Expected Sensitivity of the NOνA ν_μ Disappearance Analysis

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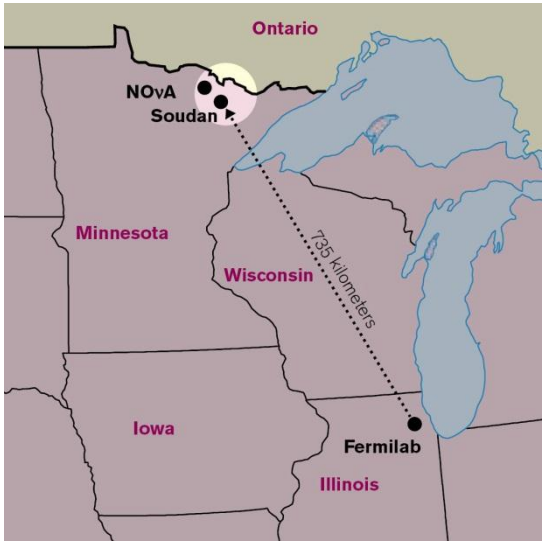
for the NOνA Collaboration
April 14, 2013
APS DPF Denver

NOνA Overview



- NOνA is a 14 kton liquid scintillator surface detector
- NOνA uses the NUMI beam at Fermilab, which:
  - is currently being upgraded to 700 kW
  - has a 810 km beamline with the detector 14 mrad off-axis
  - is comprised mostly of μ neutrinos peaked @ ~ 2 GeV

- NOνA will study:
  - ν_e appearance (see next talk)
  - ν_μ disappearance (this talk)
  - Exotic physics and more

- NOνA will precisely measure:
  - θ_{13}
  - θ_{23}
  - Δm^2_{32}

- NOνA will have a chance to:
  - Resolve the mass hierarchy
  - Resolve the octant
  - Measure δ_{CP}

NOνA at APS:

this session:

- Detector update
- ν_μ disappearance
- ν_e appearance
- Reconstruction algorithms
- ν_μ disappearance in the NDOS

also look for:

Z. Wang: Magnetic Monopoles (talk, L12, 3:30 pm today)
F. Psihas: μ Energy Estimation (poster session II, 2 pm today)
H. Sahoo: ν_e ID in NOνA (poster session II)

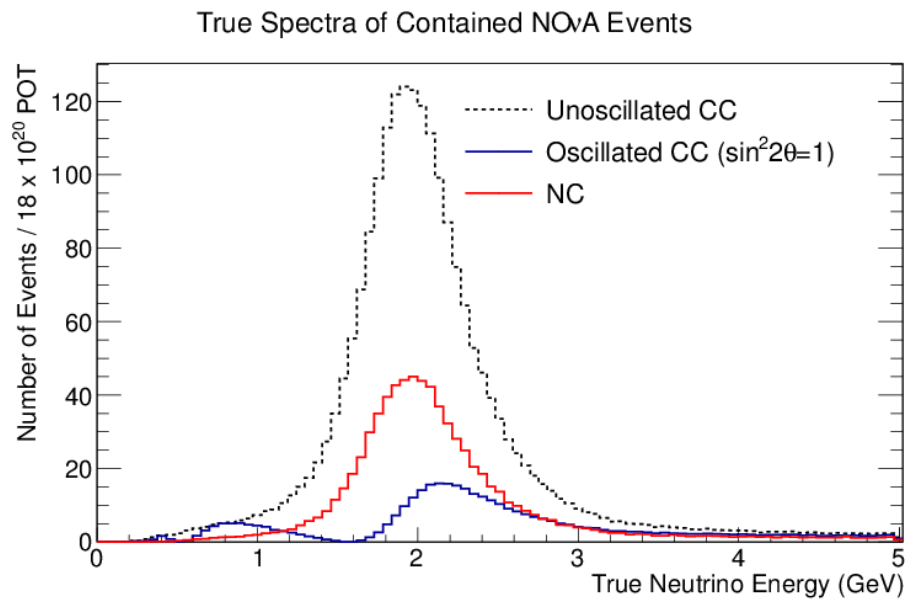
ν_μ Physics

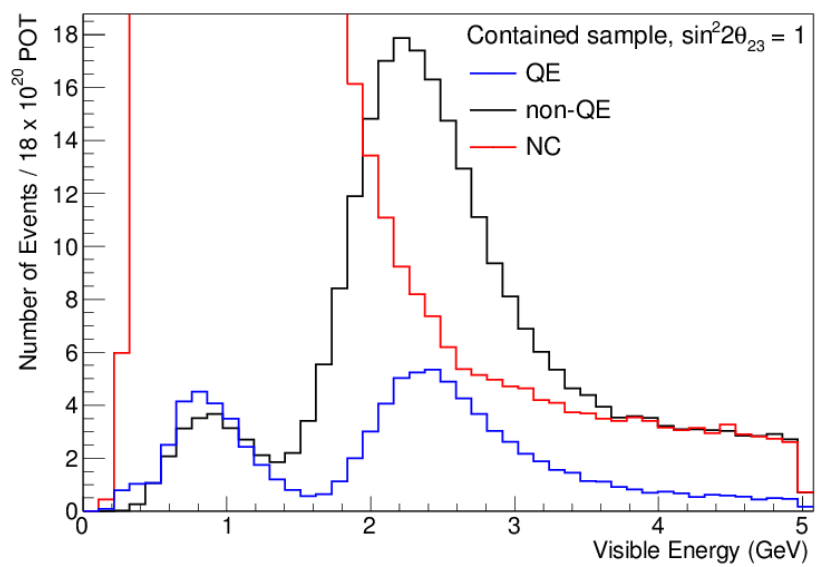
- **Muon Neutrino disappearance:**
  - $P(\nu_\mu \rightarrow \nu_\mu) \sim= 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}L/E)$
  - Direct measurement of θ_{23}, Δm^2_{23}
  - More statistics than appearance channel
  - Signature is high E muon

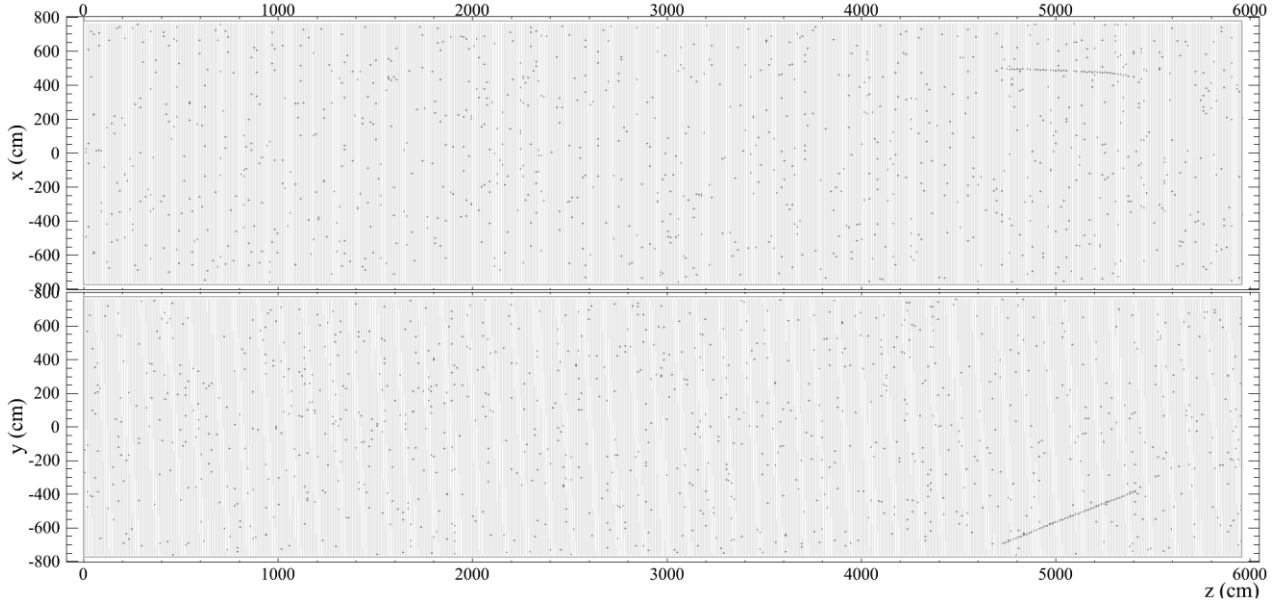
- **Multiple interaction types for CC events:**
  - Quasi-elastic (QE): $\nu_\mu + n \rightarrow \mu + p$
  - Resonance (RES): $\nu_\mu + n \rightarrow \mu + n + \pi$
  - Deep Inelastic Scatt. (DIS): $\nu_\mu + n \rightarrow \mu + c_1 n + c_2 \pi$
  - ... + anti-neutrino modes

- **Need to distinguish ν_μ CC events from:**
  - NC neutrino events
  - Cosmic ray background

- **For CP, likely to run both ν and $\bar{\nu}$ modes**
  - Forward Horn Current (FHC) 96% ν, 4% $\bar{\nu}$
  - Reverse Horn Current (RHC) 30% ν, 70% $\bar{\nu}$

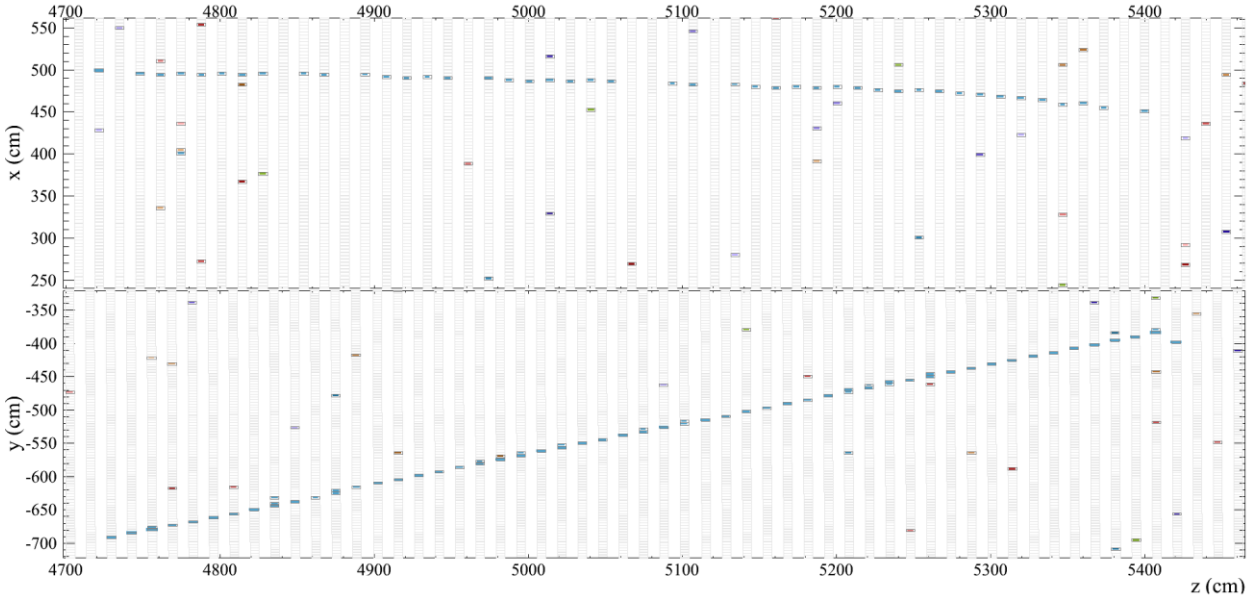




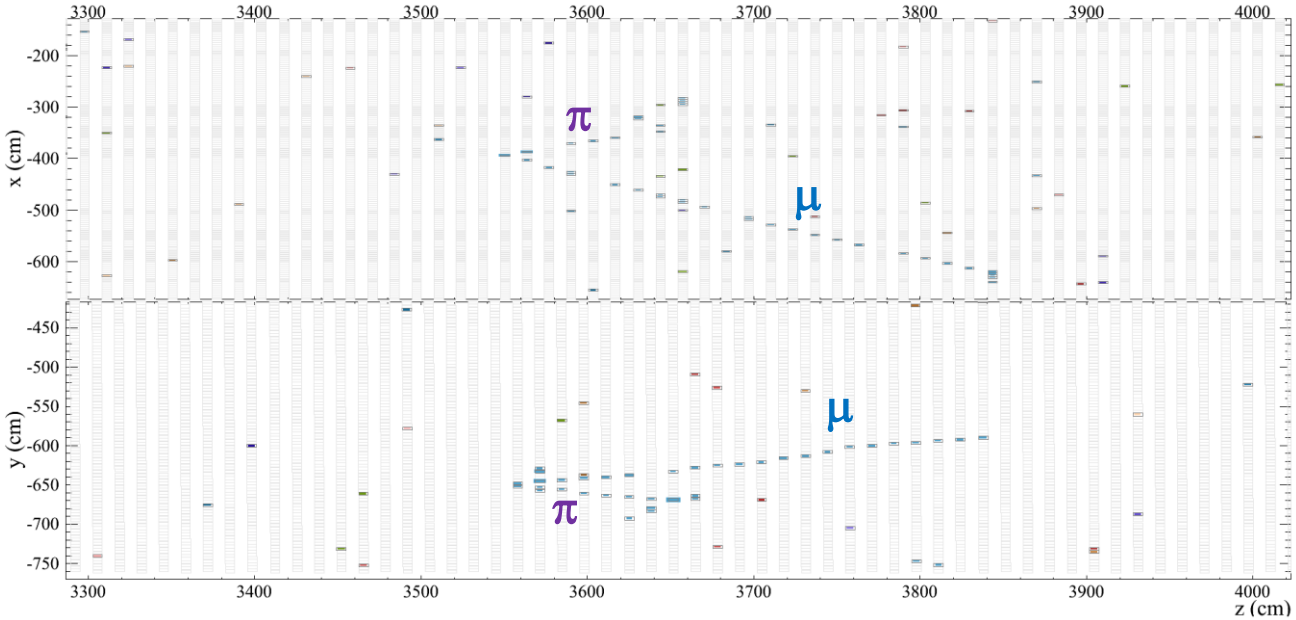


This is a 1.8 GeV ν_μ QE MC event in our full event display

NOνA MC

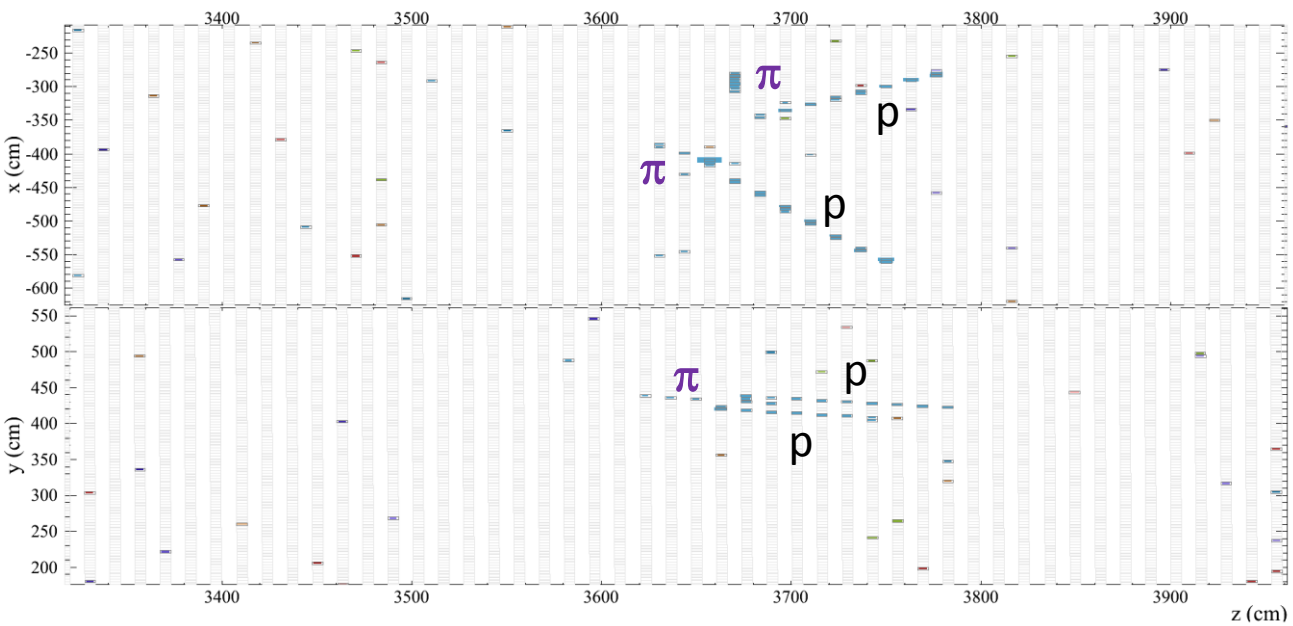


Here it is zoomed in. The QE ν transfers its E to the muon; generally there isn't other activity, except maybe a short proton.



Here is a 2.3 GeV DIS event. There is a pion as well as a muon

NOνA MC

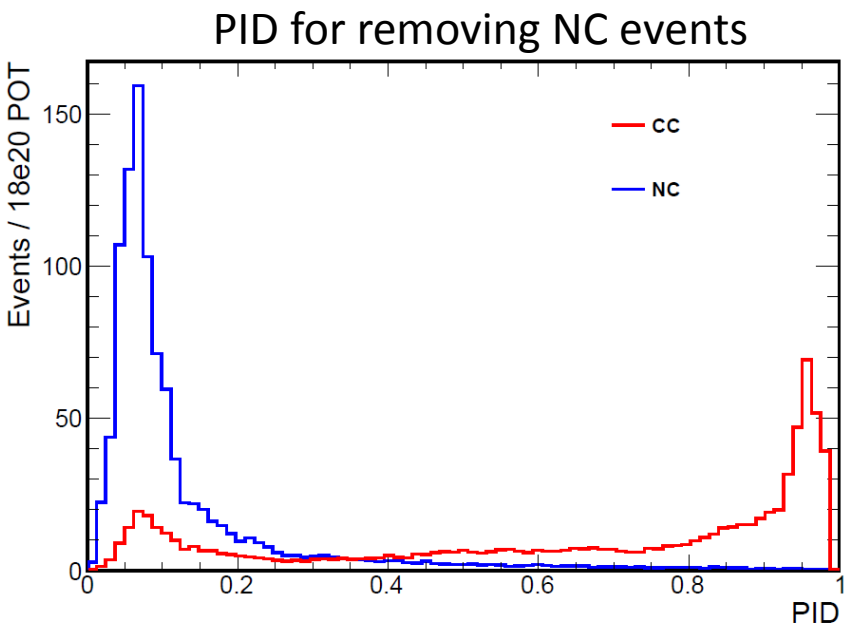


Here is a 2.4 GeV NC event. There is no muon, and the event is messier

A Basic ν_μ Disappearance Analysis

- **Expected event counts 0-5 GeV (oscillated):**
  - **150 contained CC / year**
  - **75 uncontained CC / year**
  - **300 NC / year**
  - **Note: 1 full year = 6 x 10^{20} POT**

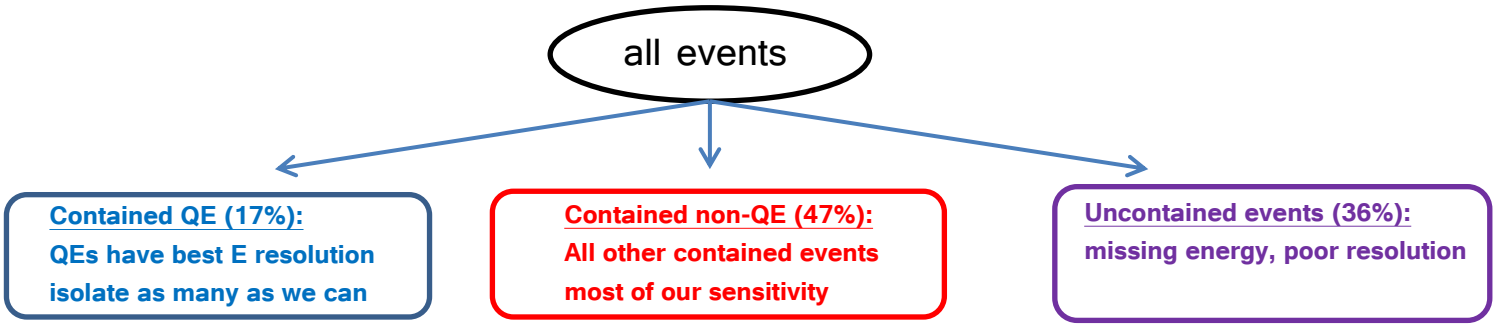
- **NC background:**
  - **Require clear μ**

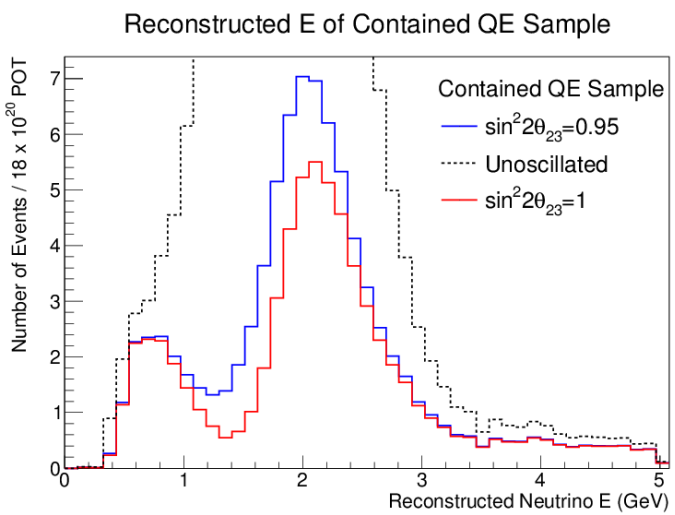


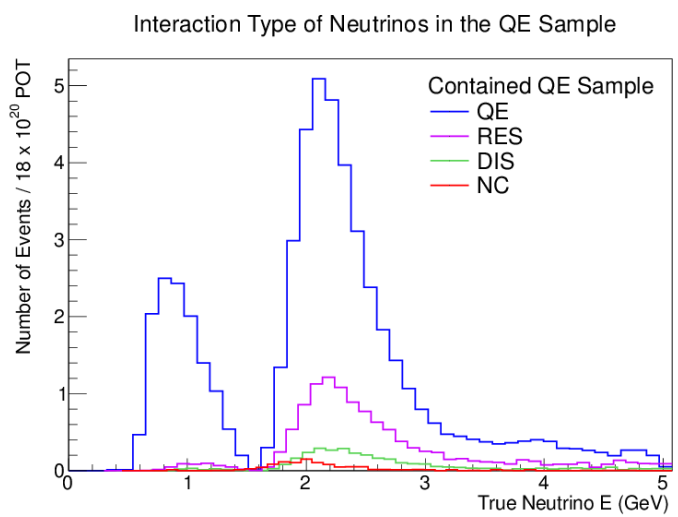
- **Cosmic ray muons:**
  - **high rate (surface); ~1 per beam spill**
  - **good rejection using timing, track direction, containment**
  - **estimate effectiveness using MC:**
  - **can remove all but 1 (out of 8,000,000) from contained sample**
  - **95% signal eff. for contained**
  - **uncontained separation still being developed**

A Basic ν_μ Disappearance Analysis

- **Separate into samples:**
  - **contained QE (can isolate most of QE events)**
  - **contained nonQE (contained DIS, RES, remaining QE)**
  - **uncontained (missing energy, poor E-estimation)**







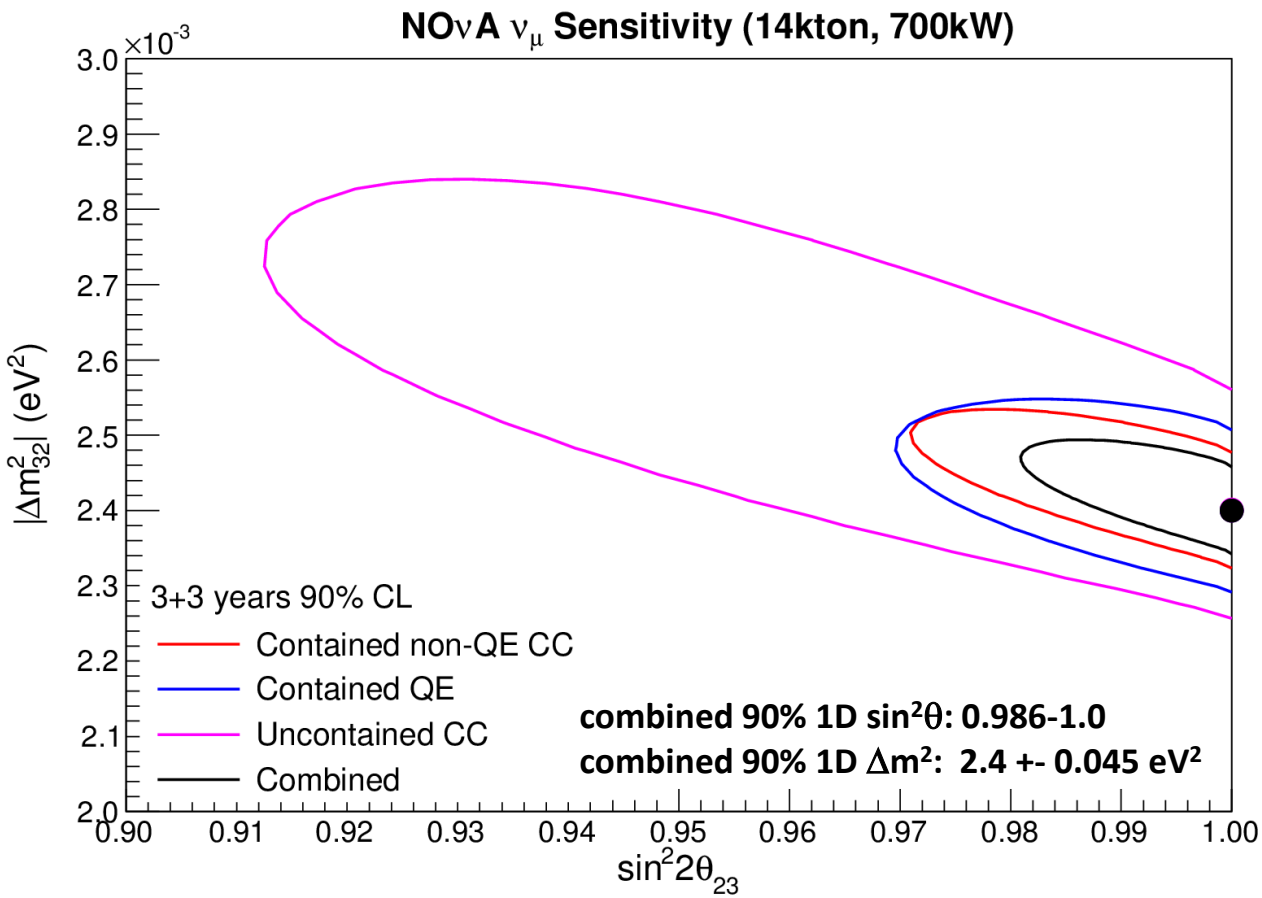
Combined Sensitivity Example

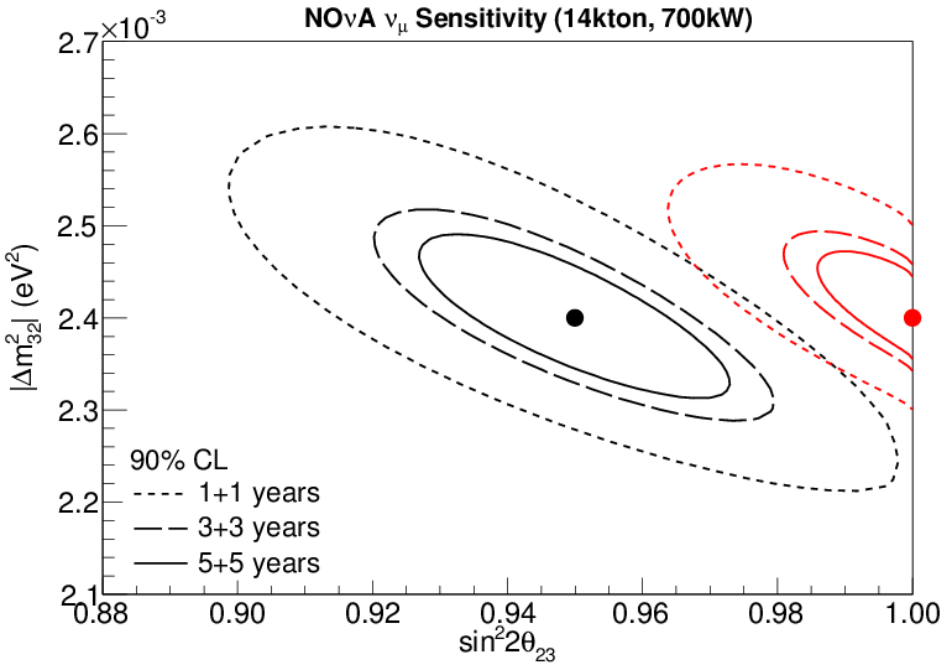
The contours assume no systematics.

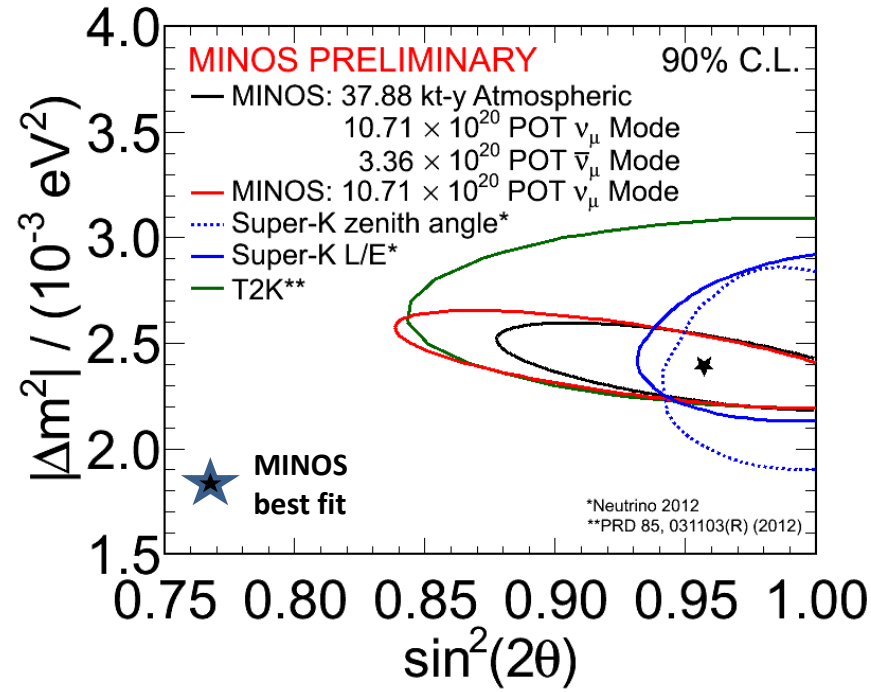
We believe that even at high exposures, we will be statistics limited, with very small systematics.

1 full run year = 6 x 10^{20} POT

n + n years means n years FHC and n years RHC





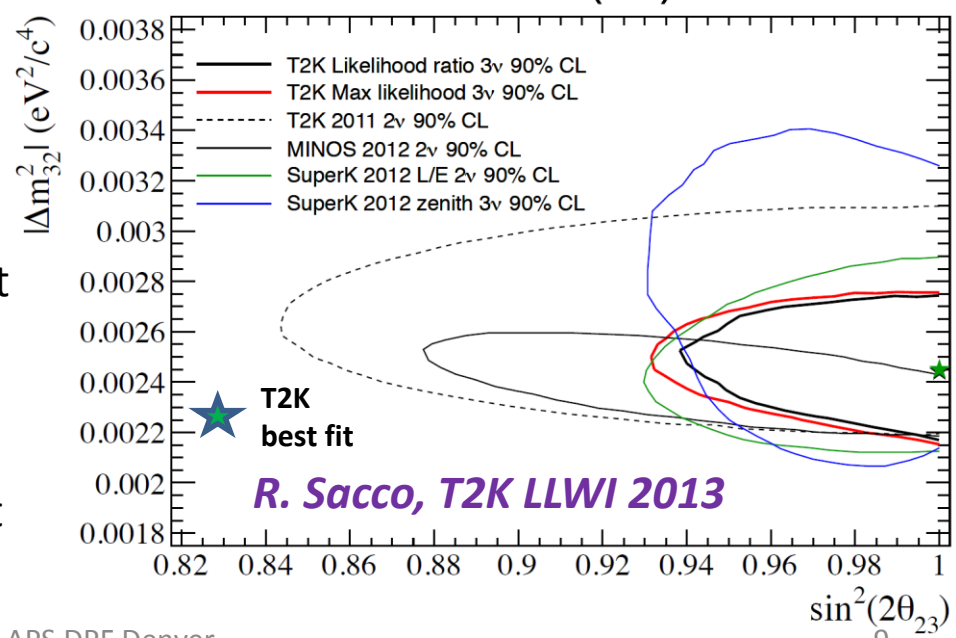


NOνA Full Reach

If $\sin^2(2\theta) = 1$, best limit by 1+1 years

For any value of θ_{23}, precision measurement will surpass any current measurement by 3+3 years

Actual run plan (when to switch to RHC) not yet decided



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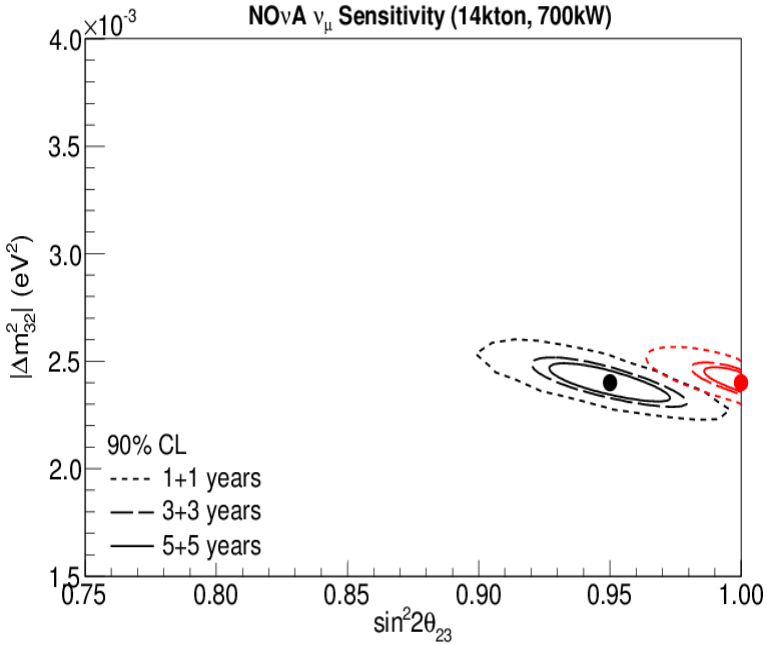

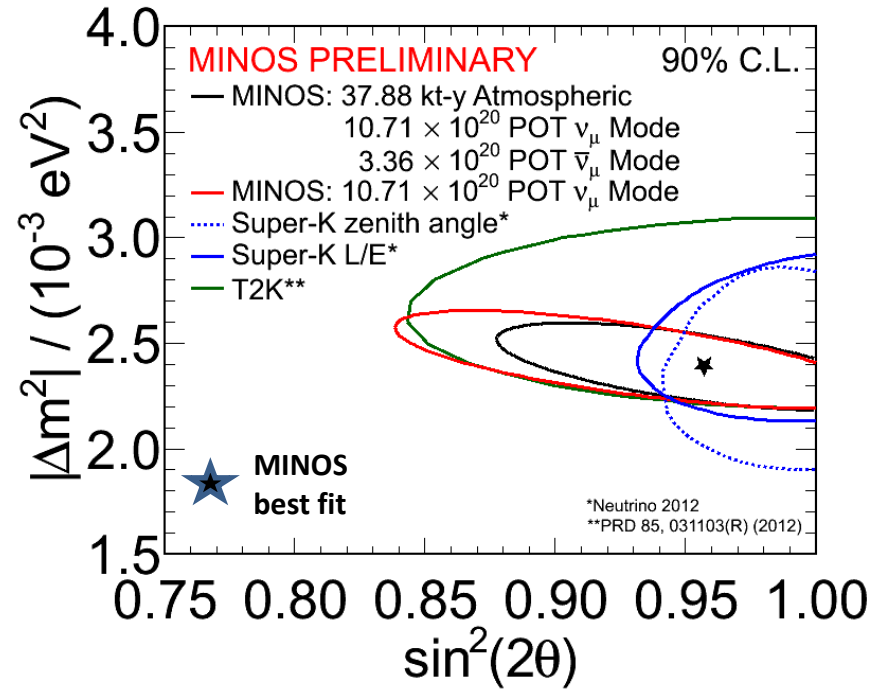

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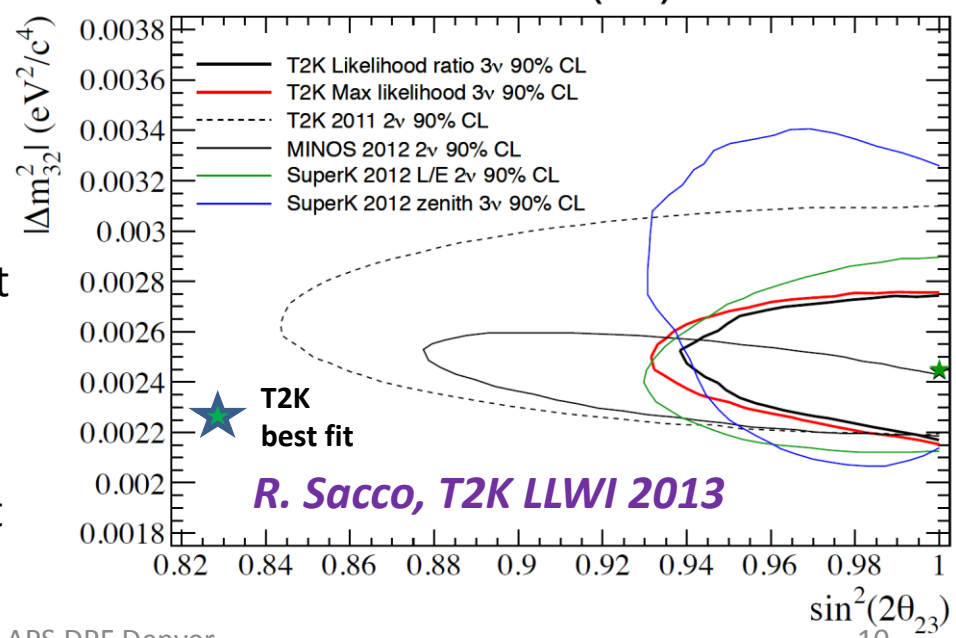

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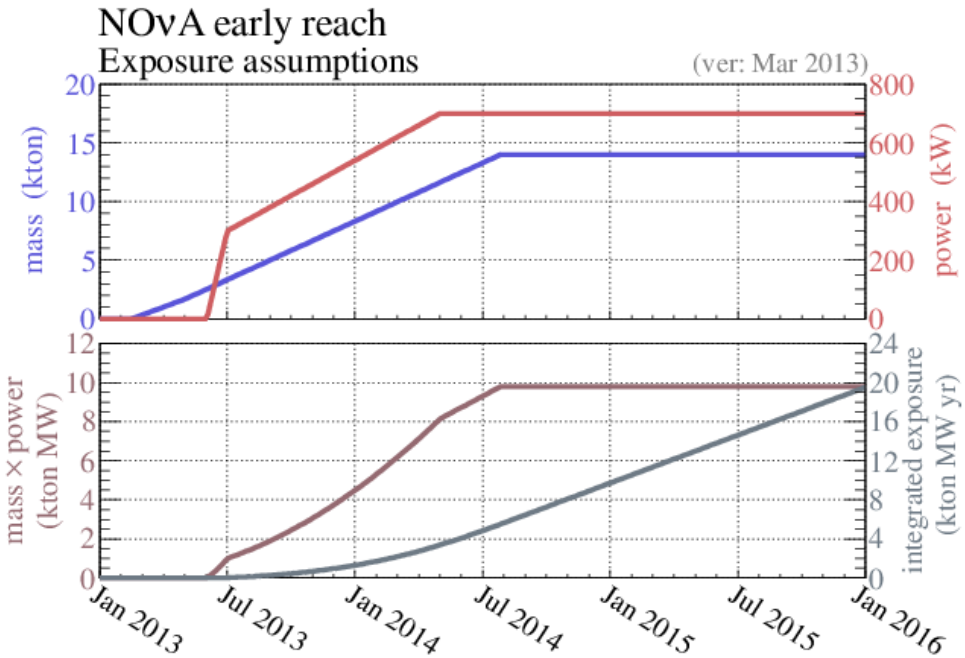
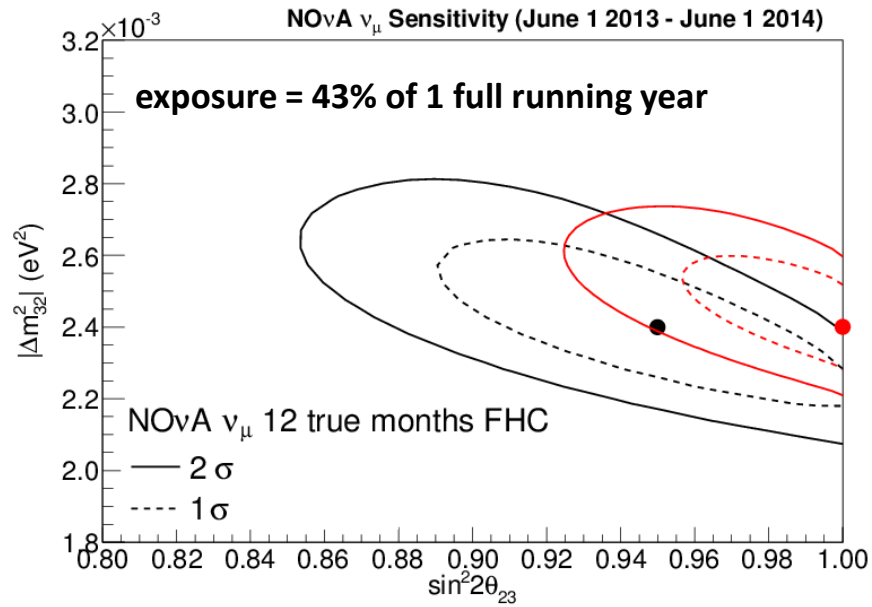


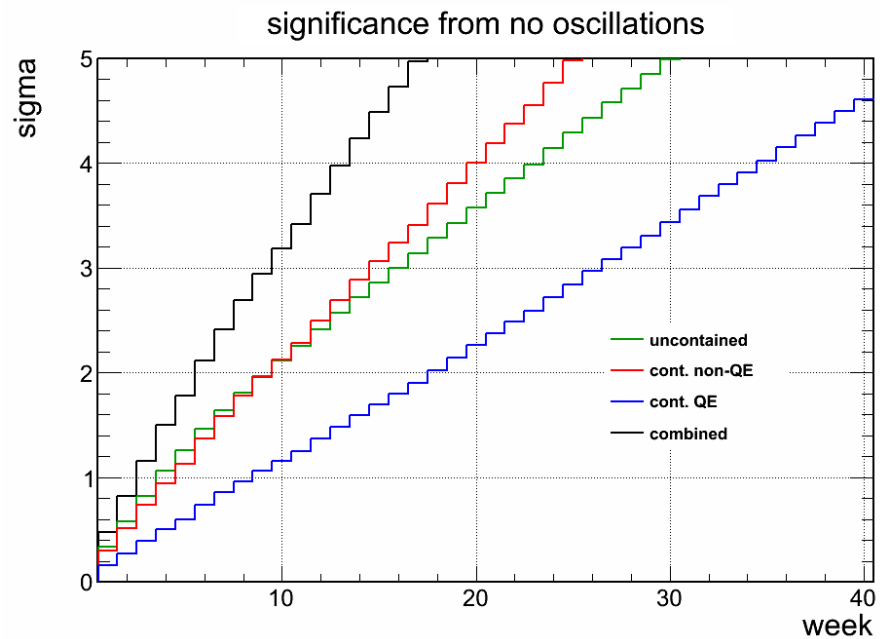


NOνA Early Reach

The beam ramps up in power
The detector is still being built then too

Not only less exposure from this, also more events are uncontained

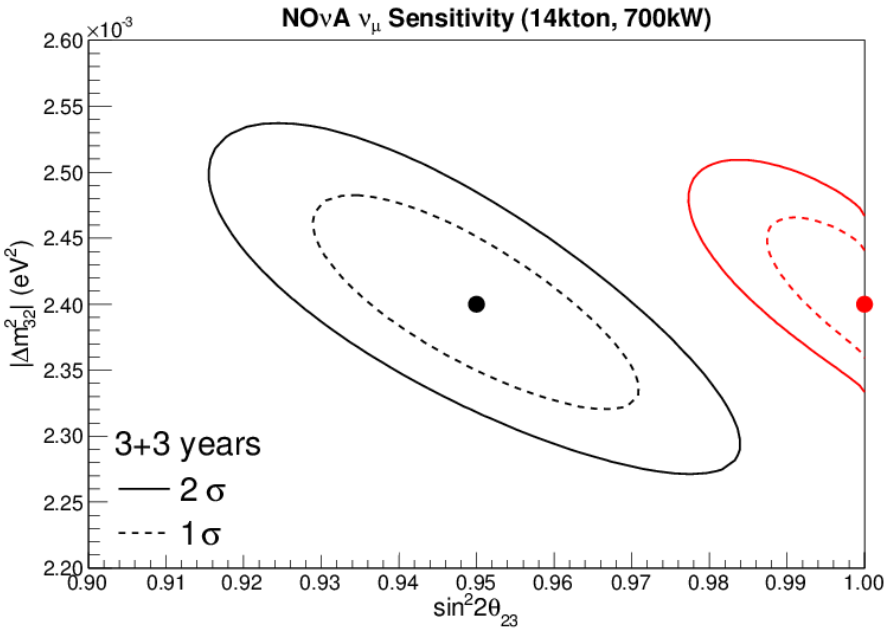
Model this ramp up to determine early reach

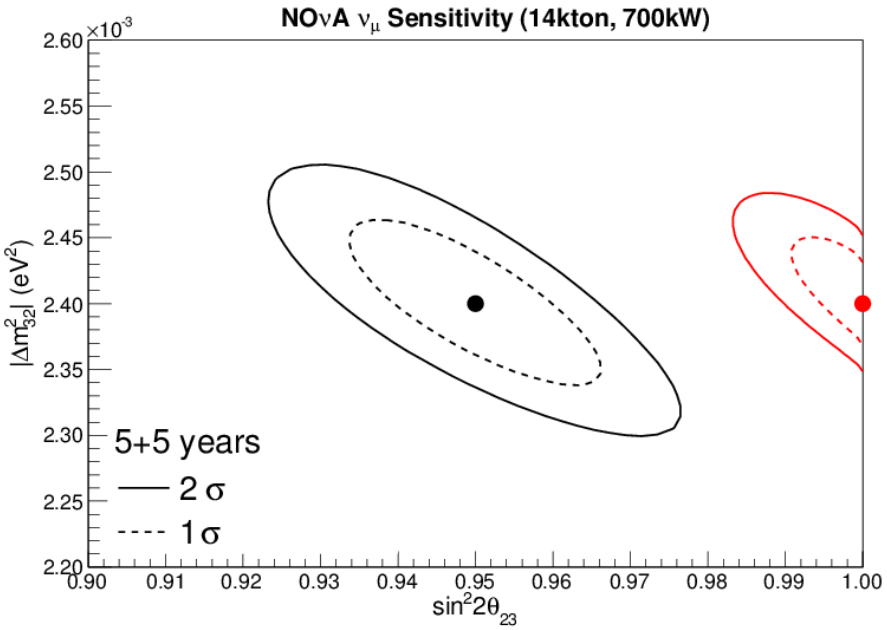


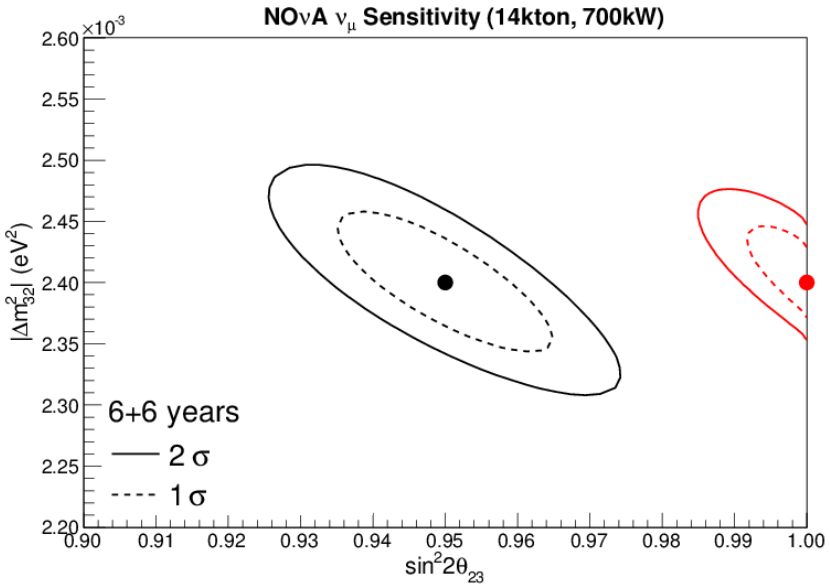
Conclusions

- NOνA data taking will begin in a few months
- We have a preliminary ν_μ analysis ready
- Good background rejection (even on surface)
- Can isolate most QE events
- Competitive with current world limits in a year
- Within a few years, precision measurements of θ_{23}, Δm^2_{32} should surpass current limit
- Expect more soon!

Backup.


NOνA ν_μ Sensitivity (14kton, 700kW)
$\times 10^{-3}$
$|\Delta m^2_{32}|$ (eV^2)
$\sin^2 2\theta_{23}$
3+3 years
2 σ
1 σ


NOνA ν_μ Sensitivity (14kton, 700kW)
$\times 10^{-3}$
$|\Delta m^2_{32}|$ (eV^2)
$\sin^2 2\theta_{23}$
5+5 years
2 σ
1 σ


NOνA ν_μ Sensitivity (14kton, 700kW)
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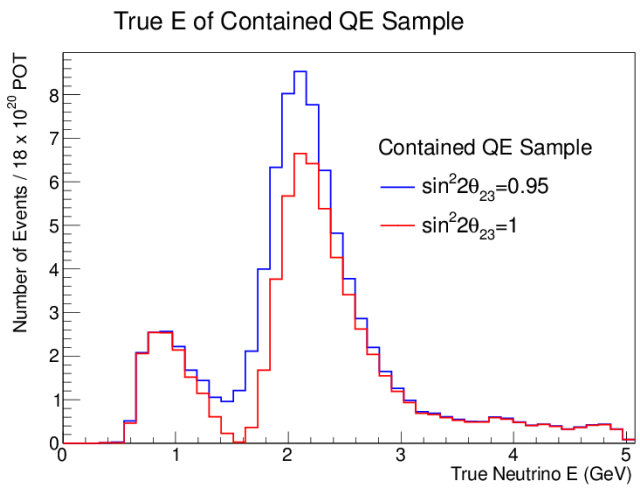
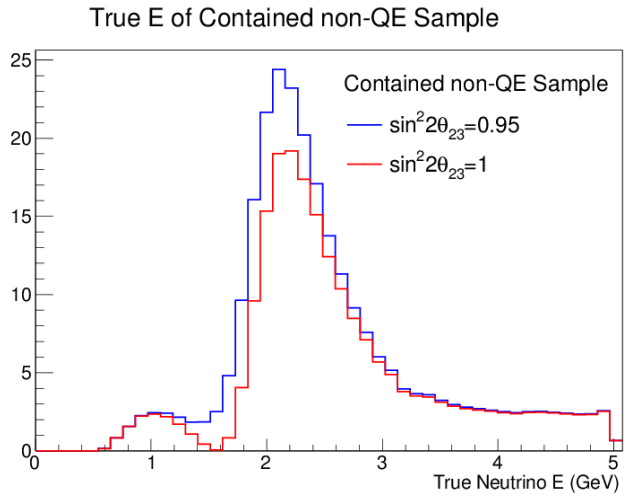
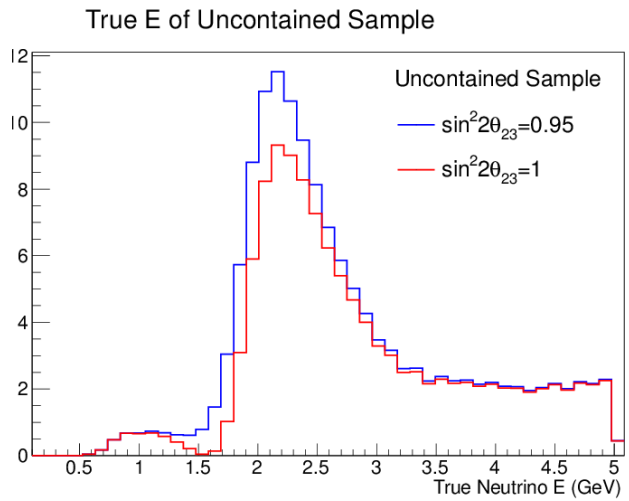
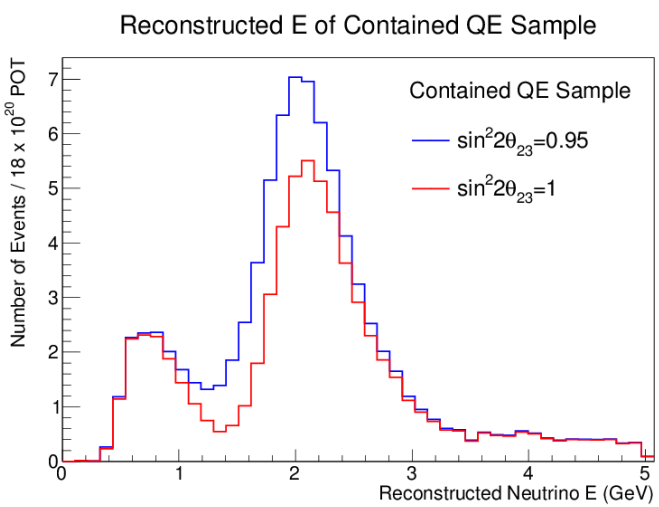
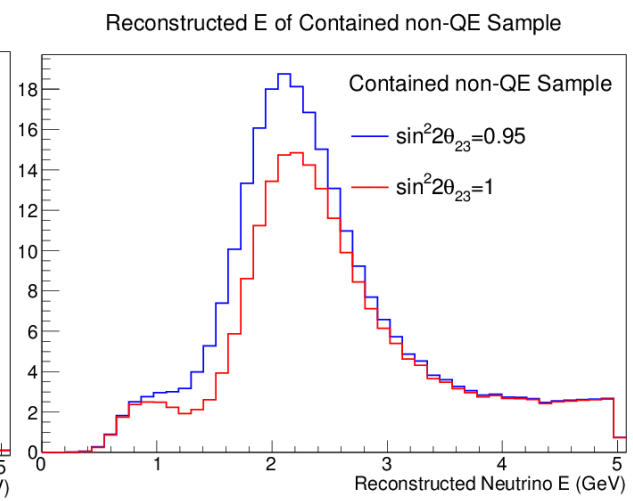
$|\Delta m^2_{32}|$ (eV^2)
$\sin^2 2\theta_{23}$
6+6 years
2 σ
1 σ

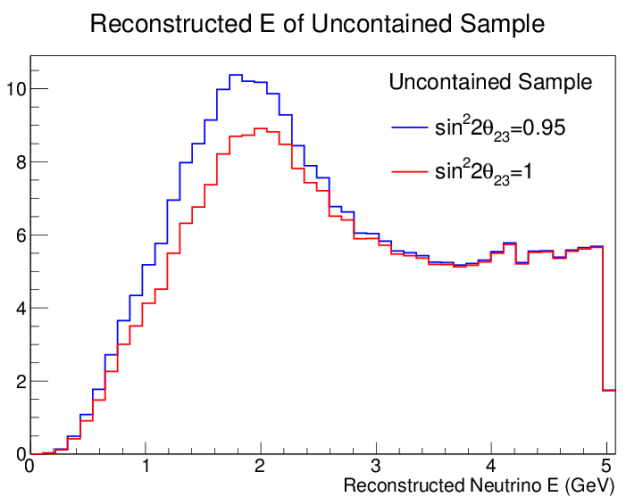

True E of Contained QE Sample
Contained QE Sample
$\sin^2 2\theta_{23}$=0.95
$\sin^2 2\theta_{23}$=1
Number of Events / 18 x 10^{20} POT
True Neutrino E (GeV)


True E of Contained non-QE Sample
Contained non-QE Sample
$\sin^2 2\theta_{23}$=0.95
$\sin^2 2\theta_{23}$=1
True Neutrino E (GeV)

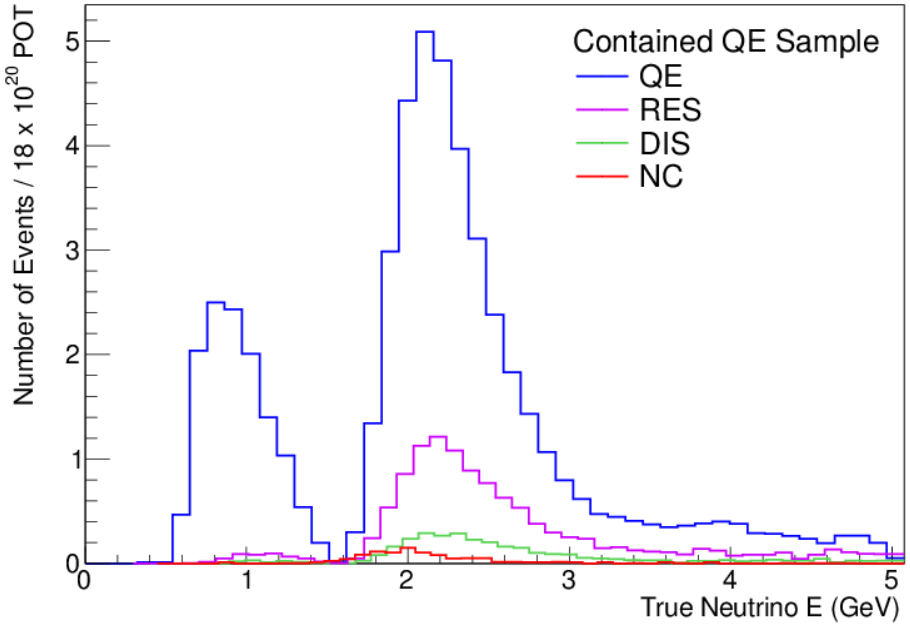

True E of Uncontained Sample
Uncontained Sample
$\sin^2 2\theta_{23}$=0.95
$\sin^2 2\theta_{23}$=1
True Neutrino E (GeV)


Reconstructed E of Contained QE Sample
Contained QE Sample
$\sin^2 2\theta_{23}$=0.95
$\sin^2 2\theta_{23}$=1
Number of Events / 18 x 10^{20} POT
Reconstructed Neutrino E (GeV)

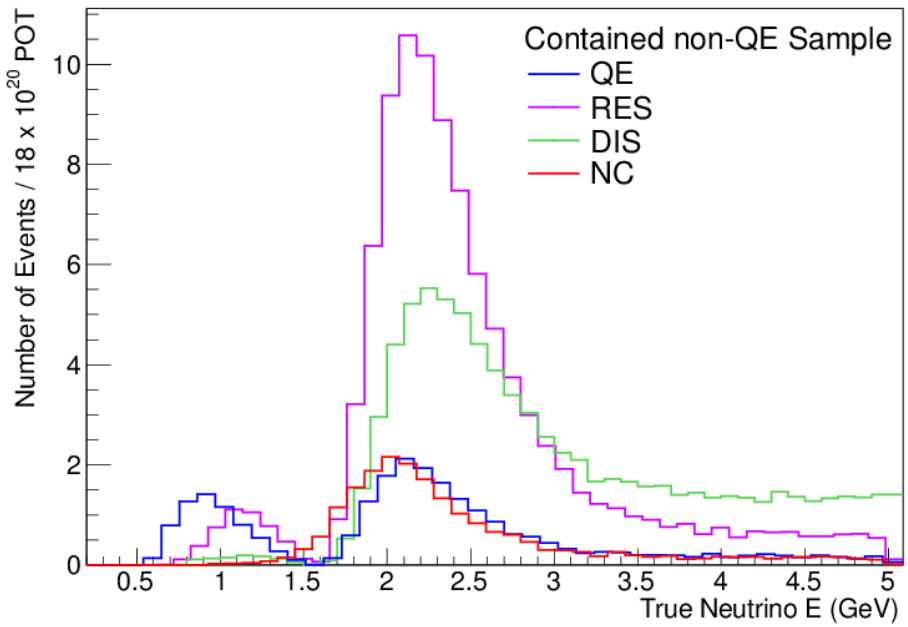

Reconstructed E of Contained non-QE Sample
Contained non-QE Sample
$\sin^2 2\theta_{23}$=0.95
$\sin^2 2\theta_{23}$=1
Reconstructed Neutrino E (GeV)


Reconstructed E of Uncontained Sample
Uncontained Sample
$\sin^2 2\theta_{23}$=0.95
$\sin^2 2\theta_{23}$=1
Reconstructed Neutrino E (GeV)

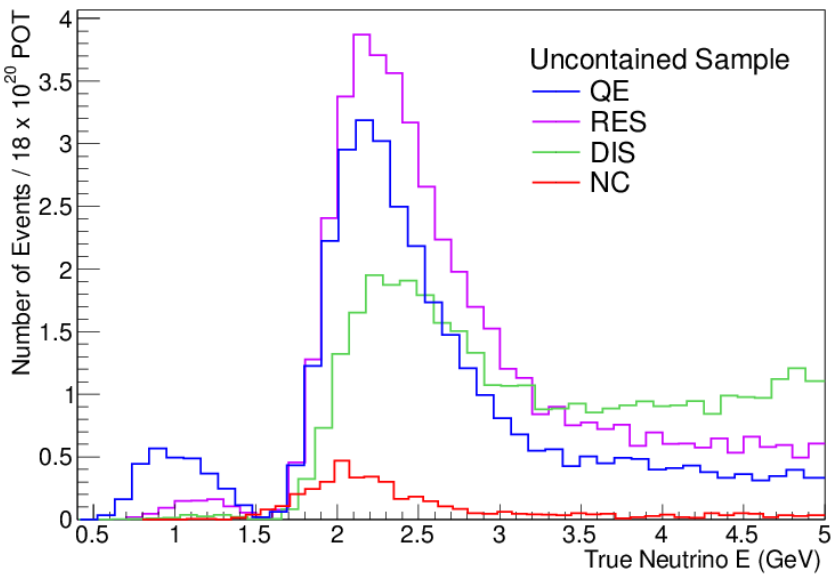
Interaction Type of Neutrinos in the QE Sample



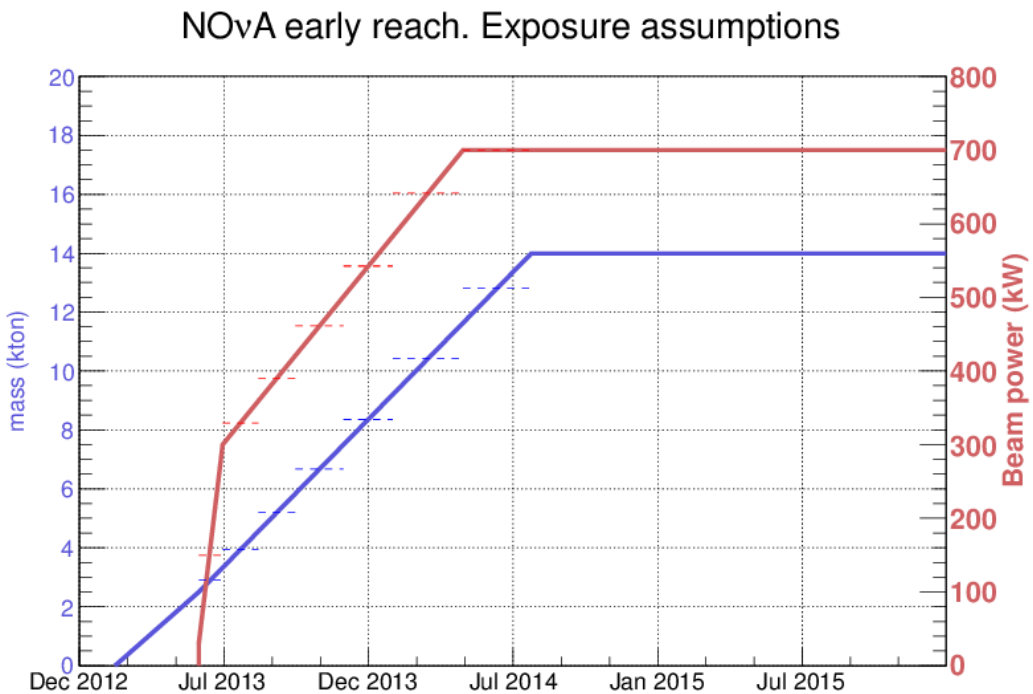
Interaction Type of Neutrinos in the Contained non-QE Sample



Interaction Type of Neutrinos in Uncontained Sample



Early Reach Model



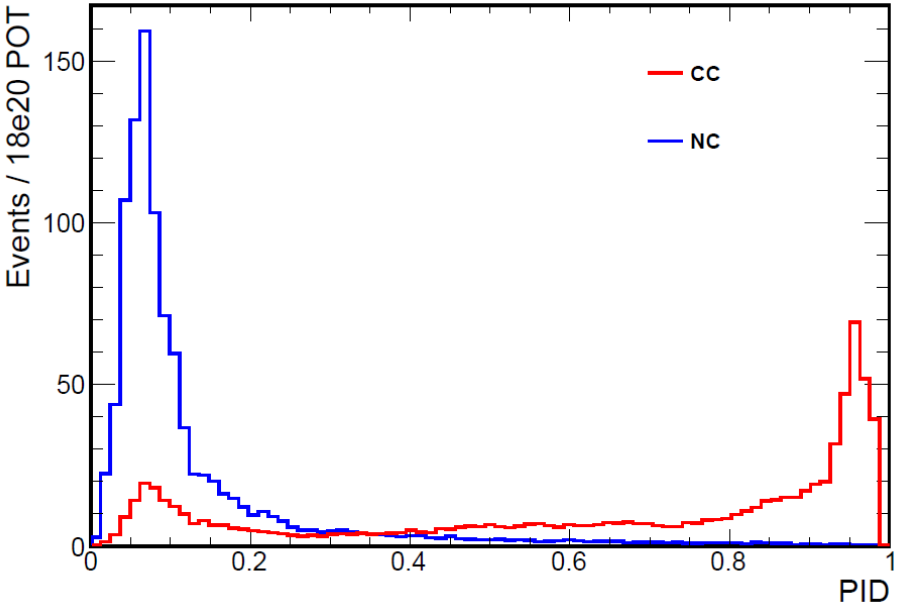
- Model smaller detector in bins (dotted blue)
- Model beam power in bins (dotted red)

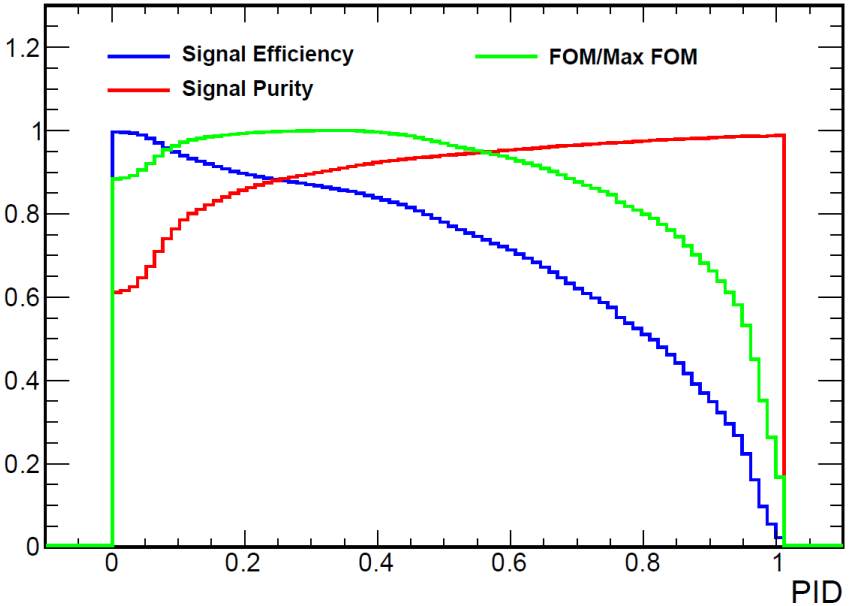
muon PID details

Log likelihood based

variables used include:
- track dE/dx
- track scattering parameters
- track length

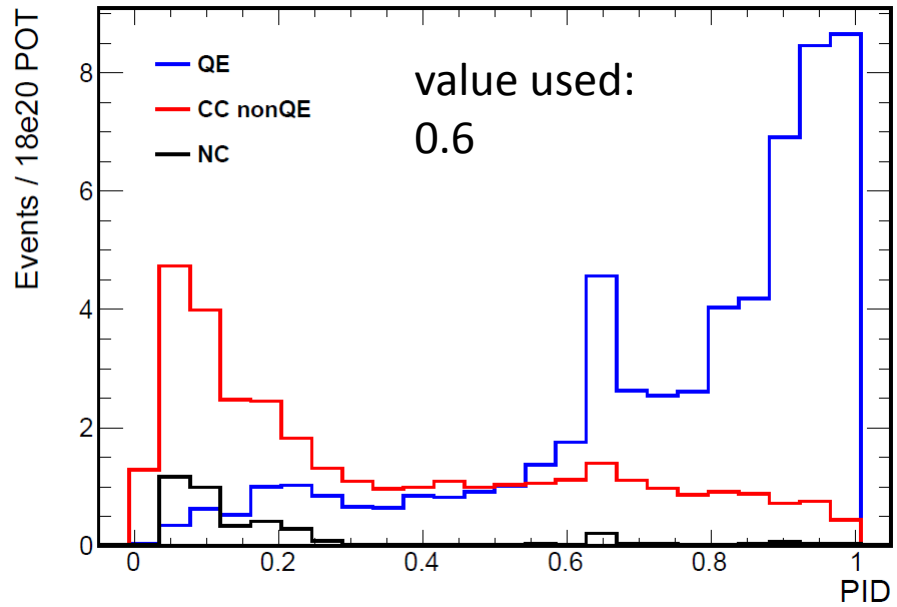
value used for this talk: 0.55

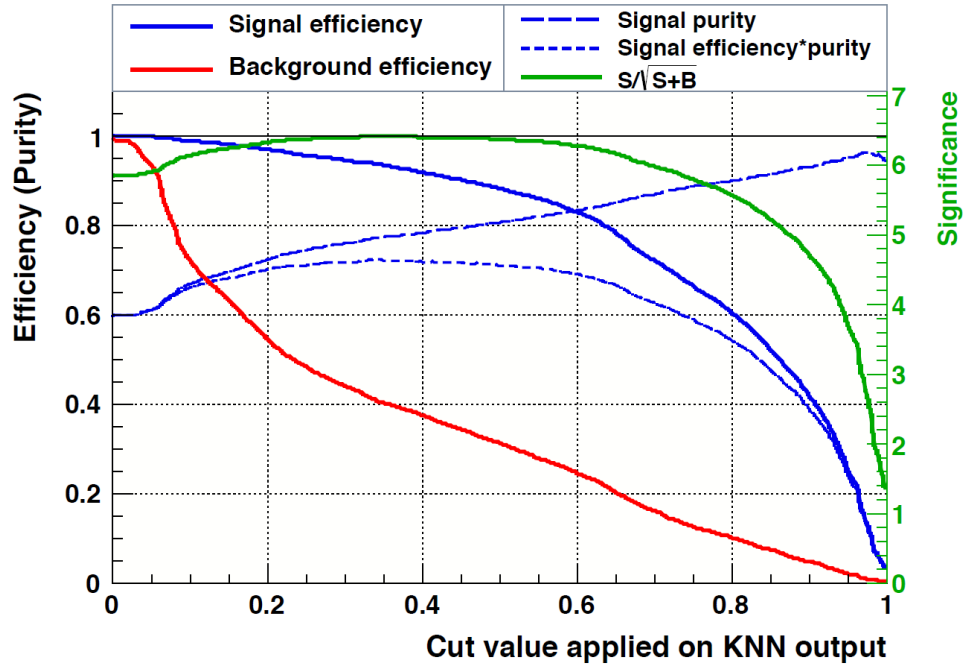




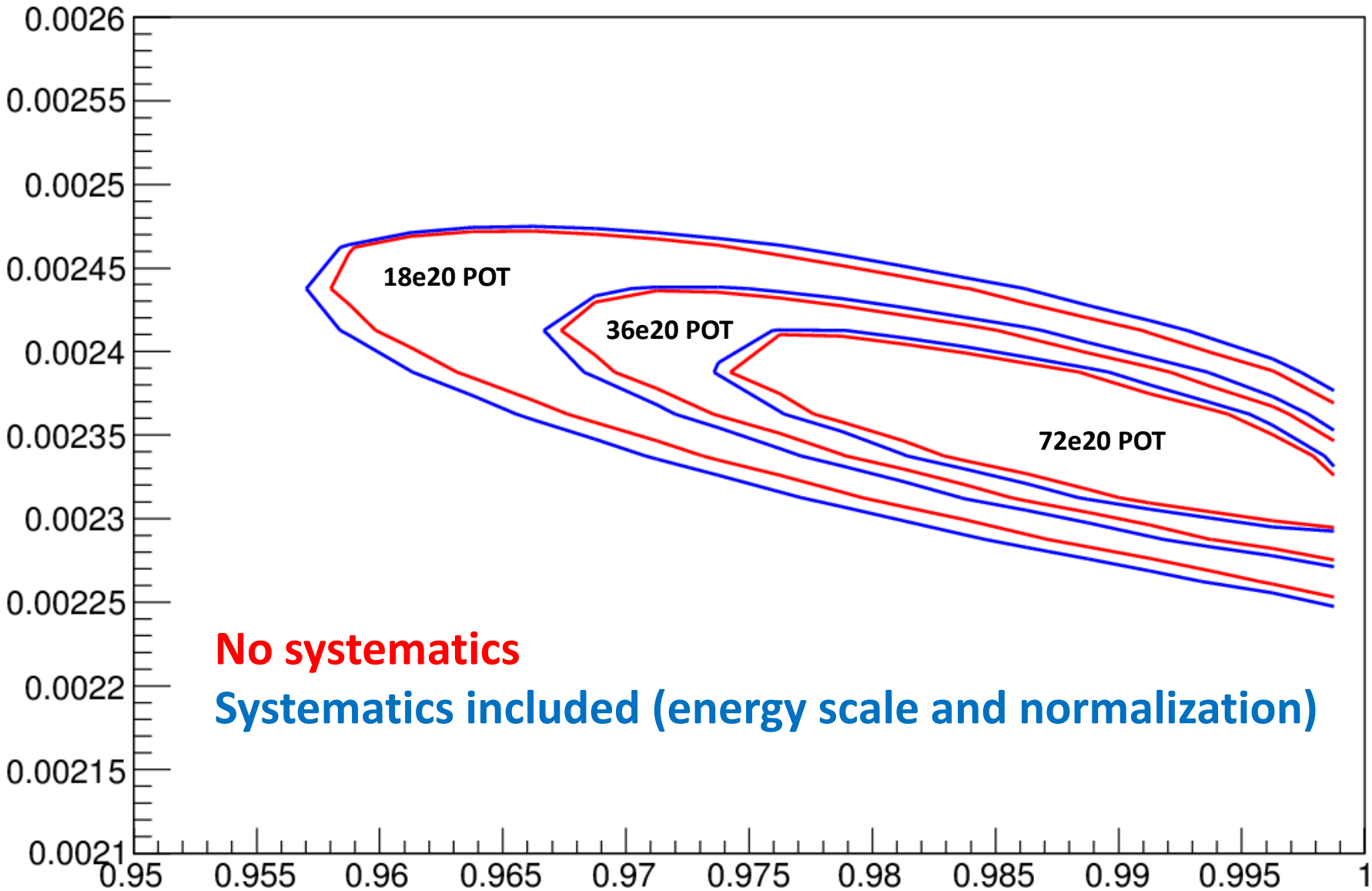
QE PID details

- kNN based
- variables include:
  - amount of E not in main track
  - dE/dx
  - difference in two different E estimators





Systematics



Containment

The detector dimension are roughly:

$-765 \text{ cm} < x < 765 \text{ cm}$

$-765 \text{ cm} < y < 765 \text{ cm}$

$0 < z < 5960 \text{ cm}$

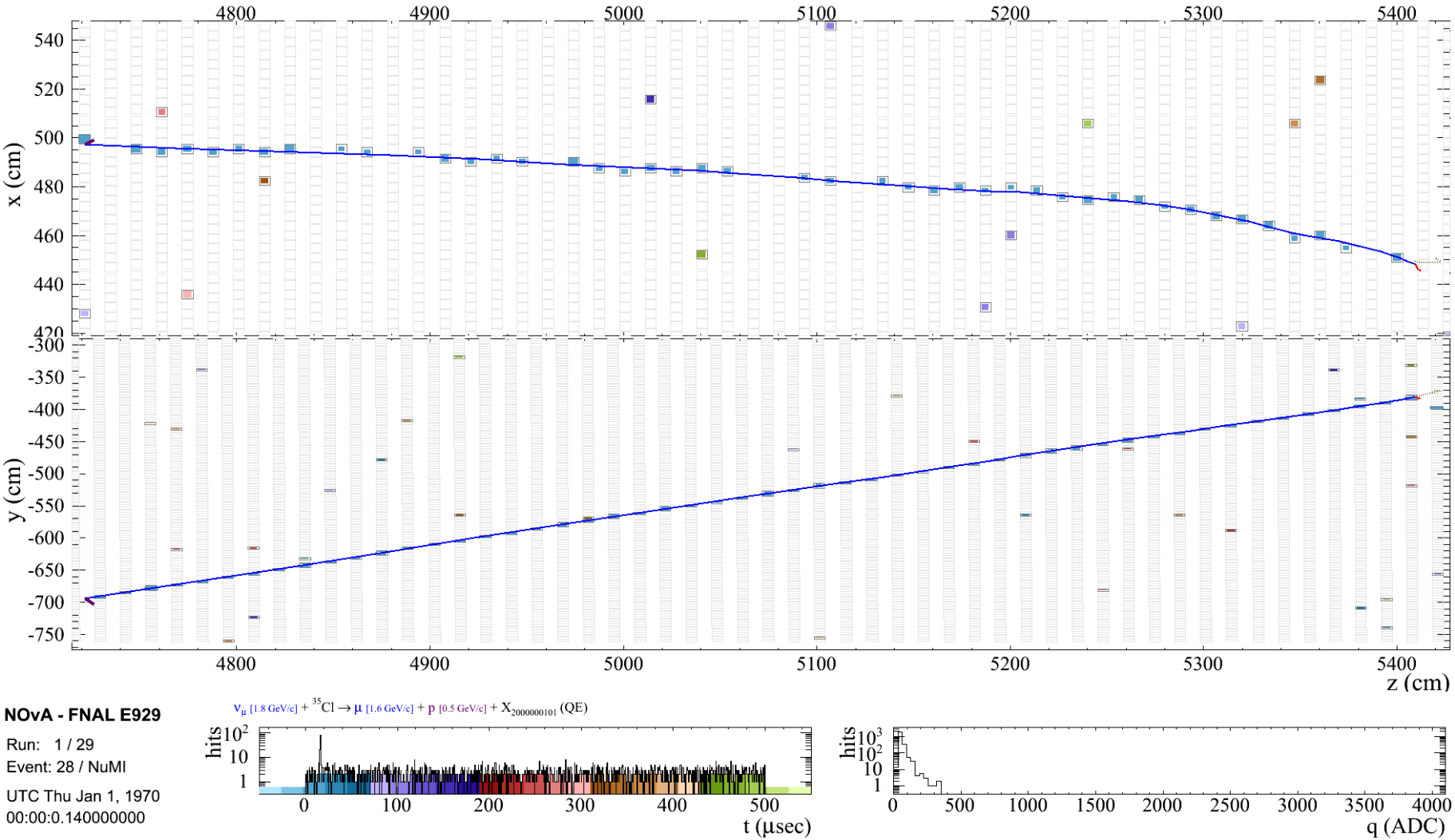
The containment cut used requires all activity in the slice (events clustered in time) be:

$-750 < x < 750$

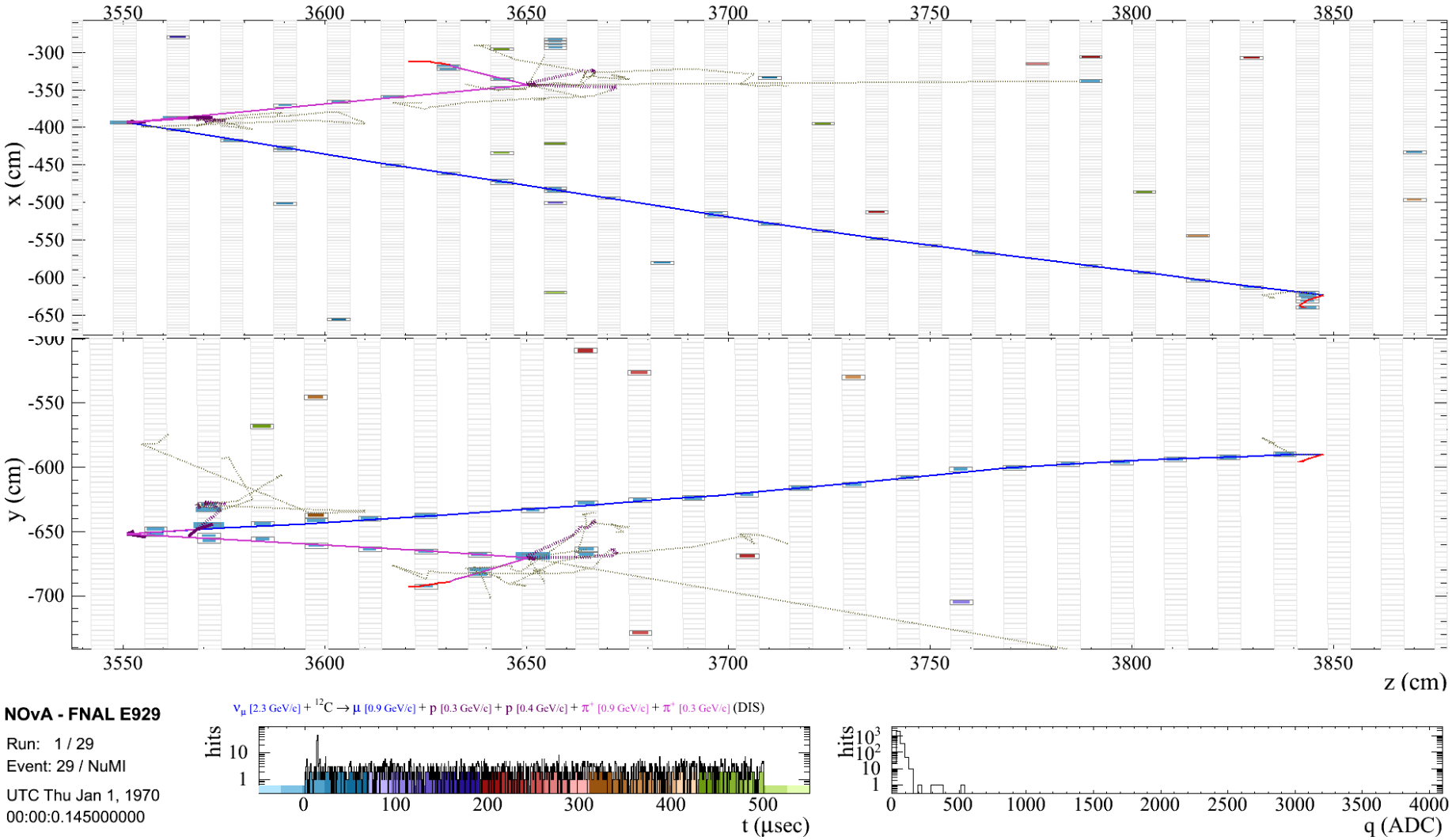
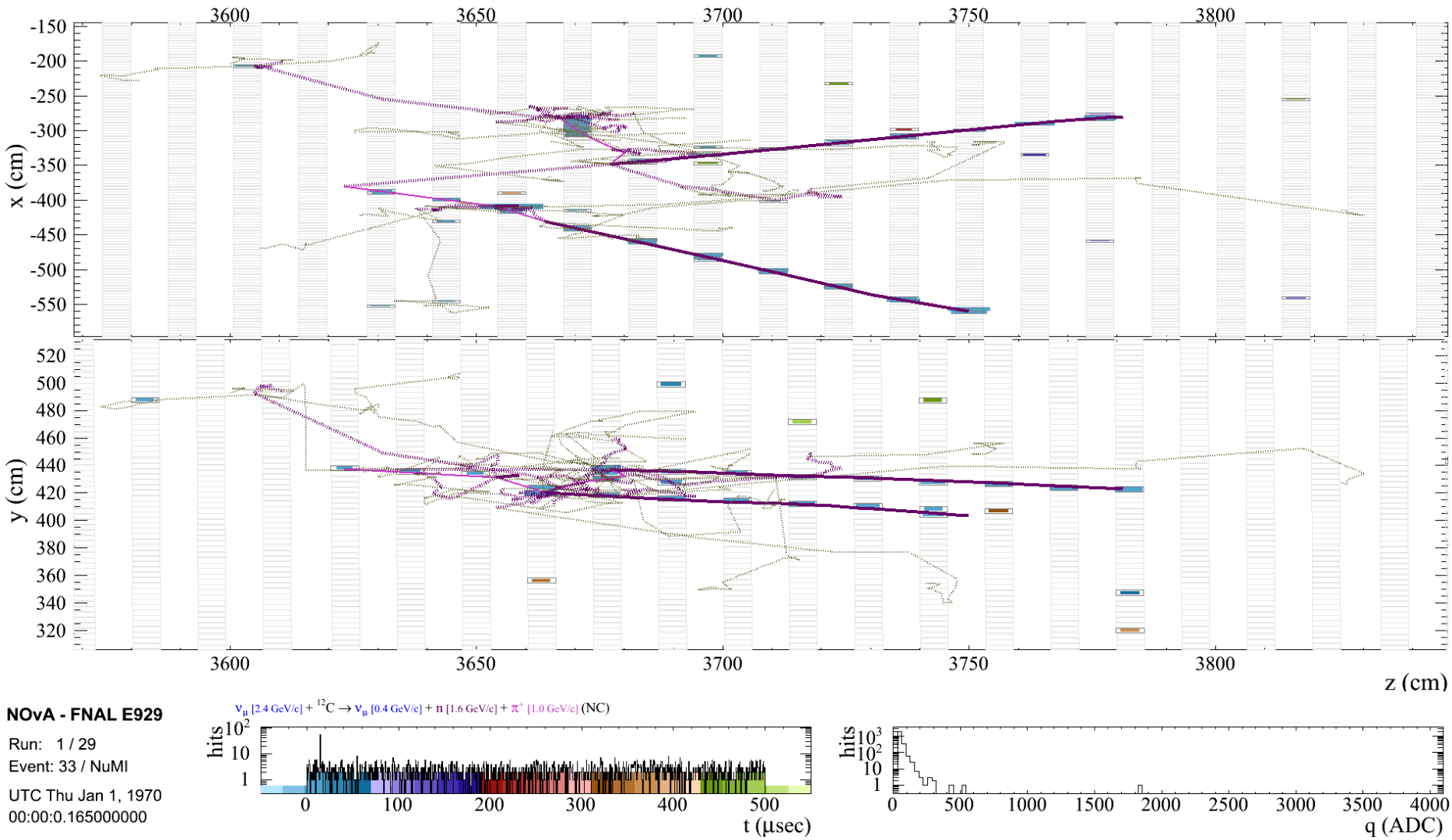
$-750 < y < 750$

$5 < z < 5950$

Example QE event display - almost all of the energy goes into the muon



Example DIS – energy goes to muon and pions



Example NC event – No muon, big mess