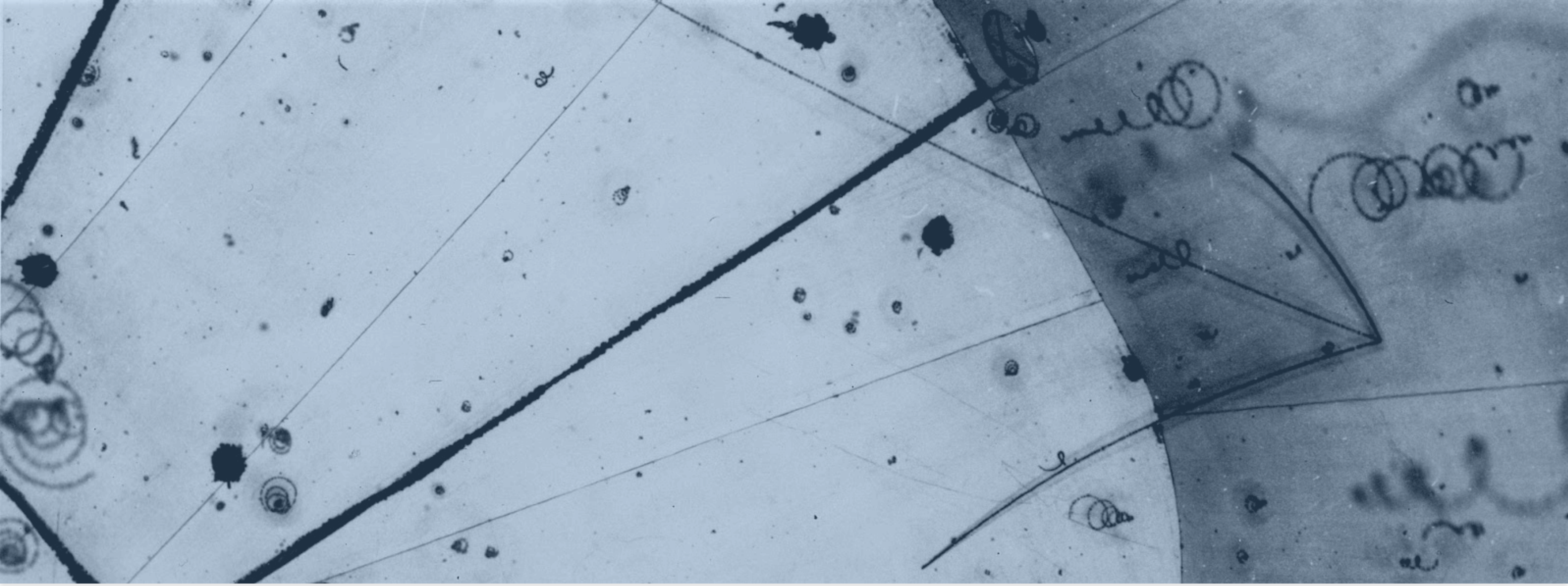

Latest Muon Neutrino Disappearance Results From The NOvA Experiment

Diana Patricia Méndez Méndez
University of Sussex
For the NOvA Collaboration

IOP Meeting | Bristol, UK | March 26th 2018

The NOvA Experiment

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Neutrino oscillation experiment

- ν_μ disapperance ($\nu_\mu \rightarrow \nu_\mu$)
- ν_e appearance ($\nu_\mu \rightarrow \nu_e$)

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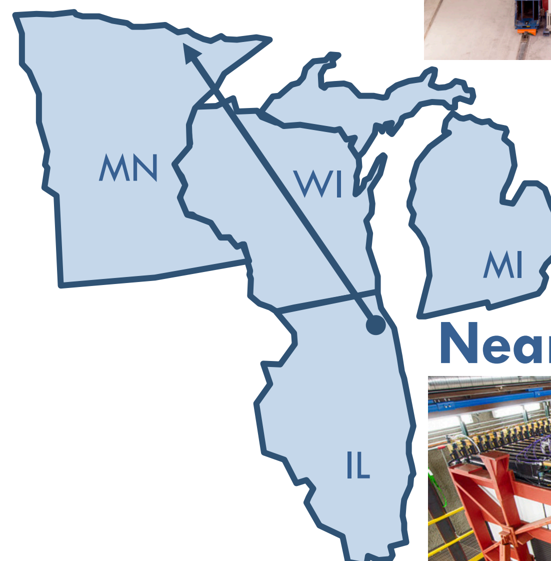
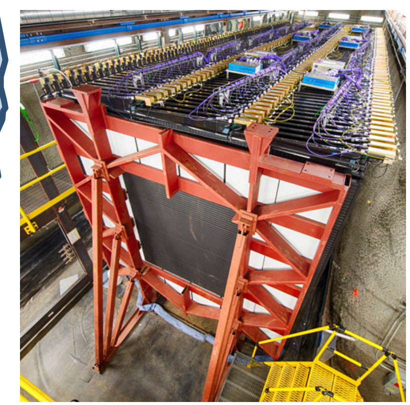
Two detectors separated by 810 km

- Near detector 300 Tons, underground
- Far detector 14 kTons, on the surface

Far Detector



Near Detector



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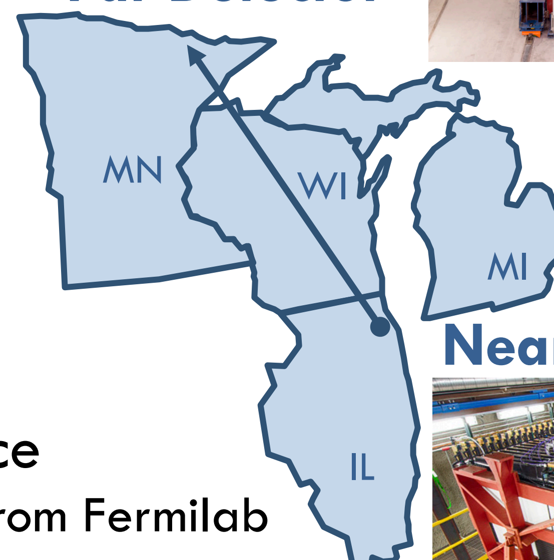

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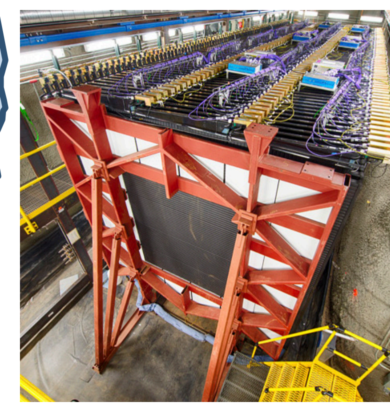

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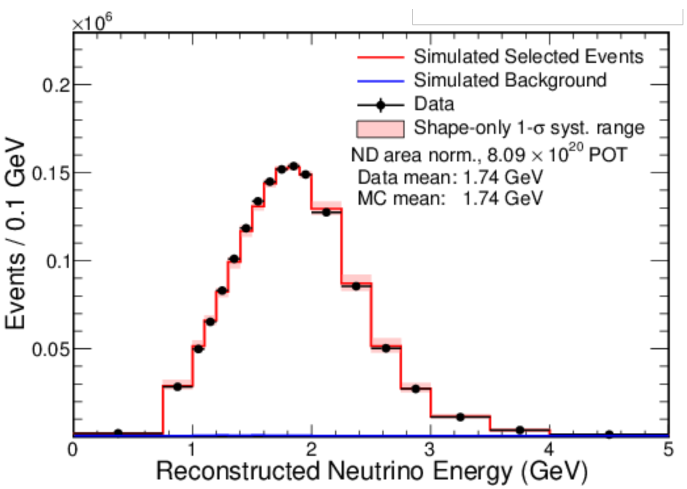

Neutrino source

- NuMI beam from Fermilab
- 14 mrad off-axis
- Narrow energy spectrum, peak ~ 2 GeV

Muon Neutrino Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right)$$

2 flavour approximation

Far Detector

L = 810 km

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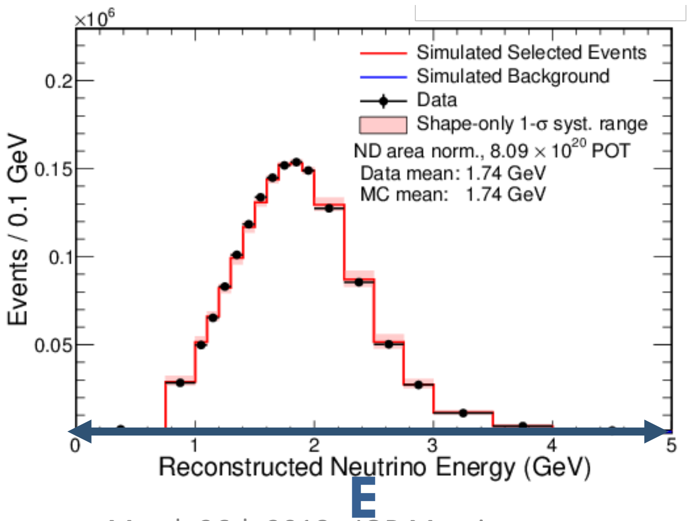

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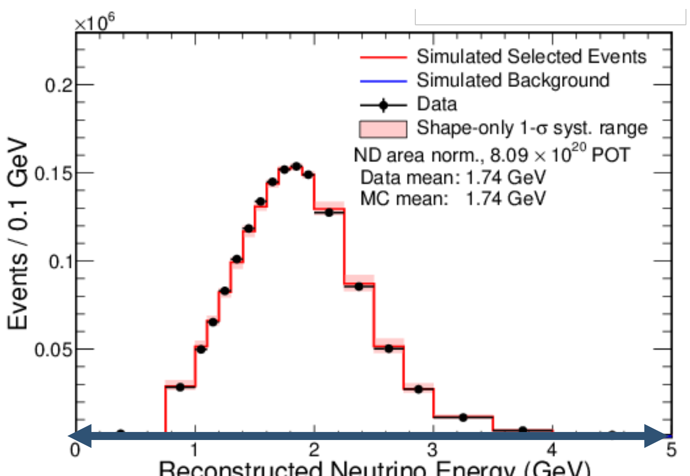
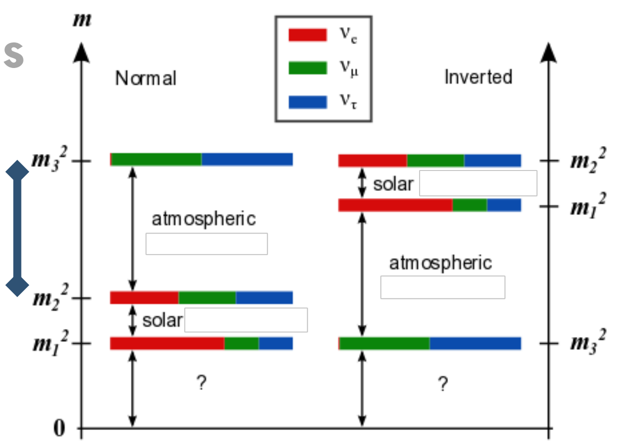


E

Squared mass difference

Δm^2_{32}



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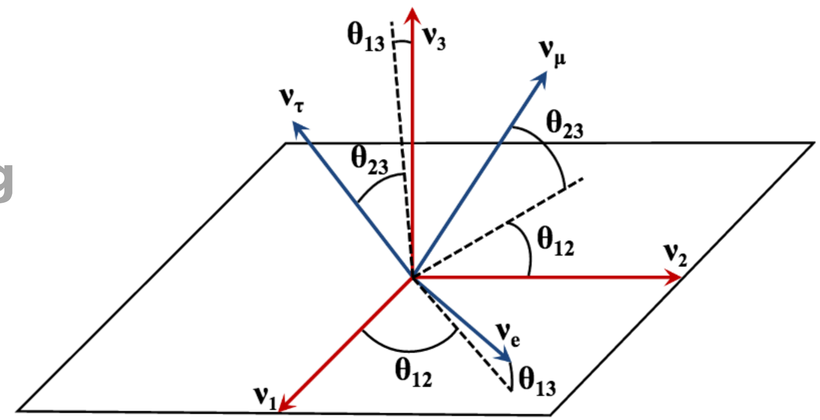
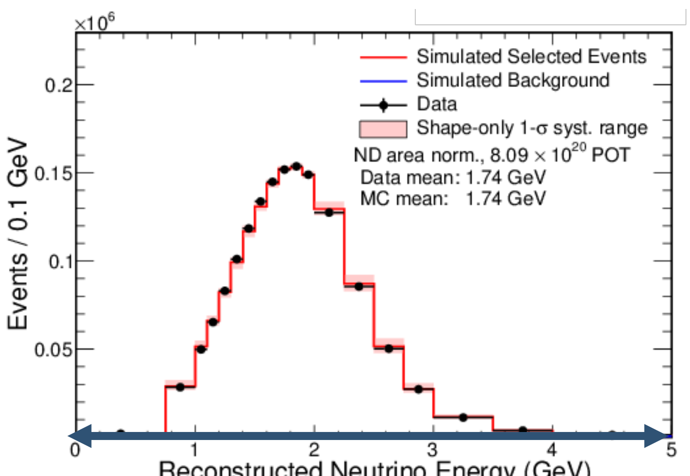
Near Detector

Mixing

θ_{23}





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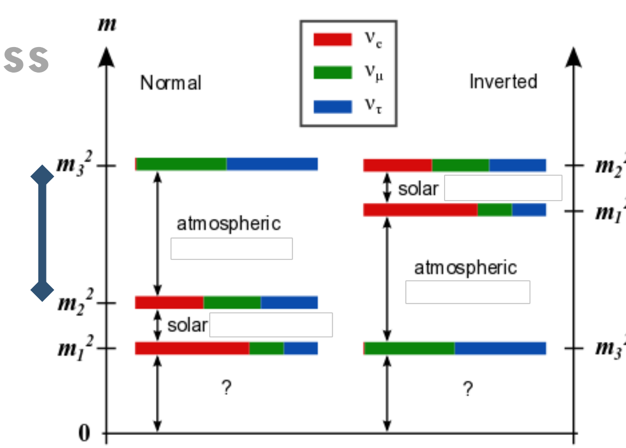
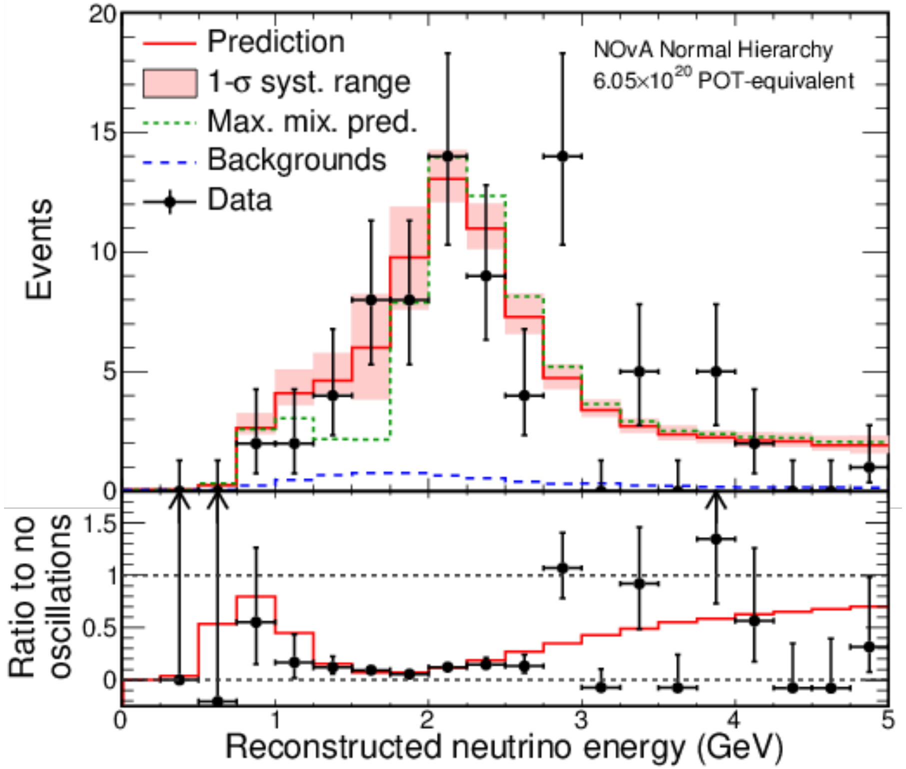
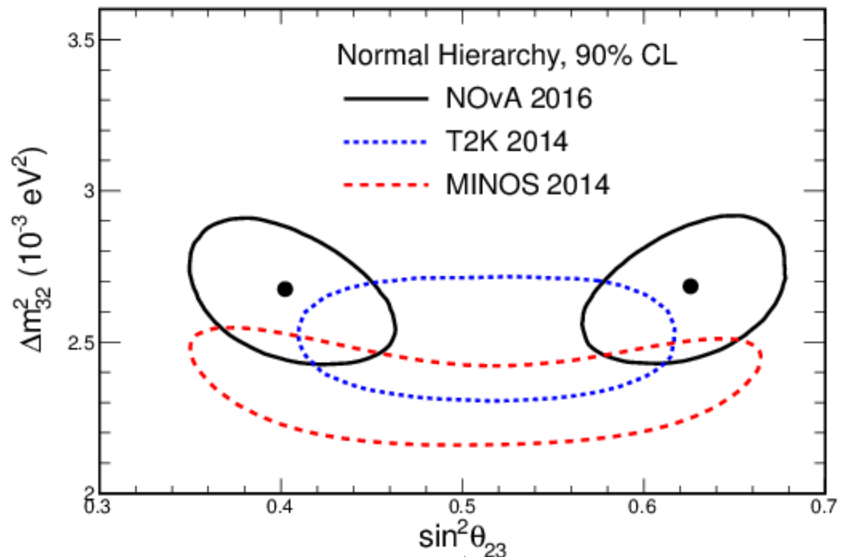


2017 Results

Phys.Rev.Lett. 118, 151802 (2017)





Maximum mixing disfavoured by 2.6 σ

Clear ν_μ disappearance

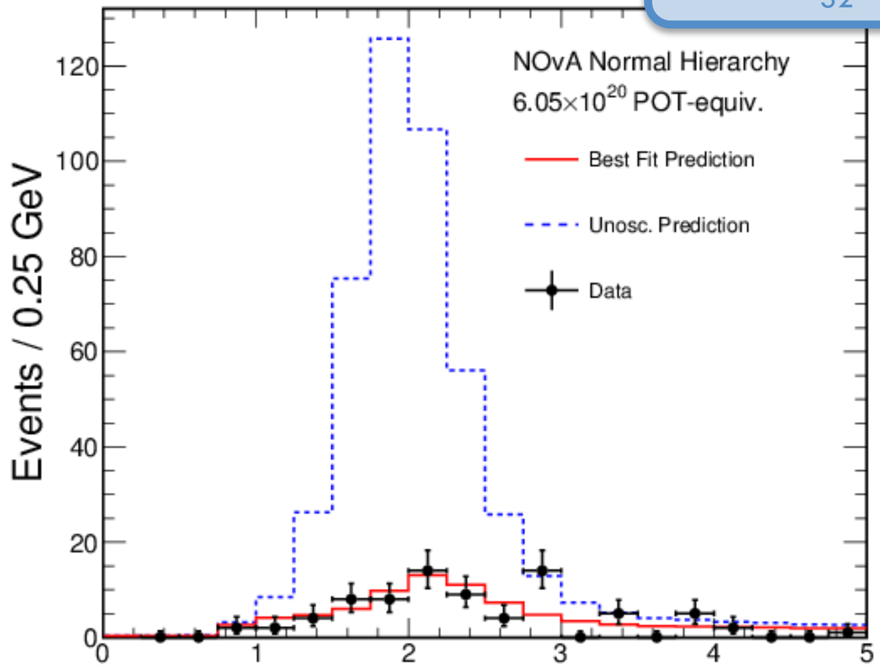
- 473 expected events without oscillations
- 78 observed events in the far detector
- 82 expected events at best fit

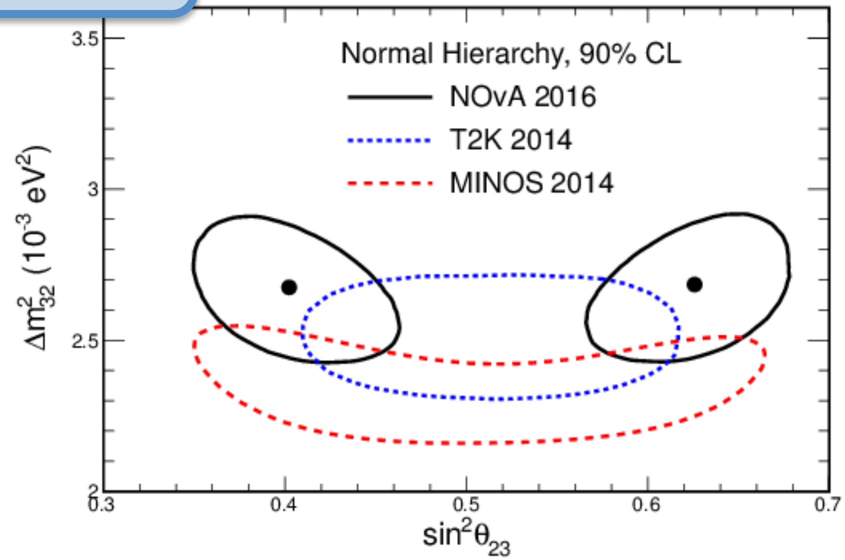
Oscillation parameters

- $\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\ \text{eV}^2$
- $\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}$, $0.624^{+0.022}_{-0.030}$

Improving the Disappearance Analysis

Improve sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$





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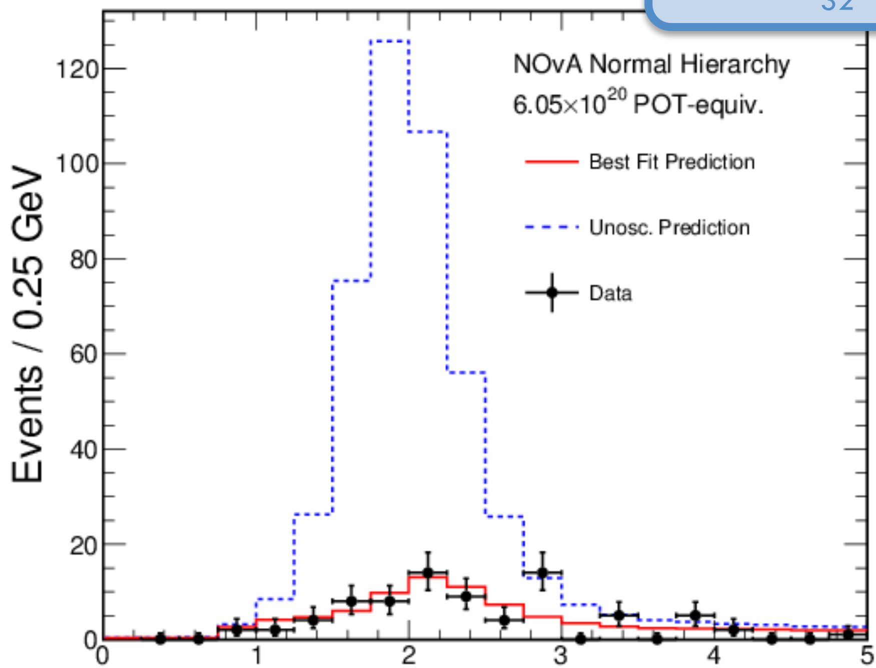
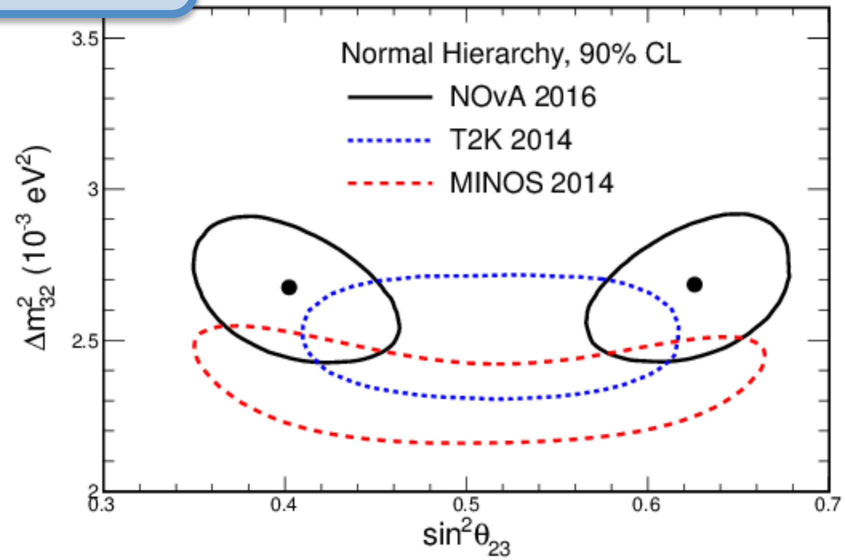


Focus on maximum disappearance region



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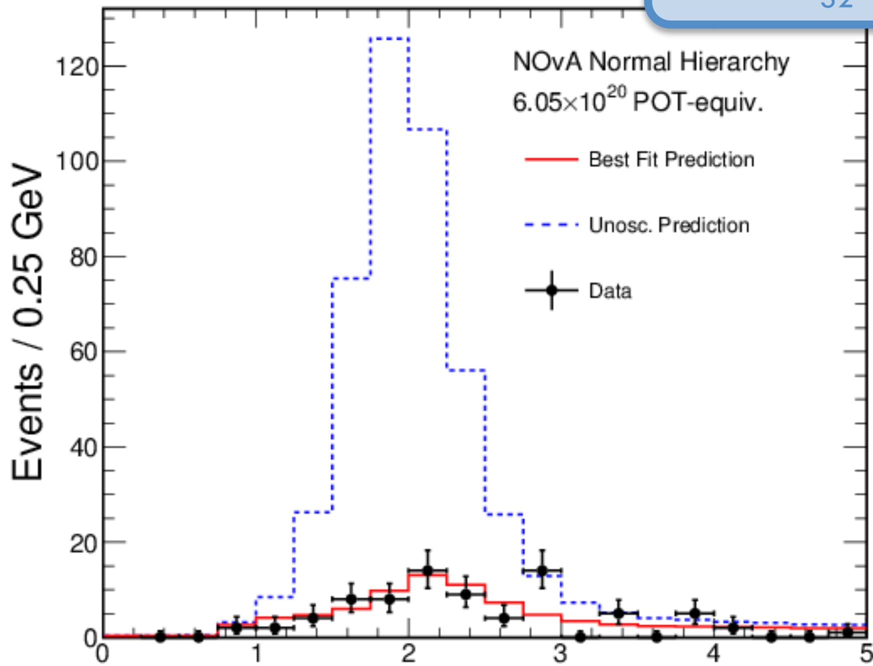

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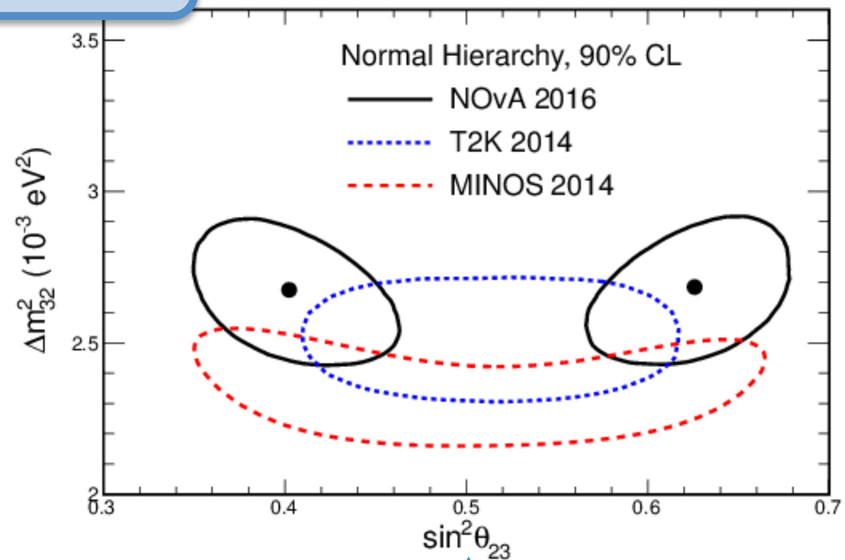

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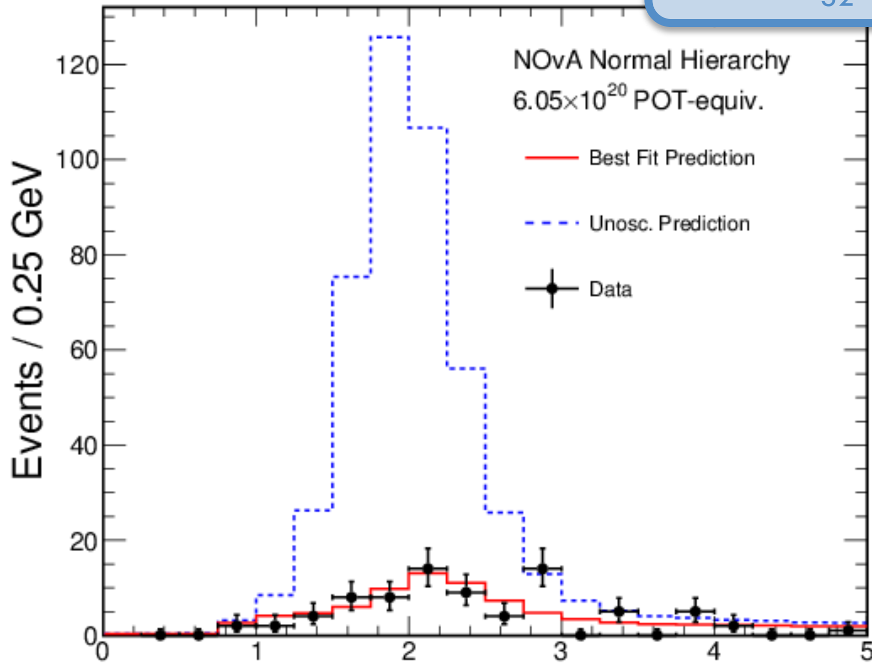
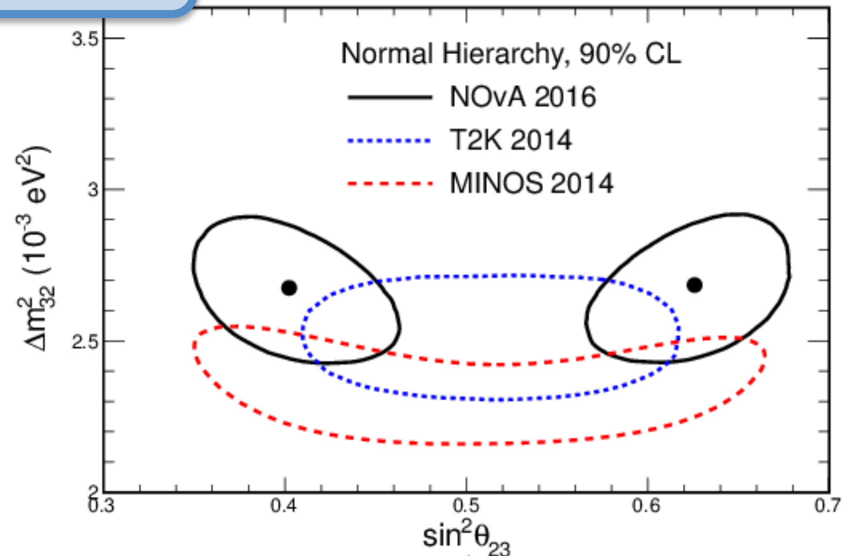




Focus on maximum disappearance region

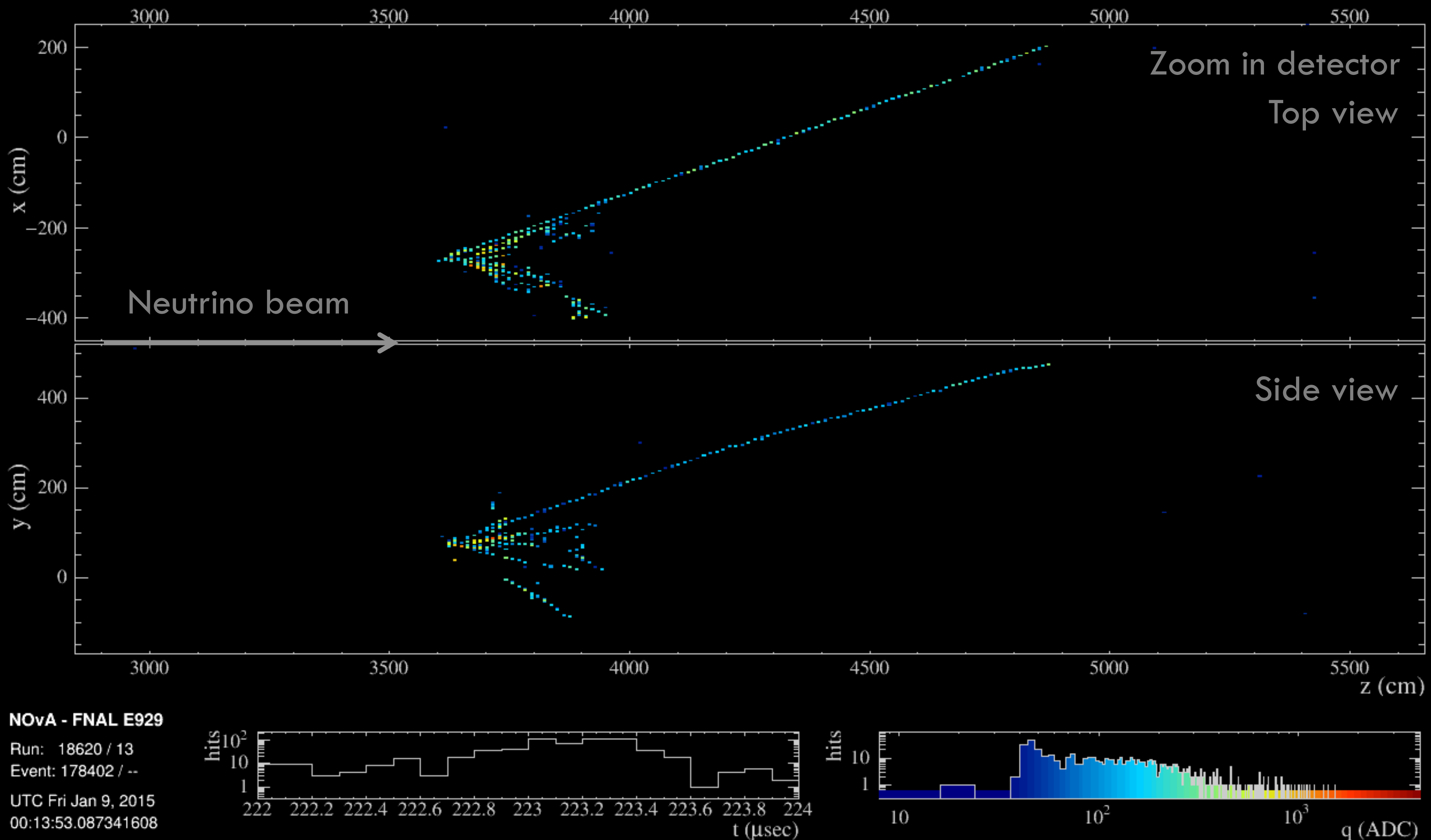
Increase sensitivity to mixing angle

- 6e20 POT

3 main analysis improvements:

- Separate neutrino events into bins of resolution
- Hybrid of two selection algorithms
- Finer energy binning around maximum oscillation

Energy Reconstruction



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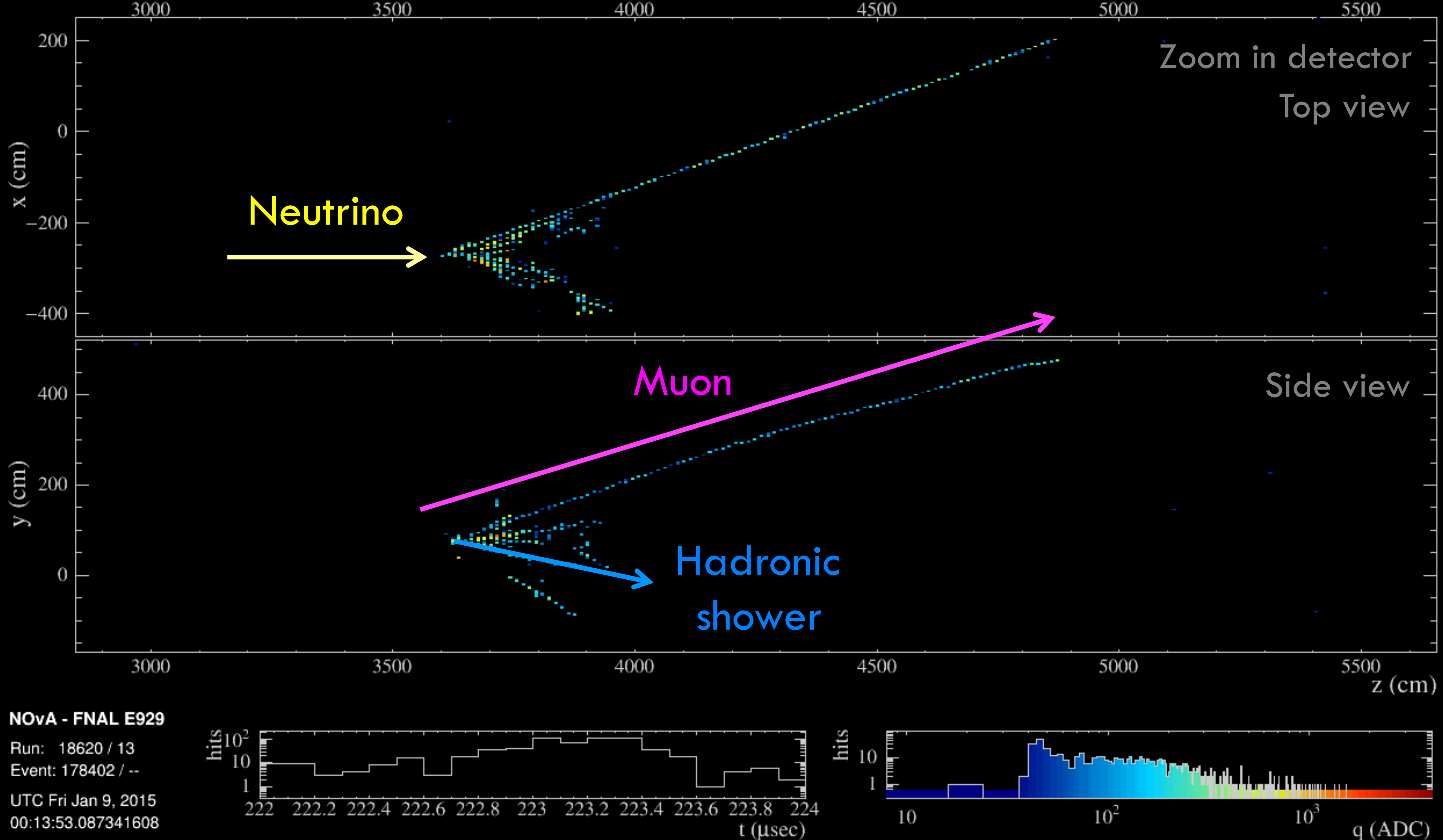

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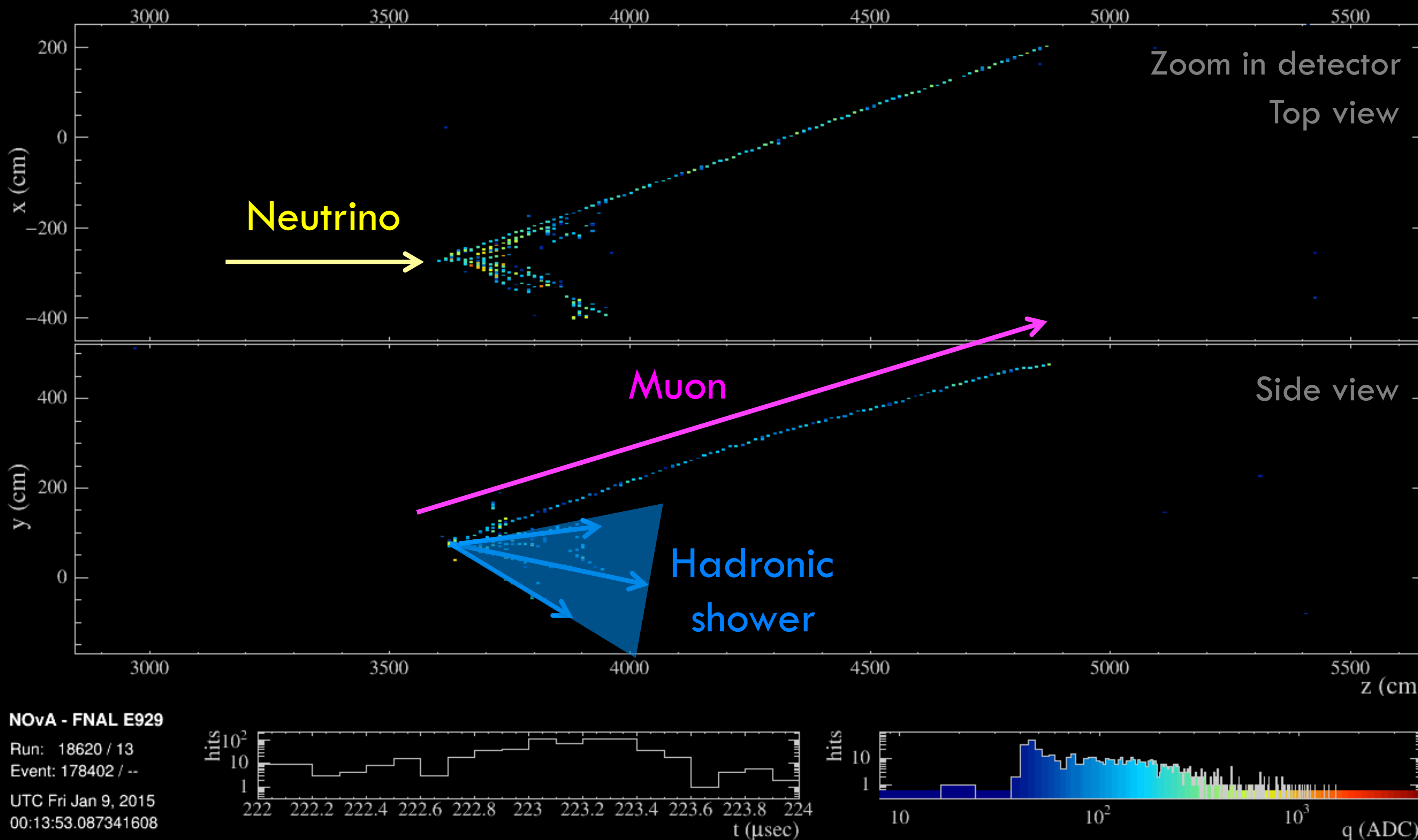

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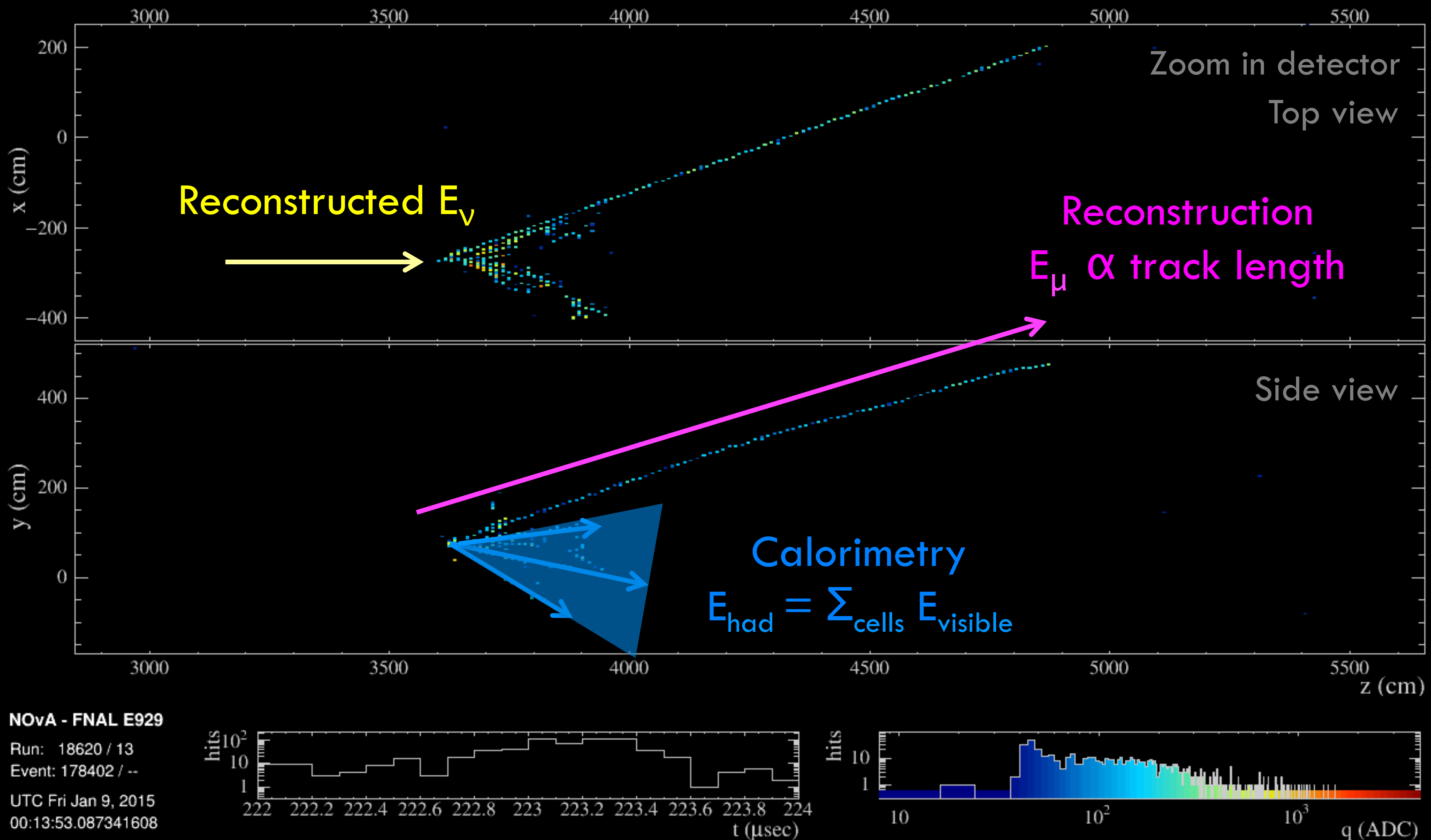

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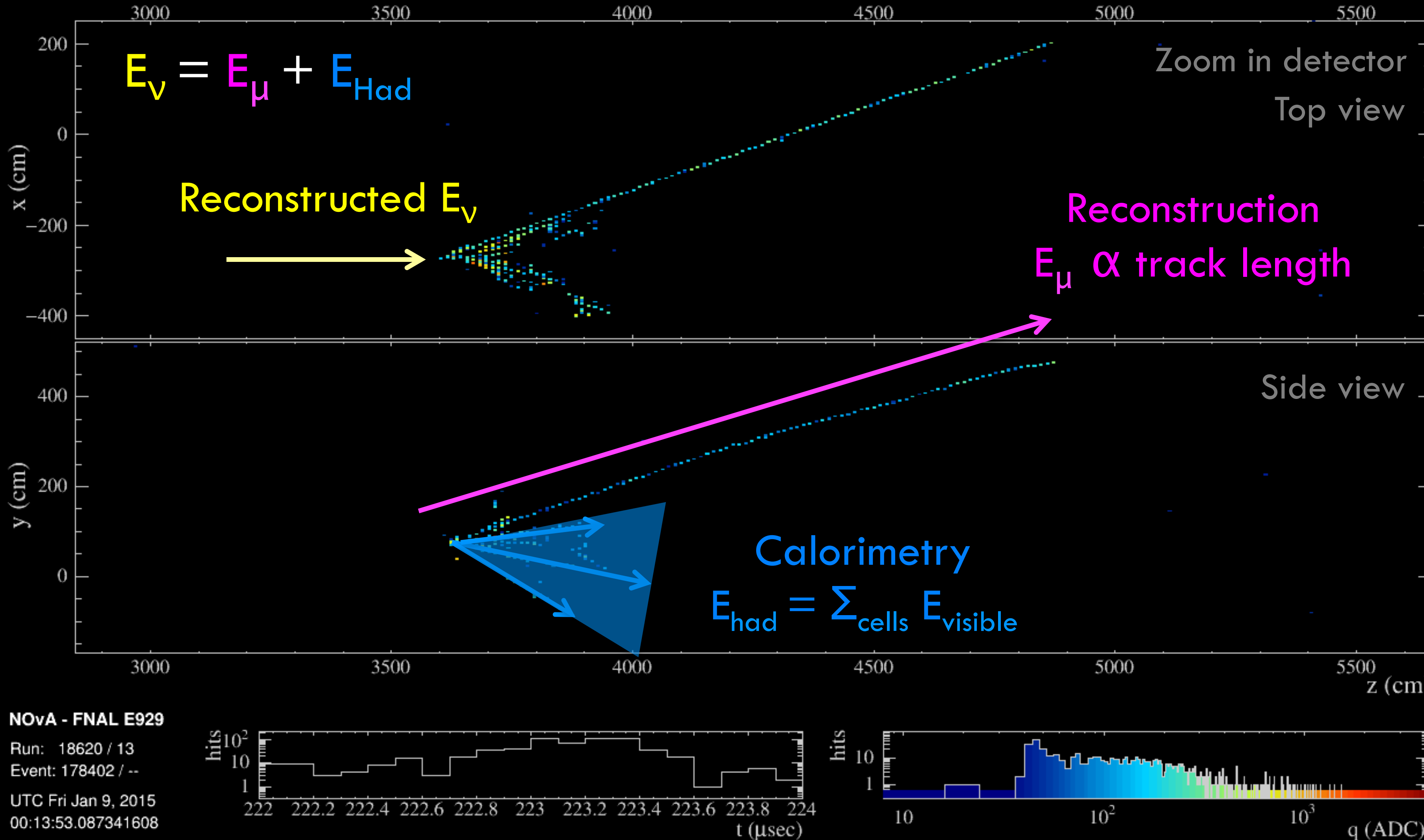

Energy Resolution

$E_\nu = E_\mu + E_{had}$ → Neutrino energy resolution = E_{Had}/E_ν

Mean resolution:

- Muon energy = 3.5 %
- Hadronic energy = 40%
- Neutrino energy = 9%

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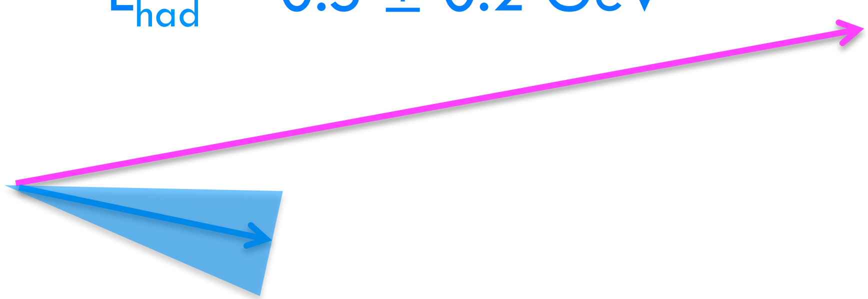
Hadronic fraction = 0.25
→ Uncertainty = 10.0%

$E_\mu = 1.5 \pm 0.06$ GeV

$E_{had} = 0.5 \pm 0.2$ GeV



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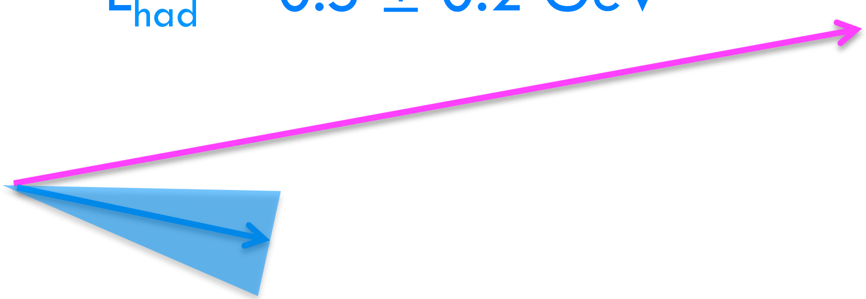
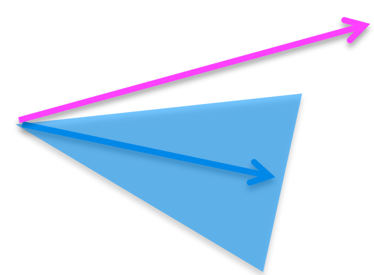


Hadronic fraction = 0.75
→ Uncertainty = 30%

$E_\mu = 0.5 \pm 0.018$ GeV

$E_{had} = 1.5 \pm 0.6$ GeV



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Separate well resolved energies by quantiles of hadronic energy fraction

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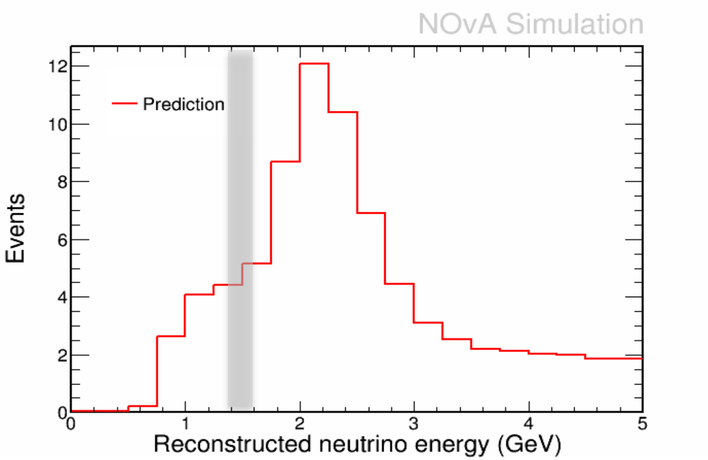

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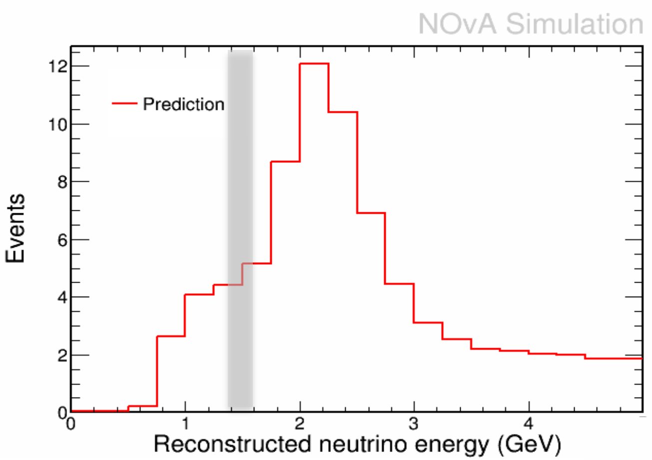
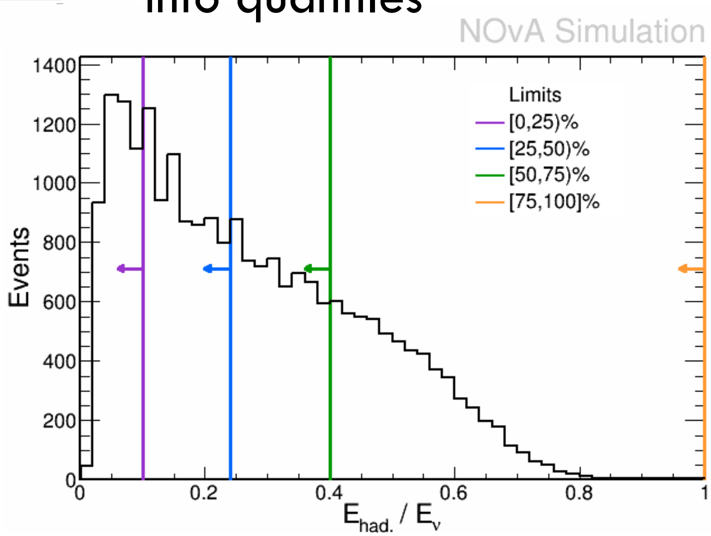


1. Take an energy bin

2. Make a distribution of E_{had}/E_ν and divide into quantiles



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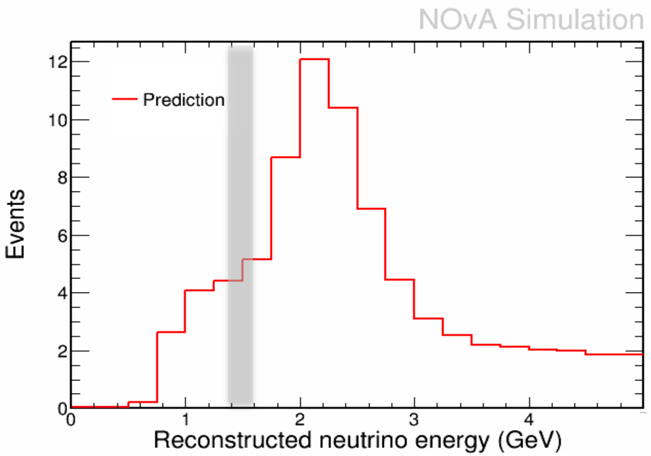

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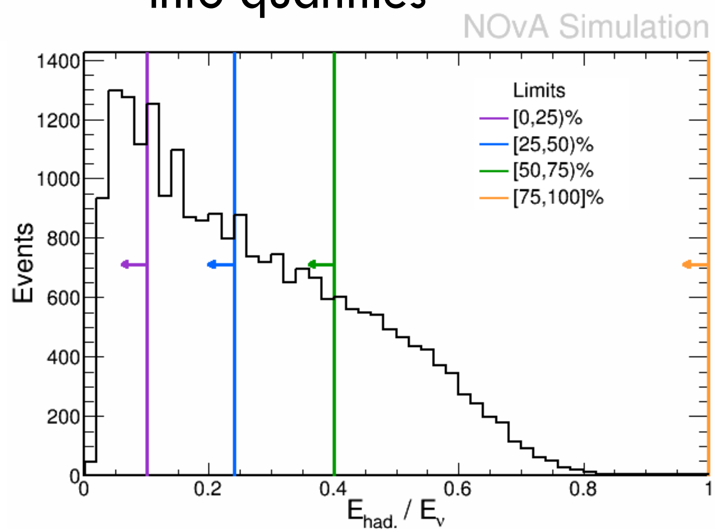
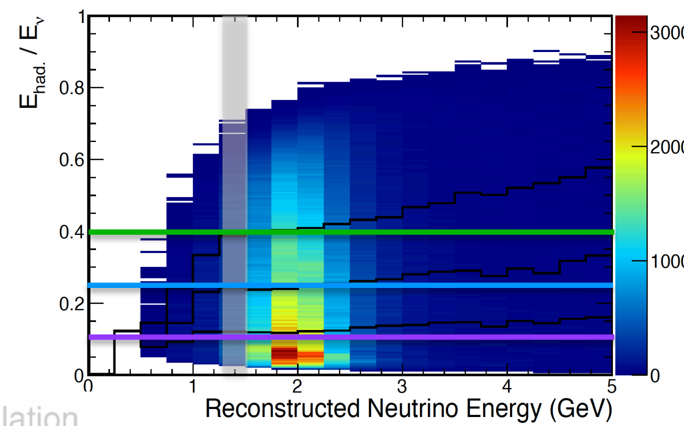


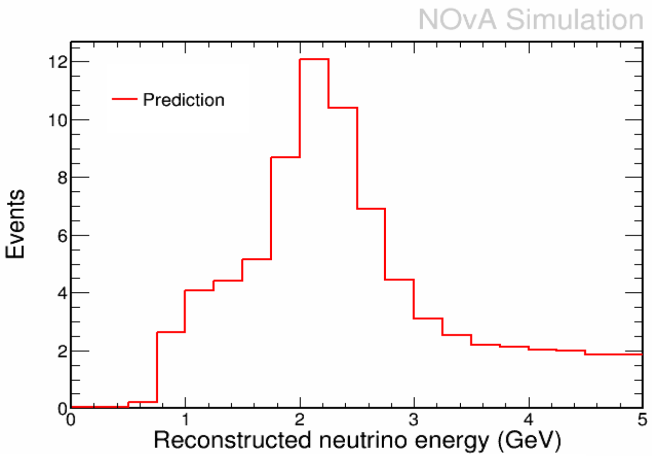


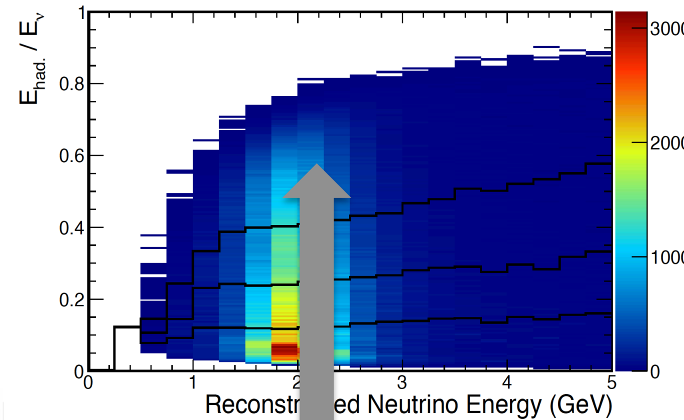
3. Find boundaries to divide the sample evenly

Energy Resolution

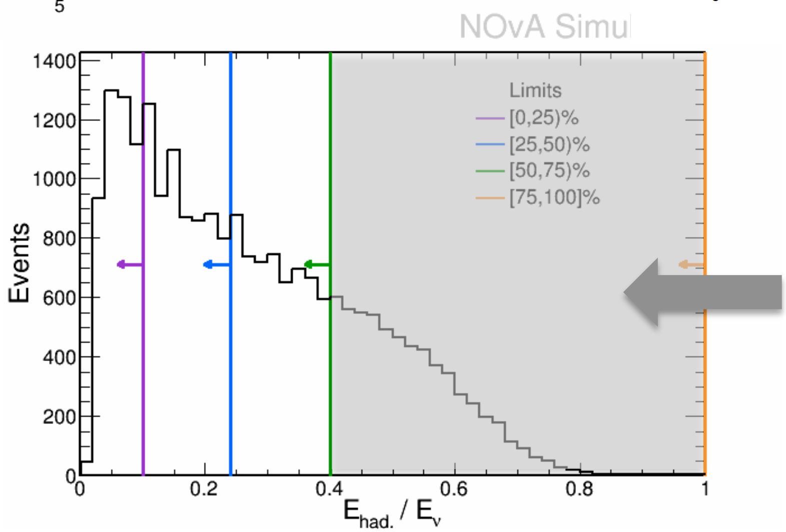
$$E_\nu = E_\mu + E_{had} \rightarrow \text{Neutrino energy resolution} = E_{Had}/E_\nu$$

Separate well resolved energies by quantiles of hadronic energy fraction





Largest **background** in the **worst energy resolution bin** (highest hadronic energy quantile).



Cosmics

NC

Particle identification

Hybrid of two selection algorithms

(and retuned cosmic BDT) background rejection with 11% more selected signal

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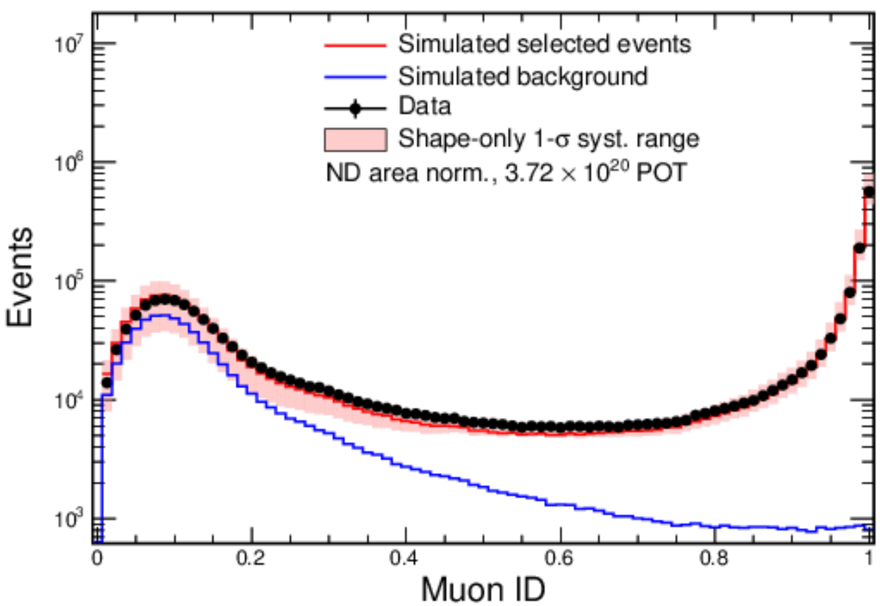
Reconstructed Muon Identification



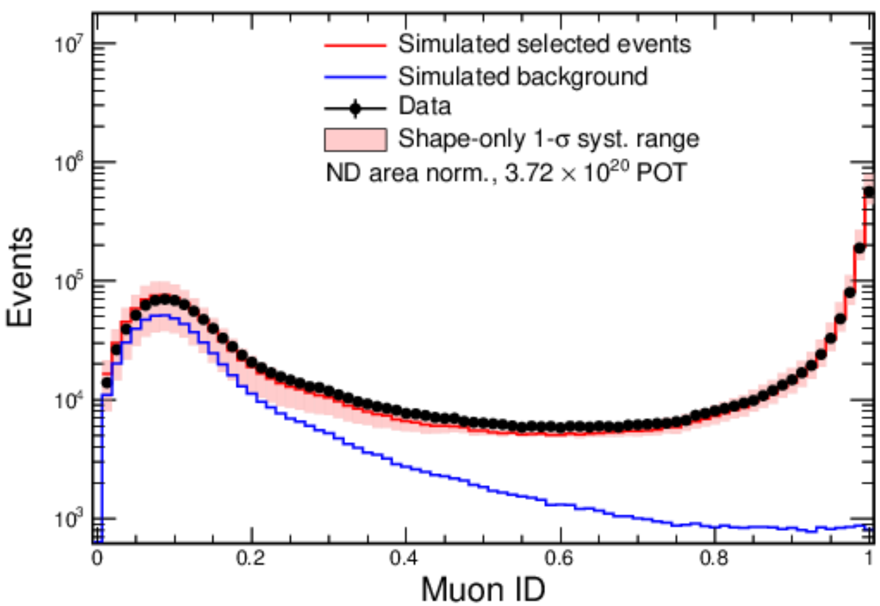
Particle identification

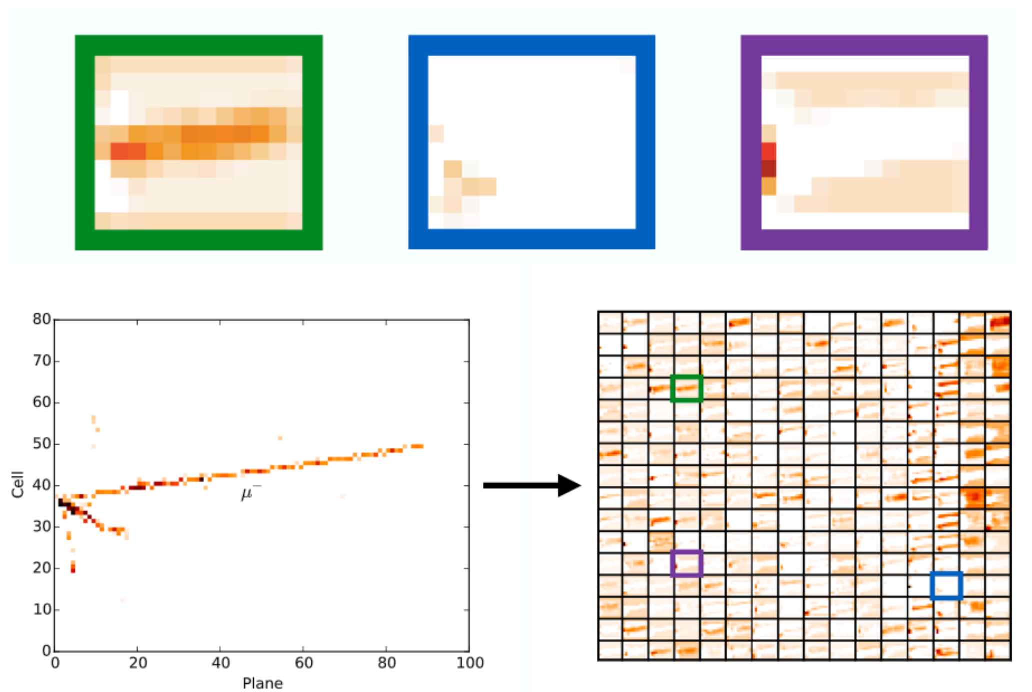
2

Hybrid of two selection algorithms

(and retuned cosmic BDT) background rejection with 11% more selected signal

Reconstructed Muon Identification + Convolusional Visual Network





Particle identification

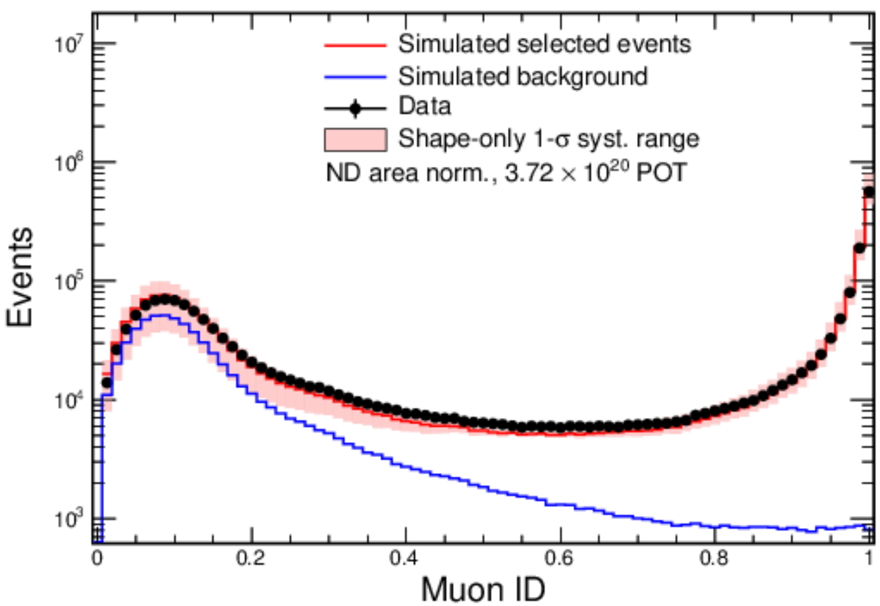
ReMId good at identifying muon tracks. kNN (k-Nearest Neighbour) with

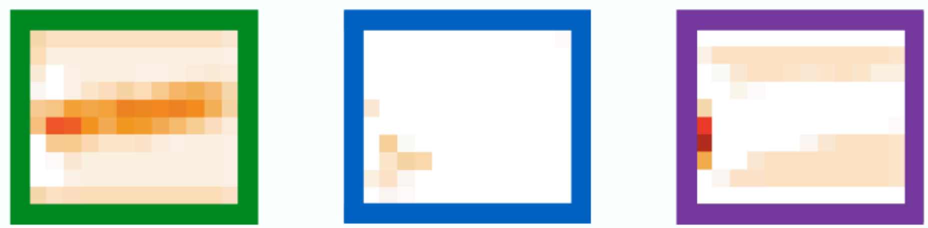
- Track length
- dE/dx
- Scattering
- Plane fraction

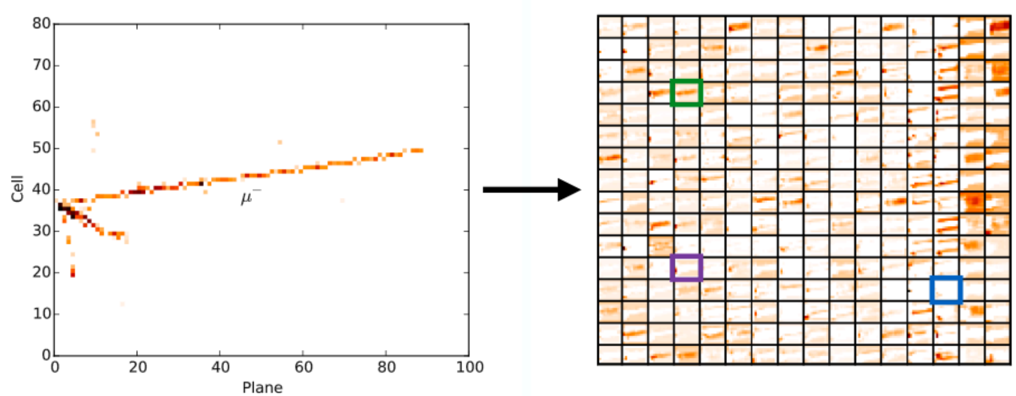
+

CVN More advanced algorithm to separate NuE-CC and NC

- Based on CNN (Convolutional Neural Networks)
- Treats events as images
- Extracts features







Energy Binning

3

Finer binning around the maximum oscillation region enhances the sensitivity of the analysis

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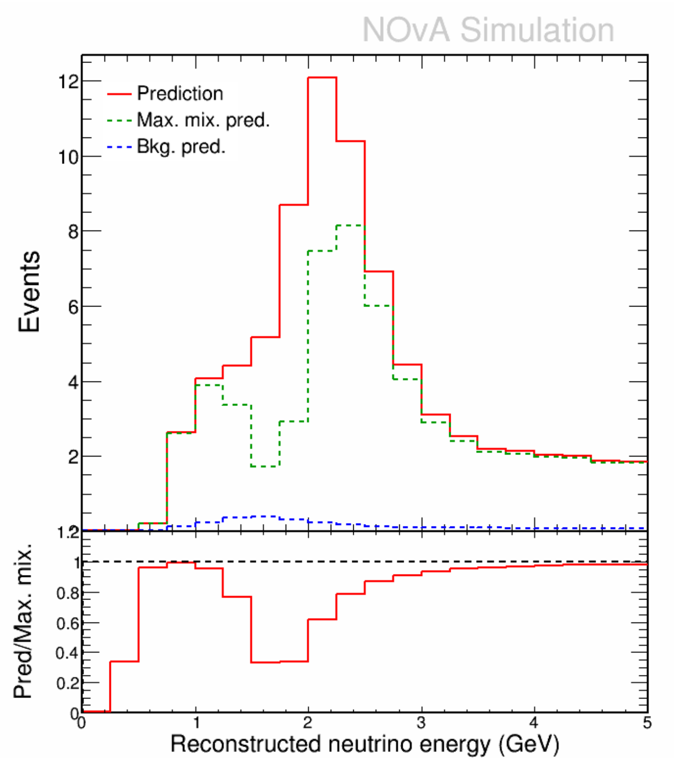
NOvA 2017 binning

Standard energy binning:
20 bins of 0.25 GeV each



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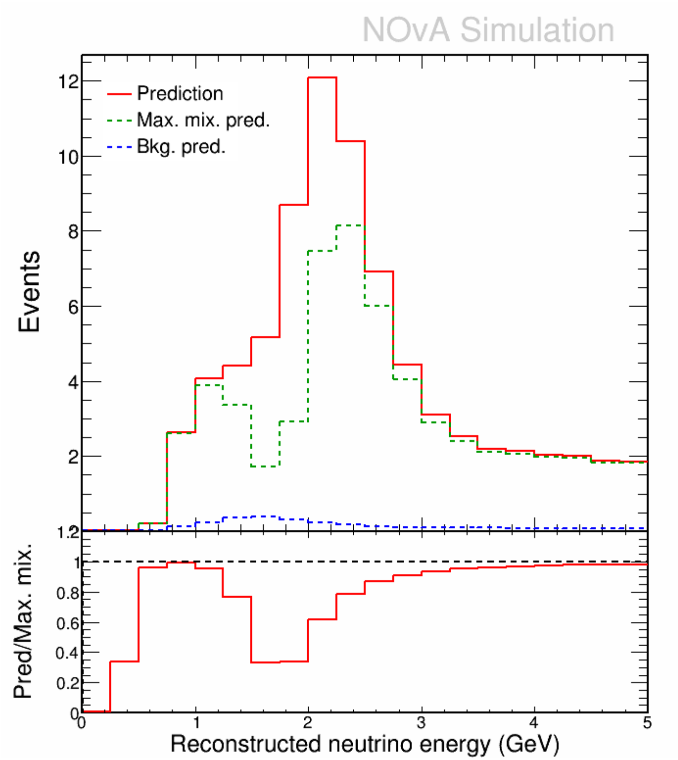
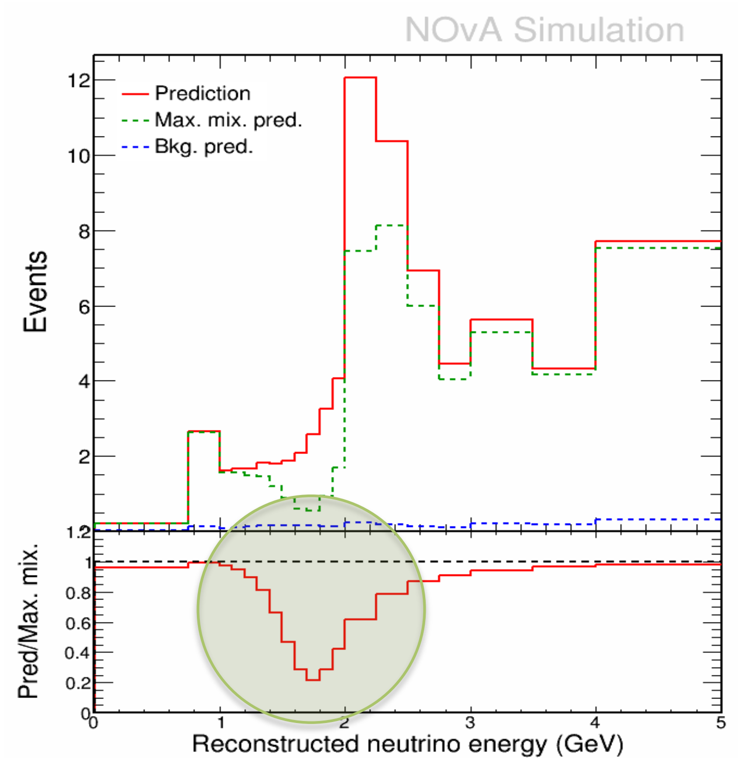


Optimised binning

Increased bin number between 1 and 2 GeV



Improving the Disappearance Analysis

- 3 analysis improvements +

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  50% more than the previous analysis, from $6x10^{20}$ POT to ~$9x10^{20}$ POT

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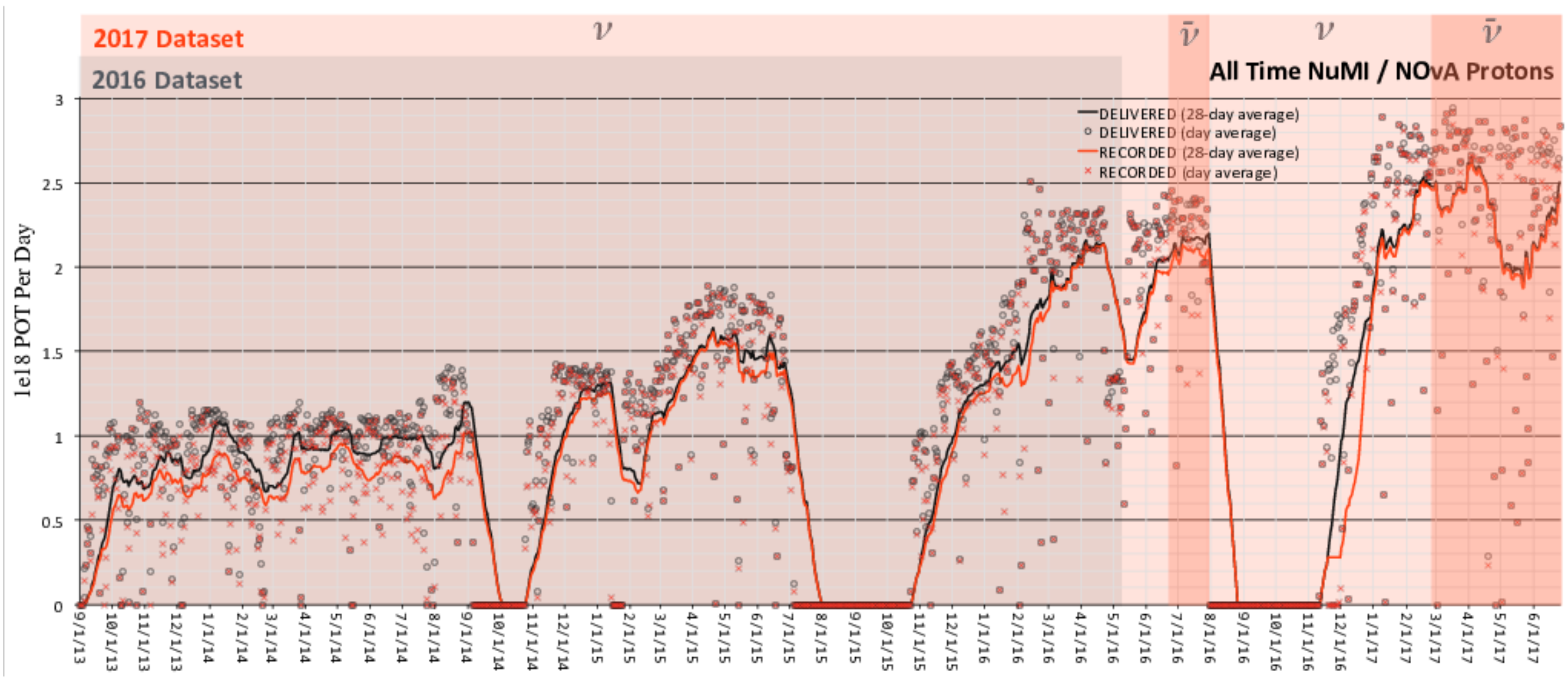
Fermilab's NuMI beam, world's most powerful at 700kW



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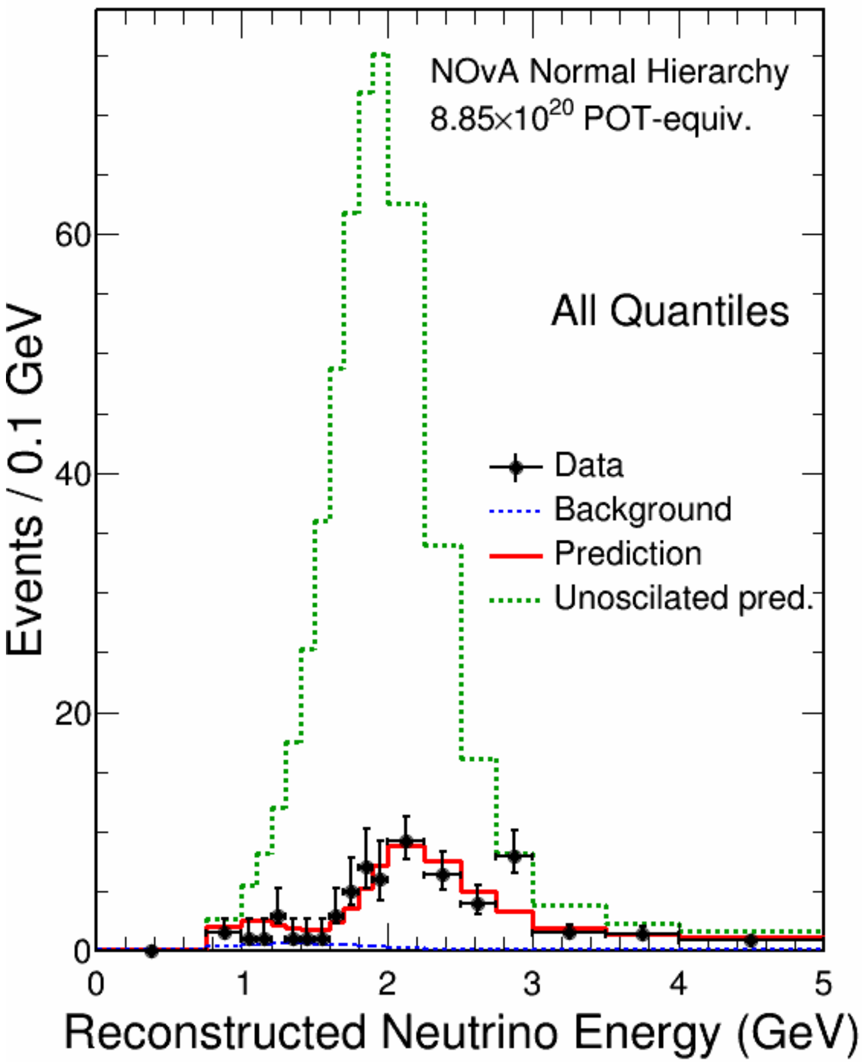
    Fermilab's NuMI beam, world's most powerful at 700kW
  - Cross sections

    Retuned model for multi nucleon processes
  - Detector simulation
  - Flux

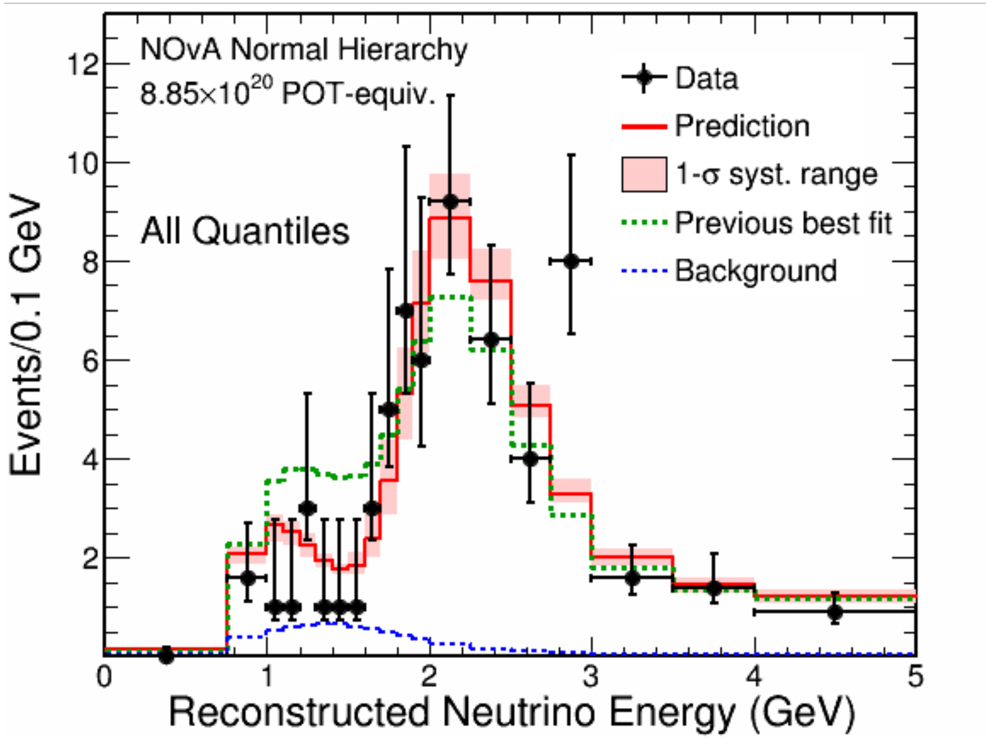
Muon Neutrino Disappearance Results with 8.85×10^{20} POT

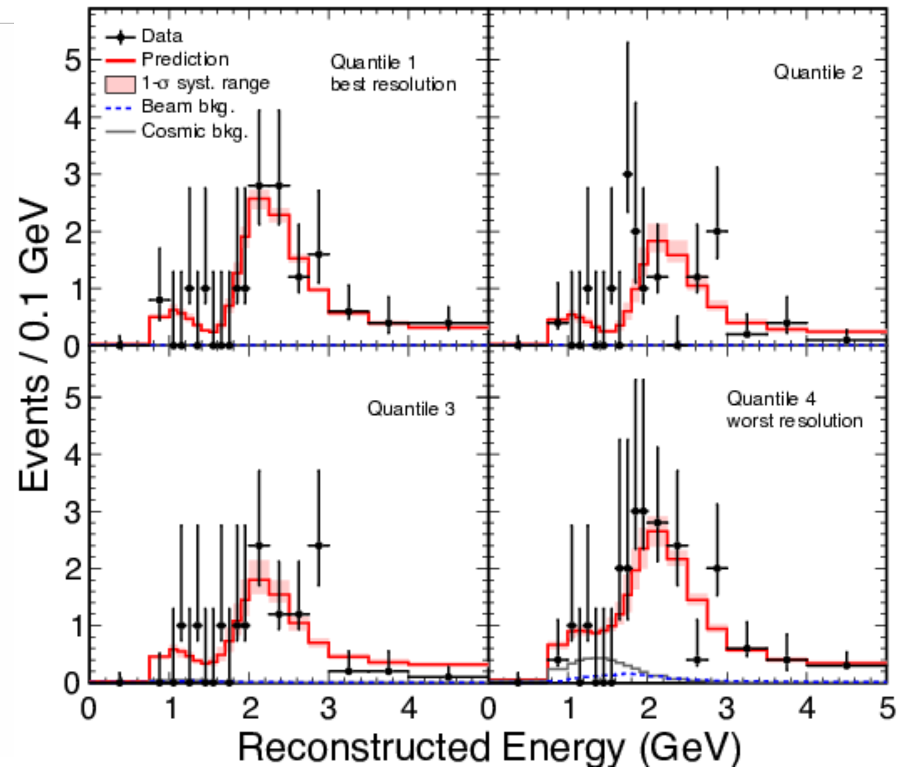
Muon Neutrino Disappearance
8.85×10^{20} POT



- 763 expected events without oscillations
- 126 observed events in the far detector
- 129 expected events at best fit

Muon Neutrino Disappearance
8.85×10^{20} POT





Muon Neutrino Disappearance
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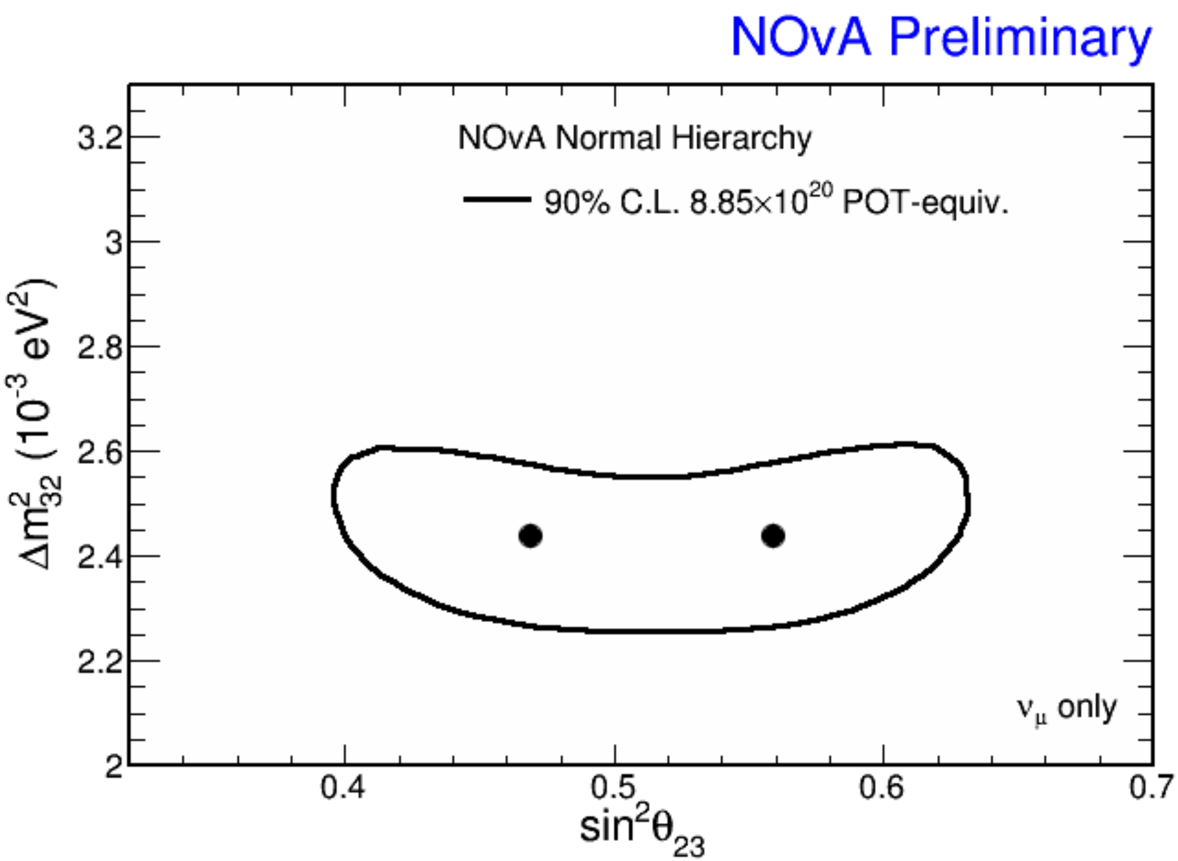
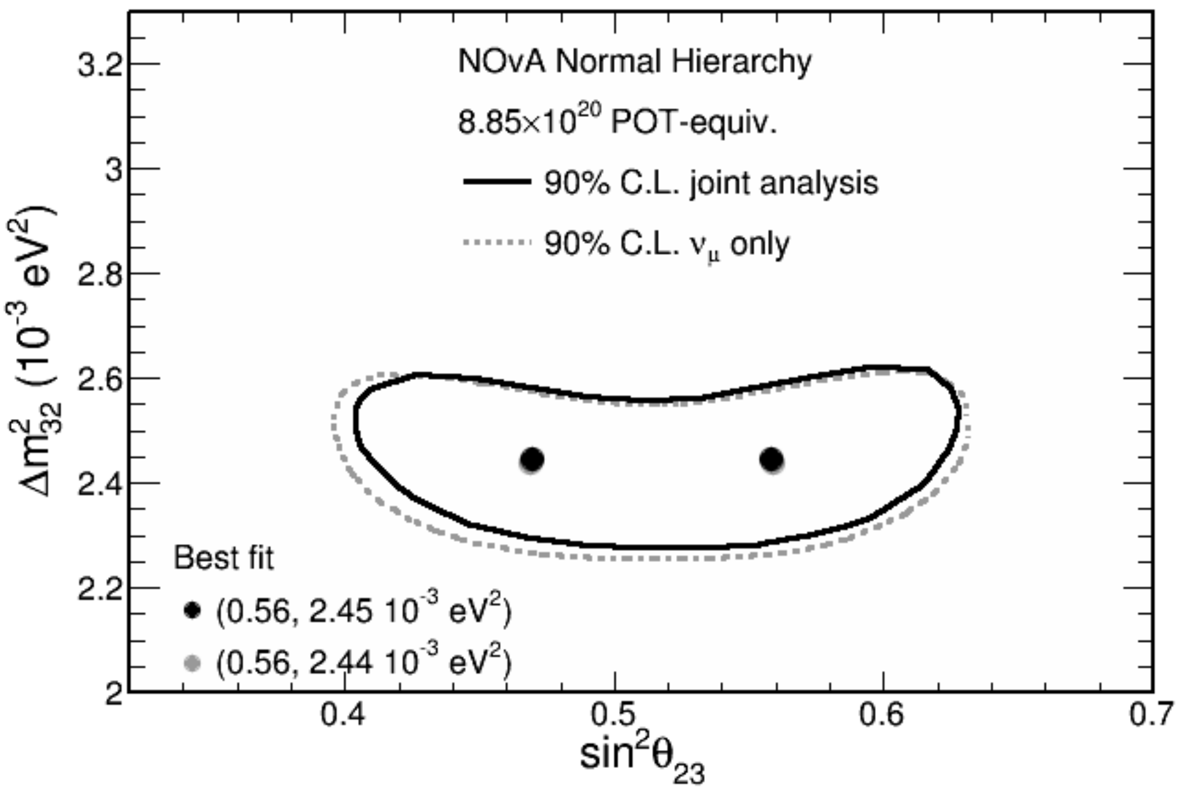


Joint Analysis
Disappearance - Appearance
8.85×10^{20} POT

NOvA Preliminary



UO preferred at 0.2 σ

$\sin^2 \theta_{23}$ =

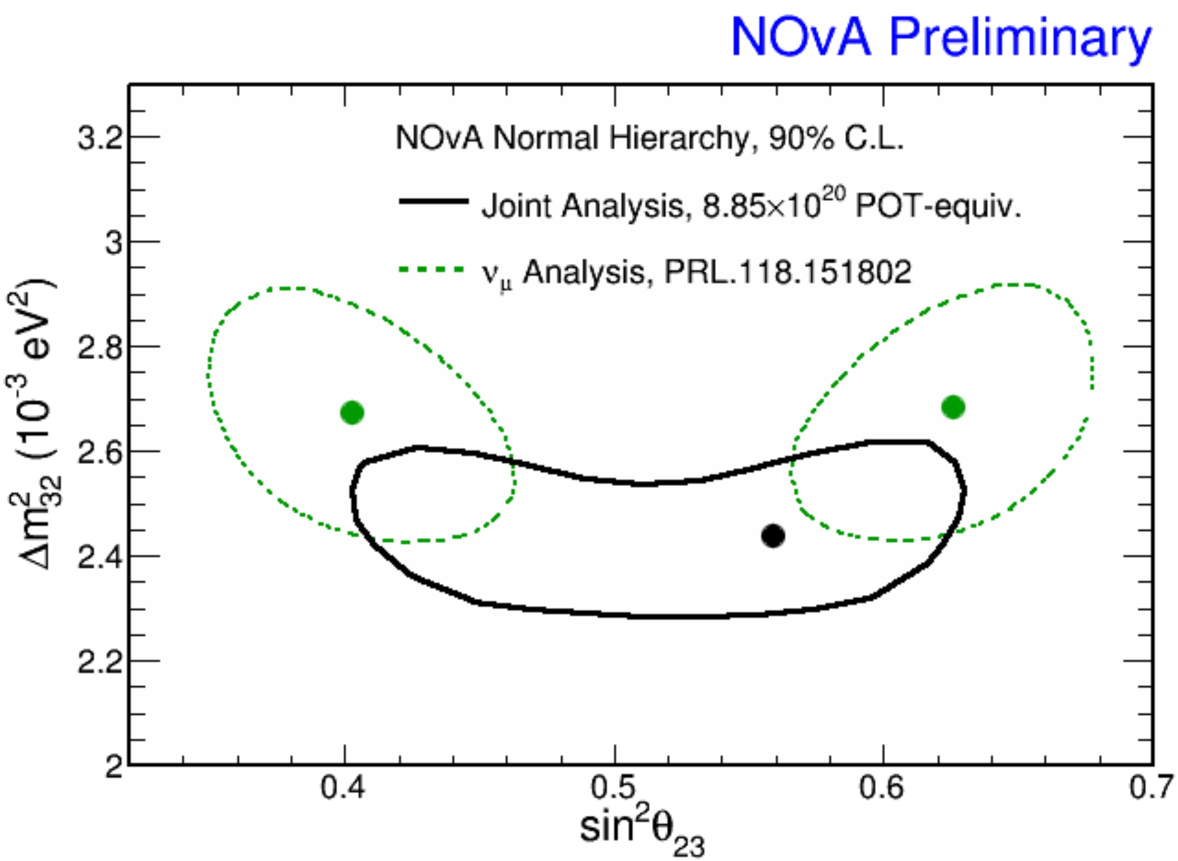
UO: $0.558^{+0.041}_{-0.033}$

LO: $0.475^{+0.036}_{-0.044}$

Δm^2_{32} =

$2.444^{+0.079}_{-0.077} \times 10^{-3}\ eV^2$

Joint Analysis
Disappearance - Appearance
8.85x10^{20} POT

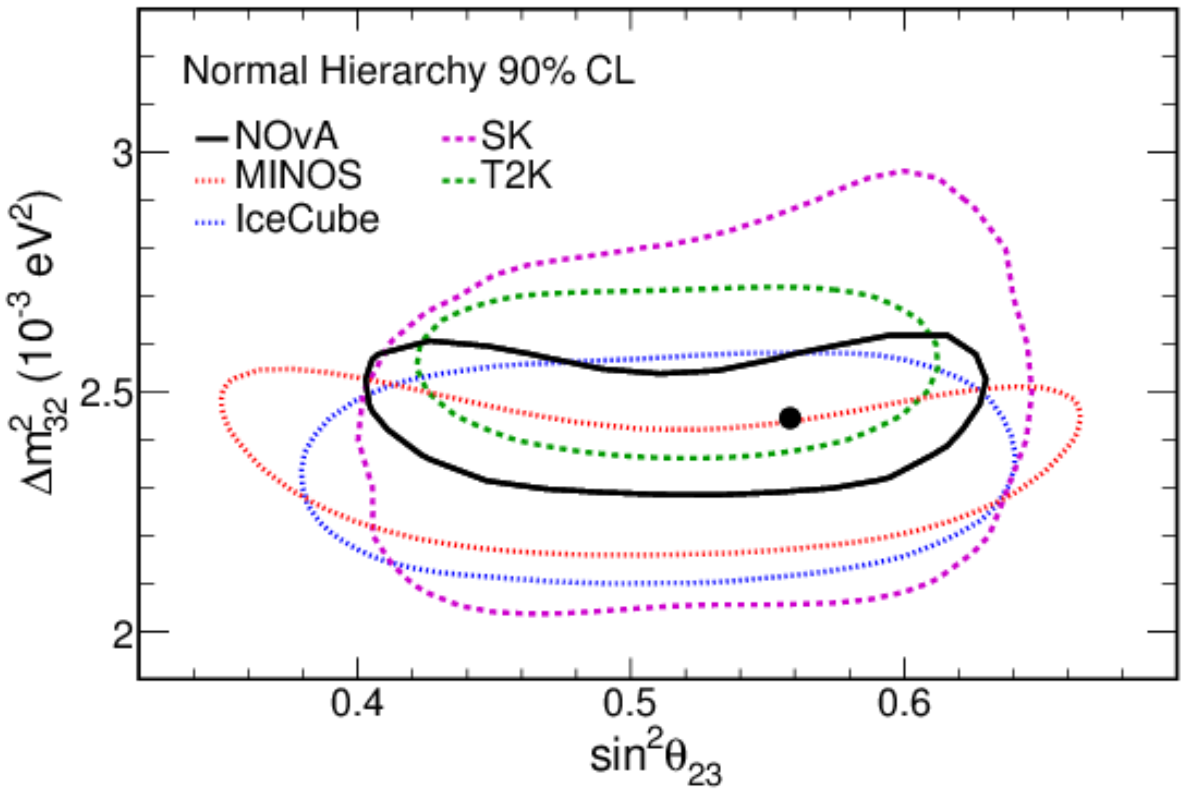


Previous rejection of maximal mixing with 2.6 σ

More recent result down to:

- **1.8 σ** from new simulation and calibration
- **0.5 σ** from new selection and analysis
- **0.4 σ** from new data

Summary

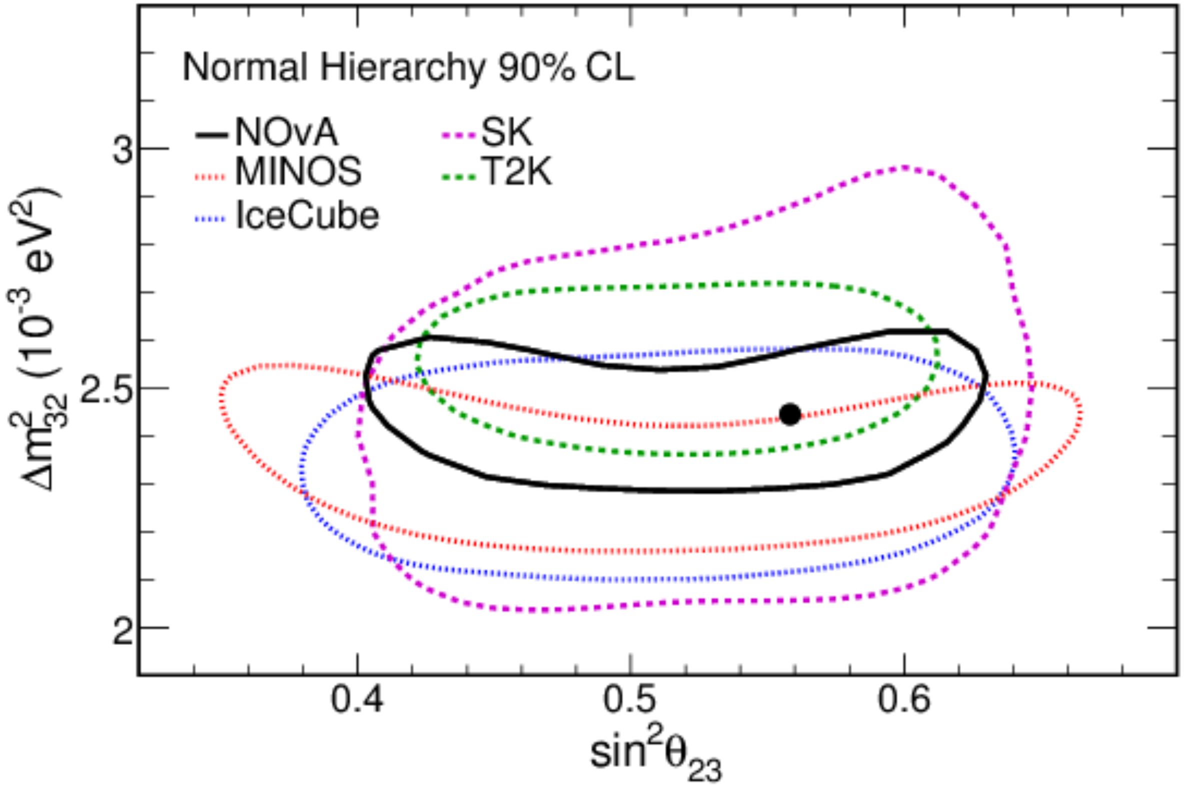


With 8.85×10^{20}POT exposure and a clear ν_μ disappearance

- Significant improvement to the analysis
- Competitive measurement of Δm^2_{32}
- Preference to mixing angle near maximal

MINOS Phys. Rev. Lett. 112, 191801 (2014), Ice-Cube Phys. Rev. Lett. 120, 071801 (2018)
T2K Phys. Rev. D 96, 092006 (2017), SK arXiv:1710.09126

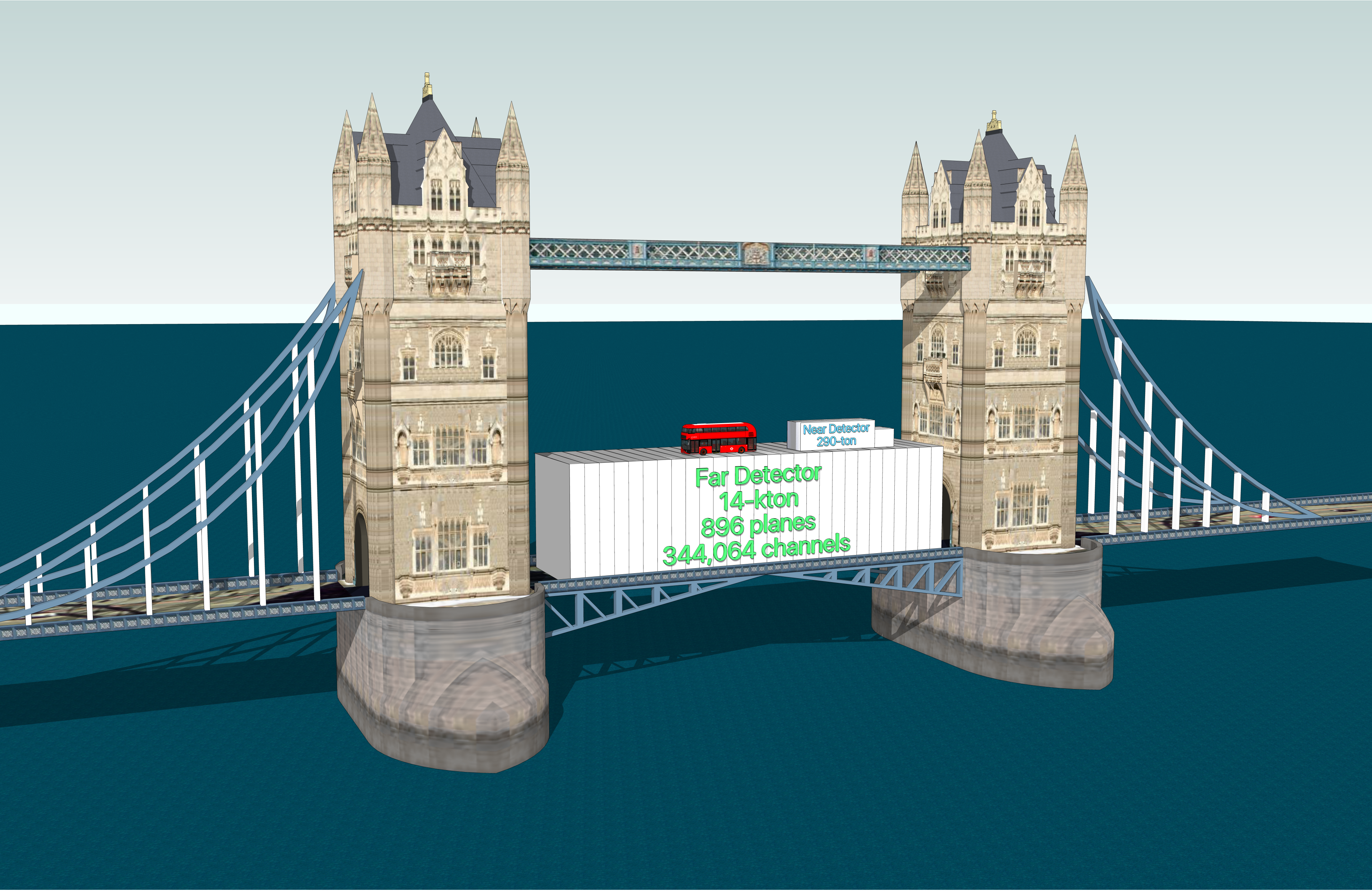
Summary



All together as friends!

MINOS Phys. Rev. Lett. 112, 191801 (2014), Ice-Cube Phys. Rev. Lett. 120, 071801 (2018)
T2K Phys. Rev. D 96, 092006 (2017), SK arXiv:1710.09126

Expect new results with **antineutrinos** in **Neutrino 2018**



BACKUP

Muon Neutrino Disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right)$$

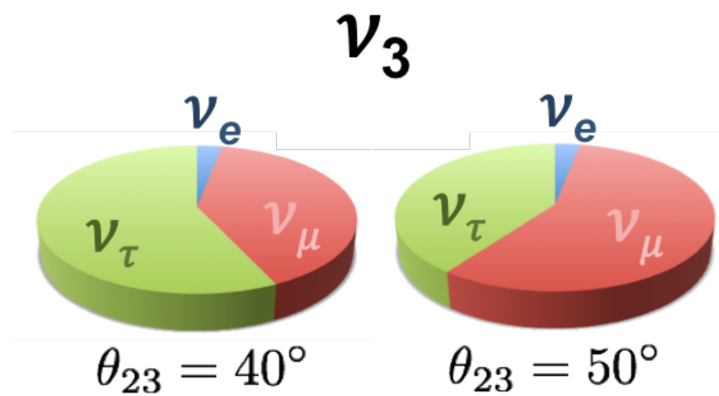
2 flavour approximation

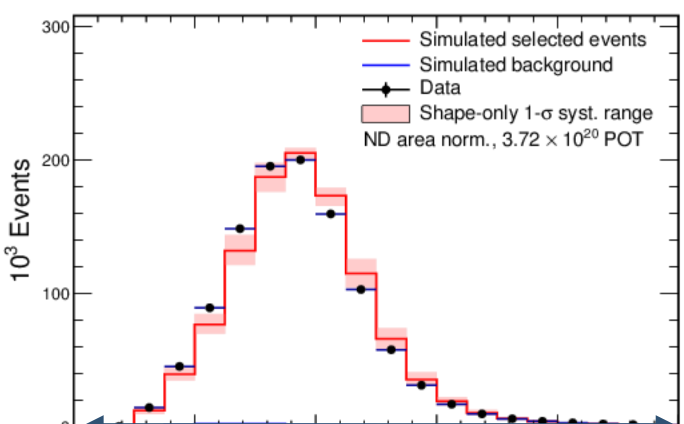
Far Detector

$L = 810km$

Near Detector

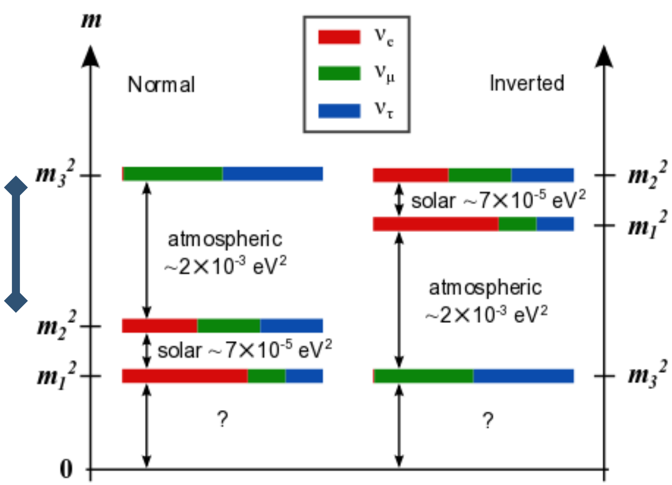
$\sin^2\theta_{23}$



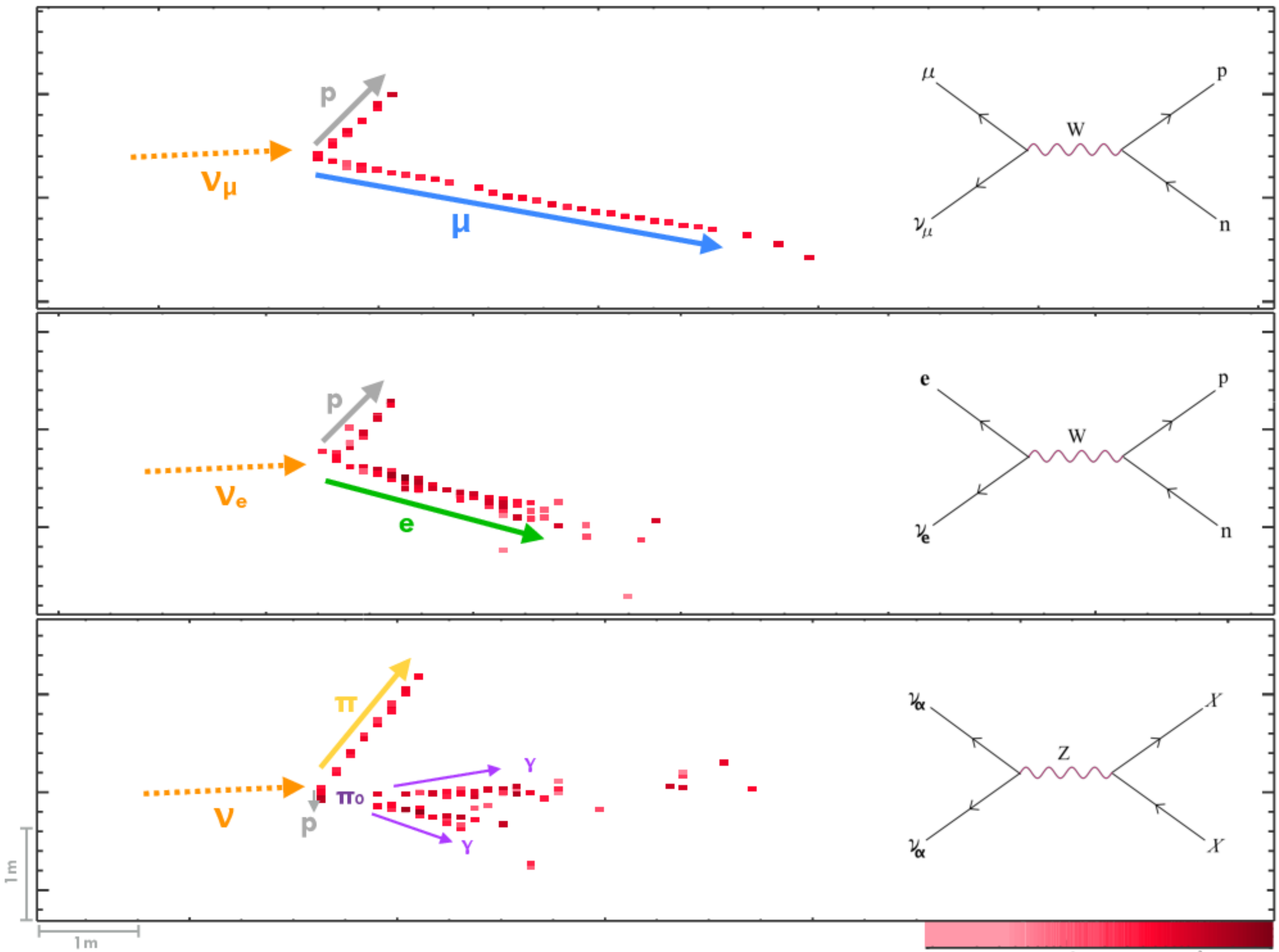


E

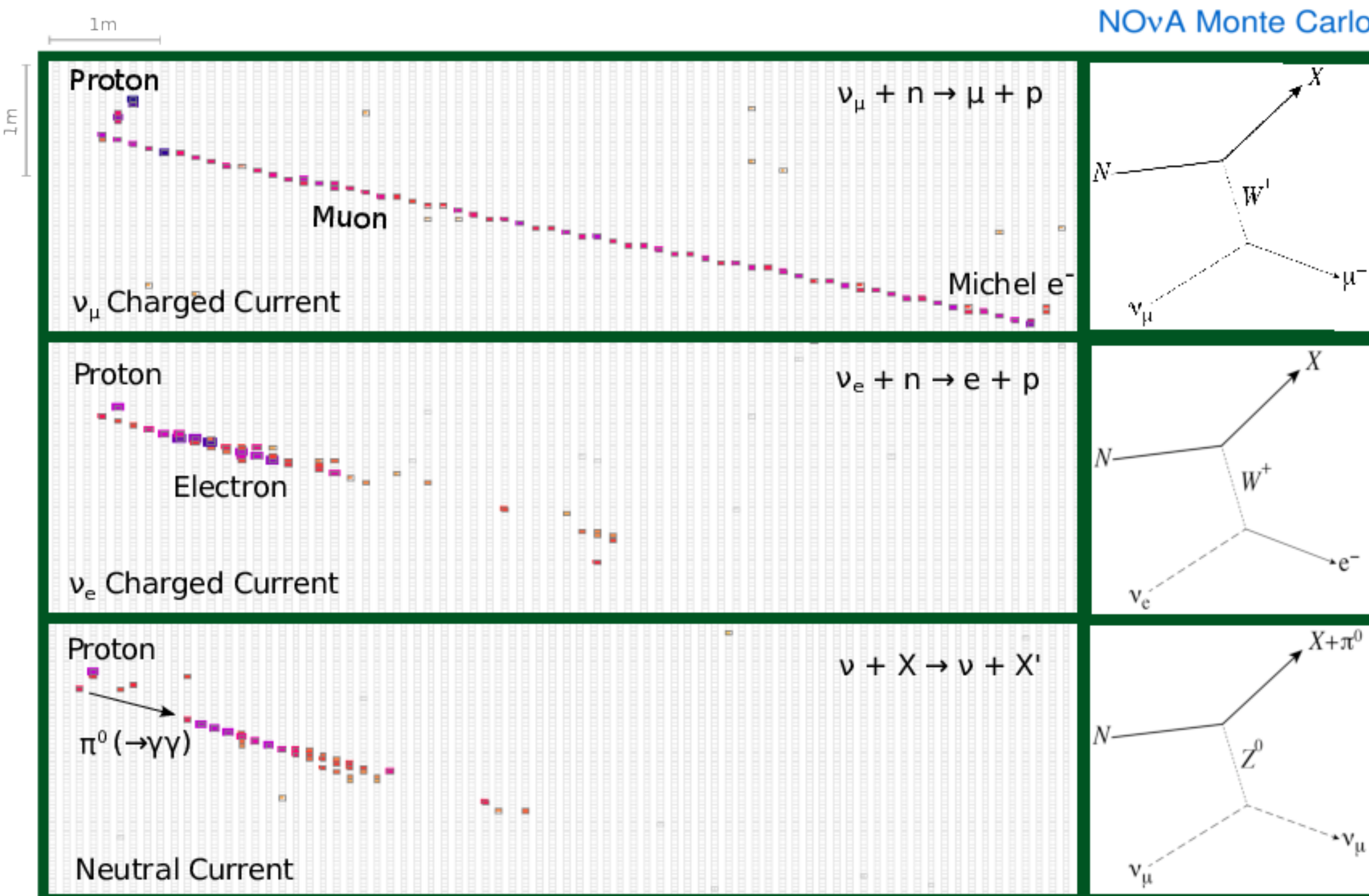
Δm^2_{32}



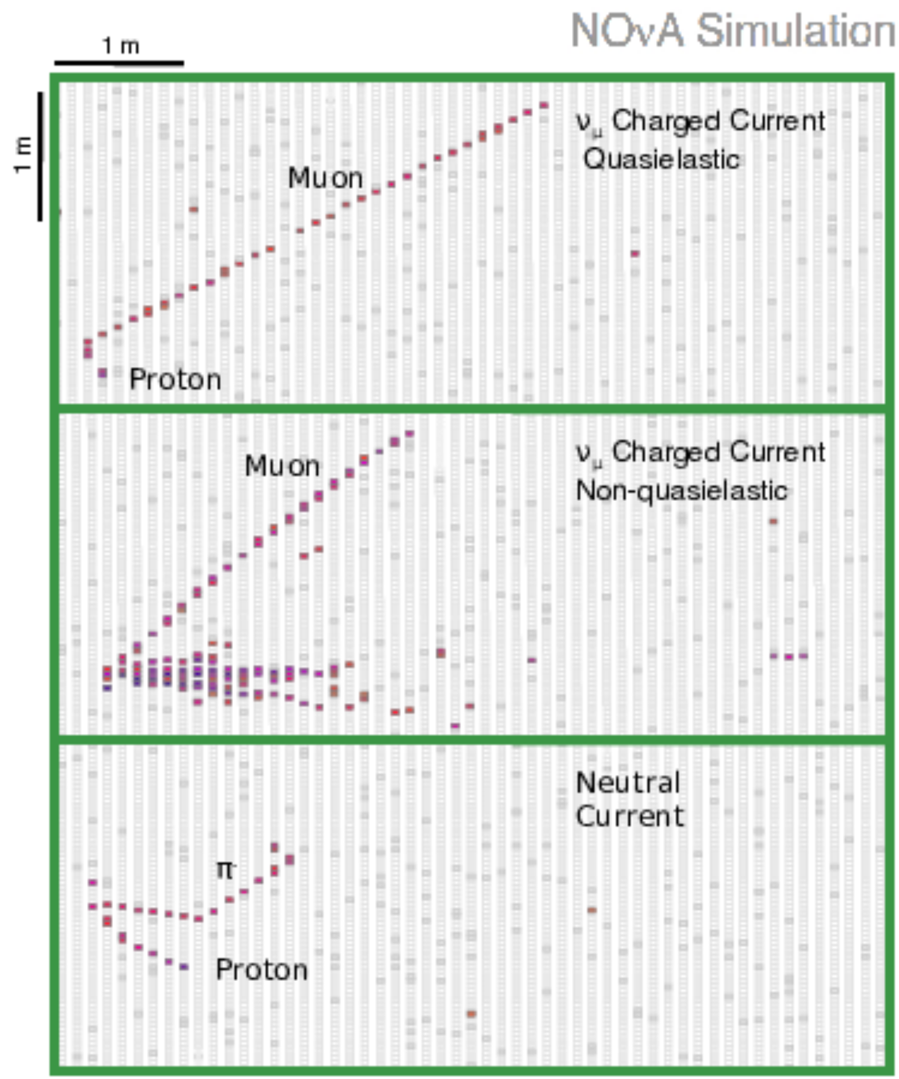
Event topology



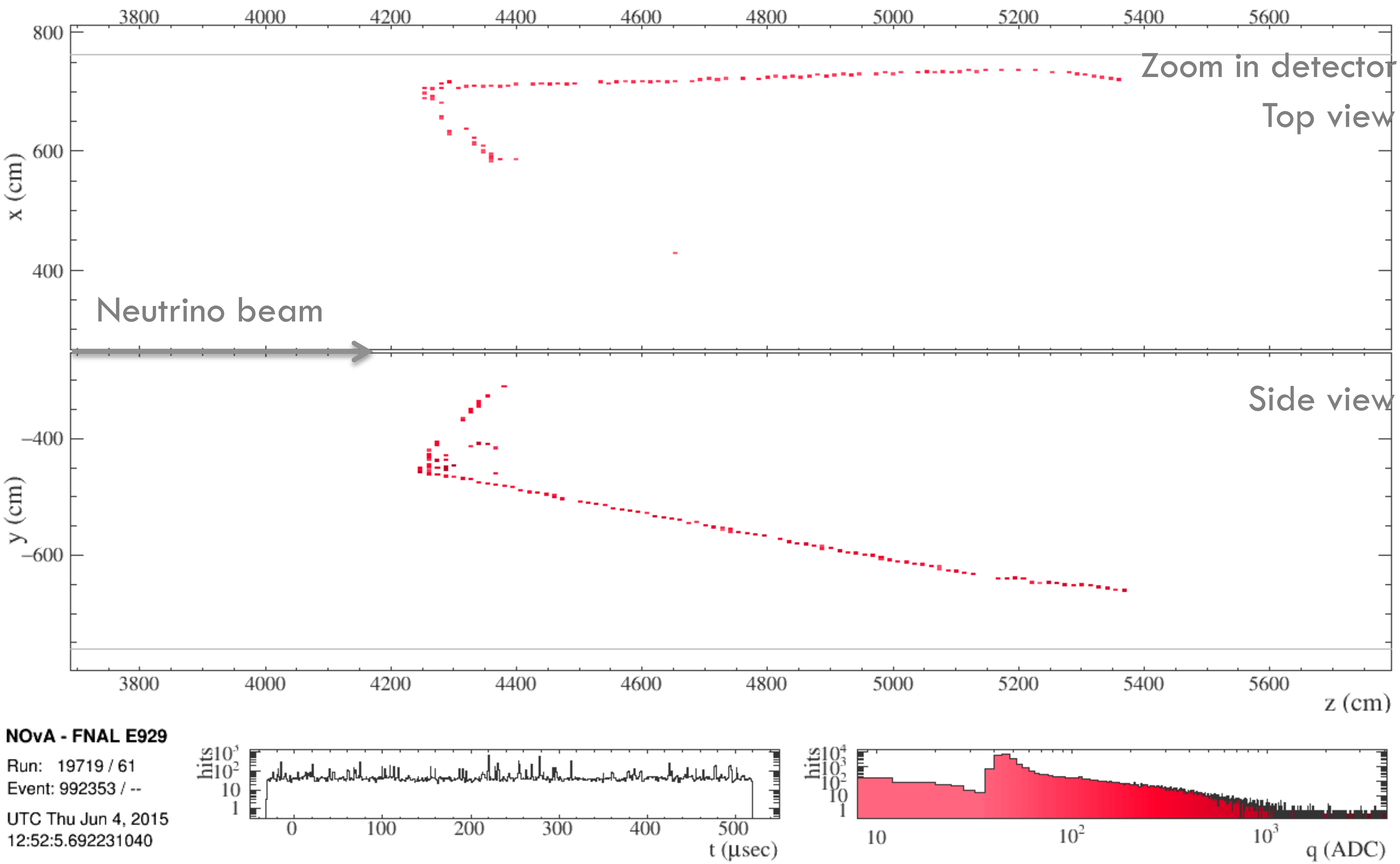
Event topology



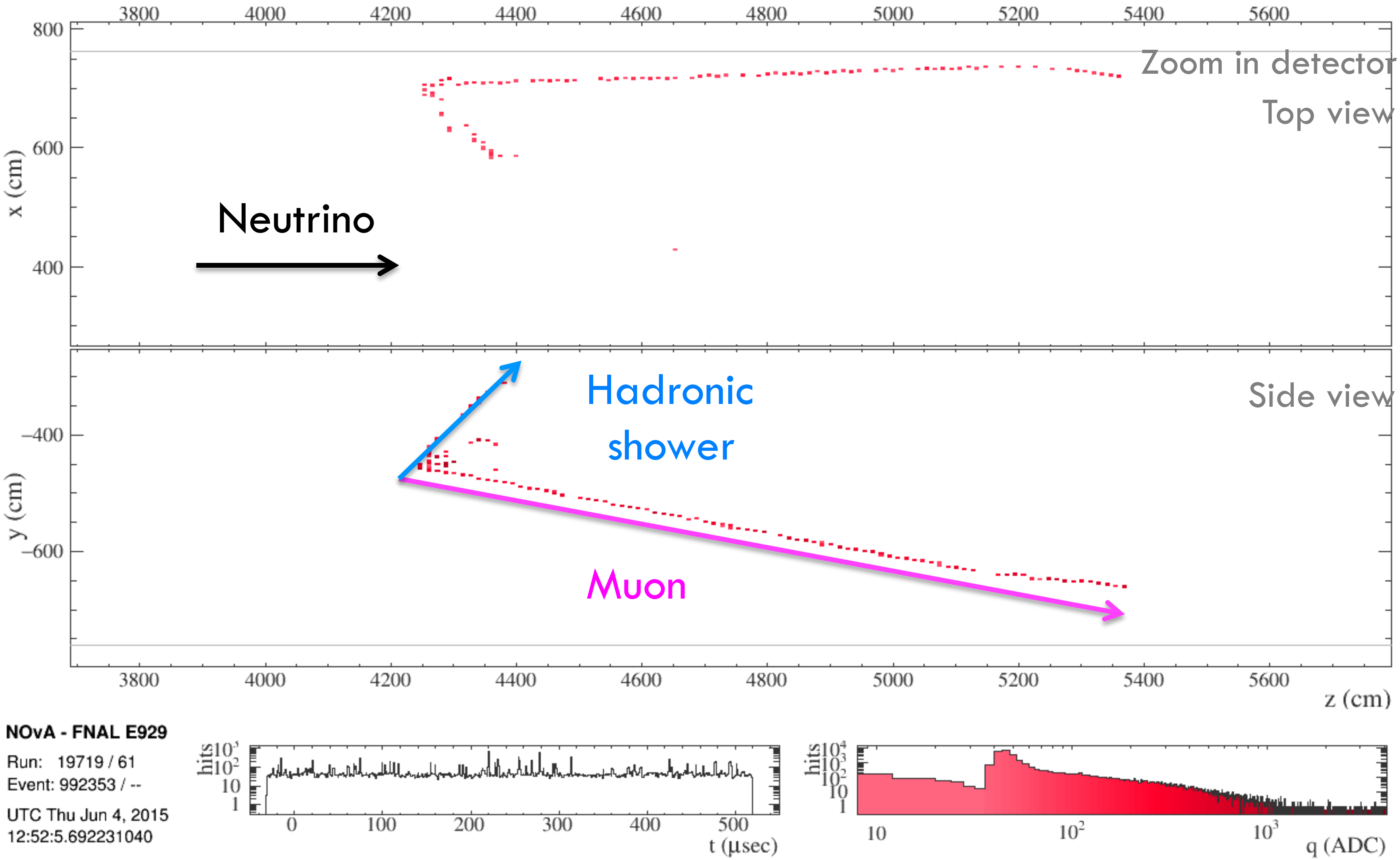
Event topology



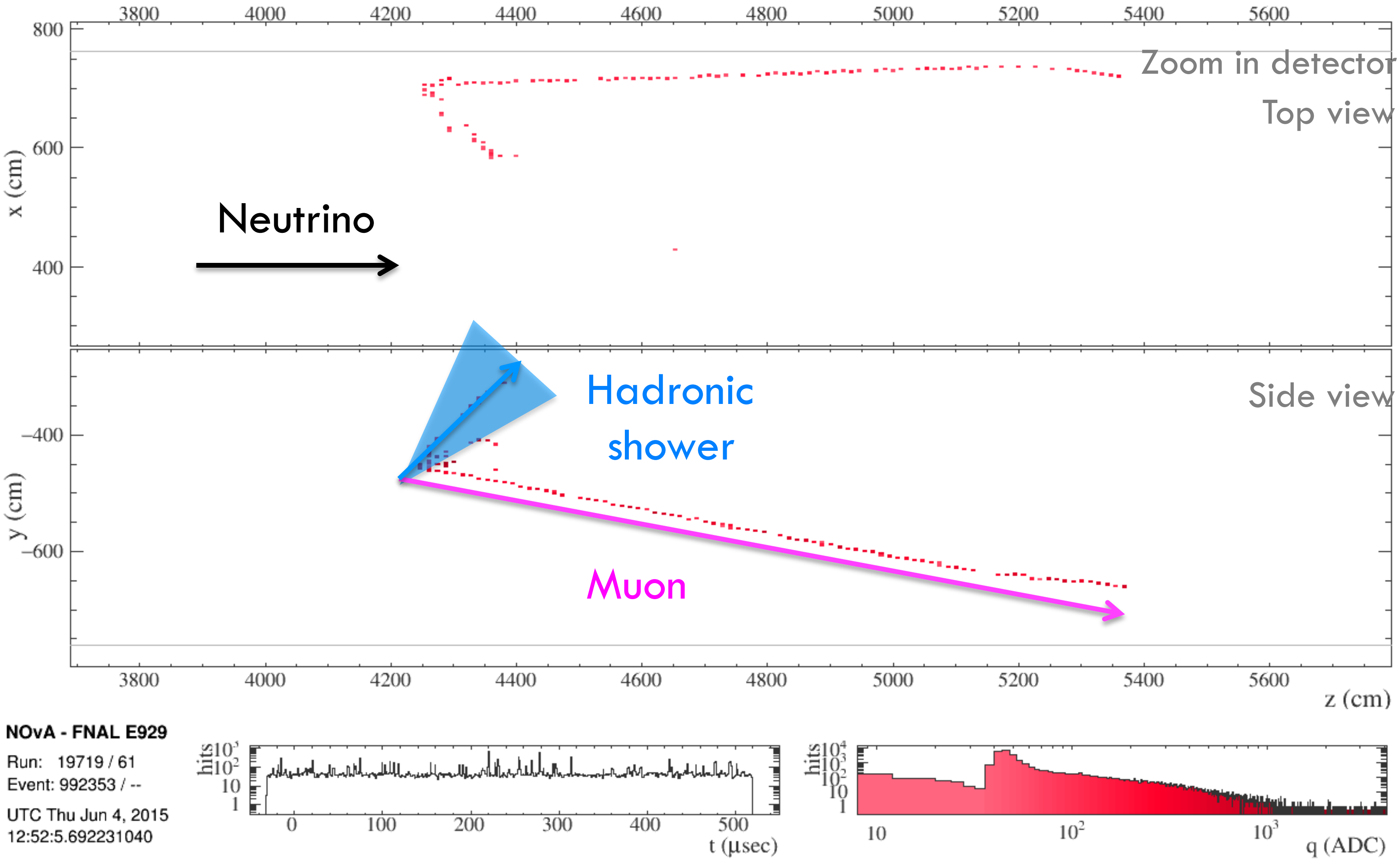
Energy Reconstruction



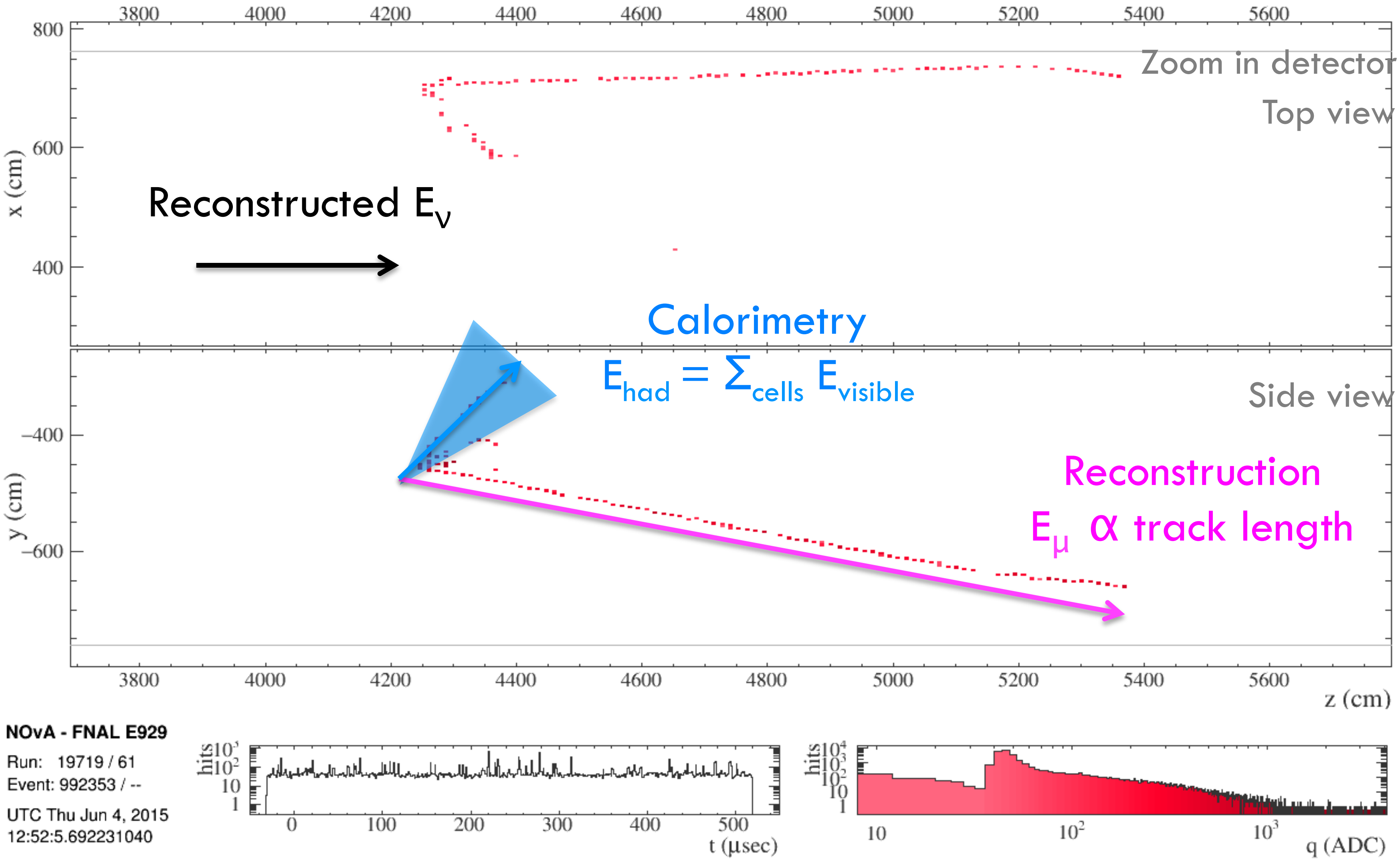
Energy Reconstruction



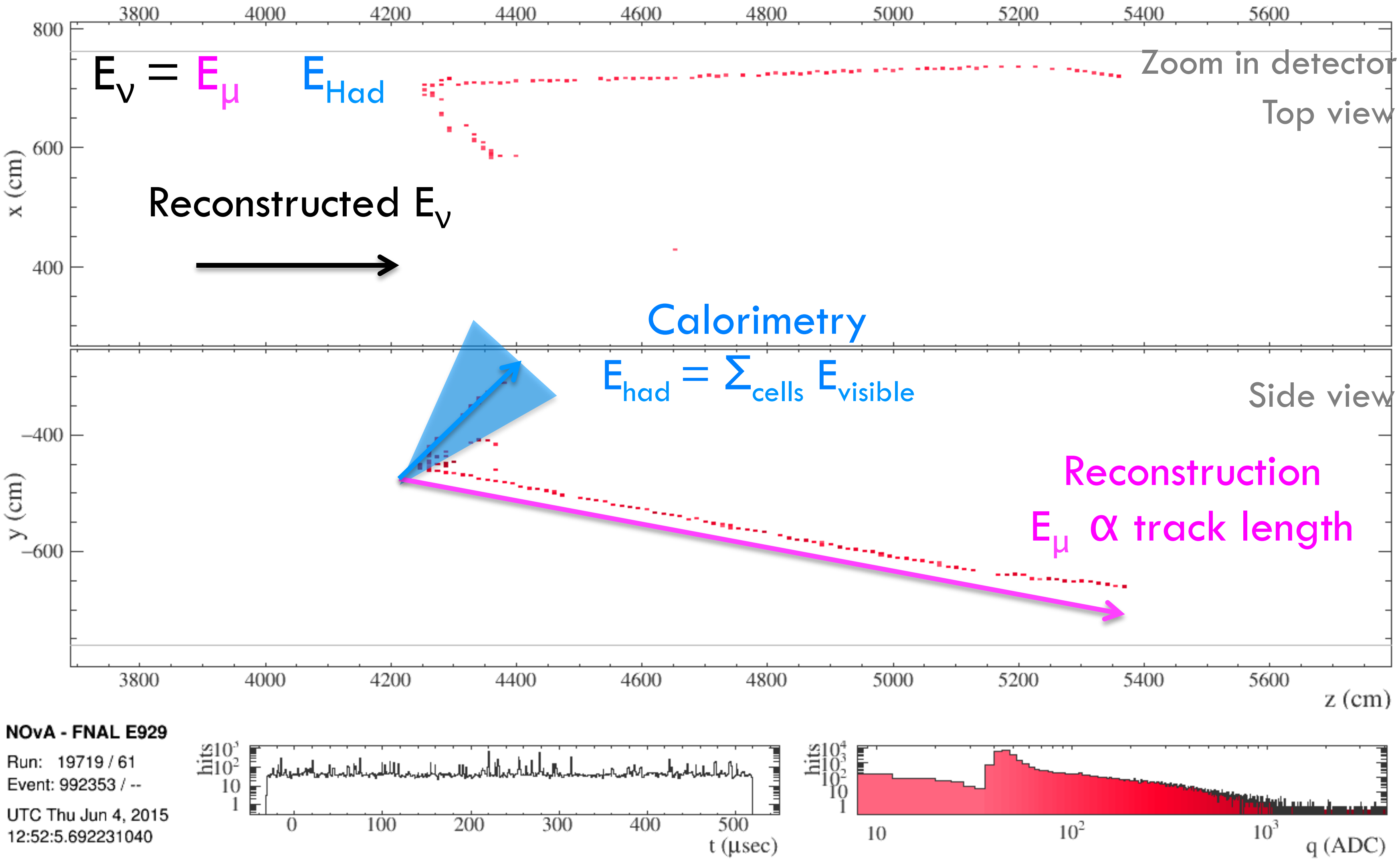
Energy Reconstruction



Energy Reconstruction



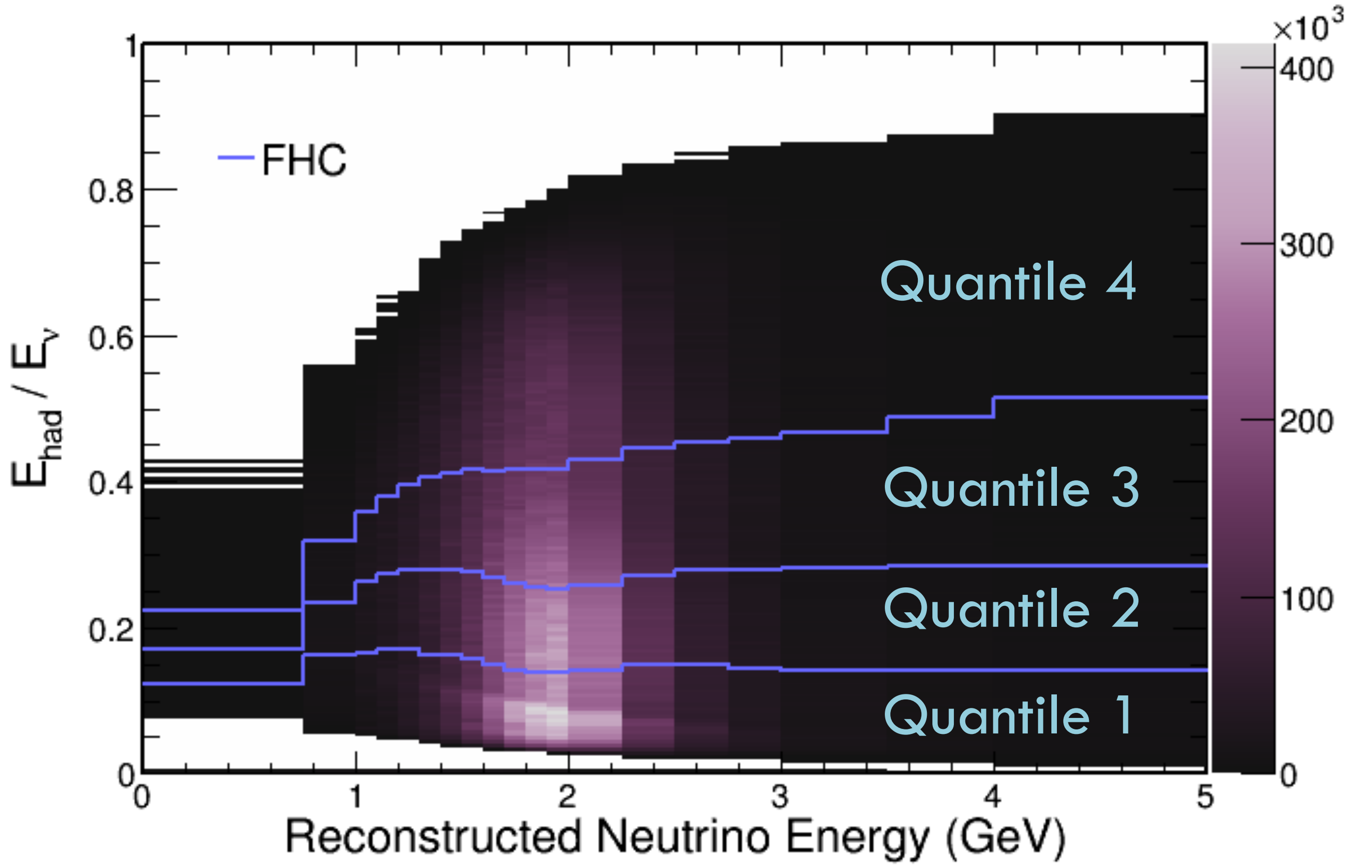
Energy Reconstruction



Energy Resolution

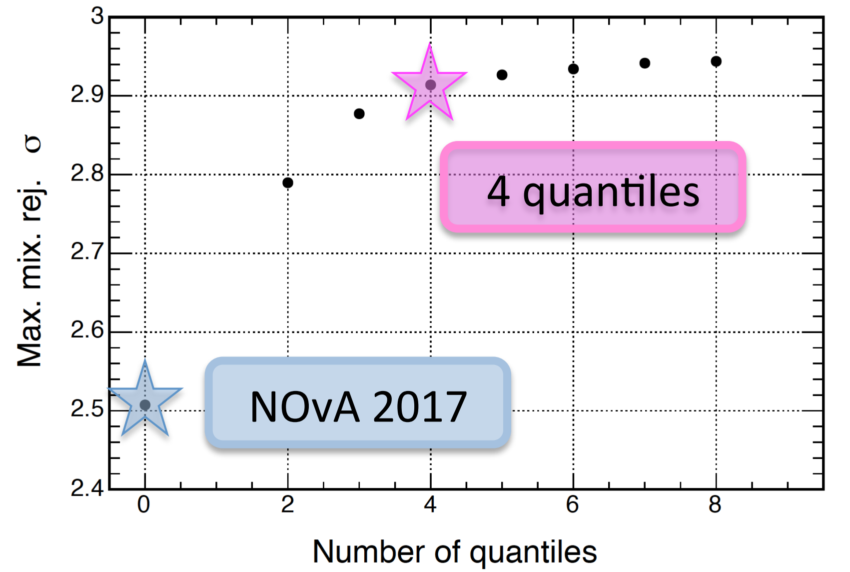
$E_\nu = E_\mu + E_{had}$ → Neutrino energy resolution = E_{Had}/E_ν

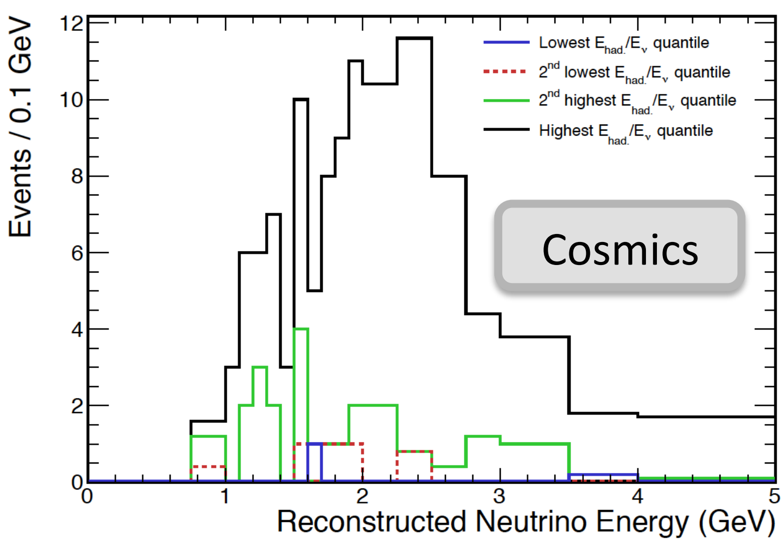
Separate well resolved energies by quantiles of hadronic energy fraction

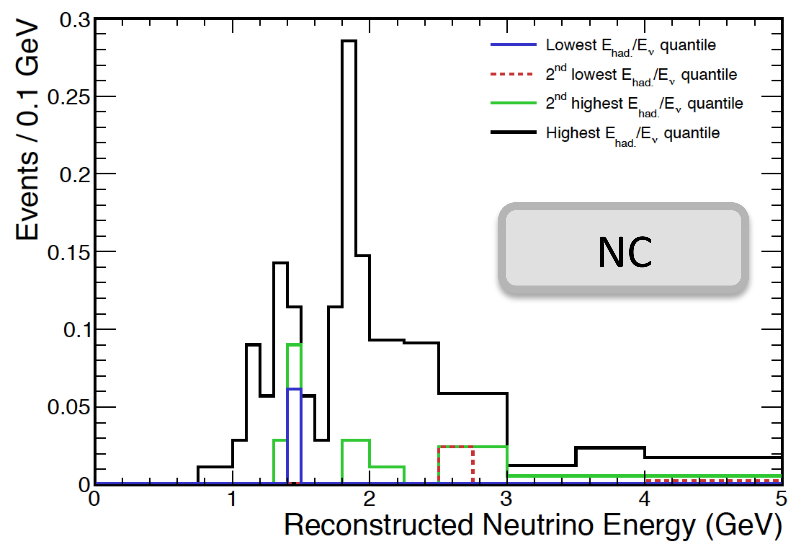


Energy Resolution

Largest **background**, cosmic and neutral current events, in the **worst energy resolution** (highest hadronic energy quantile).

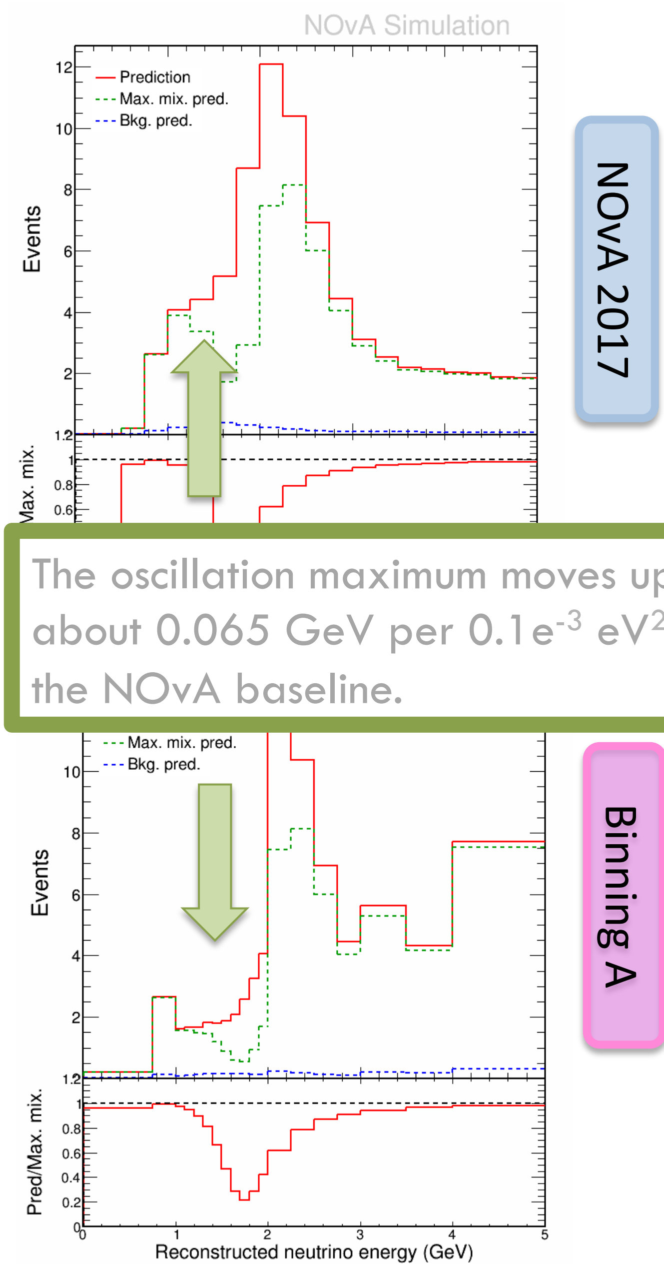






Energy Binning

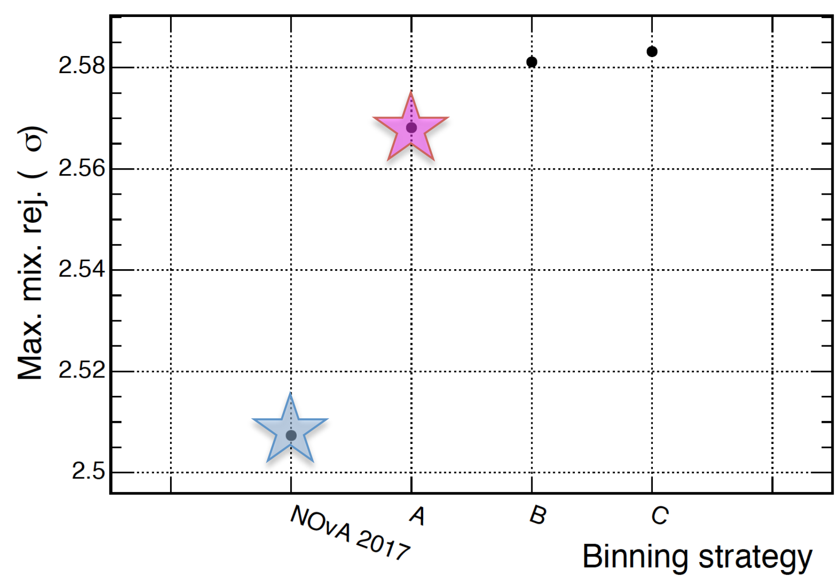
3



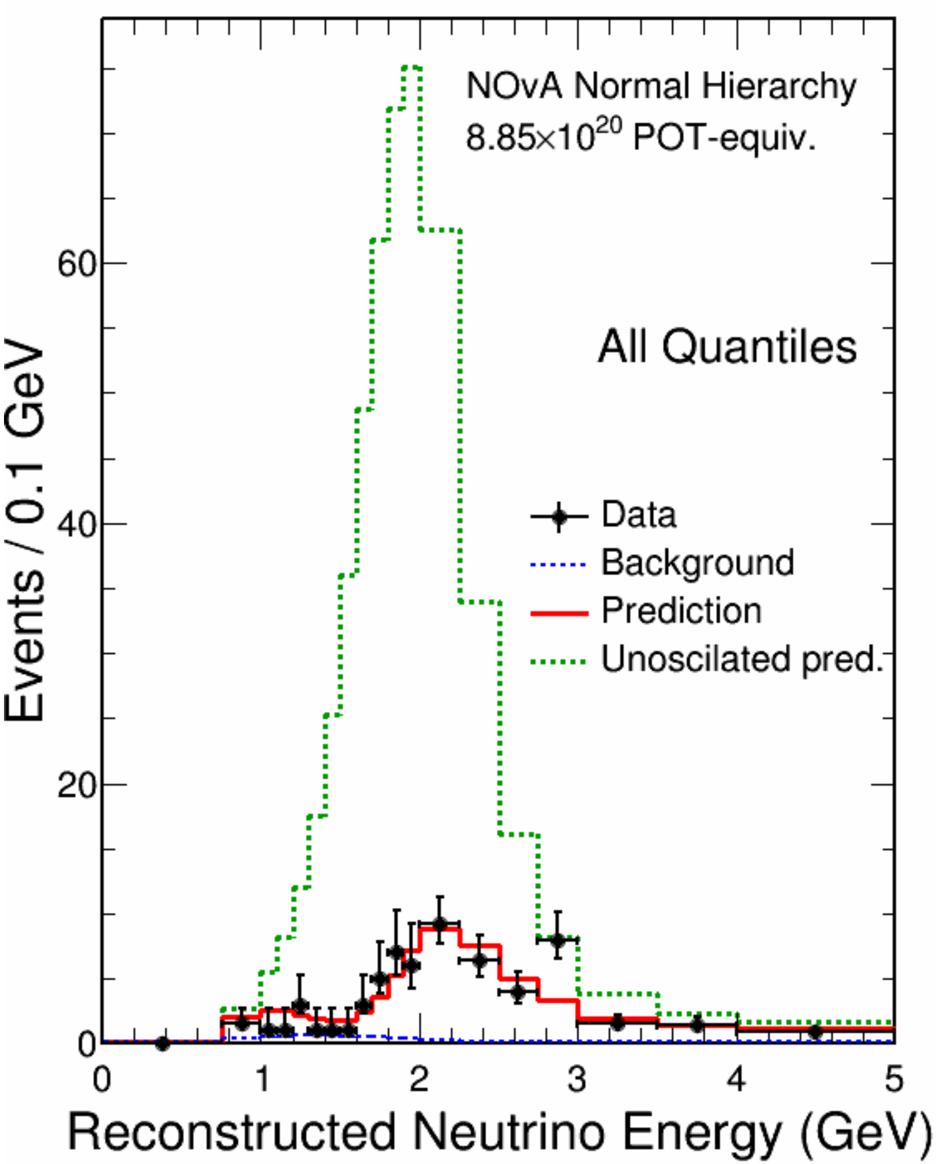
The oscillation maximum moves up by about 0.065 GeV per 0.1e^{-3} eV^2 at the NOvA baseline.

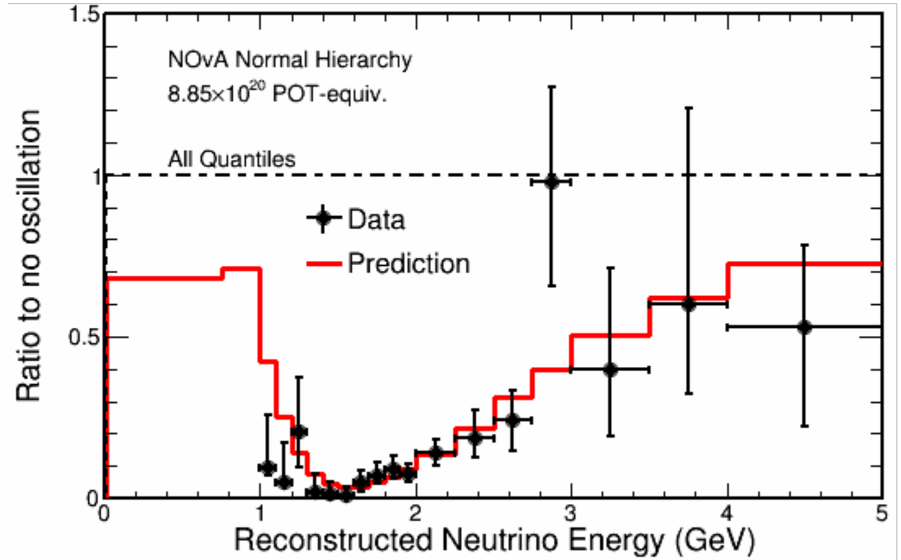
Finer binning around the maximum oscillation region could enhance the sensitivity of the analysis

- NOvA' standard energy binning: 20 bins of 0.25 GeV each
- Optimum binning: increased number of bins between 1 and 3 GeV



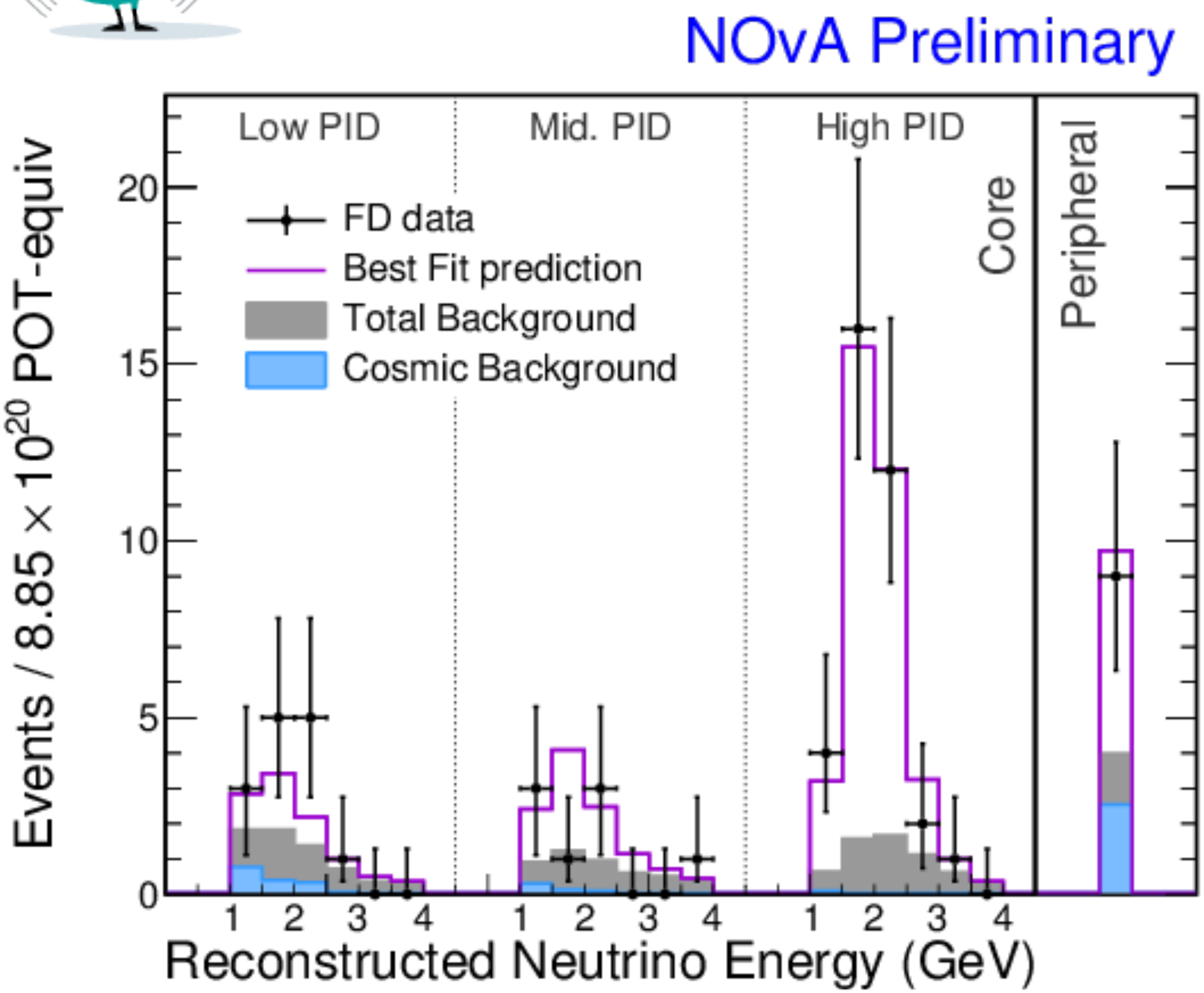
No oscillations





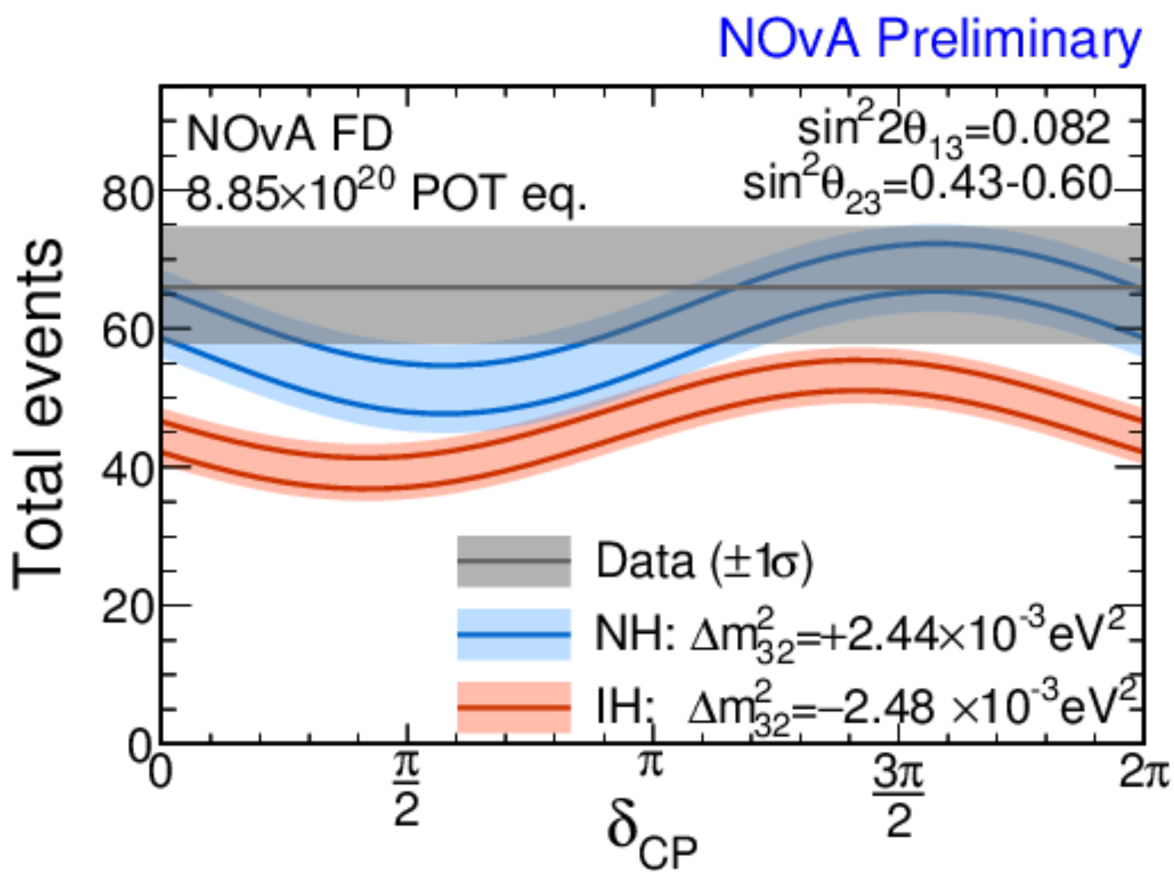
- 763 expected events without oscillations
- 126 observed events in the far detector
- 129 expected events at best fit
- 5.82 cosmics events
- 2.50 neutral current events
- 0.96 rom other beam bkg

Electron Neutrino Appearance 8.85×10^{20} POT



- 66 observed events in the far detector
- 20.5 +-2.5 bkg events

Electron Neutrino Appearance
8.85×10^{20} POT



- 66 observed events in the far detector
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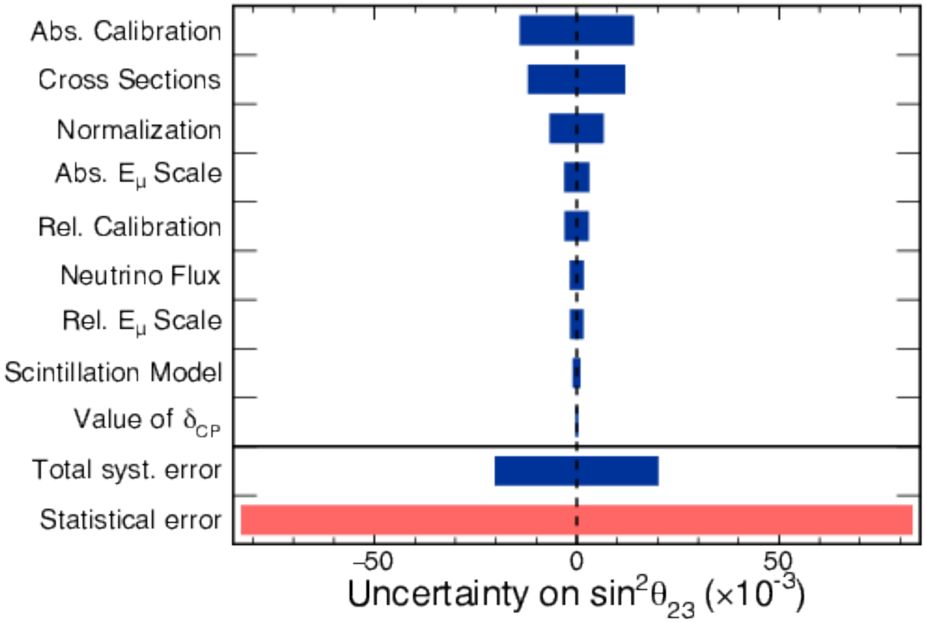
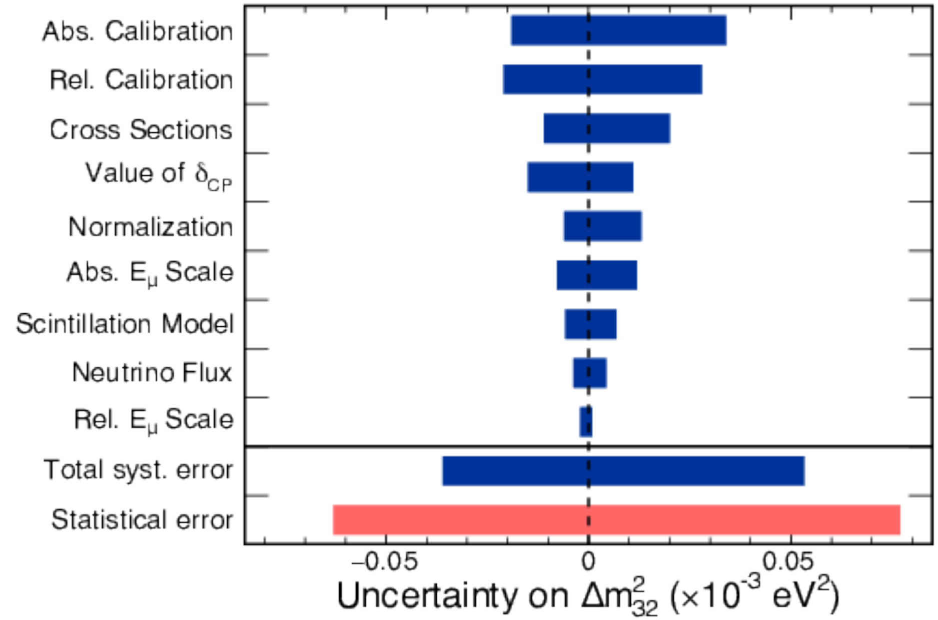
Uncertainties





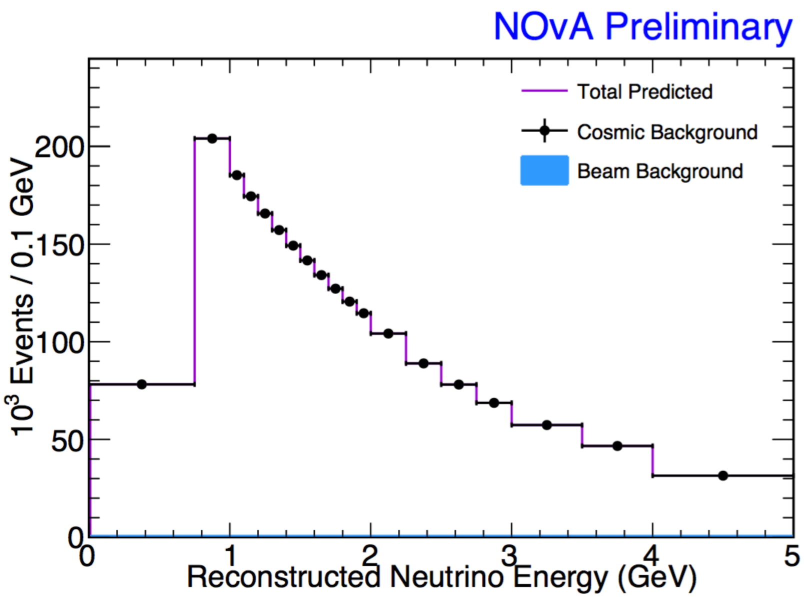
Combination of the improvements reduces uncertainties and increases NOvA's sensitivity:

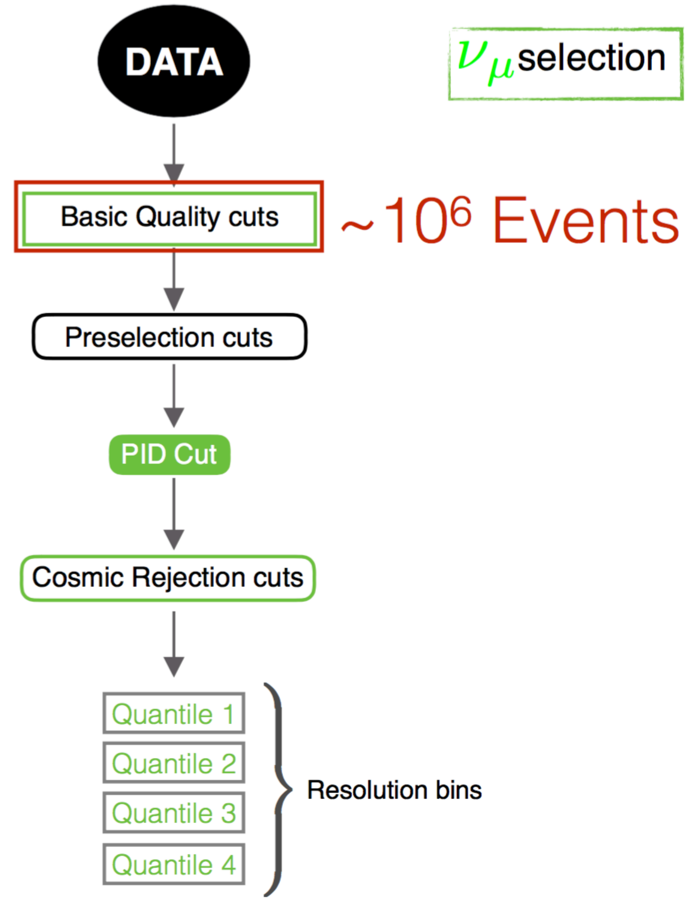
- **Systematic uncertainties reduced** from 2.2% to 2.0% on Δm^2_{32} and from a 2.1% to 1.5% on $\sin^2\theta_{23}$

Improved ν_μ Selection

30 A. Radovic, JETP January 2018

Even with excellent timing resolution cosmogenic activity at the Far Detector remains a challenging background due to raw rate.





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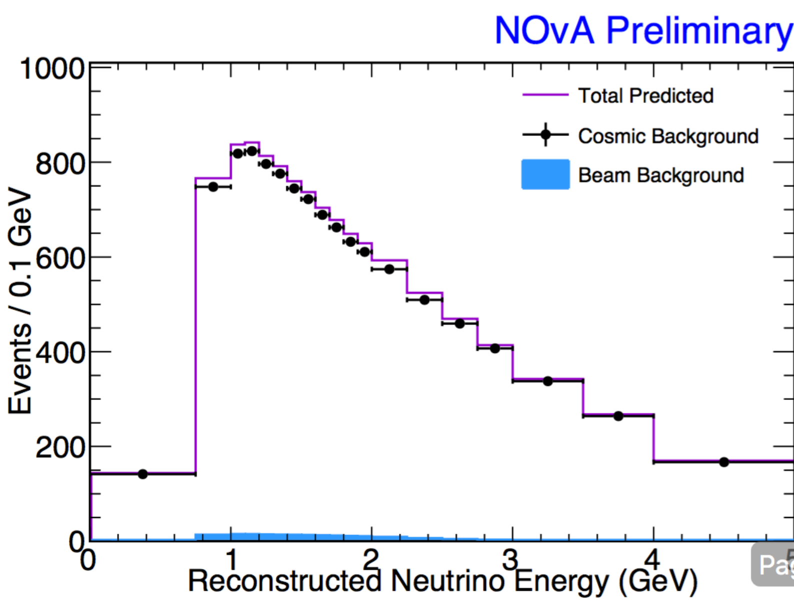
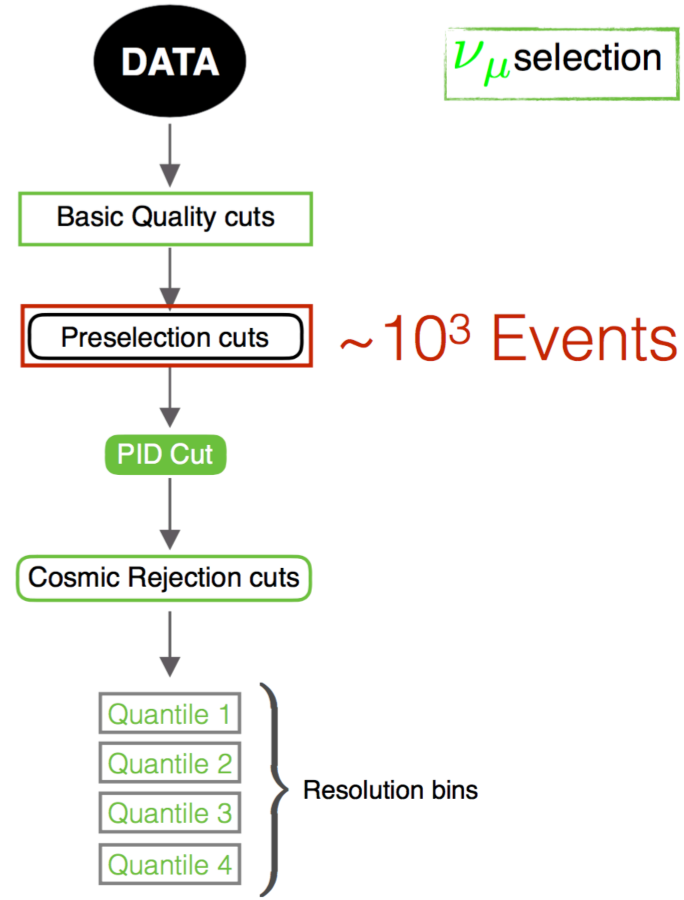
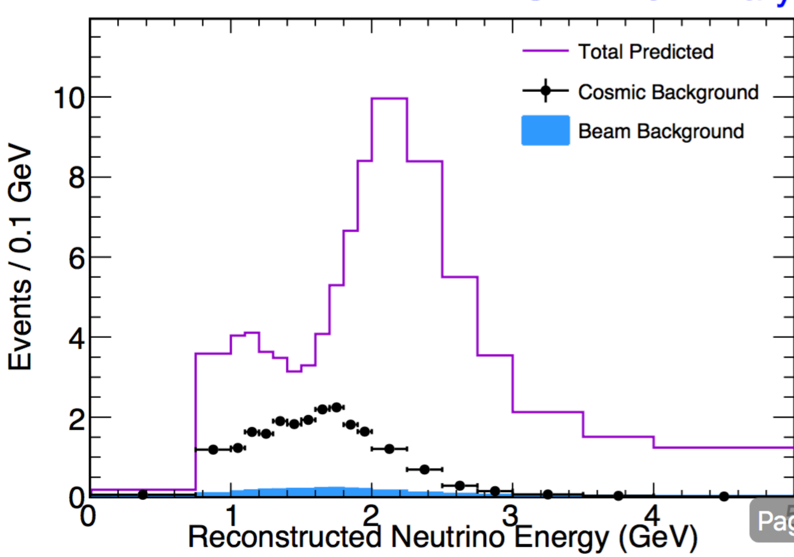
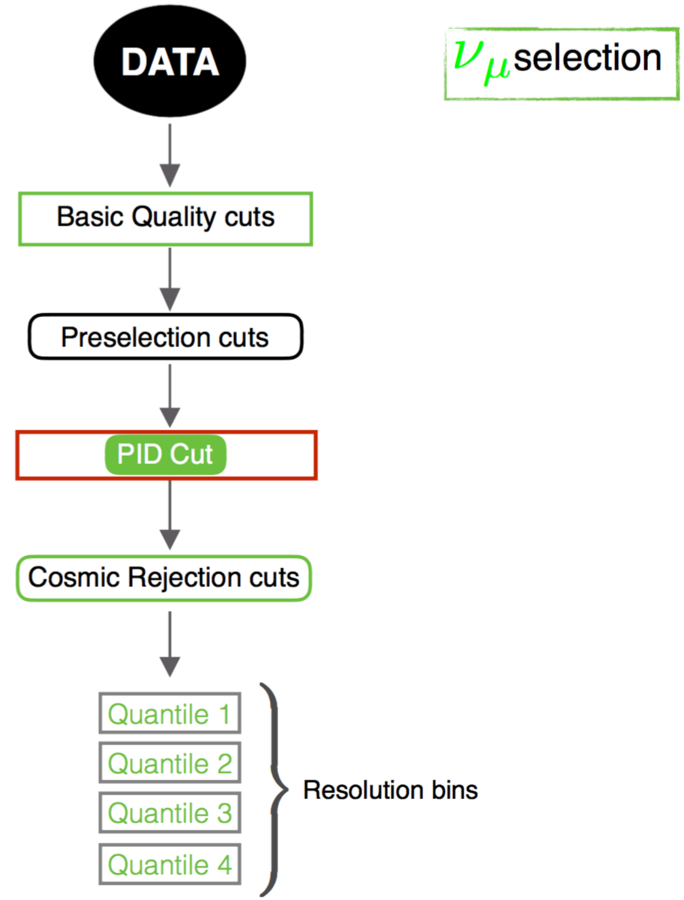




Improved ν_μ Selection

- New selection using CVN, a retuned cosmic rejection BDT, and a new PID cut
- Equivalent background rejection with 11% more signal selected.





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