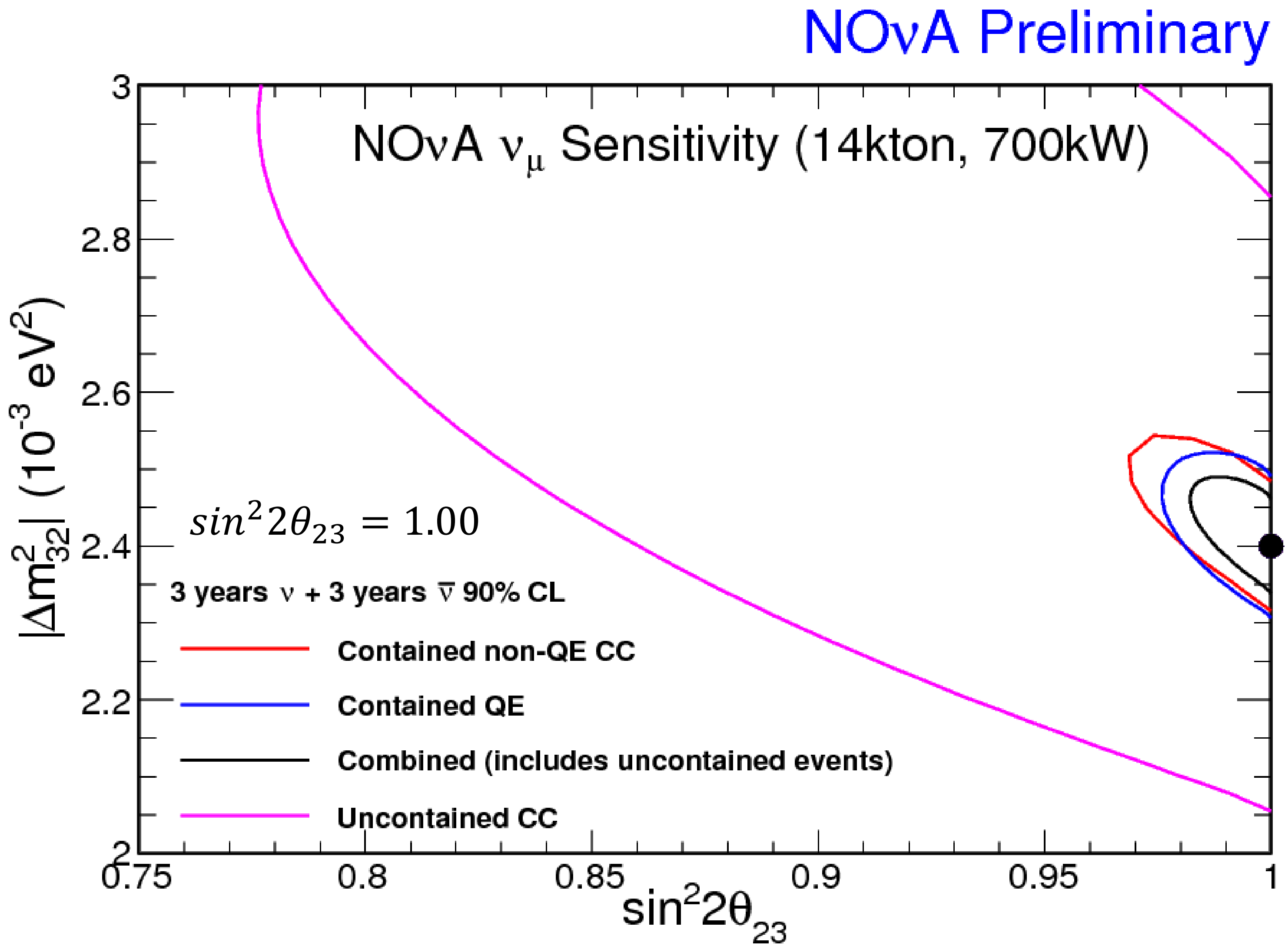
True Neutrino Energy Spectra:



Reconstructed Neutrino Energy Spectra:

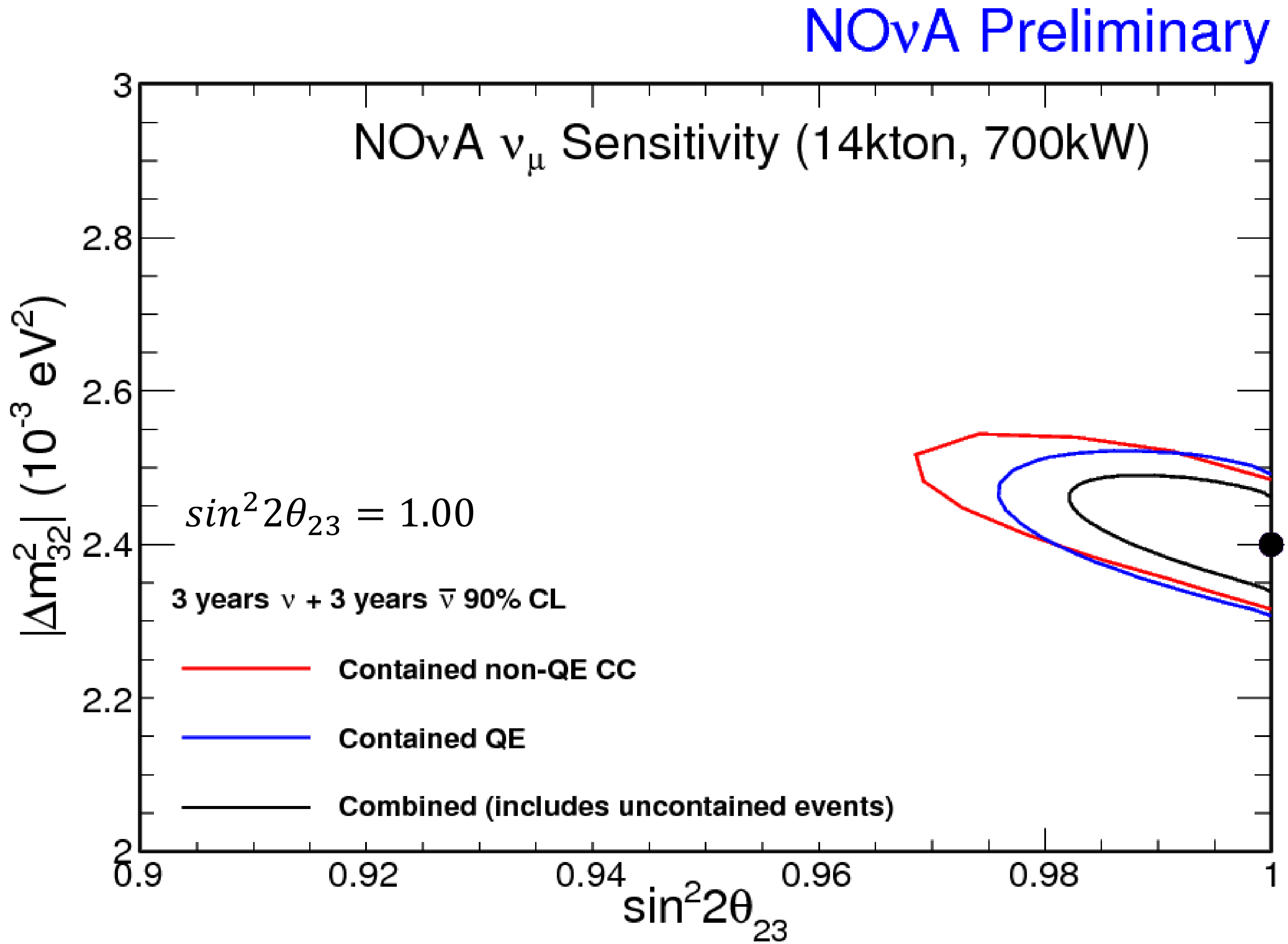


Combined Sensitivity Example



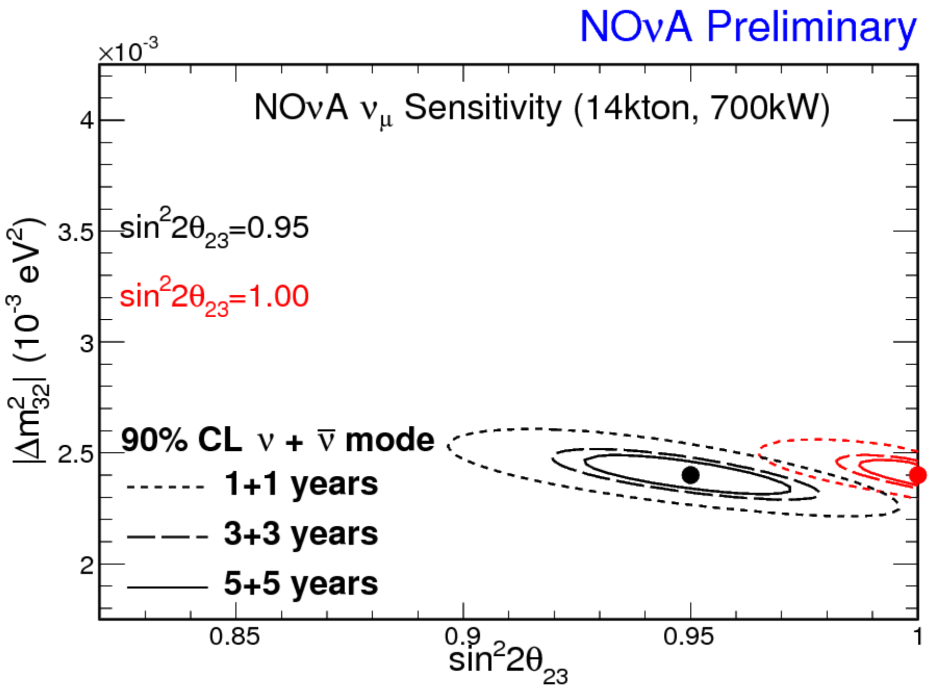
This plot does not include any systematic errors (we will be limited primarily by our statistics.)

Combined Sensitivity Example

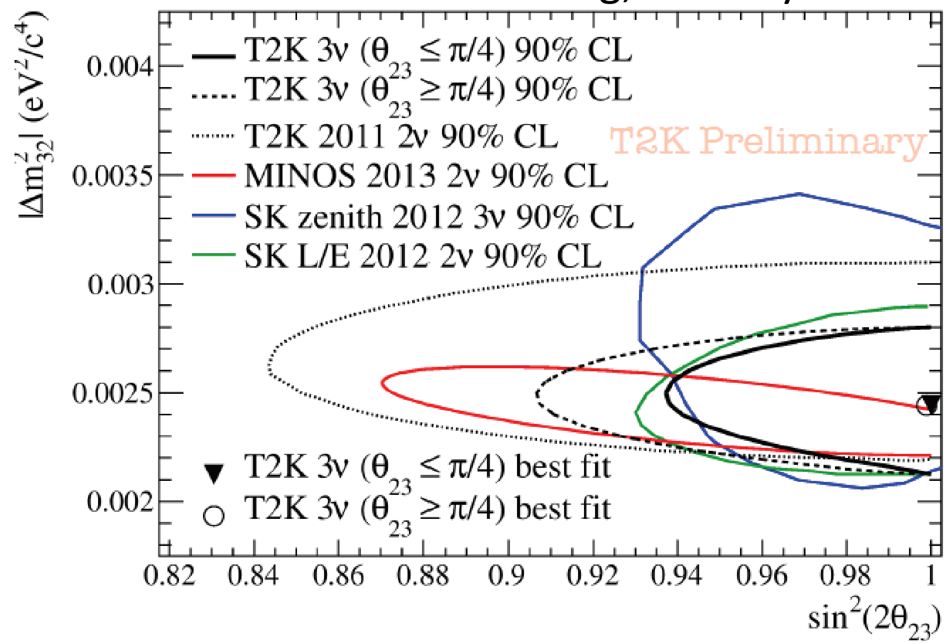


This plot does not include any systematic errors (we will be limited primarily by our statistics.)

NOνA Full Reach Sensitivities



Wilking, EPS July 2013



- **We expect to be able to surpass the current measurement of θ_{23} after 3+3 years of running.**
- **If $\sin^2 2\theta_{23}$ = 1.00, we expect to surpass the current best measurement after only 1+1 years of running.**
- **If $\sin^2 2\theta_{23}$ = 0.95, we will be able to exclude (at the 90% CL) maximal θ_{23} after 1+1 years of running.**

Conclusions:

- A precision measurement of θ_{23} is important and NO*v*A is getting ready to take data for our ν_μ disappearance measurements.

- We have a good ν_μ CC analysis structure in place including systems for background rejection of NC events and cosmic rays and isolation of ν_μ CC QE events for increased sensitivity.

- We anticipate being able to surpass the current measurements for $\sin^2 2\theta_{23}$ and Δm^2_{23} within a few years!

Special thanks to UCSC for hosting DPF 2013!

Your campus is wonderful!

We can detect neutrinos but so far, we can not detect these…

Backups

Expected Number of Events:

All neutrino energies: Expected total numbers for 1 year with no cuts: 621

numuCC event type	3 yrs nu-mode sin^2(2*th) = 1.0	3 yrs nu-mode sin^2(2*th) = .95	1 yr nu-mode sin^2(2*th) = 1.0	1 yr nu-mode sin^2(2*th) = .95
Cont. QE	93.5	109	31.2	36.3
Cont. non-QE	435	460	145	153
Uncontained	937	952	312	317

Neutrinos with 0 < E < 5 GeV: Expected total numbers for 1 year with no cuts: 194

numuCC event type	3 yrs nu-mode sin^2(2*th) = 1.0	3 yrs nu-mode sin^2(2*th) = .95	1 yr nu-mode sin^2(2*th) = 1.0	1 yr nu-mode sin^2(2*th) = .95
Cont. QE	85	101	28.3	33.7
Cont. non-QE	192	216	64	72
Uncontained	253	267	84	89

All numbers here are assuming a 700 kW beam and a 14 kTon detector with 65% beam up time.

Basic ν_μ CC Analysis:

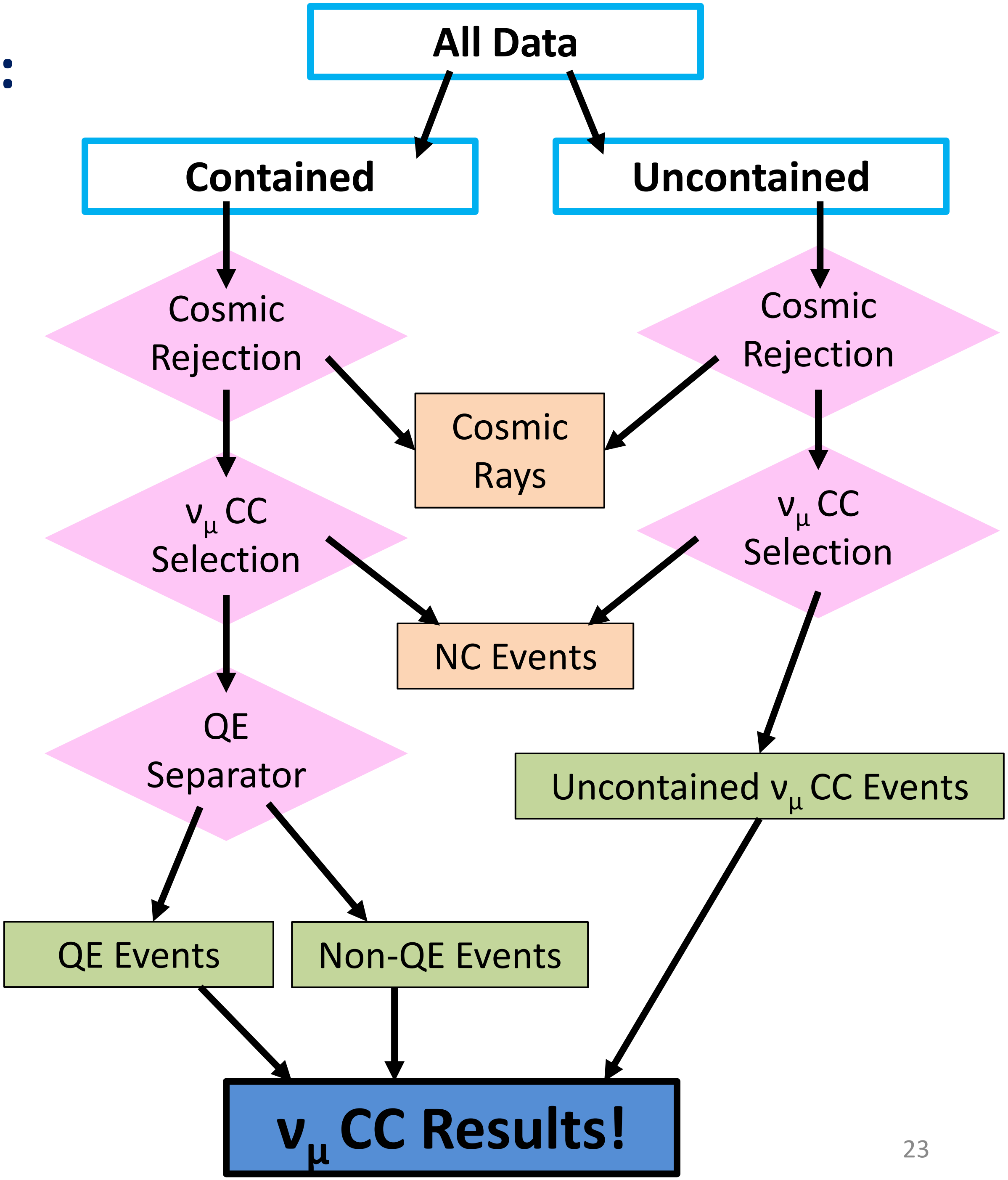
1. Separate event sample into contained and uncontained events

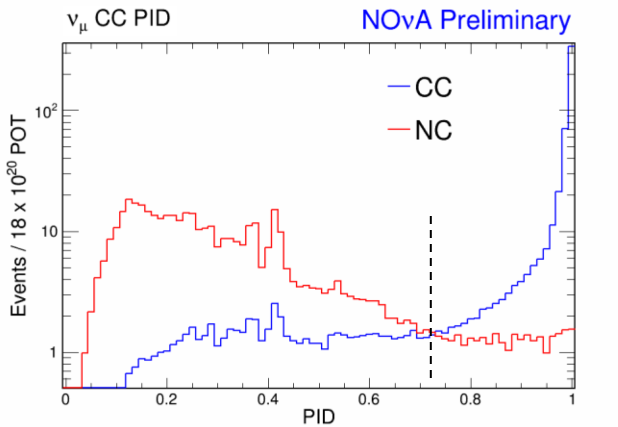
2. Apply cosmic ray rejection

3. Select ν_μ CC events by identifying muon tracks

4. For contained sample, separate out quasi-elastic events to increase sensitivity

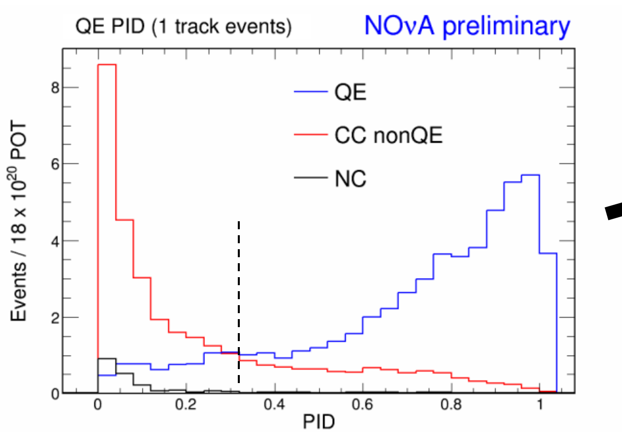
5. Perform full three flavor fit with our three samples!



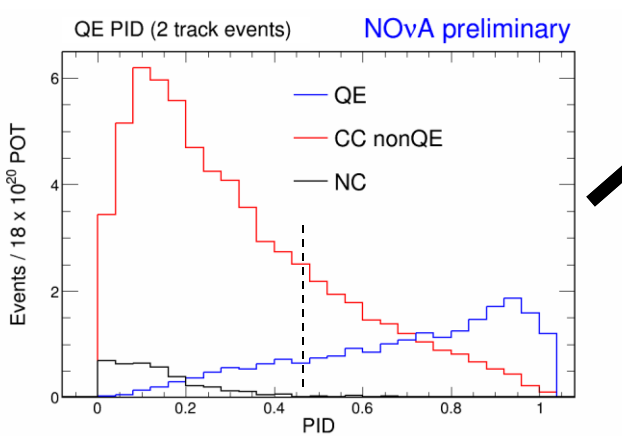


Current cut is PID > 0.725
numuCC that pass cut = 496
NC that pass cut = 30

% NC in numuCC sample = 5.7 %



Current cut is PID > 0.3
QE that pass cut = 50
non-QE that pass cut = 10
NC that pass cut = 0.5



Current cut is PID > 0.45
QE that pass cut = 17
non-QE that pass cut = 17
NC that pass cut = 0.2

% of CC non-QE in QE sample = 28.6 %
% of NC in QE sample = 0.78 %

Basic ν_μ CC Cuts:

Cut definitions:

- **Containment (in cm)**: -745 < X < 745 && -745 < Y < 720 && 12 < Z < 5950 && mincell > 10
- **Mincell**: the minimum of cosrej.kalfwdcell, cosrej.kalbakcell, cosrej.cosfwdcell, and cosrej.cosbakcell
- **Quality**: number of hits in slice > 20 && number of continuous planes in slice > 4 && cosrej.nhitkal > 10 && cosrej.anglebest > 0.3 && remid > 0.725
- **QE events**: (# of tracks == 1 && qepid > 0.3) || (# of tracks == 2 && qepid > 0.45)

numuCC event samples:

- **Contained QE events**: containment &&quality && QE && cosrej.cospid > 0.2
- **Contained nonQE events**: containment && quality && !QE && cosrej.cospid > 0.2
- **Uncontained events**: !containment && quality && cosrej.uncontcospid > 0.9999999

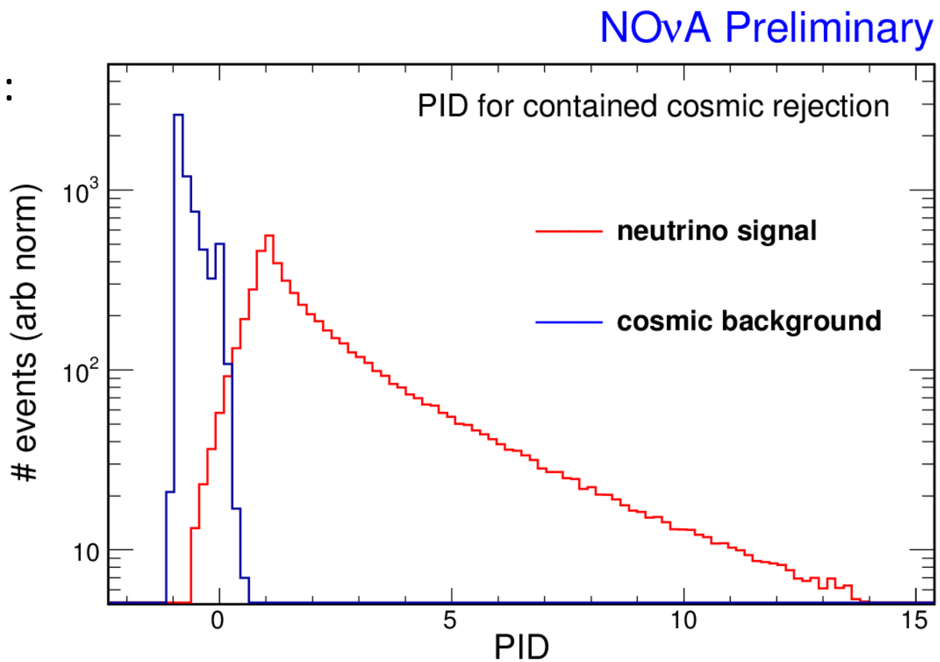
Major handles for cosmic rejection include:

Angle of muon w.r.t. beam

Projected number of cells from muon track start/end, along track direction, to detector edge

Vertical direction of muon track

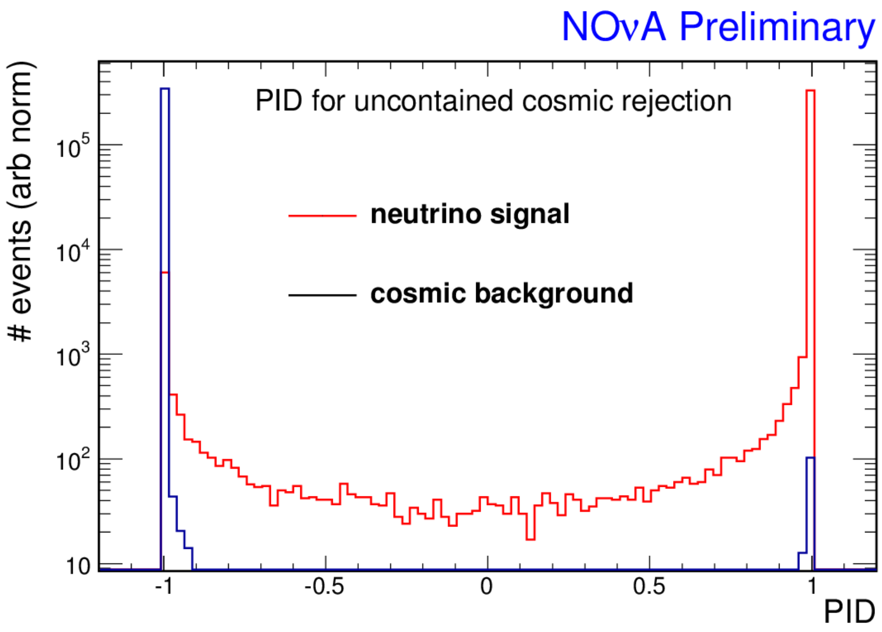
These are combined into a cosmic PID for contained cosmic rejection



After applying some basic quality cuts, for every 1 contained numuCC event, we expect ~3200 cosmic ray events in the beam trigger window. Removal is critical!

% remaining after cut	Cosmics	ν MC
precuts	**100% (5.5 x 10^6 events)**	**100% (7.1 x 10^5 events)**
contained	**1%**	**52%**
Cosmic cuts	**0% (all removed)**	**50% (97% of contained)**

After cosmic cuts, we expect > 100 neutrinos for every 1 cosmic in the contained sample.



To remove uncontained cosmics, we use the same handles and more:

muon scattering

muon vs hadronic energy fraction

muon track direction from hit timings

activity near track ends

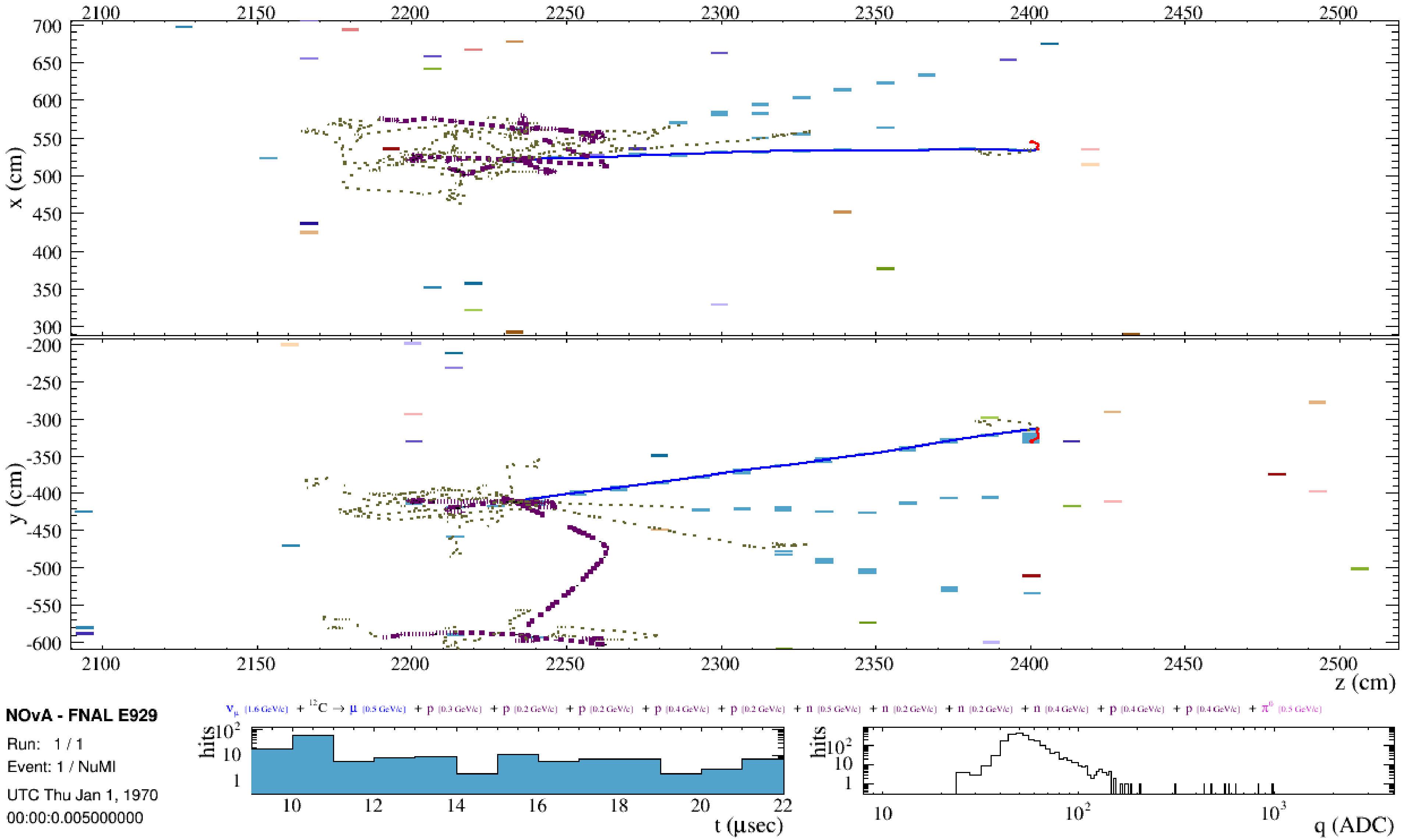
plus other variables…

These are combined in a BDT as the uncontained cosmic PID

After some basic quality cuts, we will have 1 numuCC event for every 80,000 cosmics in the uncontained sample. Even removing 99.99% of cosmics isn't enough.
Still working to improve!

% remaining after cut	Cosmics	ν MC
precuts	100% (5.5 x 10^6 events)	100% (7.1 x 10^5 events)
uncontained	99%	48%
Cosmic cuts	0.007% remaining	43% (90% of uncontained)

Event Displays with Truth



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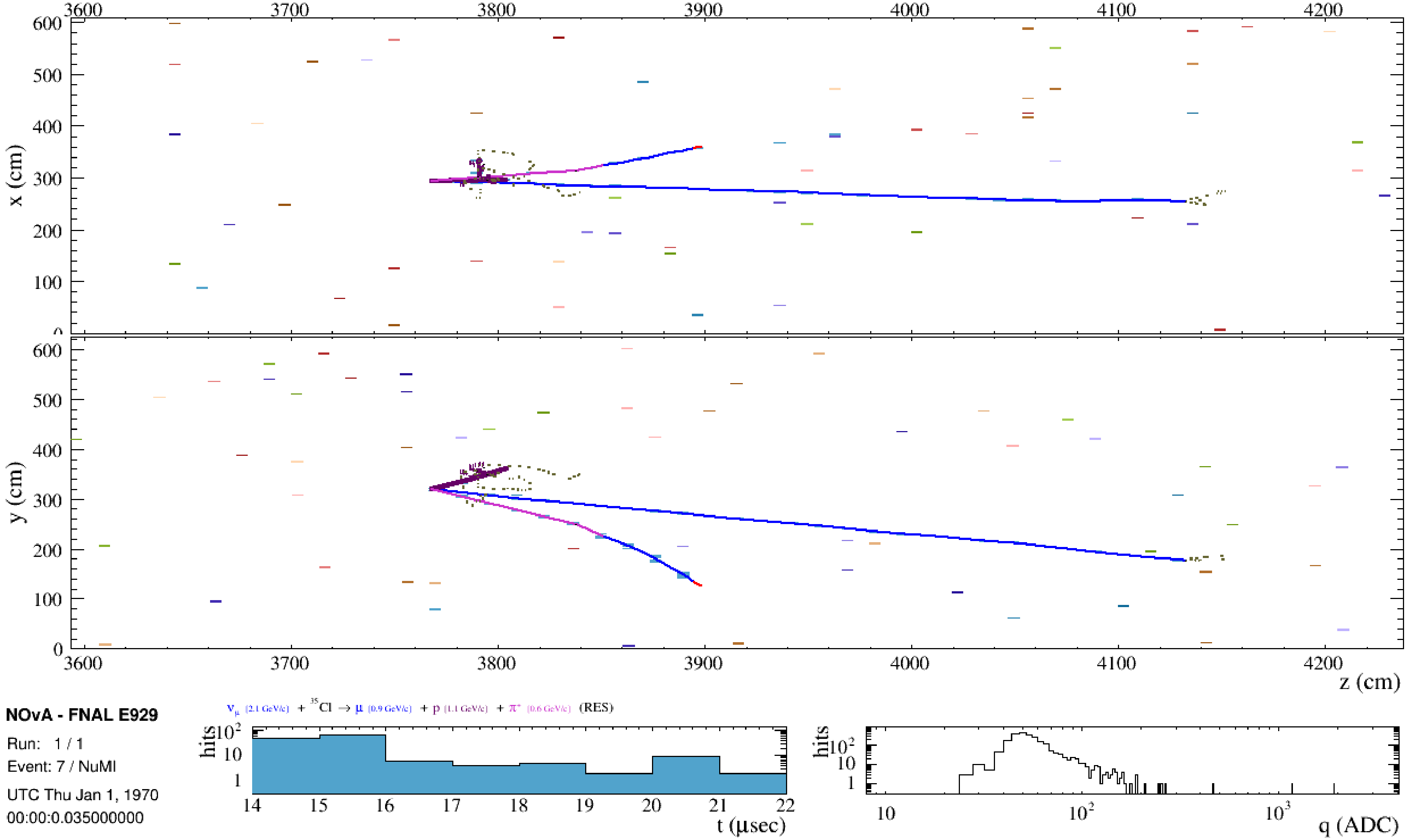
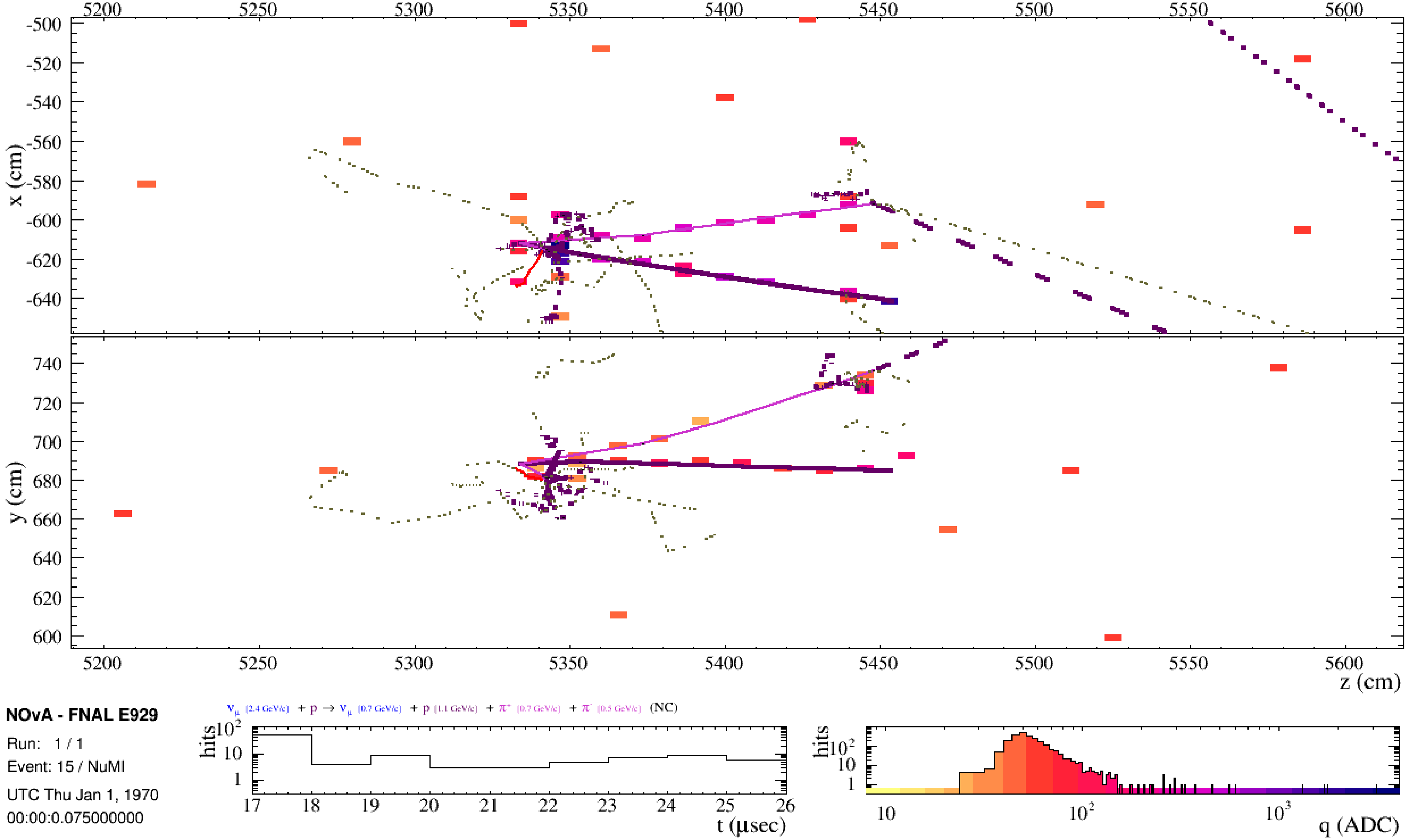
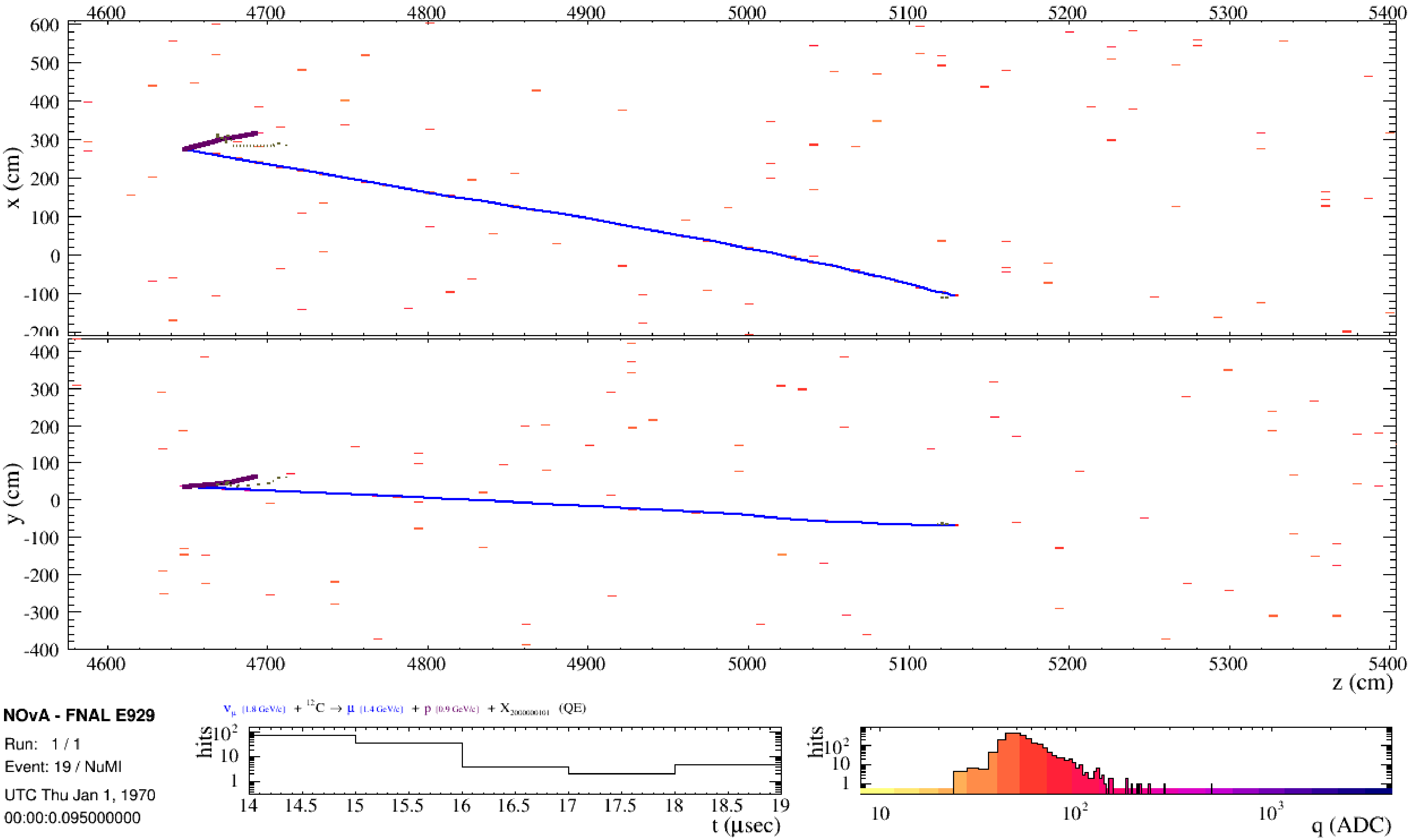


Event Displays with Truth

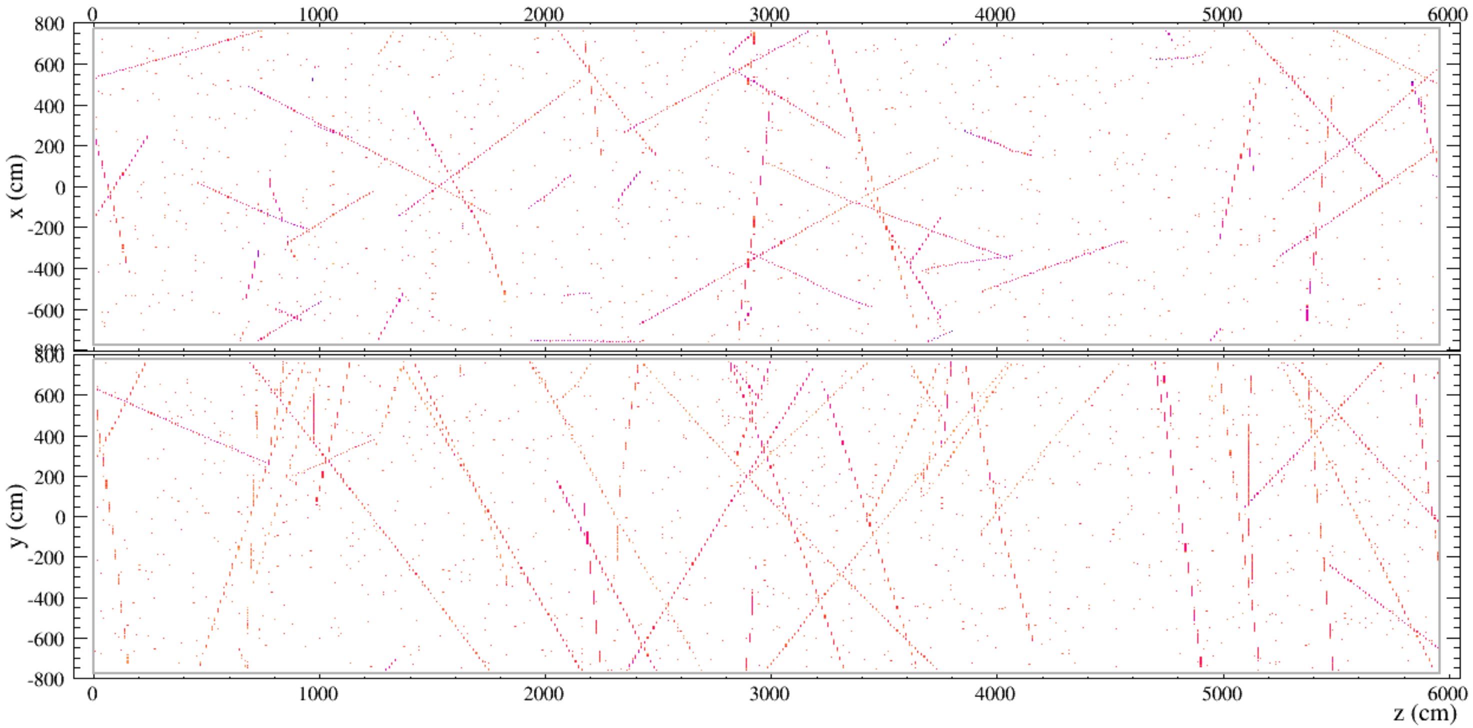


Event Displays with Truth



Rejection of Cosmic Rays

- Applying a clustering algorithm, we can group all of the hits together that belong to the same "source" (i.e. – a cosmic ray or a neutrino event.)



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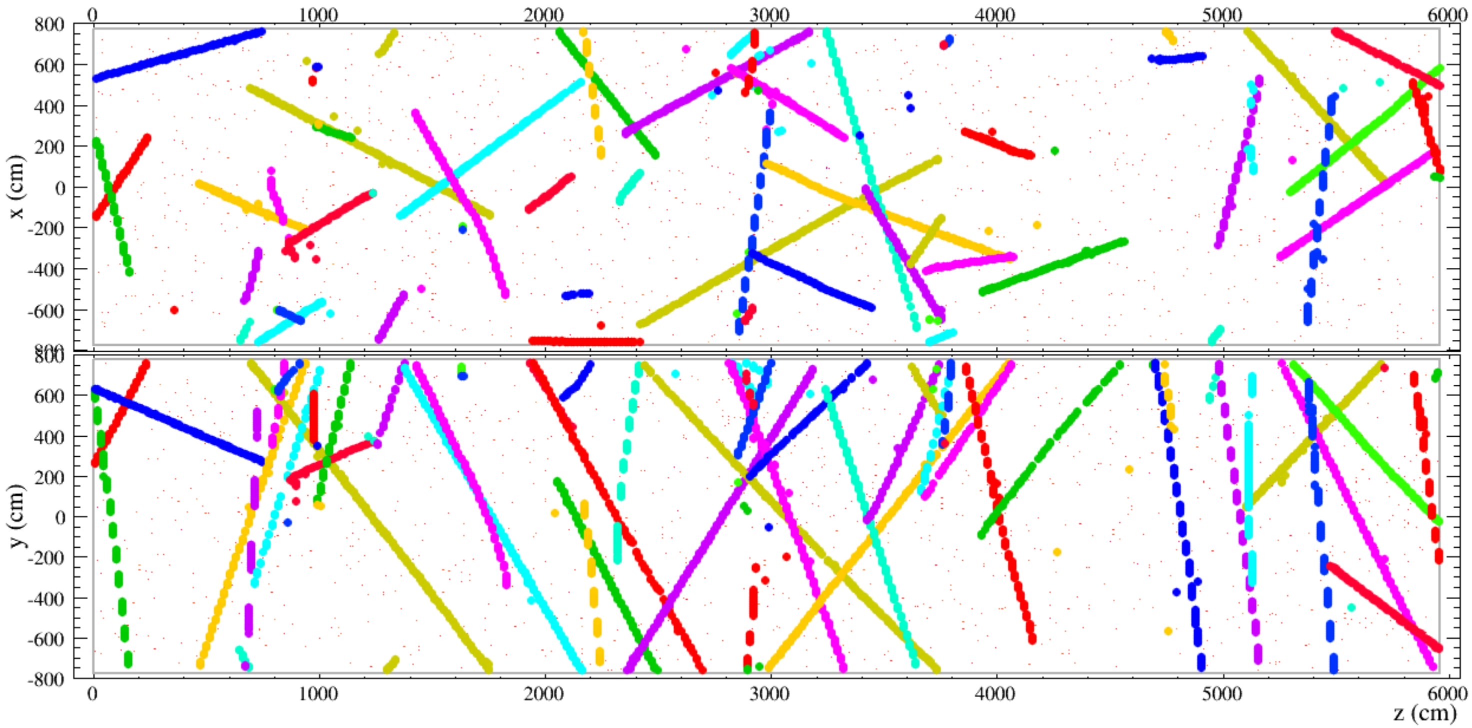

Rejection of Cosmic Rays

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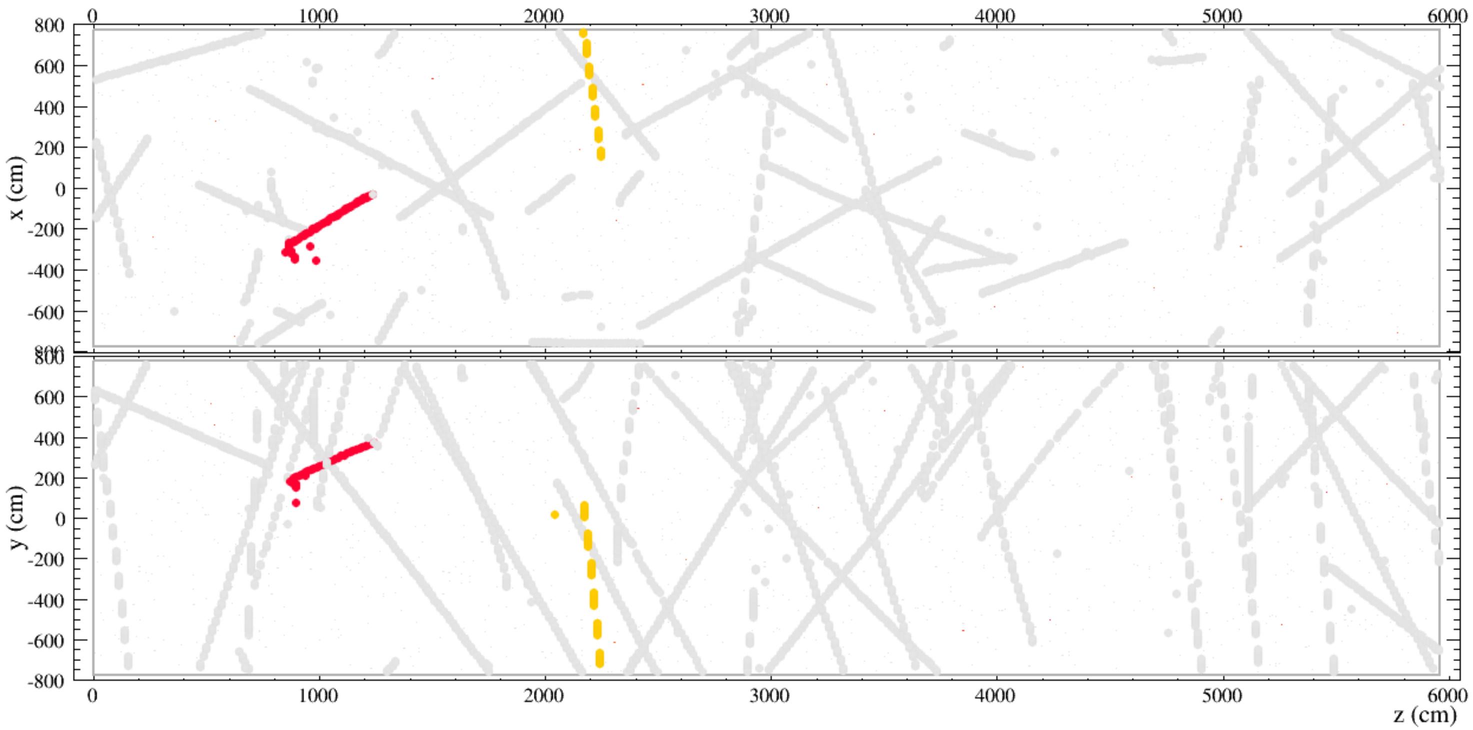
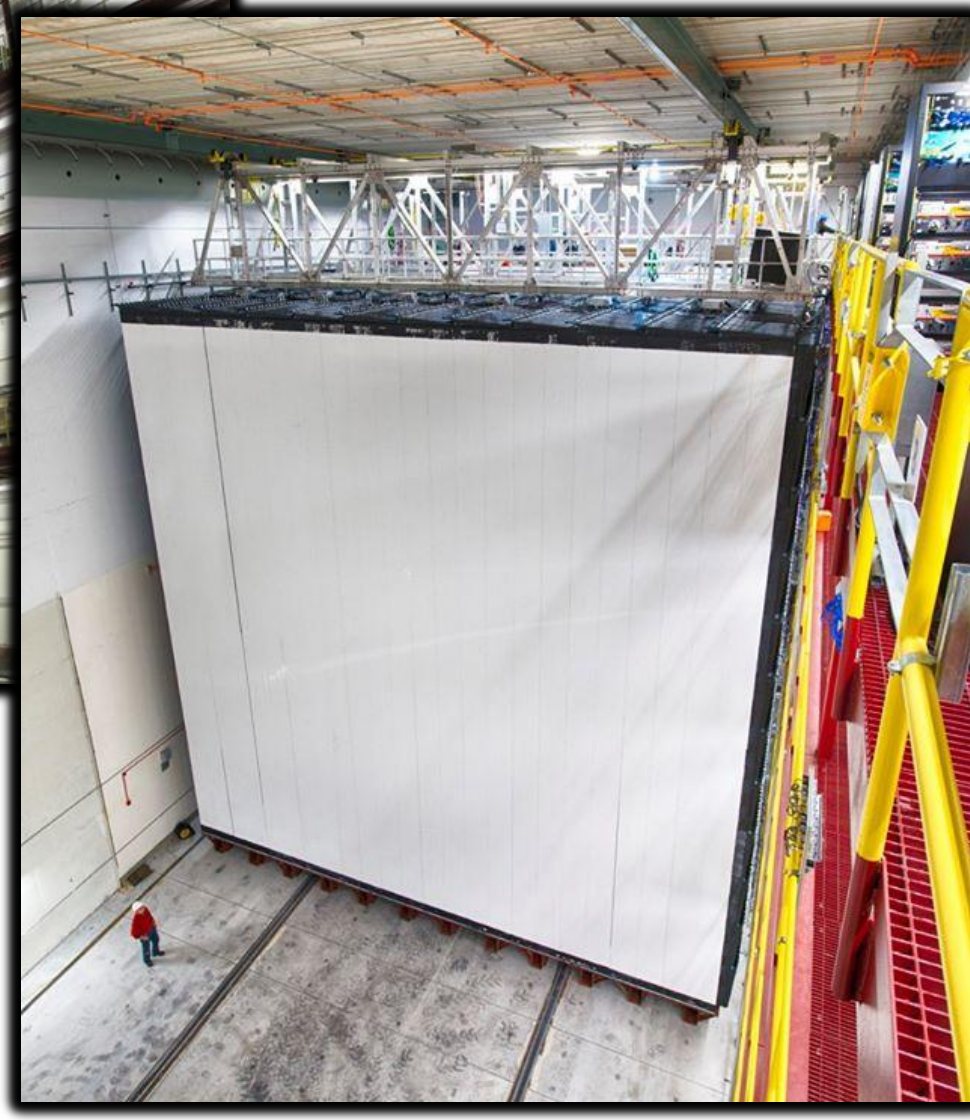
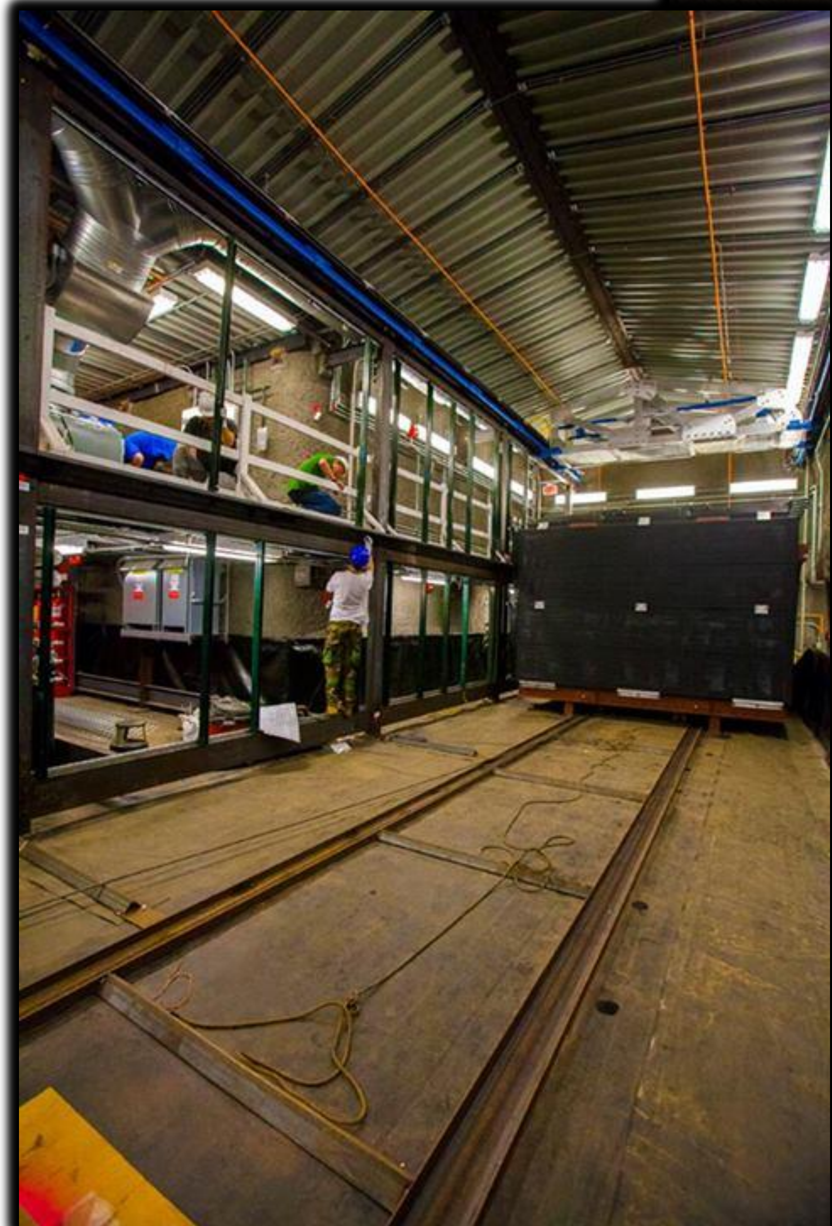


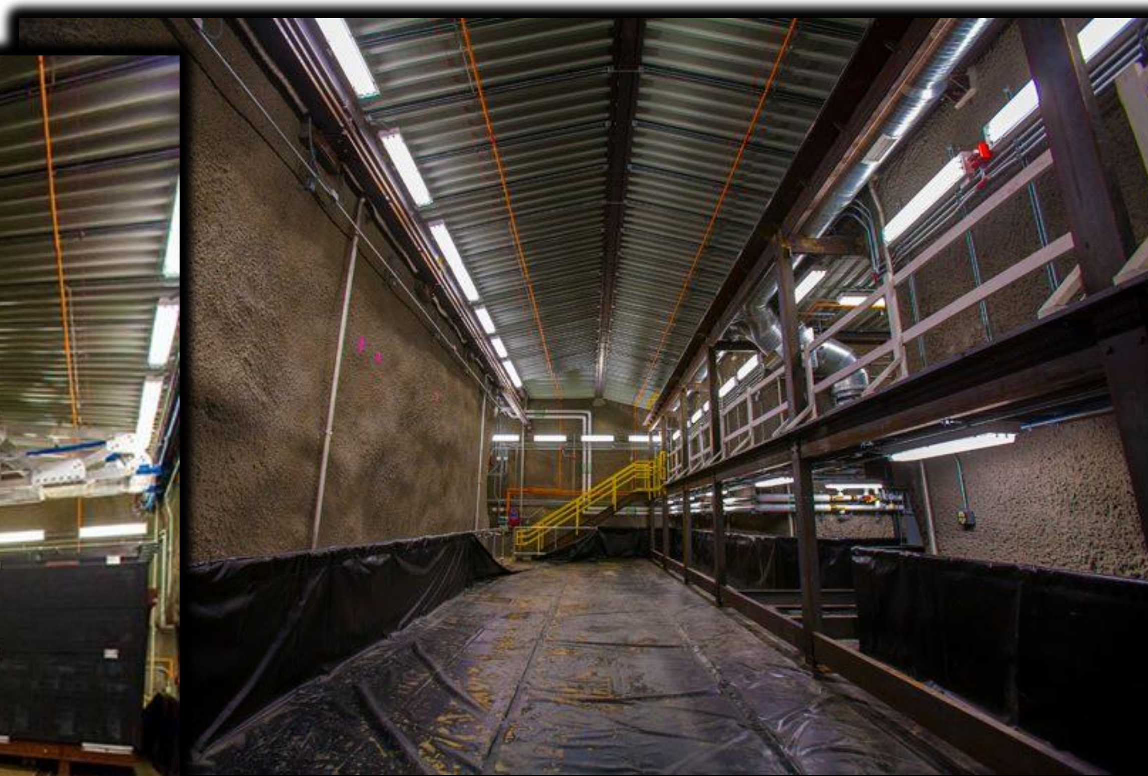
Perspective on the NOvA Far Detector



Far detector construction is progressing…

Perspective on the NOνA Near Detector





Near detector construction has begun!

Instillation of the muon catcher.

$\nu_\mu \rightarrow \nu_e$ Oscillation Probability

$$P(\overset{(-)}{\nu_\mu} \rightarrow \overset{(-)}{\nu_e}) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}[\cos(\Delta_{32})\cos(\delta) \mp \sin(\Delta_{32})\sin(\delta)]$$

$$P_{atm} \equiv \sin^2(\Theta_{23})\sin^2(2\Theta_{13})\frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2}(\Delta_{31})^2$$

$$P_{sol} \equiv \cos^2(\Theta_{23})\sin^2(2\Theta_{12})\frac{\sin^2(\mp aL)}{(\mp aL)^2}(\Delta_{21})^2$$

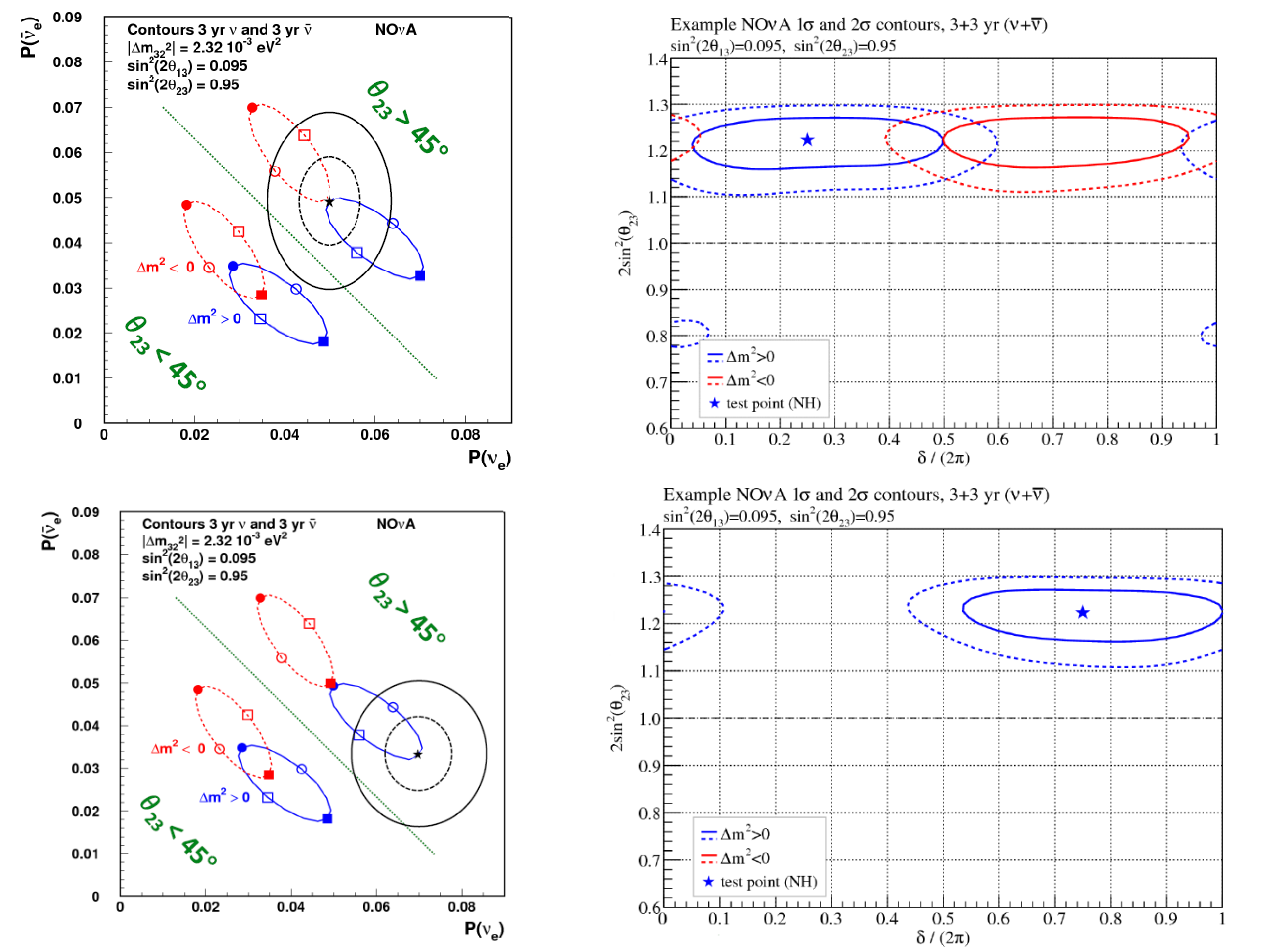
$$"-" = neutrinos$$

$$"+" = anti-neutrinos$$

$$a \equiv G_F N_e/\sqrt{2}$$

$$N_e = electron\ density\ in\ Earth$$

- This contains **CP violation**.
- Since the Earth is made of electrons, ν_e will be affected in a way that that won't occur for the ν_μ or the ν_τ. This is the **matter effect**.
  (For L = 810 km, aL ≈ 0.23.)
- The dominant term above is proportional to **$\sin^2(\Theta_{23})$** meaning it is possible to determine if $\Theta_{23} > 45^o$ or $\Theta_{23} < 45^o$ ("resolving the octant.")

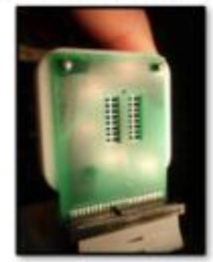


Contours 3 yr ν and 3 yr ν̄
NOνA
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ13) = 0.095
sin²(2θ23) = 0.95
θ23 > 45°
θ23 < 45°
Δm² < 0
Δm² > 0
P(ν̄e)
P(νe)
Example NOνA 1σ and 2σ contours, 3+3 yr (ν+ν̄)
sin²(2θ13)=0.095, sin²(2θ23)=0.95
2sin²(θ23)
δ / (2π)
Δm²>0
Δm²<0
test point (NH)
Contours 3 yr ν and 3 yr ν̄
NOνA
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ13) = 0.095
sin²(2θ23) = 0.95
θ23 > 45°
θ23 < 45°
Δm² < 0
Δm² > 0
P(ν̄e)
P(νe)
Example NOνA 1σ and 2σ contours, 3+3 yr (ν+ν̄)
sin²(2θ13)=0.095, sin²(2θ23)=0.95
2sin²(θ23)
δ / (2π)
Δm²>0
Δm²<0
test point (NH)

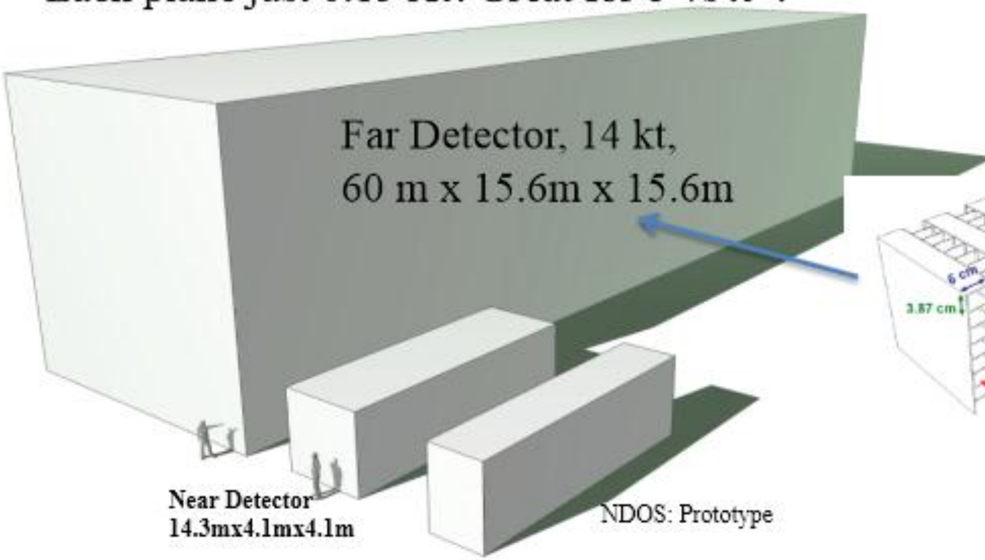
The NOνA Detectors

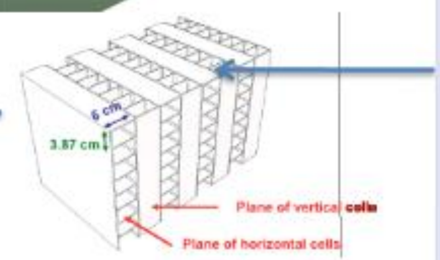
- 14-kton Far Detector (~3x MINOS).
- 65% active detector.
- 344,064 detector cells read by APDs.
- 0.3 kton Near Detector 18,000 cells/channels.
- Each plane just 0.15 X_0. Great for e^- vs π^0 .

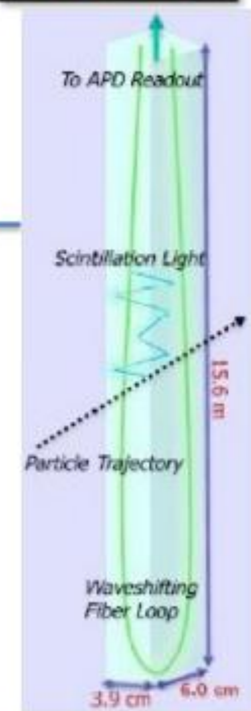
32-pixel APD



Fiber pairs from 32 cells





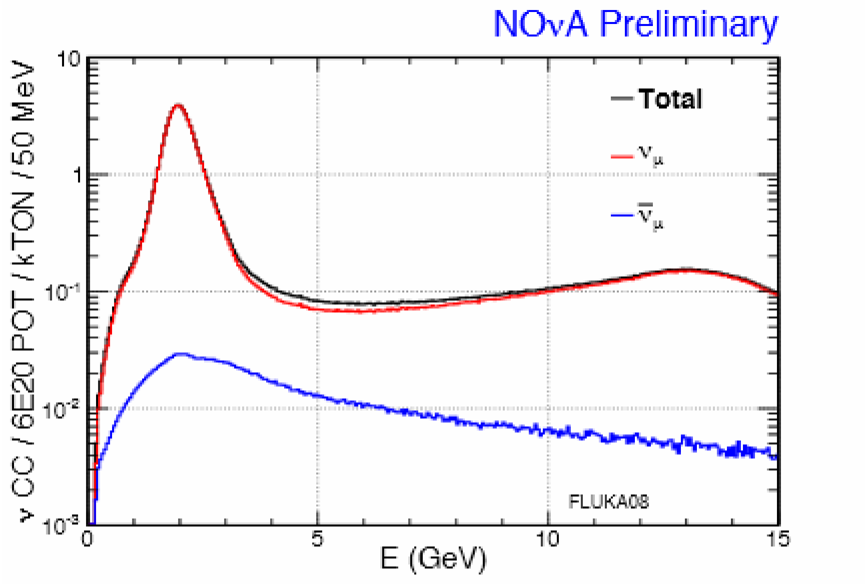


NOνA basic cell

Consist of plastic (PVC) extrusions filled with liquid-scintillator, with WLS fibers connected to APDs. Assembled in alternating layers of vertical and horizontal extrusions.

FHC ν_μ CC

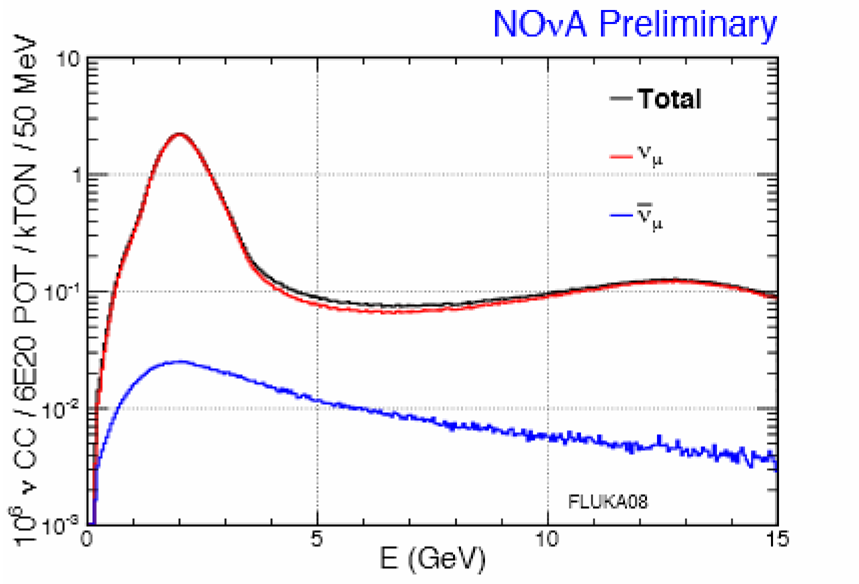
FD



	[1,3]GeV	[0,120]Gev
Total	63.1	101.5
Numu	62.1	97.6
Anti-Numu	1.0	3.9

[0,3]GeV: anumu/numu = 1.6%

ND

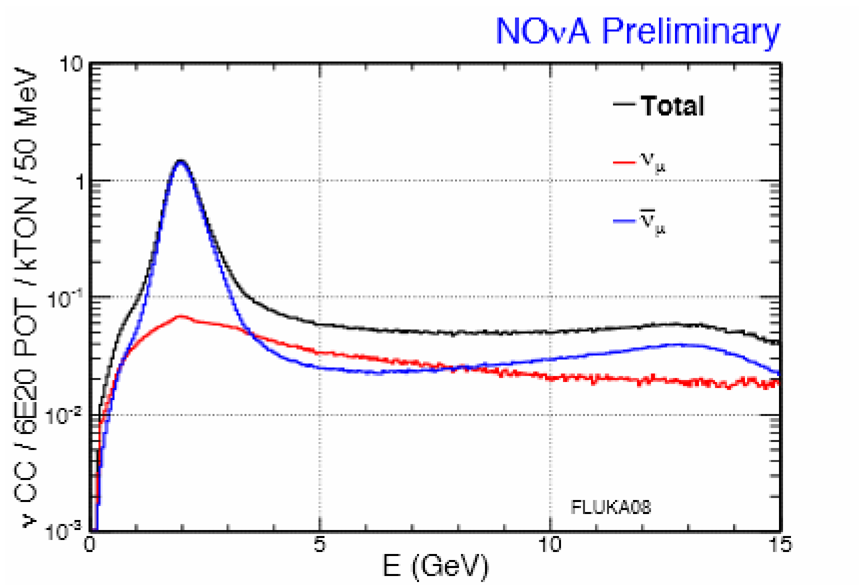


$\times 10^6$	[1,3]GeV	[0,120]Gev
Total	53.5	93.0
Numu	52.6	89.5
Anti-Numu	0.9	3.5

[0,3]GeV: anumu/numu = 1.7%

RHC ν_μ CC

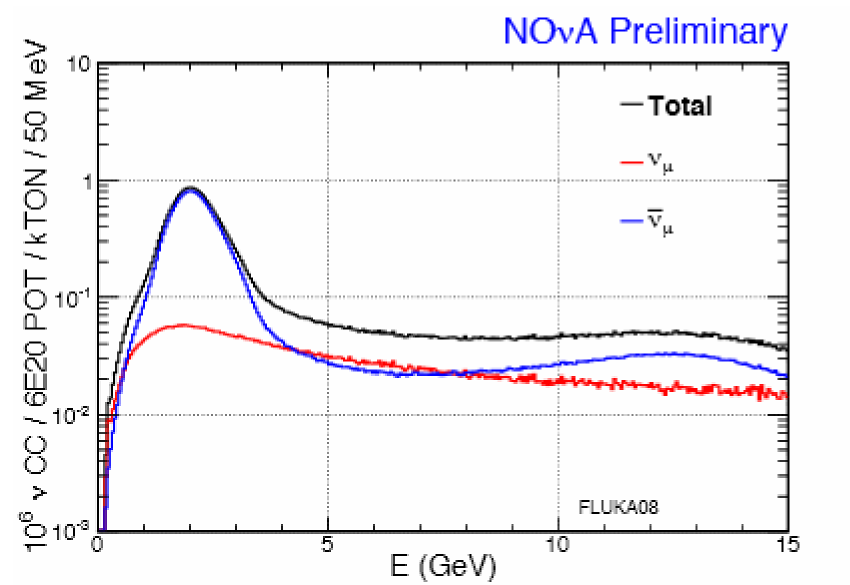
FD



	[1,3]GeV	[0,120]Gev
Total	24.9	45.4
Numu	2.4	13.2
Anti-Numu	22.5	32.2

[0,3]GeV: numu/anumu = 10%

ND



$\times 10^6$	[1,3]GeV	[0,120]Gev
Total	21.2	41.2
Numu	2.1	11.9
Anti-Numu	19.1	29.3

[0,3]GeV: numu/anumu = 10%