New results on θ_{23} from NOvA

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On behalf of NOvA Collaboration

Recontres de Moriond
March 24th, 2017, La Thuile, Italy

NuMI Off-axis ν_e Appearance

Neutrino
Oscillation
Experiment

Neutrino oscillation

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

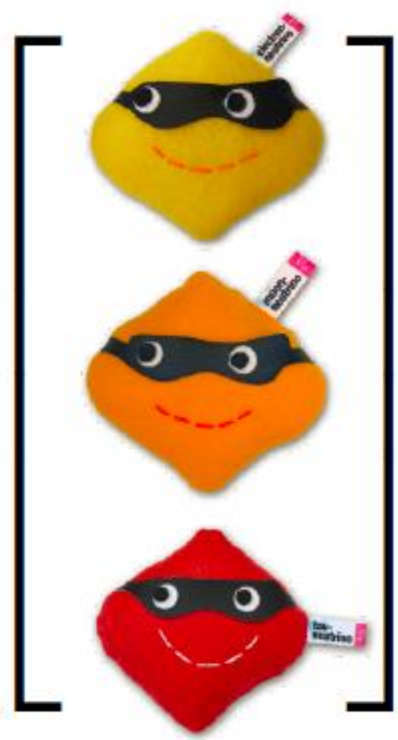
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\overset{(+)}{-}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

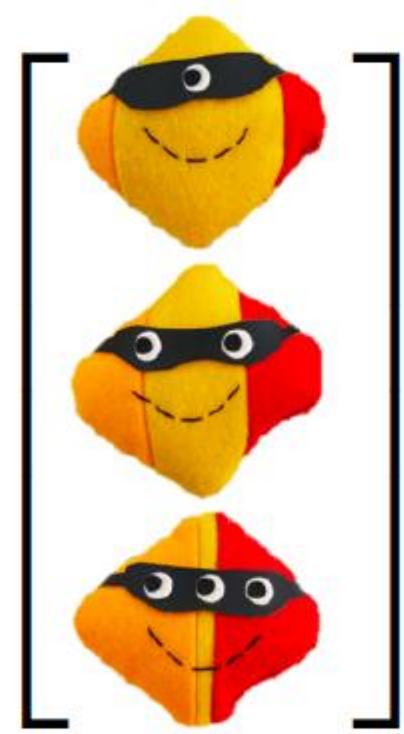
$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ $\Delta = \Delta m^2_{31} L/(4E)$ $A = \overset{(-)}{+} G_f n_e L/(\sqrt{2}\Delta)$

Neutrino oscillation

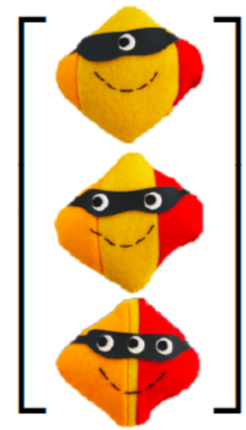


$$= U_{\mathrm{PMNS}}$$

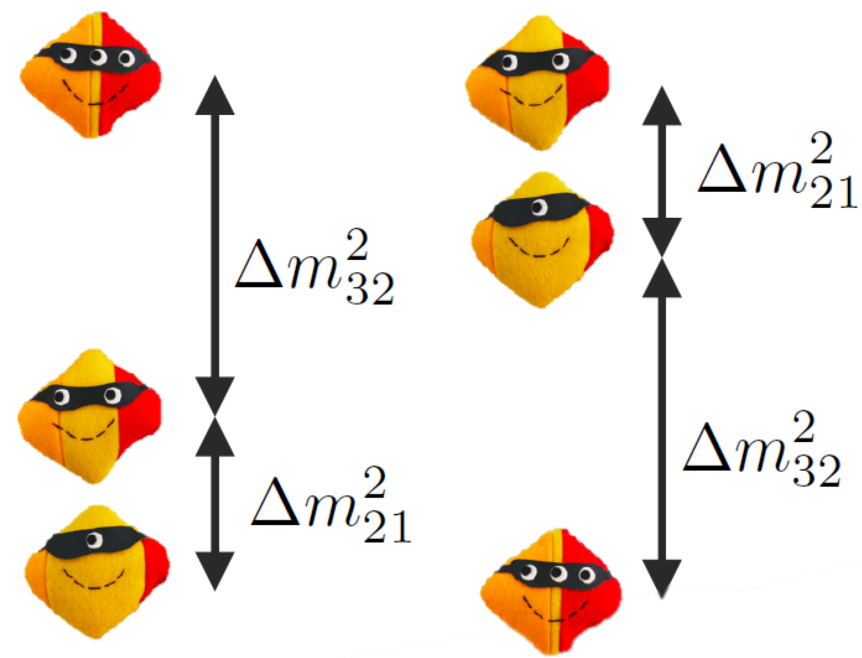


Neutrino oscillation parameters

$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



- The mixing matrix
  - θ_{23}, θ_{13}, δ_{CP}, θ_{12}
- The mass differences
  - Δm^2_{32}, Δm^2_{21}
- The mass hierarchy
  - sign of Δm^2_{32}



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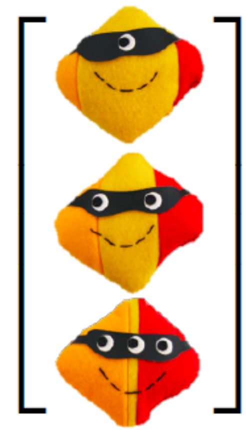
$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



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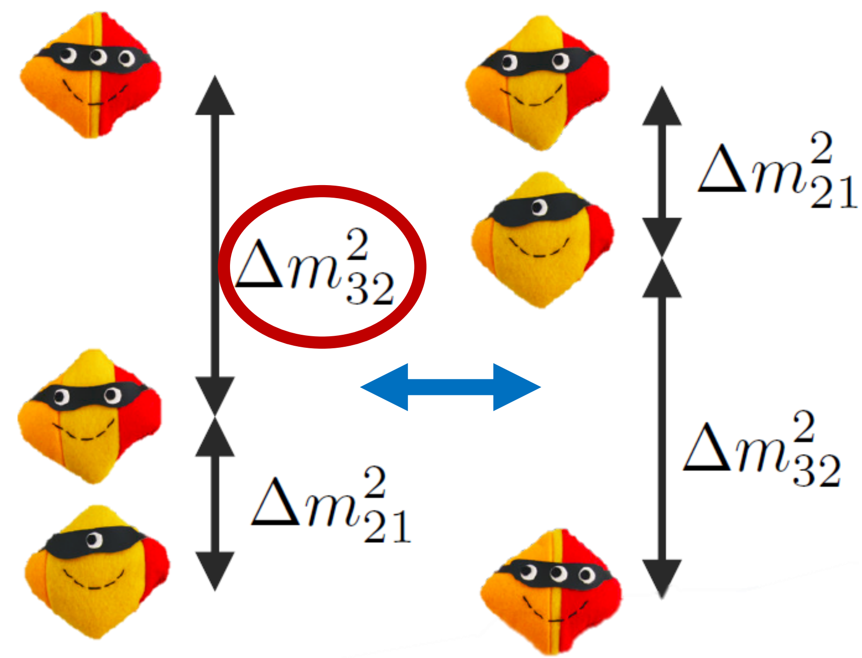
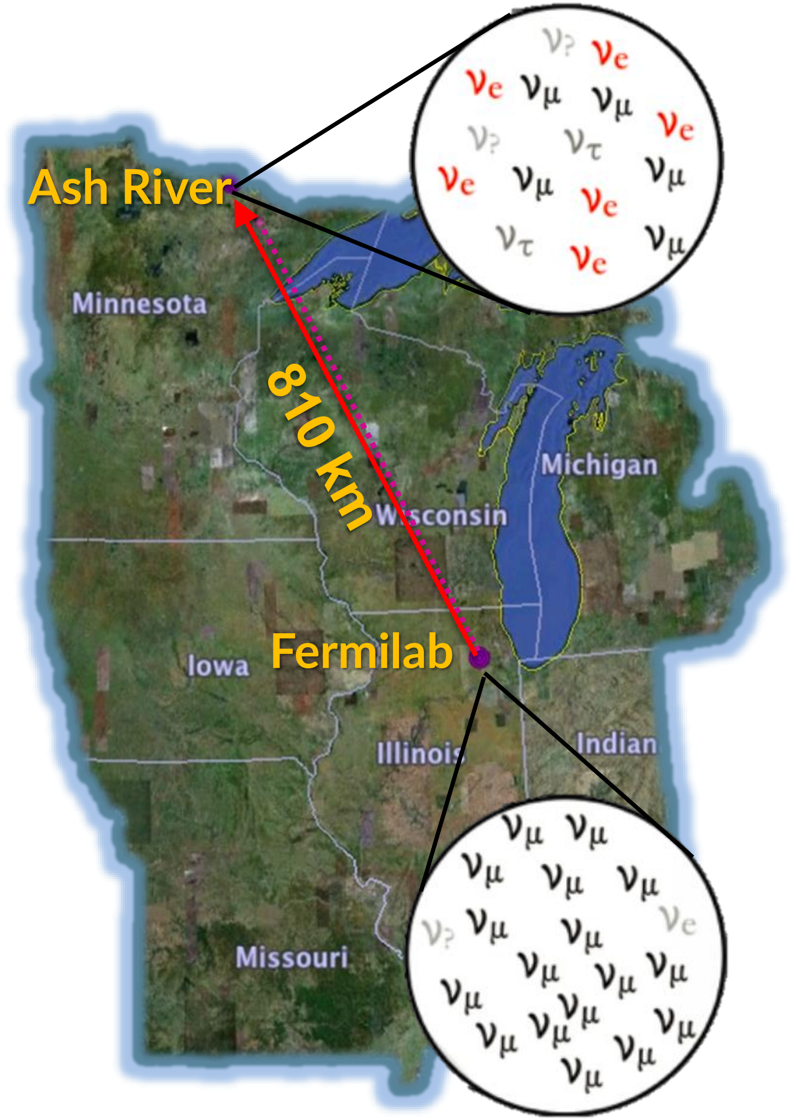


NuMI Off-axis ν_e Appearance Experiment

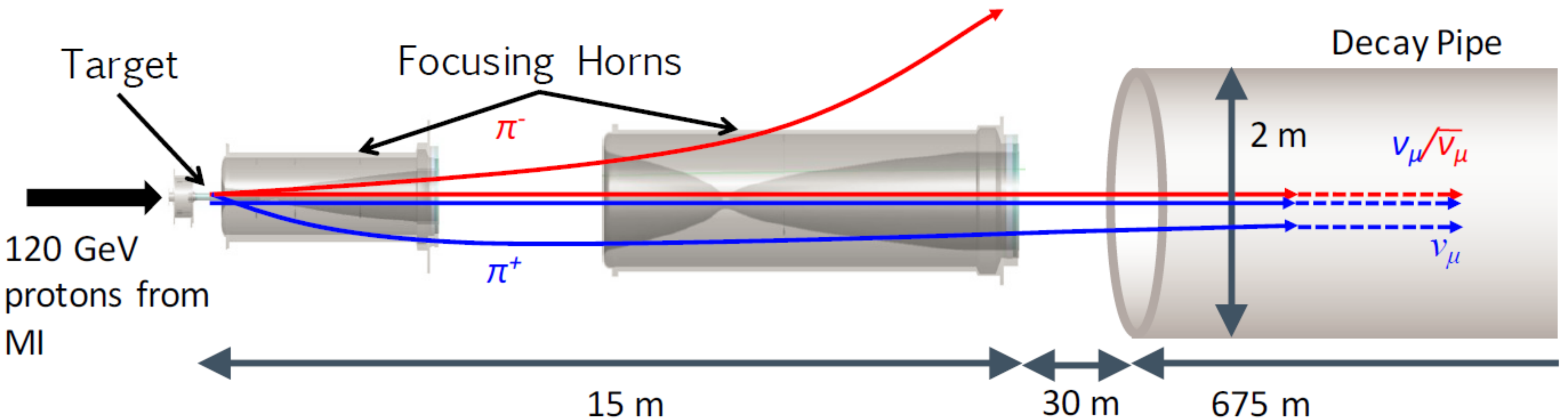
- Long-baseline, two-detector ν oscillation experiment
- Looks for ν_e in ν_μ NuMI beam
- 14 mrad off-axis
- 2 liquid scintillator detectors
- FD (14 kton), ND (0.3 kton)
- Cooled APD readout (live)
- Appearance & disappearance
- Exotics, non-beam…



How to make a neutrino beam

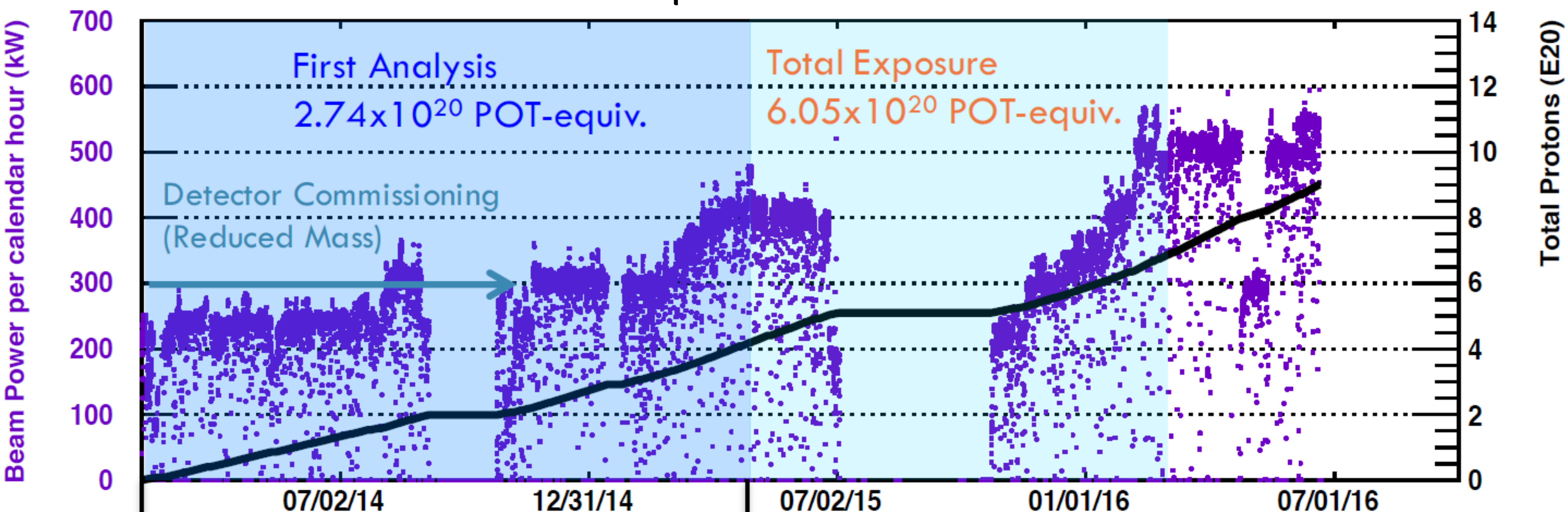
NuMI Off-axis ν_e Appearance

- NuMI - Neutrinos at the Main Injector, both ν_μ and $\bar{\nu}_\mu$
- 120GeV *p* on 1m graphite target - 10μs beam spill every 1.3 s
- Secondary pions decay – tertiary neutrino beam
- Beam 97.5% ν_μ with 0.7% ν_e and 1.8% wrong-sign
- 4.9×10^{13} POT/pulse – 6×10^{20} POT/year



Beam status

- Data from Feb 6, 2014 – May 2, 2016
- Achieved the 700kW design goal (750 kW)
- Switched to RHC ($\bar{\nu}_\mu$) Feb 20th, 2017



$\nu_\mu \rightarrow \nu_\mu$: Phys.Rev.D93.051104

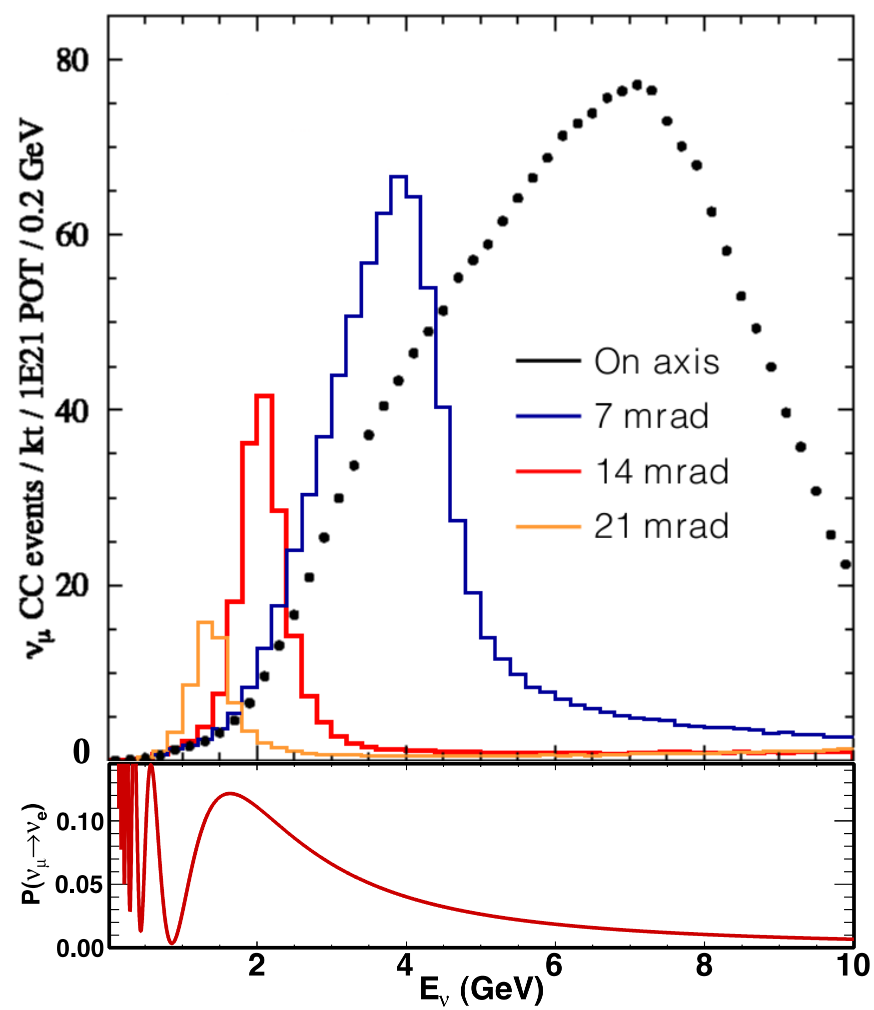
$\nu_\mu \rightarrow \nu_e$: PRL.116.151806

Why off-axis?

NuMI Off-axis ν_e Appearance

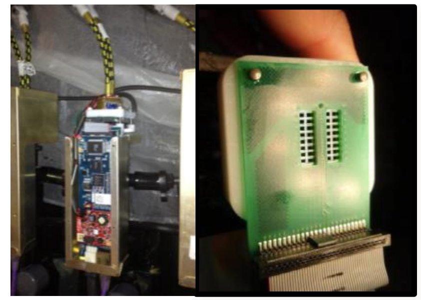
The choice of a 14 mrad off-axis position from the NuMI beam for the NOvA detector, allows for a narrow band beam which in conjunction with topology of final state particles, allows one to more easily reject potential backgrounds

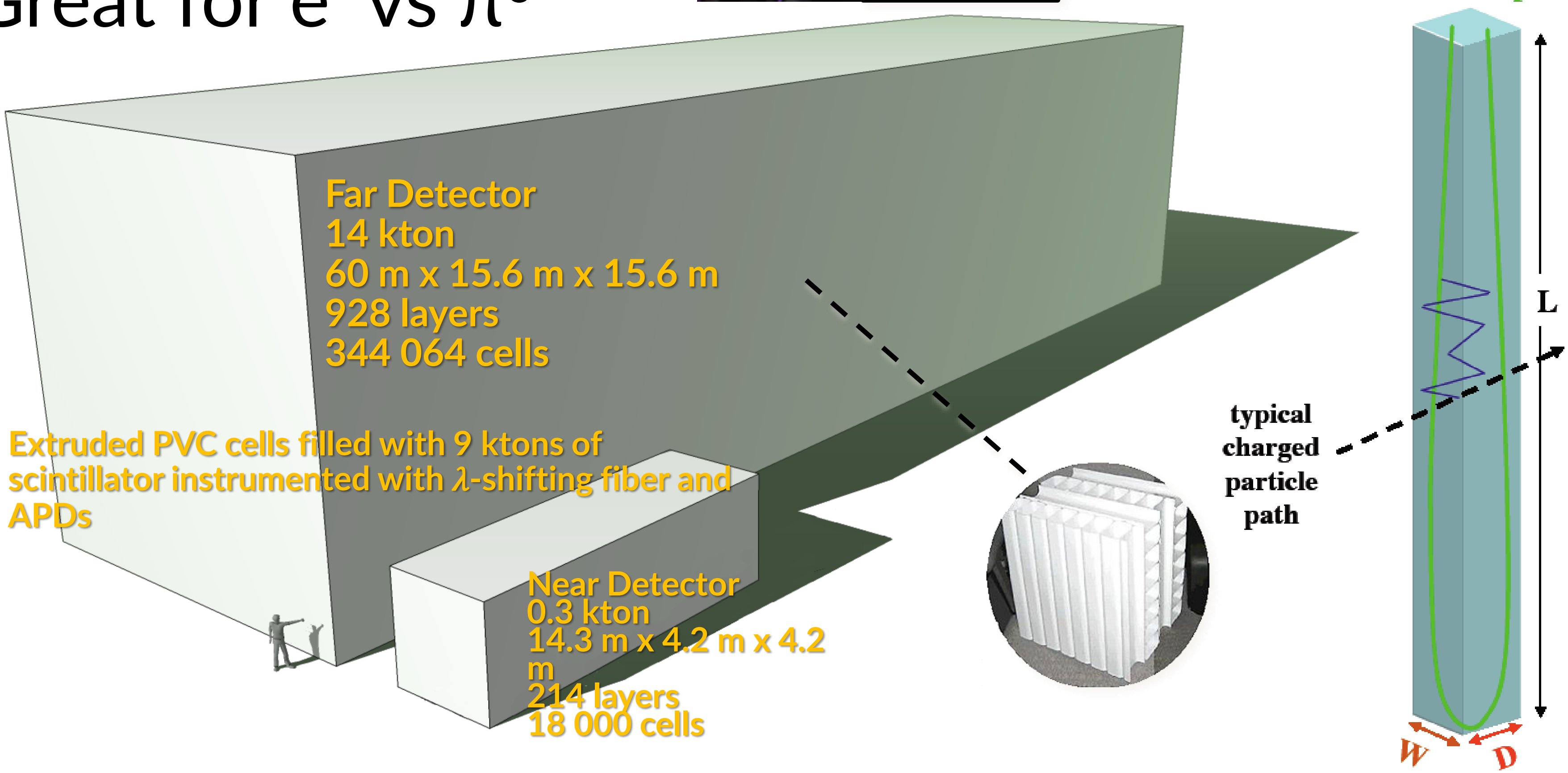
The peak of the beam coincides with the oscillation maximum for ν_e appearance at 810km distance



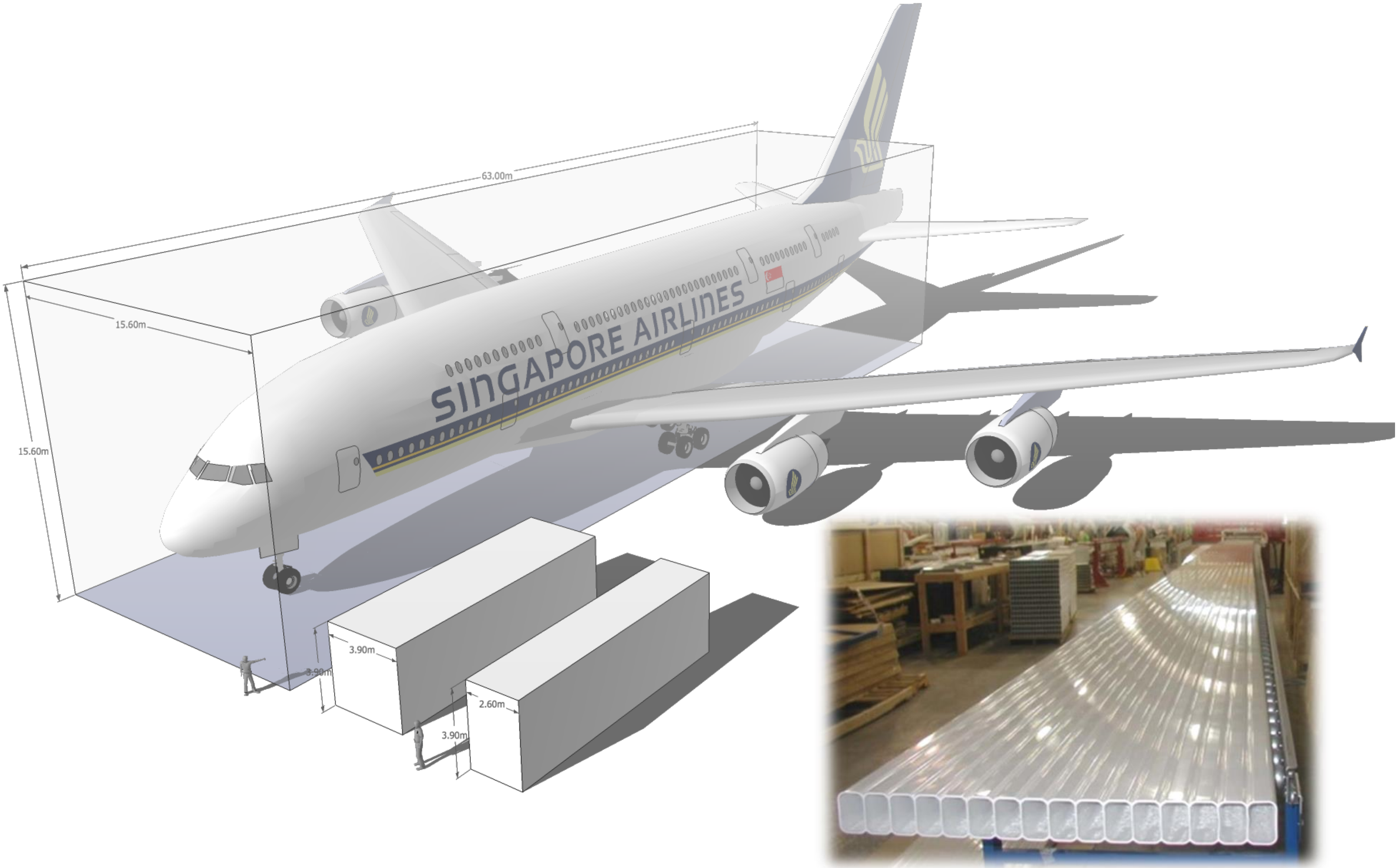
The NOvA detectors

- 65% active detectors
- Each plane 0.17 X_0
  Great for e^- vs π^0

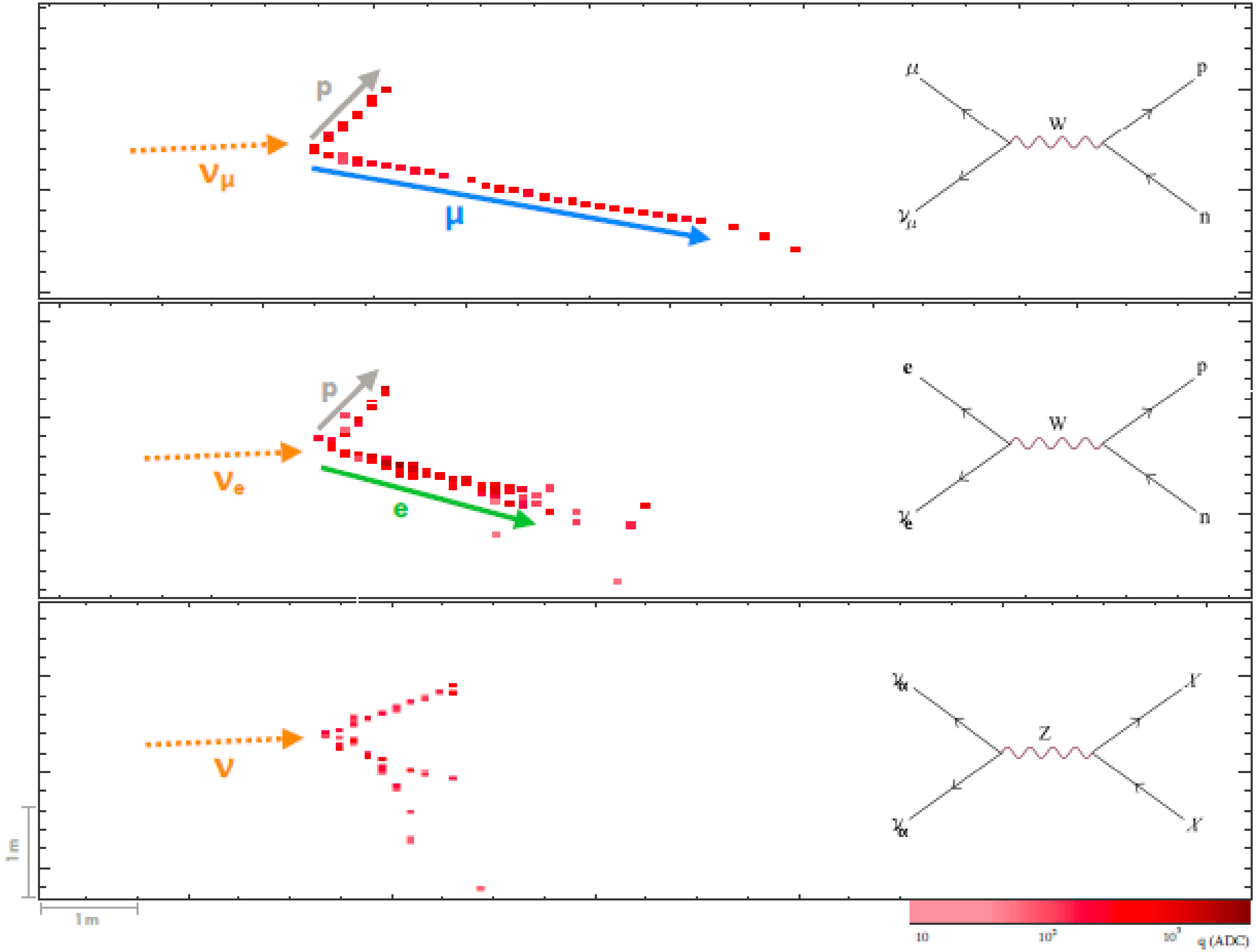




The NOvA detectors



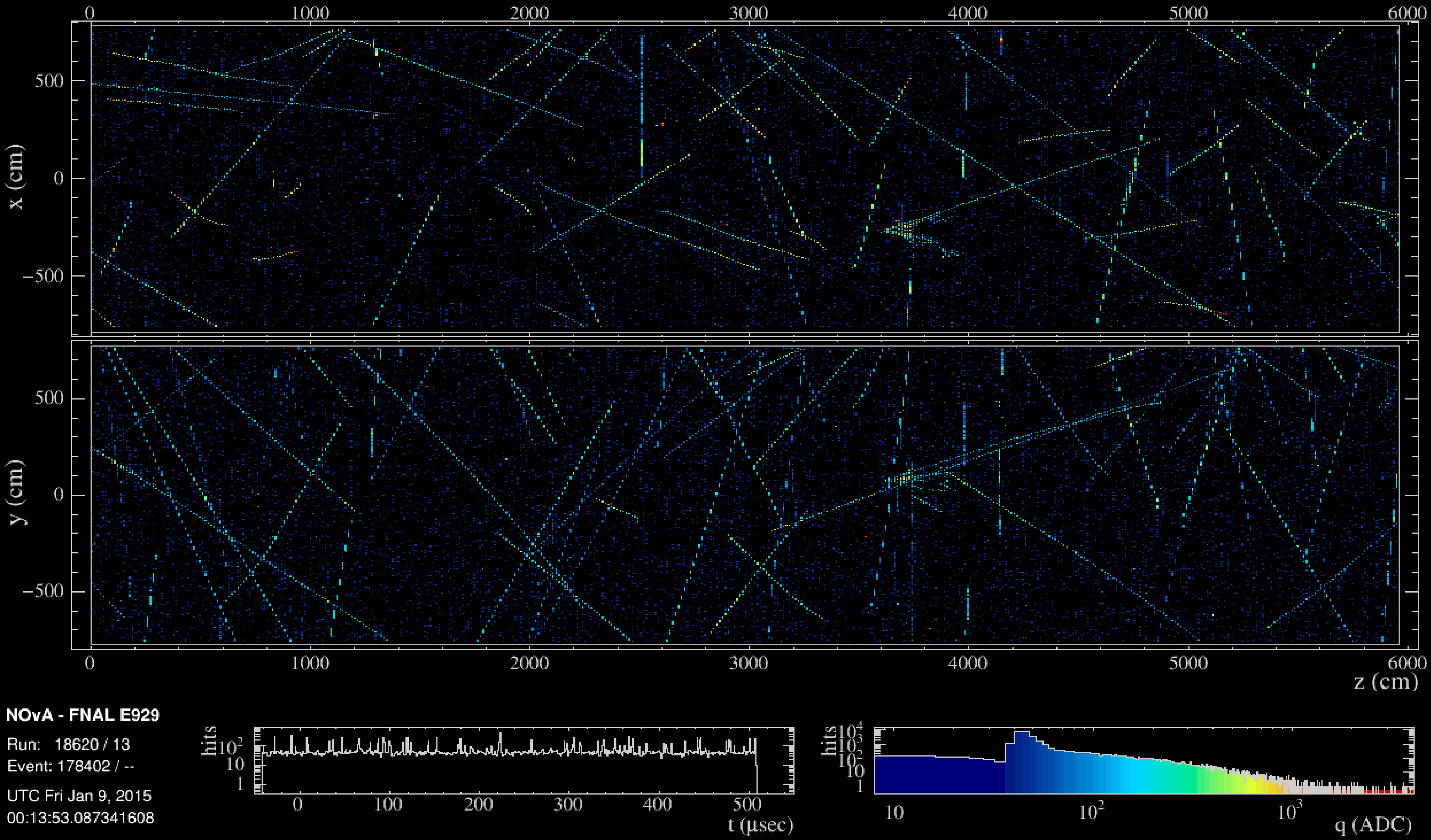
NOvA Neutrino Event Topologies



ν_μ CC

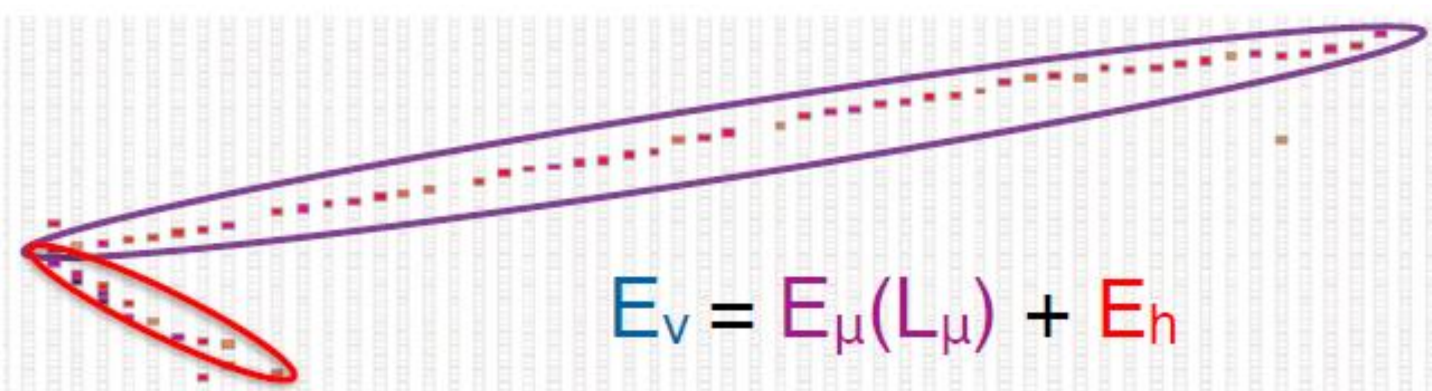
ν_e CC

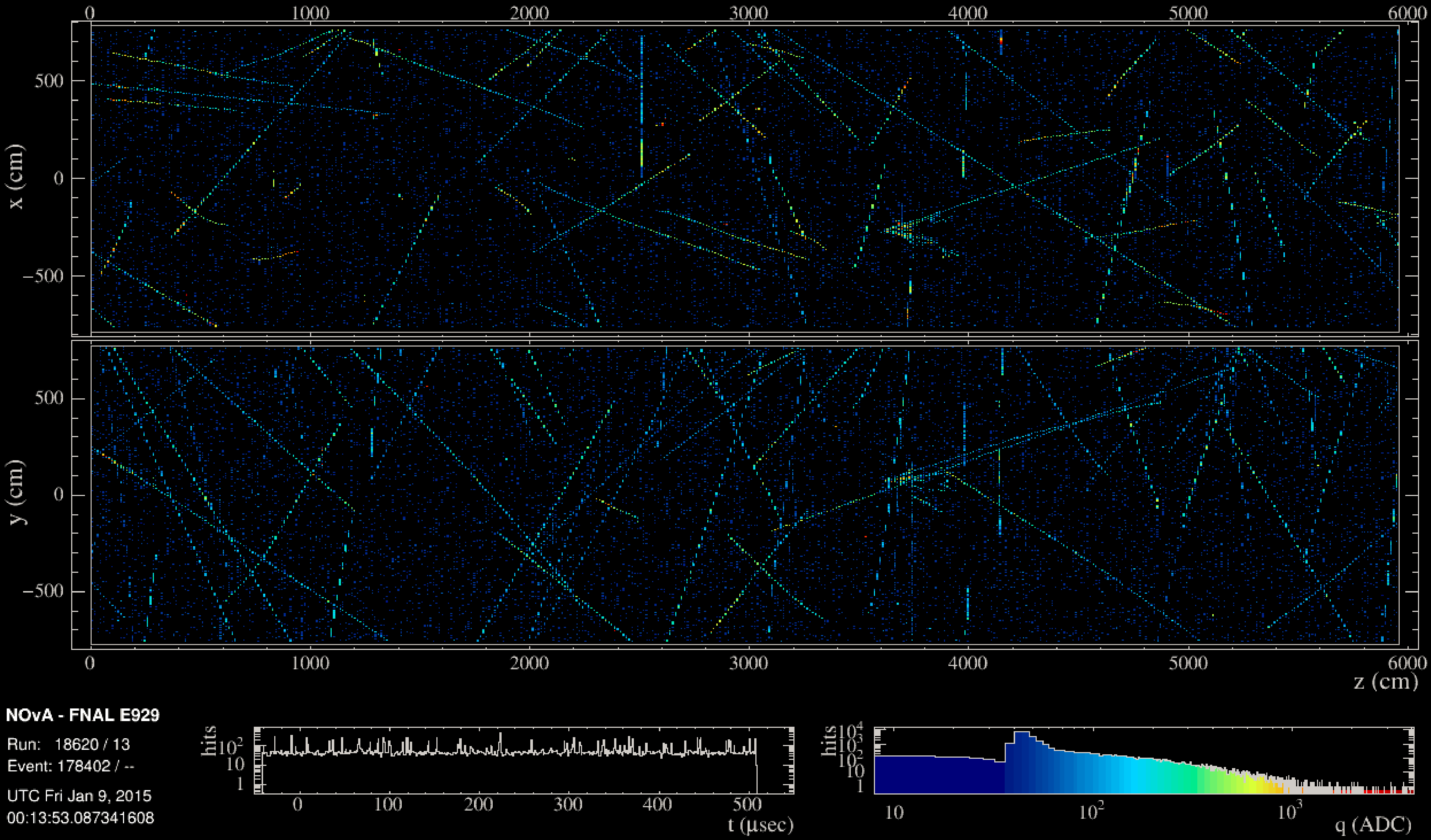
NC


x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)

ν_μ disappearance analysis

- kNN (length, dE/dx, scattering, plane fraction
  - excluding NC, long pions…
- Rock muons (ND)
- Cosmic rejection – 150kHz (10^5 pulsed beam, 10^7 BDT)
  - 2.7 cosmic background in our sample
- Energy estimation (μ + shower) ~7% resolution
- Near to Far extrapolation (reduces systematics)
  - high statistics ND data/MC to adjust prediction at FD





x (cm)
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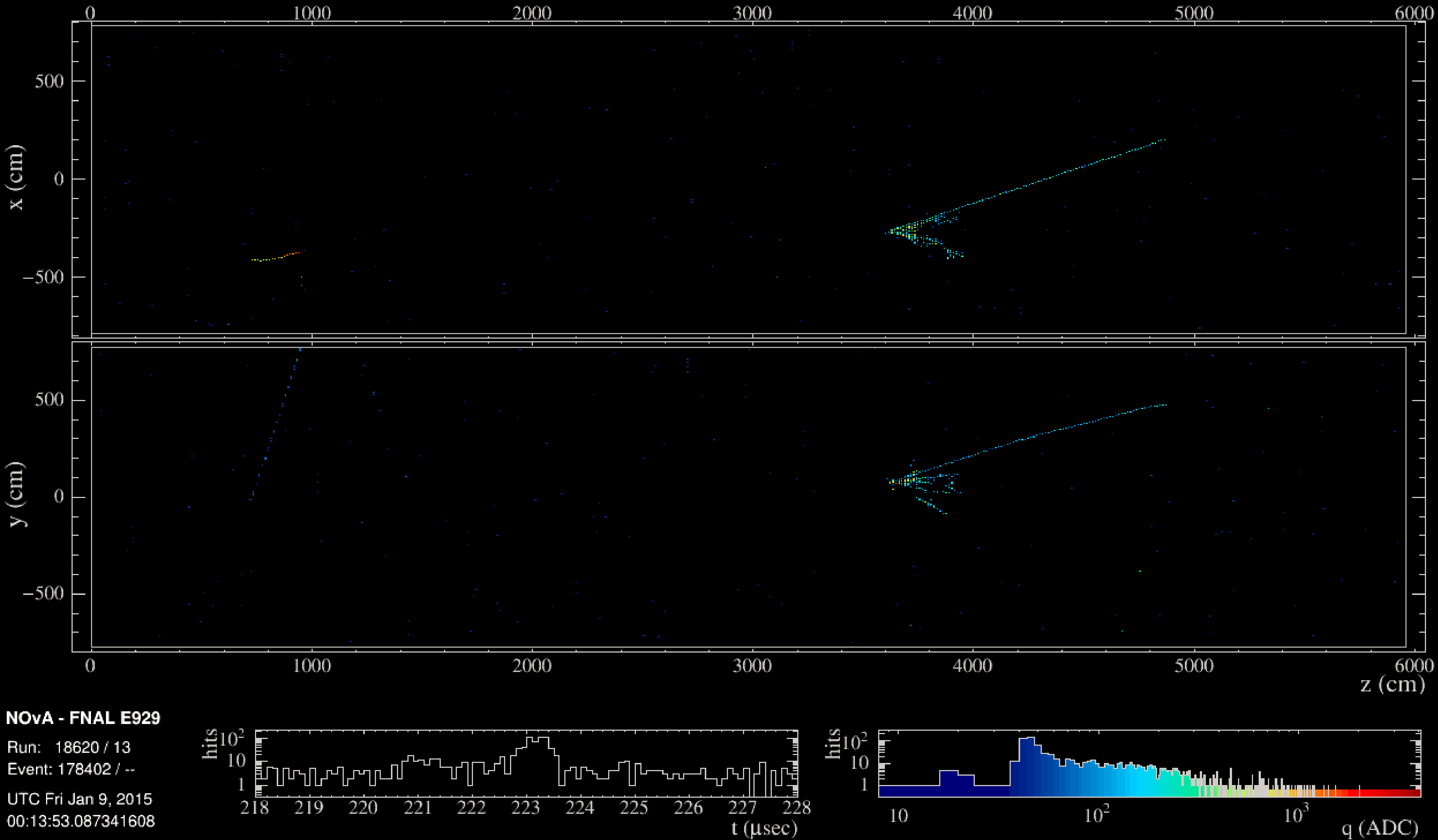

x (cm)
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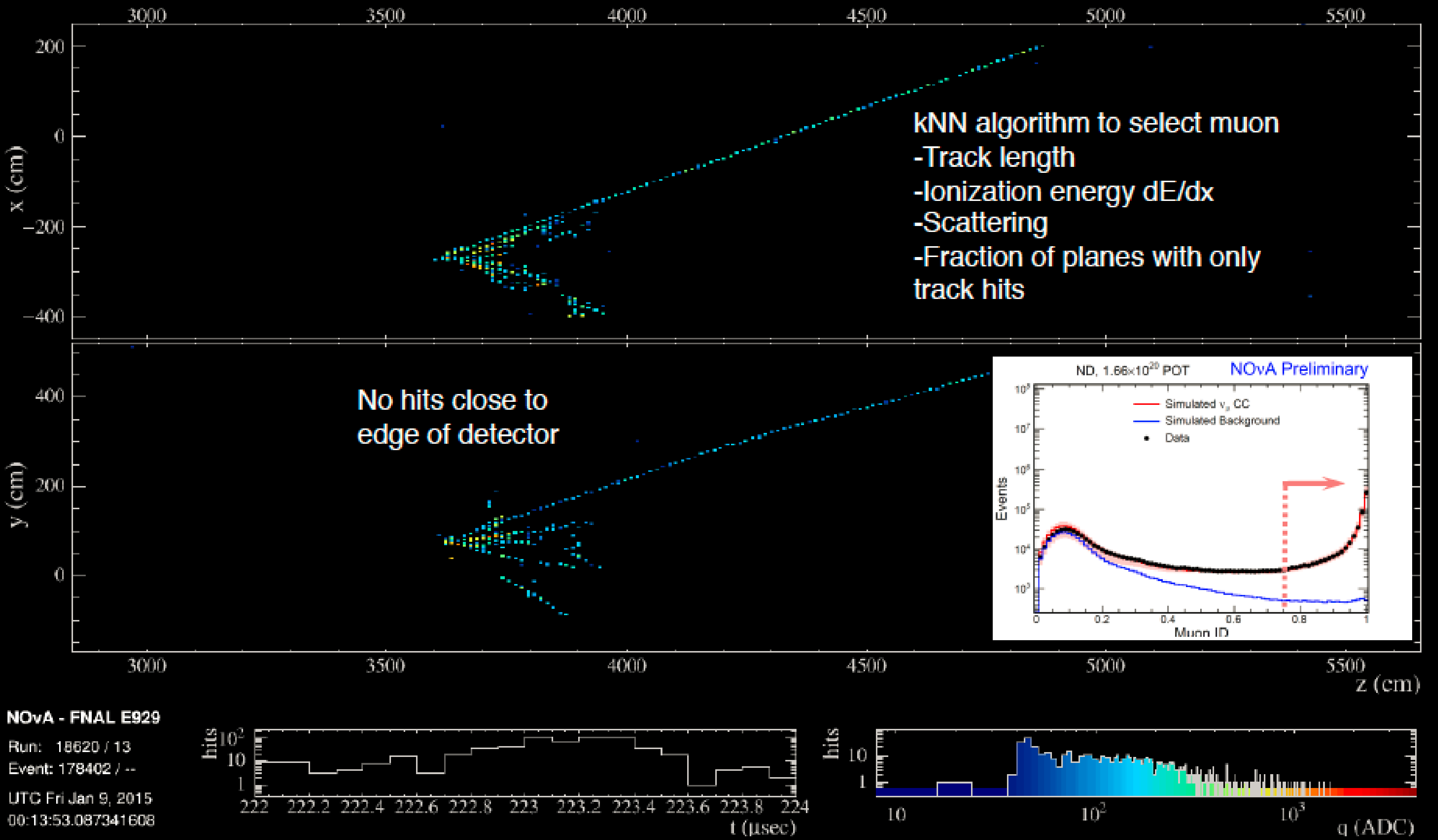
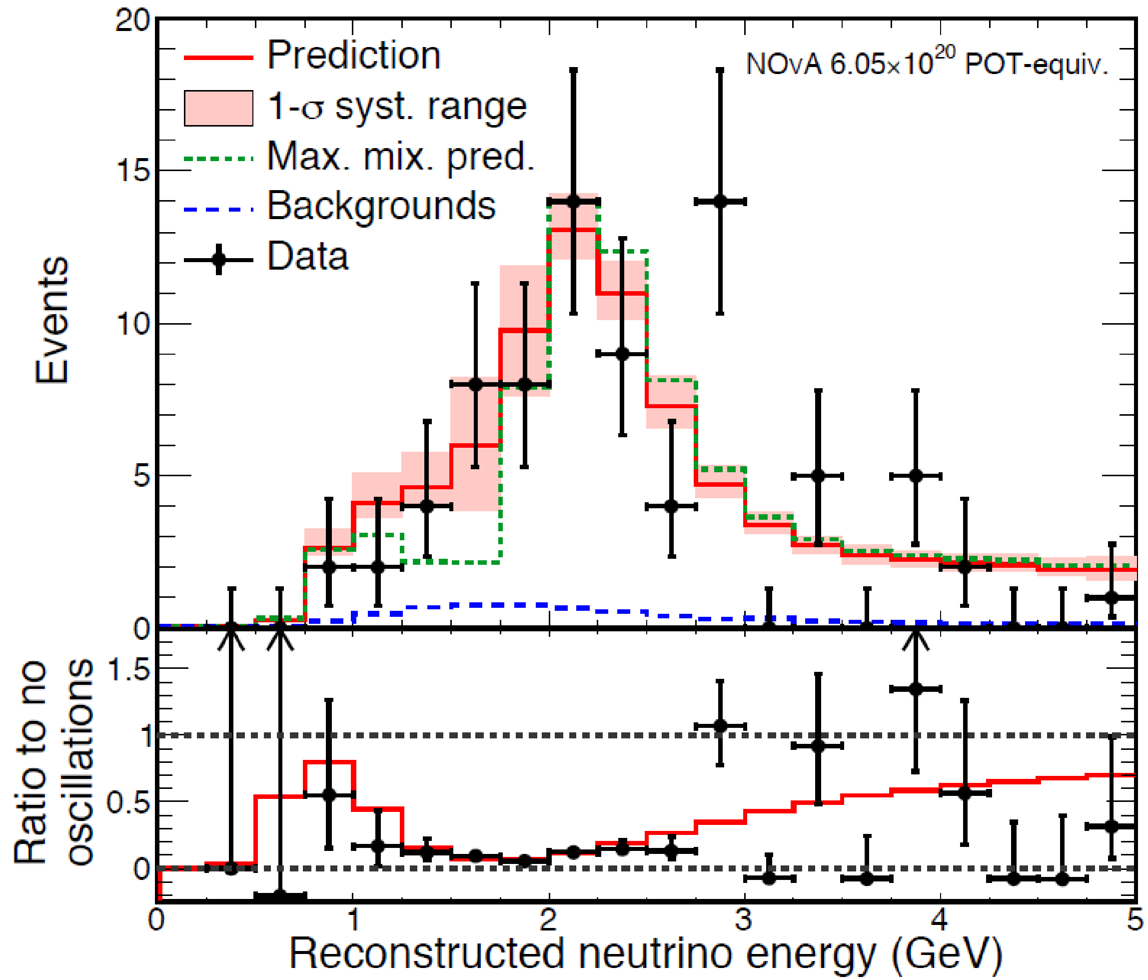
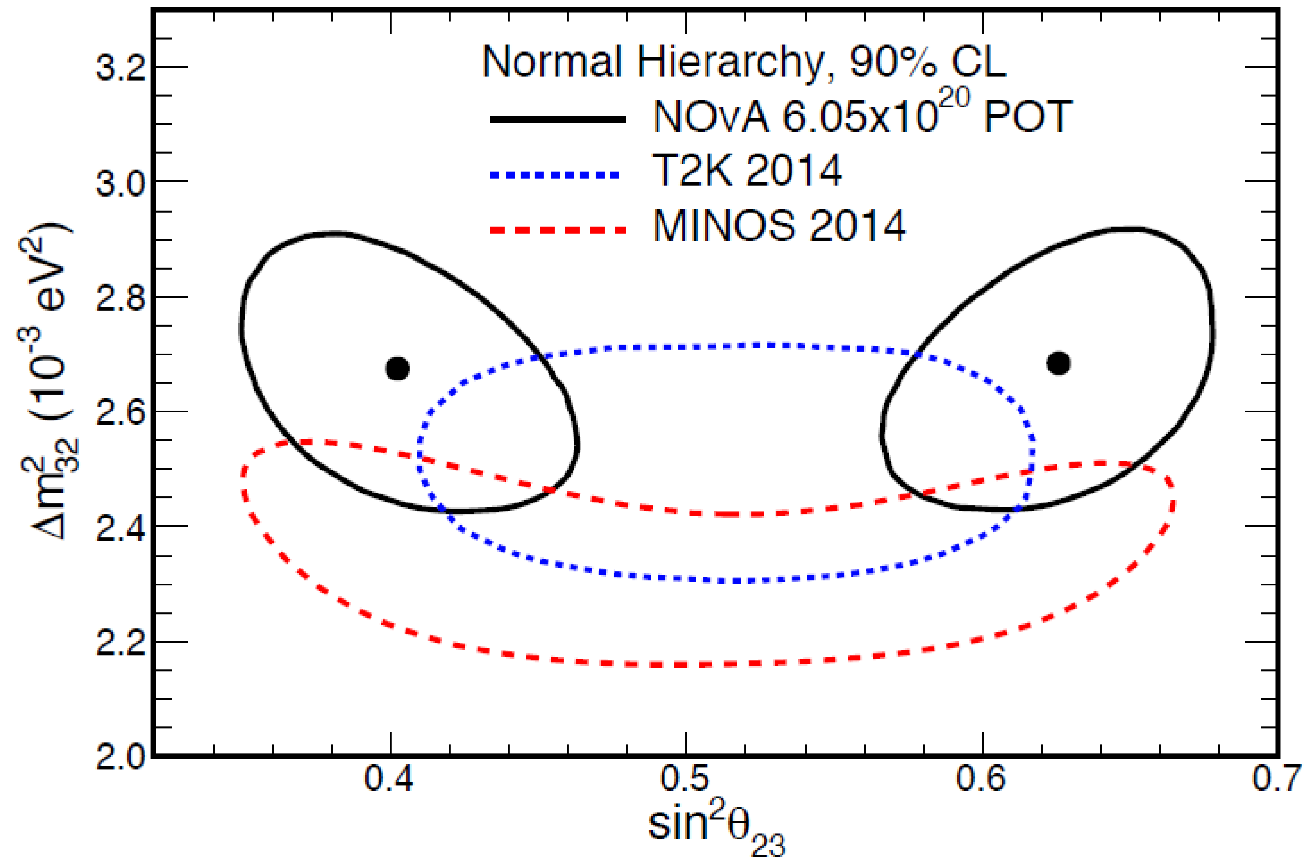

kNN algorithm to select muon
-Track length
-Ionization energy dE/dx
-Scattering
-Fraction of planes with only track hits
No hits close to edge of detector
ND, 1.66×10^20 POT
NOvA Preliminary
Simulated ν_μ CC
Simulated Background
Data
Events
Muon ID
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)

ν_μ disappearance results

- 473 ± 30 events predicted in the absence of oscillations
- 78 events observed
- 82 events predicted at the best fit point
  - including 3.7 beam bkg
  - 2.9 cosmic induced



ν_μ disappearance results

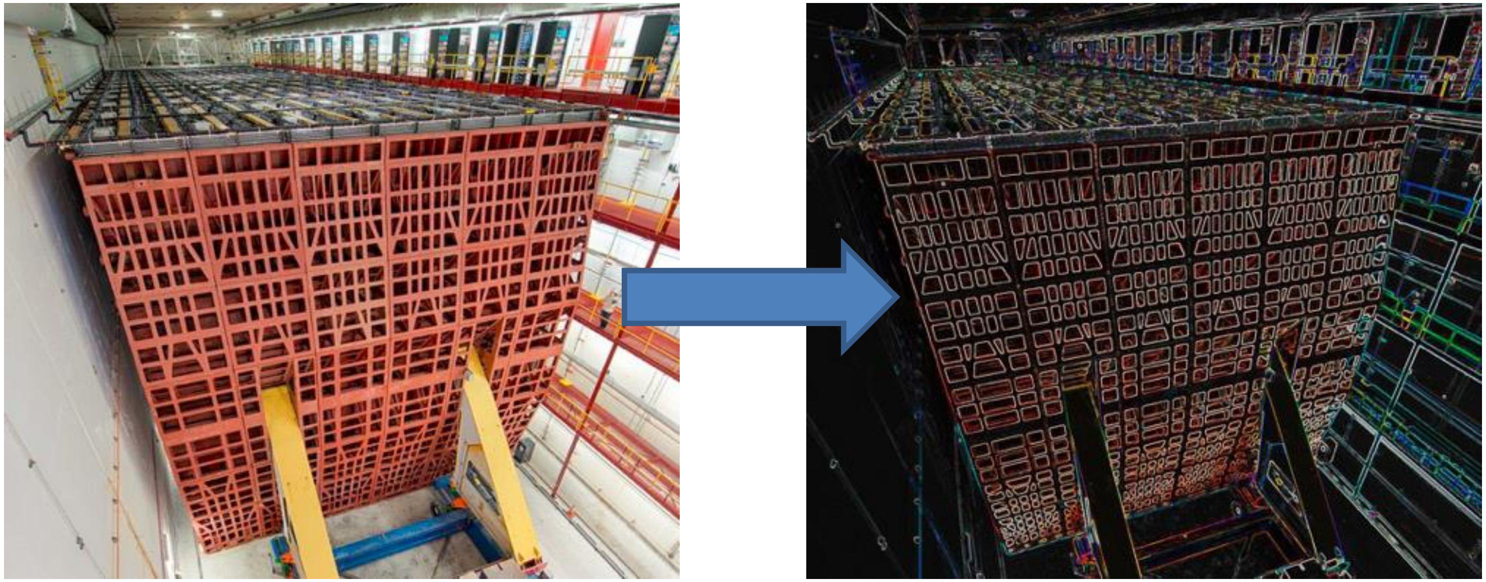


$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022} (0.624^{+0.022}_{-0.030})$$

Maximal mixing disfavored at 2.6 σ

ν_e appearance analysis - CVN

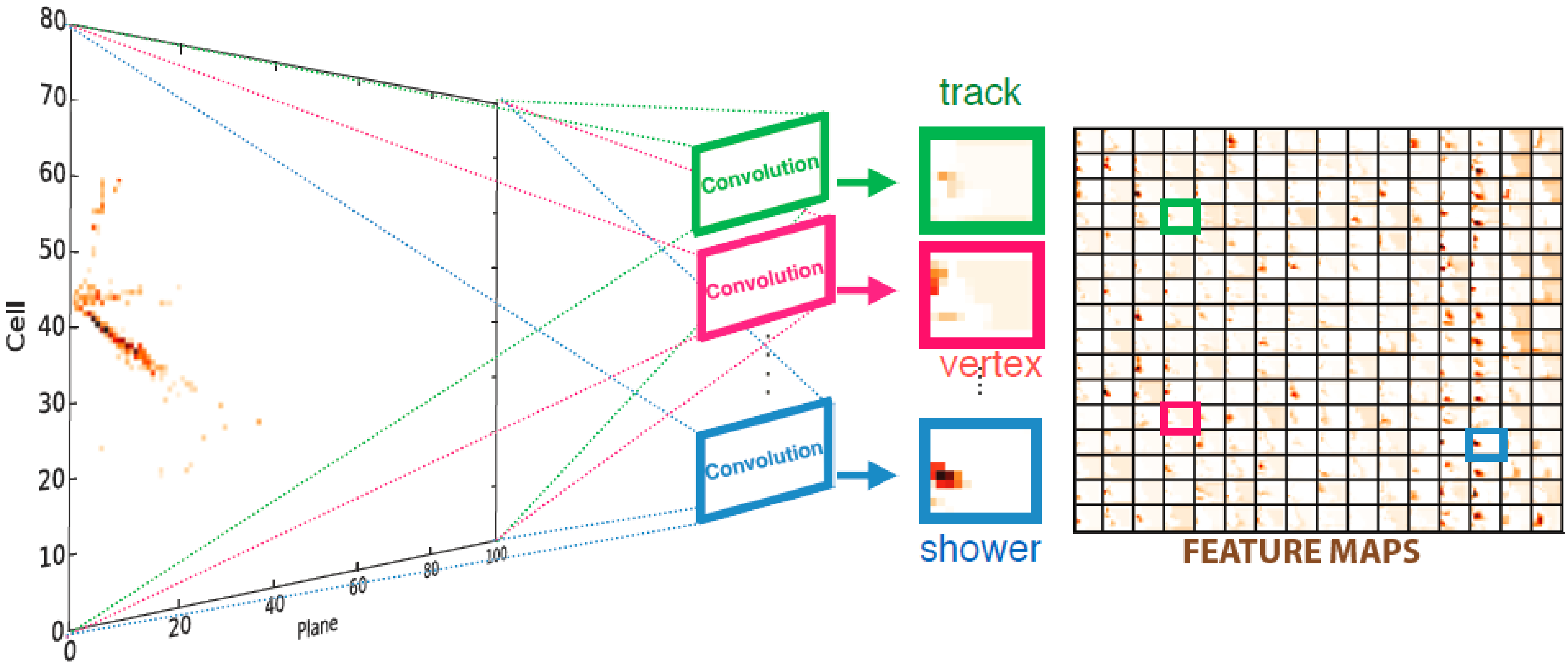


- Use recent development in computer vision:
  - CNN - convolutional neural networks
  - Act on an “image” – treat detector cells as pixels - **CVN**
  - Apply ***convolutional kernels*** to pull out event features
- Deep neural networks extract increasingly complex features from input data
  - GPUs greatly improve training time

arXiv:1604.01444

ν_e appearance analysis - CVN

- Showing an electron neutrino interaction and the first layer of feature maps extracted from the convolutional kernels
- The strong features extracted are the shower as opposed to the muon track



ν_e appearance analysis - CVN

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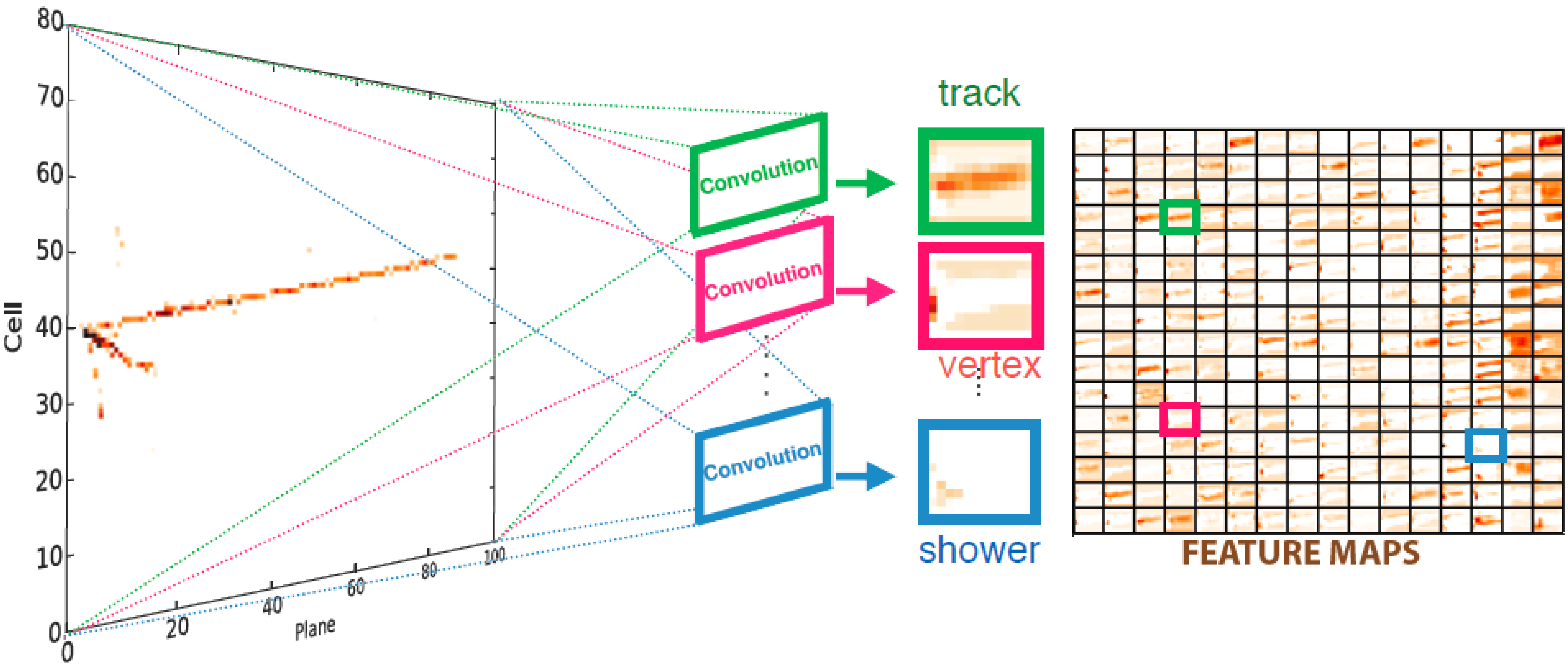
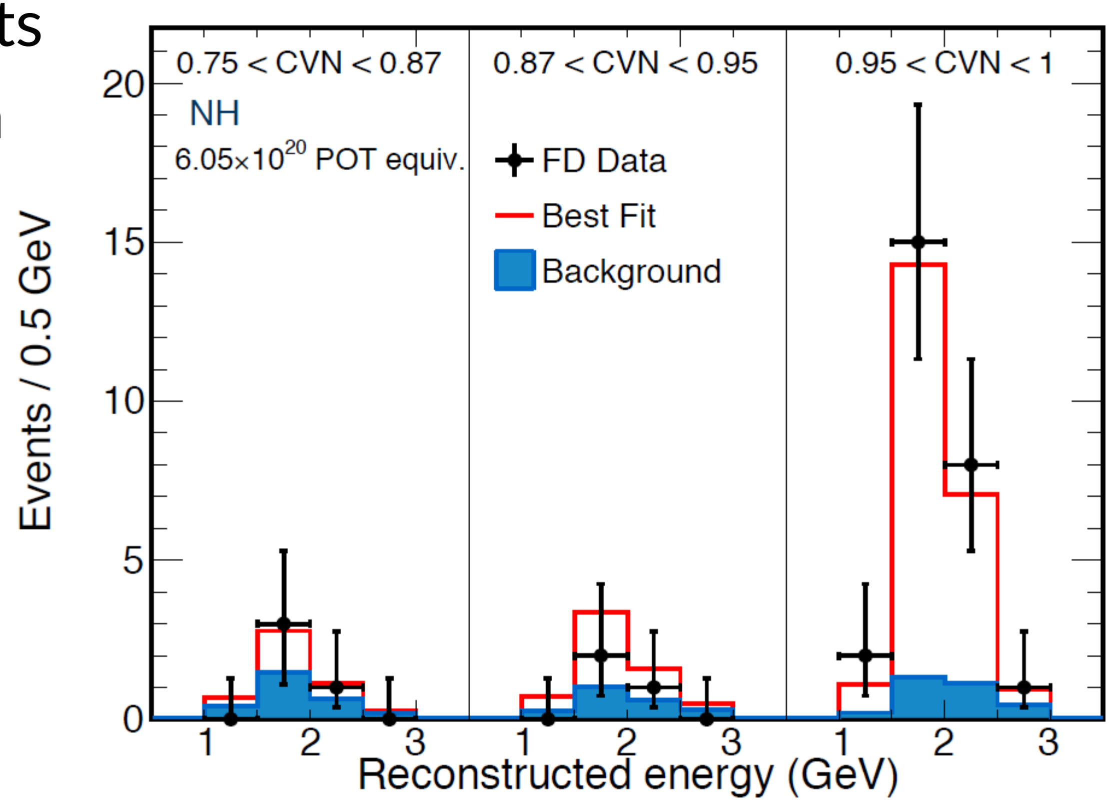


ν_e appearance analysis

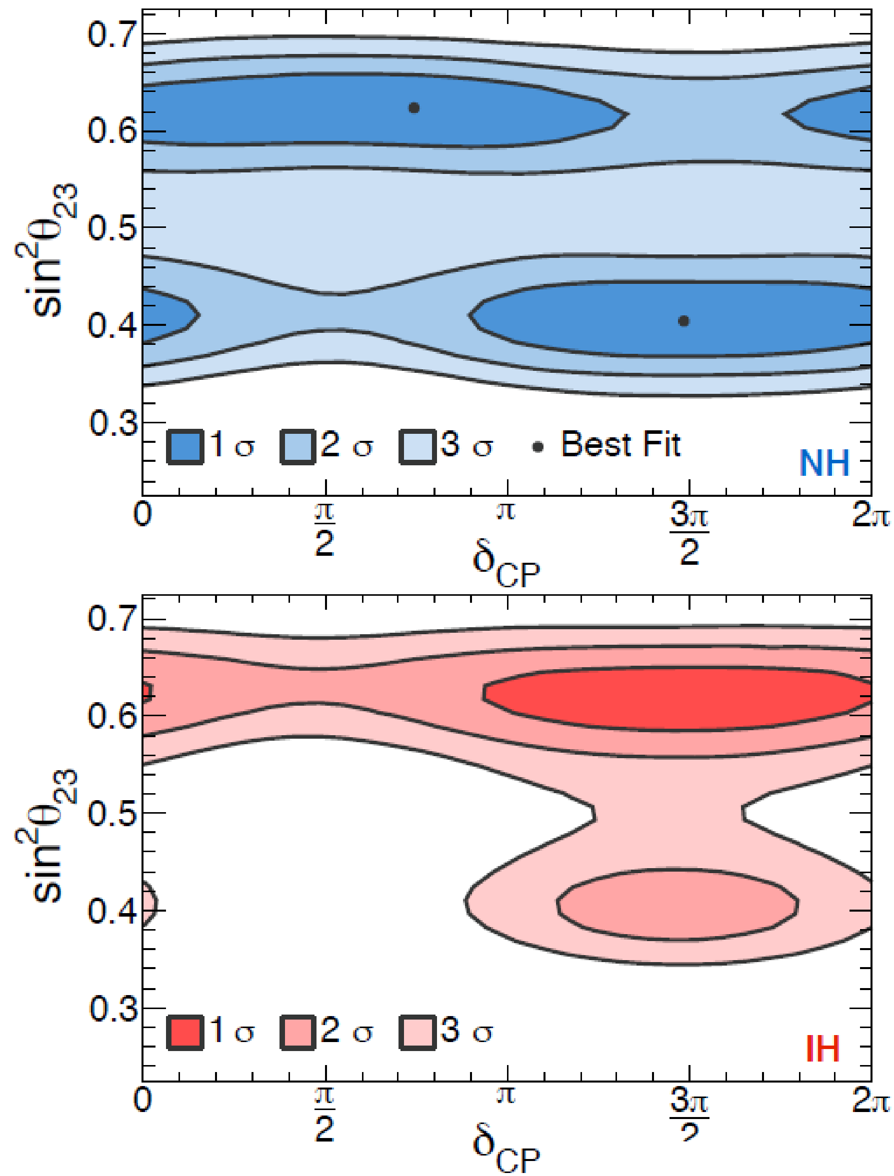
- ~30% more efficient than previous PID
- 4 energy bins, 3 PID bins
- Observe 33 events on a background of 8.2 ± 0.8
- θ_{13} to reactor experiments
- Joint fit with ν_μ spectrum



ν_e appearance results

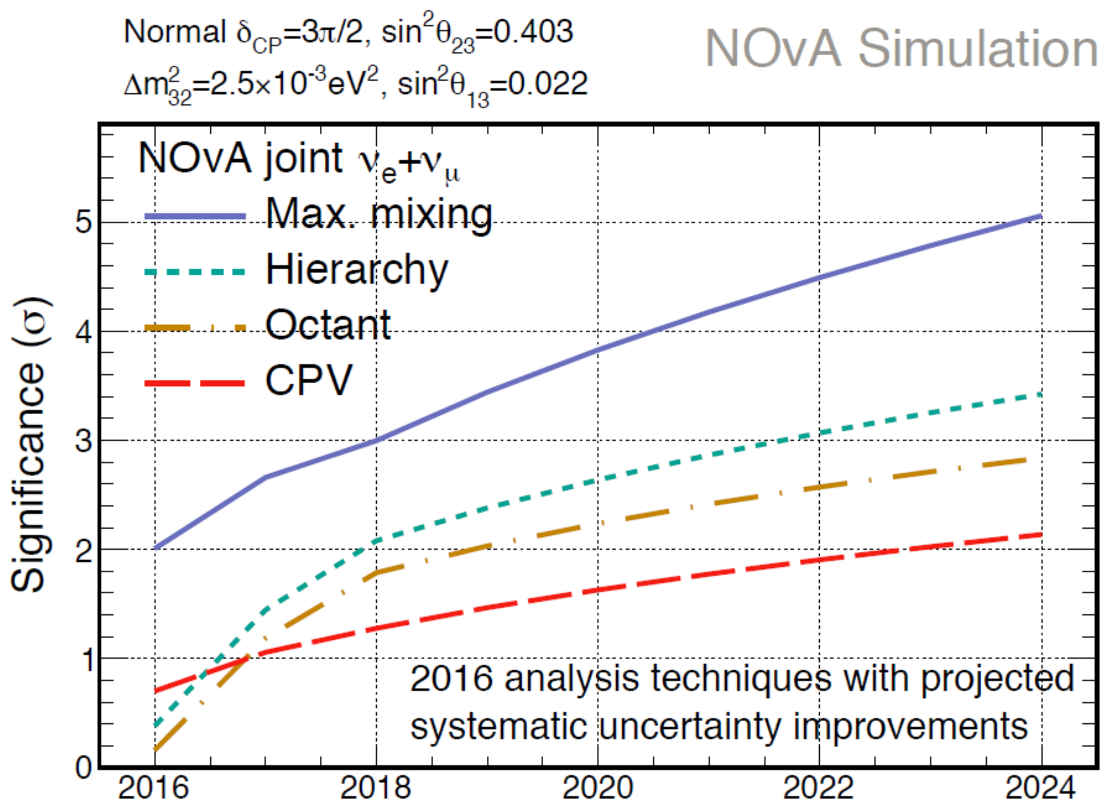
- 2 degenerate best fit points:
  - NH, $\delta_{CP} = 1.48\pi$
    $\sin^2\theta_{23} = 0.404$
  - NH, $\delta_{CP} = 0.74\pi$
    $\sin^2\theta_{23} = 0.623$
- Inverted hierarchy slightly disfavored - $\Delta\chi^2 = 0.47$
- Lower octant in the IH is disfavored at 93% CL

- arXiv:1703.03328



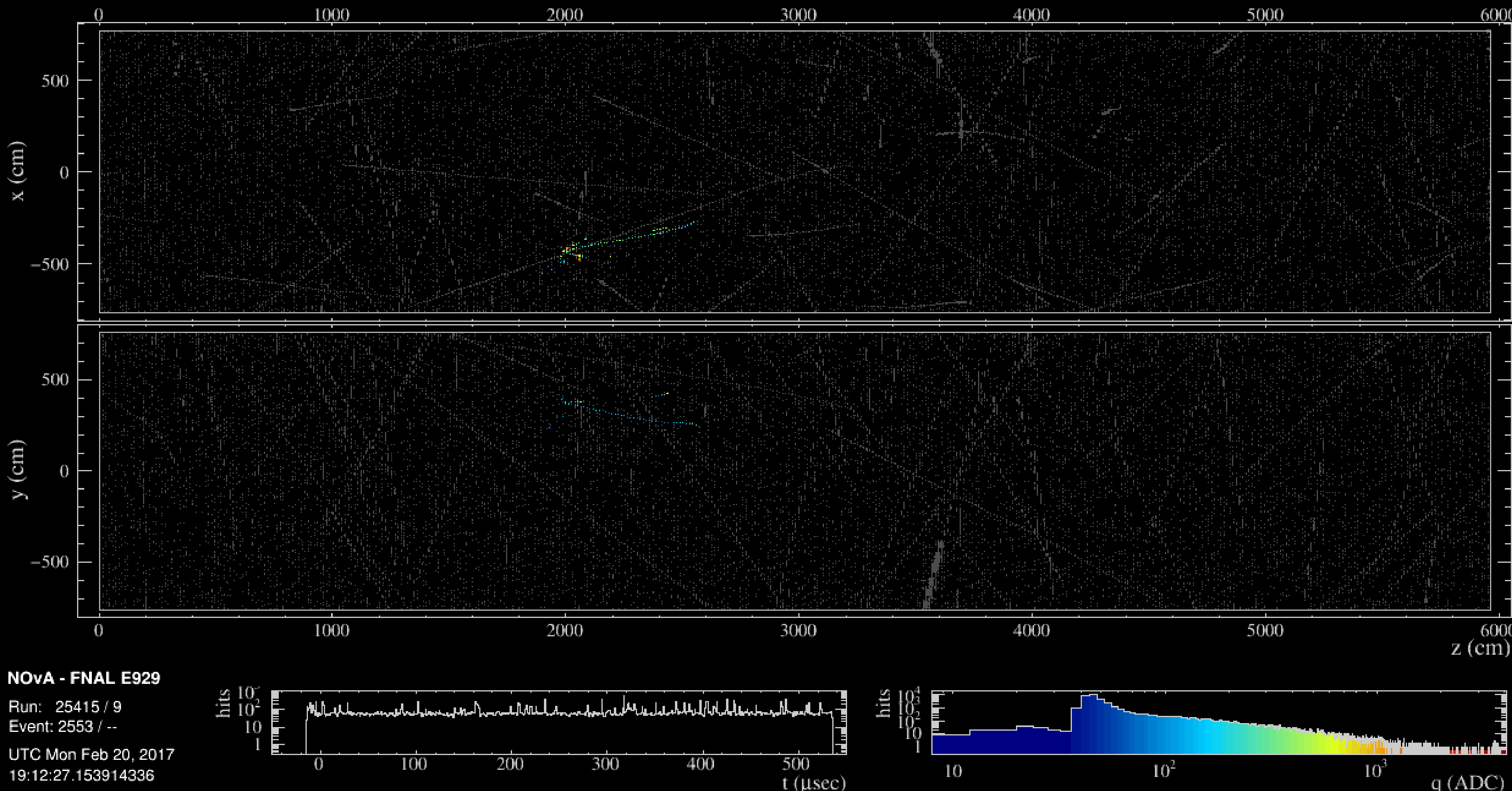
Outlook

- RHC anti-neutrino running from February 2017
- Run 50% neutrino, 50% anti-neutrino past 2018
  - 3σ sensitivity to maximal mixing of θ_{23} in 2018
  - 2σ sensitivity to mass hierarchy and θ_{23} octant in 2018-19

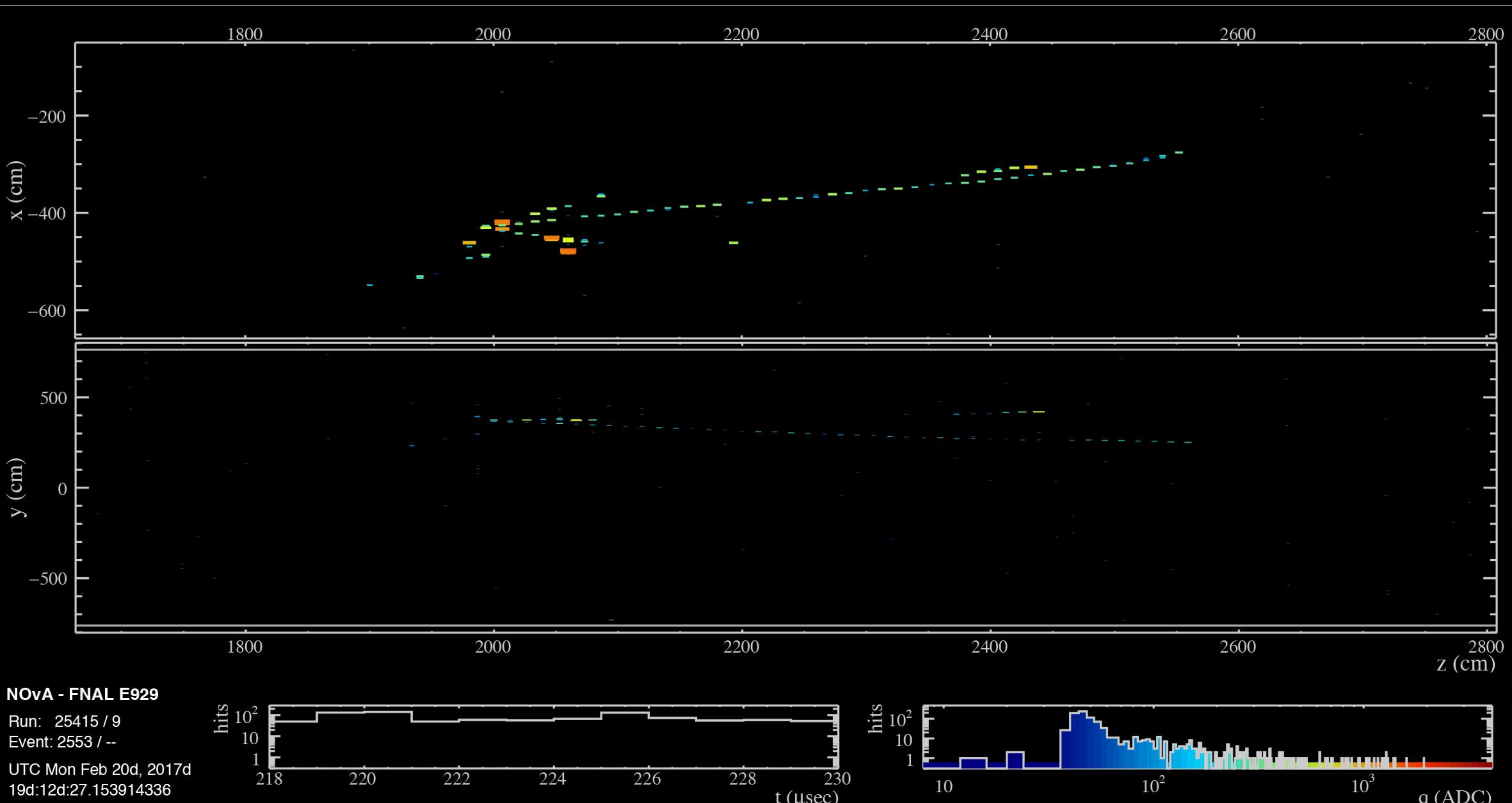


Summary

- 6.05×10^{20} POT NOvA data analyzed, 3 flavor fit
- ν_μ disappearance favors non-maximal mixing
  - **Exclude $\sin^2\theta_{23} = 0.5$** at 2.6σ
  - arXiv:1701.05891
- Joint fit to ν_μ disappearance and ν_e appearance
  - Novel CVN PID used
  - **Excludes inverted hierarchy, lower octant** at 93% C.L.
  - Weak preference for the normal hierarchy overall
  - arXiv:1703.03328
- Anti-neutrino mode beam from last month
  - First antineutrino few hours after launch



NOvA - FNAL E929
Run: 25415 / 9
Event: 2553 / --
UTC Mon Feb 20, 2017
19:12:27.153914336
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)



1800
2000
2200
2400
2600
2800
−200
−400
−600
x (cm)
500
0
−500
y (cm)
z (cm)
NOvA - FNAL E929
Run: 25415 / 9
Event: 2553 / --
UTC Mon Feb 20d, 2017d
19d:12d:27.153914336
hits
t (μsec)
q (ADC)

Stay tuned

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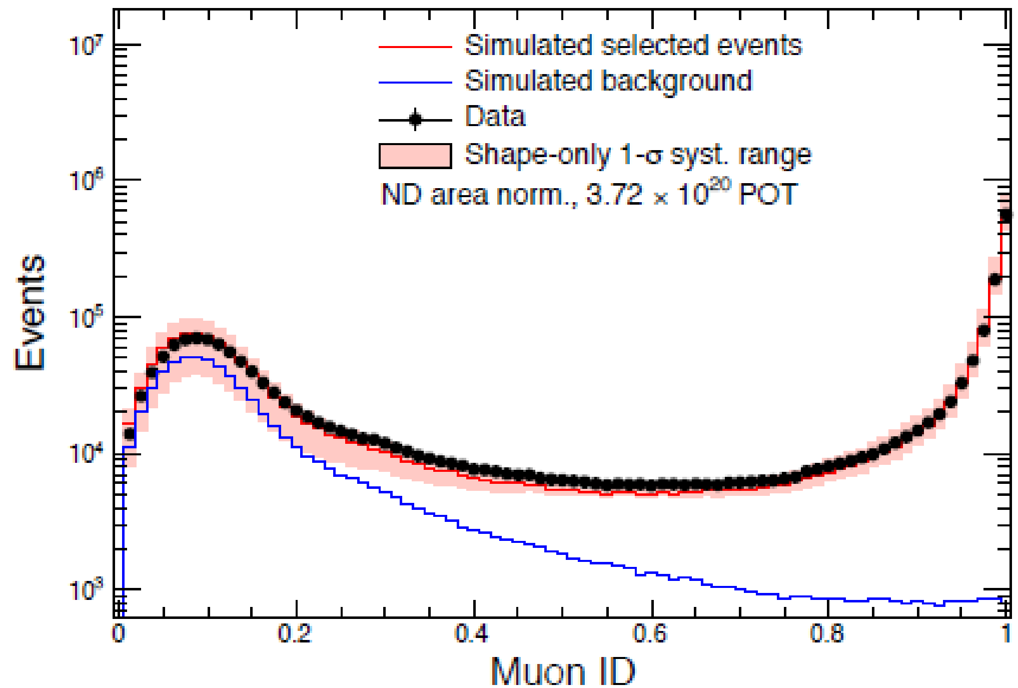
www-nova.fnal.gov

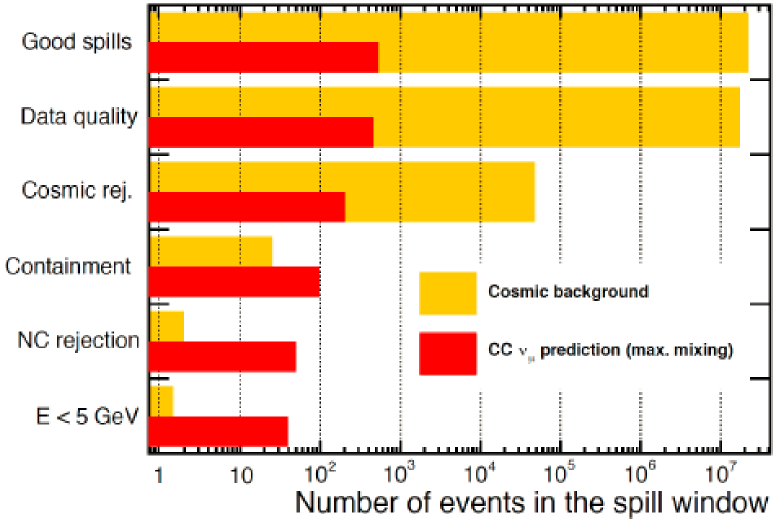
Backup

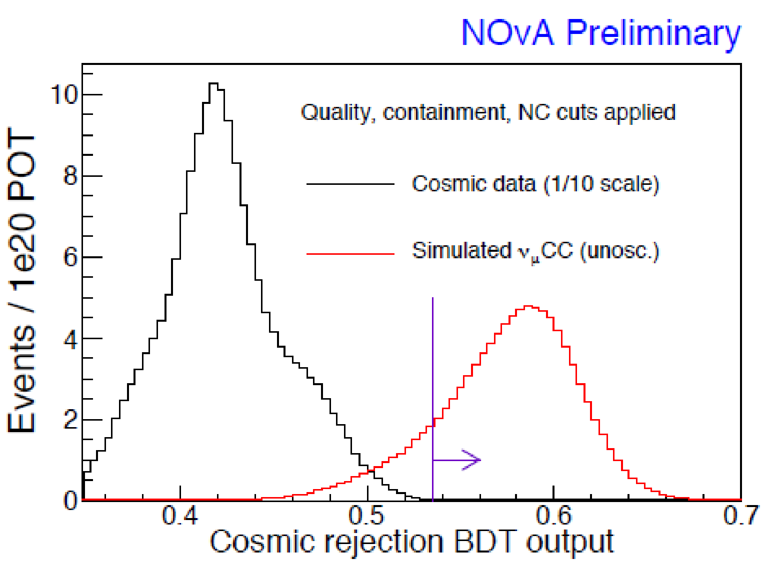
Selecting ν_μ's: Excluding NC Events

- No flavor ID → no oscillation information.
- Long $\pi^\pm$ can mimic a μ
  - Important background in both detectors.
- Exclude using a kNN
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction
- Performance:
  - 81% efficiency
  - 91% purity



Cosmic rejection

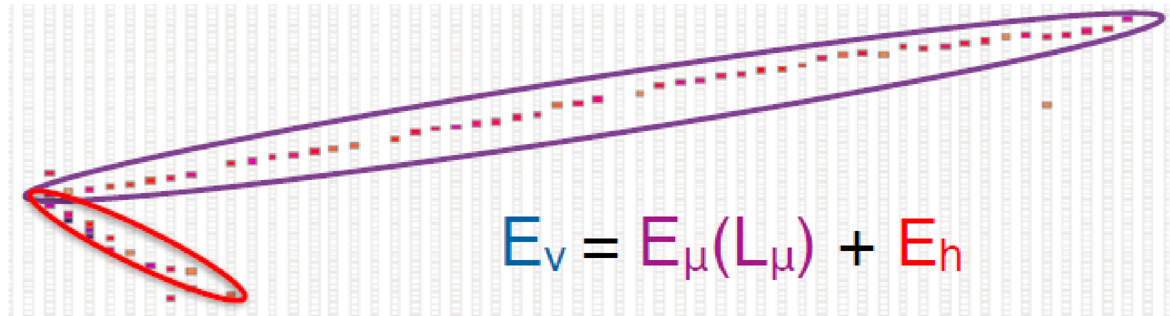




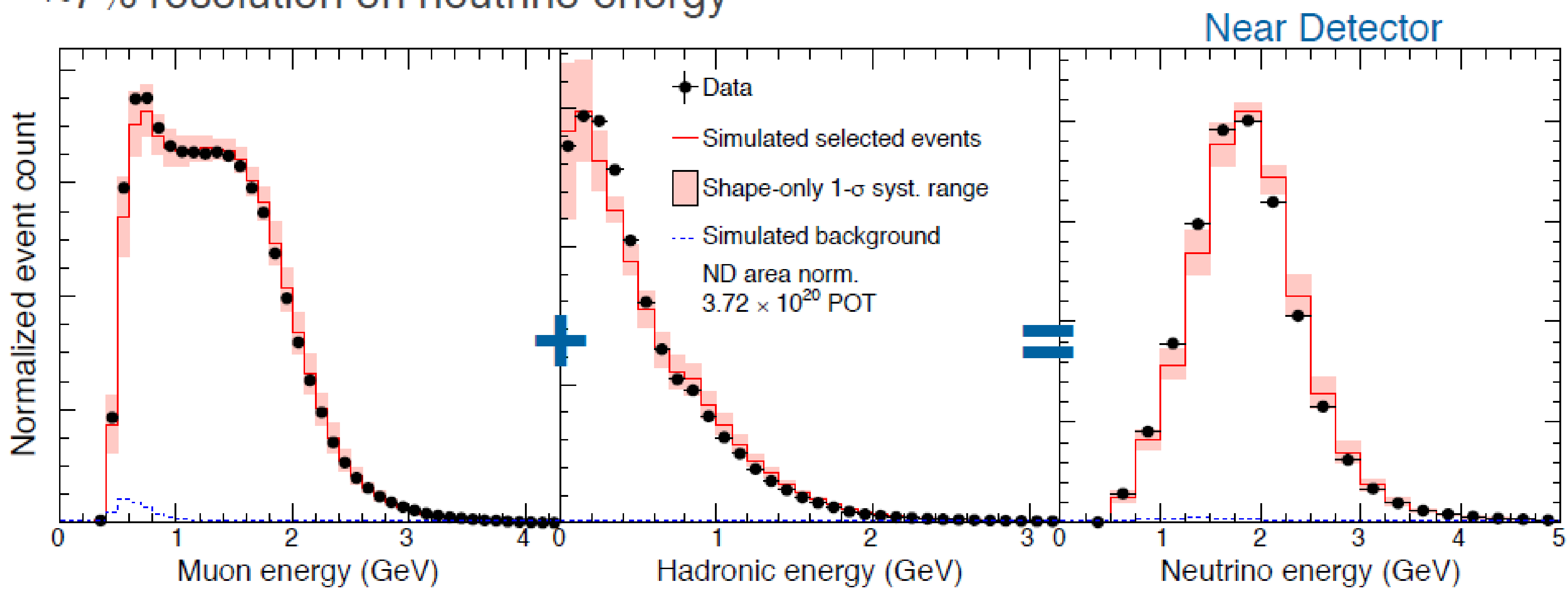
- Far Detector sees 150 kHz of cosmic induced events
- 10 μs beam window at a rate of ~0.8 Hz reduces background by 10^5
- Additional factor of 10^7 rejection achieved from event topology and a boosted decision tree (BDT) based on:
  - track direction
  - start/end points of track
  - track length
  - energy
  - number of hits
- Predict 2.7 cosmic background events

Numu energy estimation

Energy Estimation

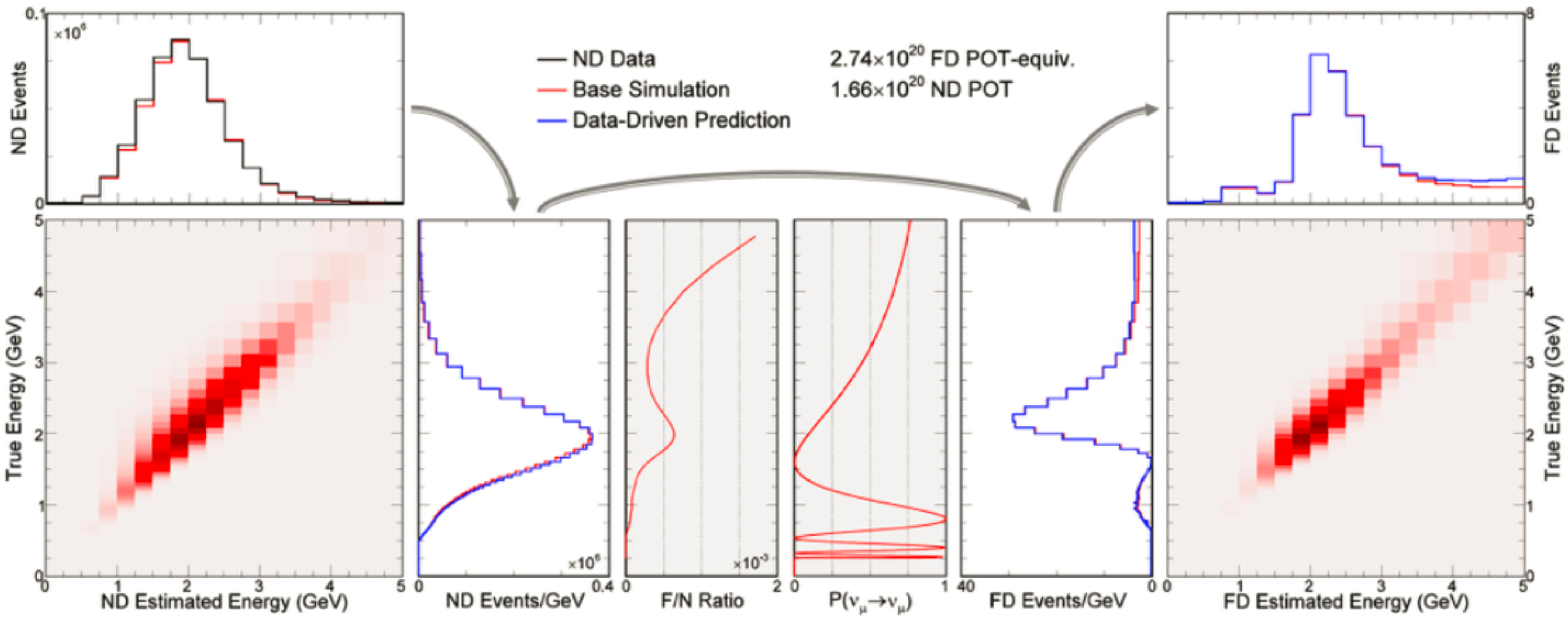


- Muon dE/dx used in length-to-energy conversion
- Hadronic energy estimated calorimetrically from off-track hits
- ~7% resolution on neutrino energy

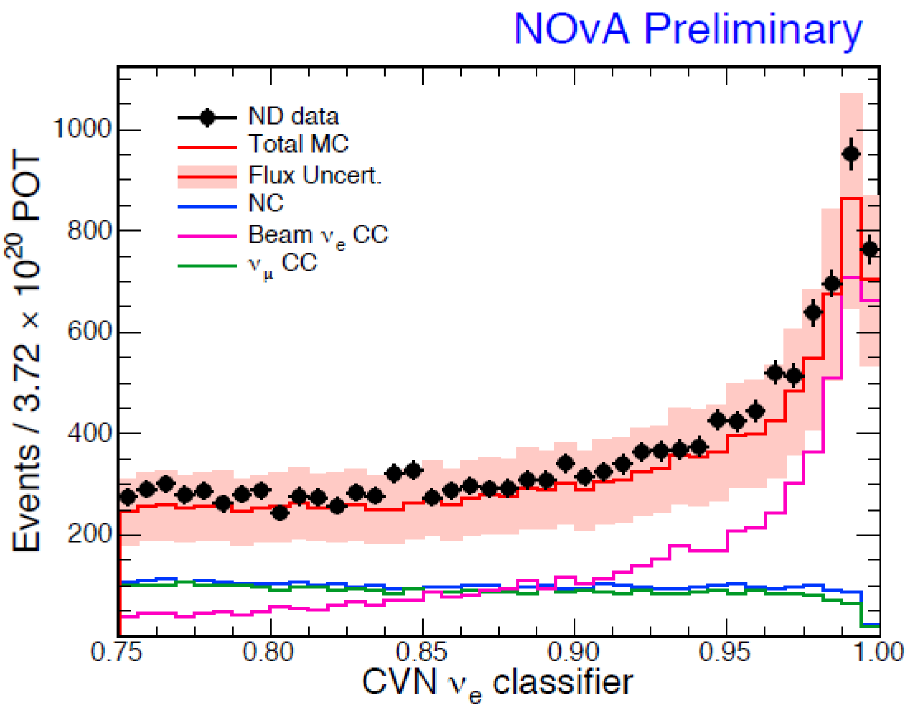


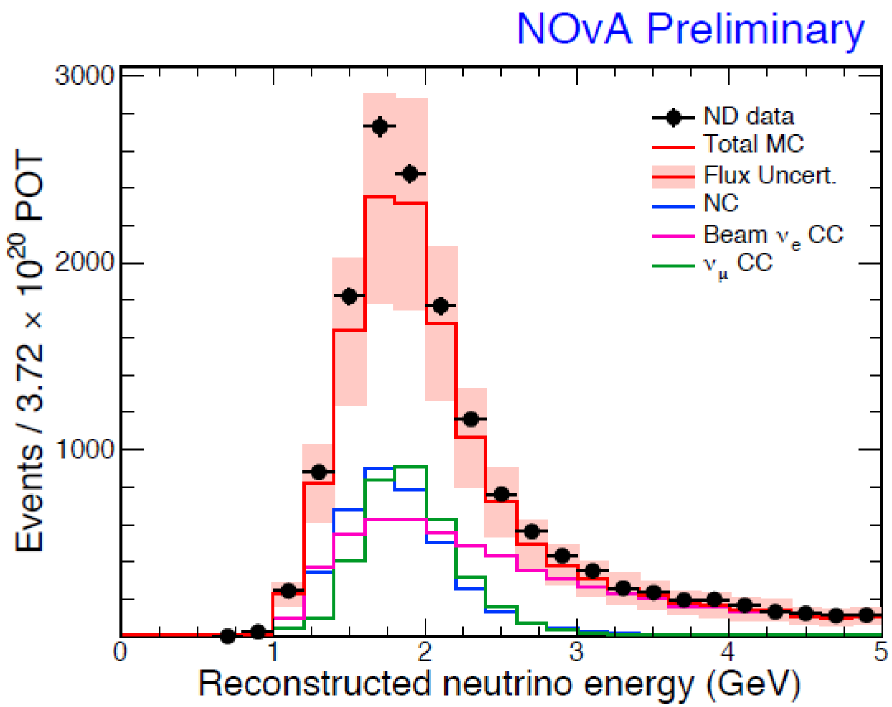
Extrapolation

- Use high statistics ND data/MC to adjust prediction at FD
  - Translate ND data/MC observation to true energy
  - Oscillate ratio to the FD
  - Smear back into reconstructed energy
- Reduces systematic uncertainties



Electron neutrino selection

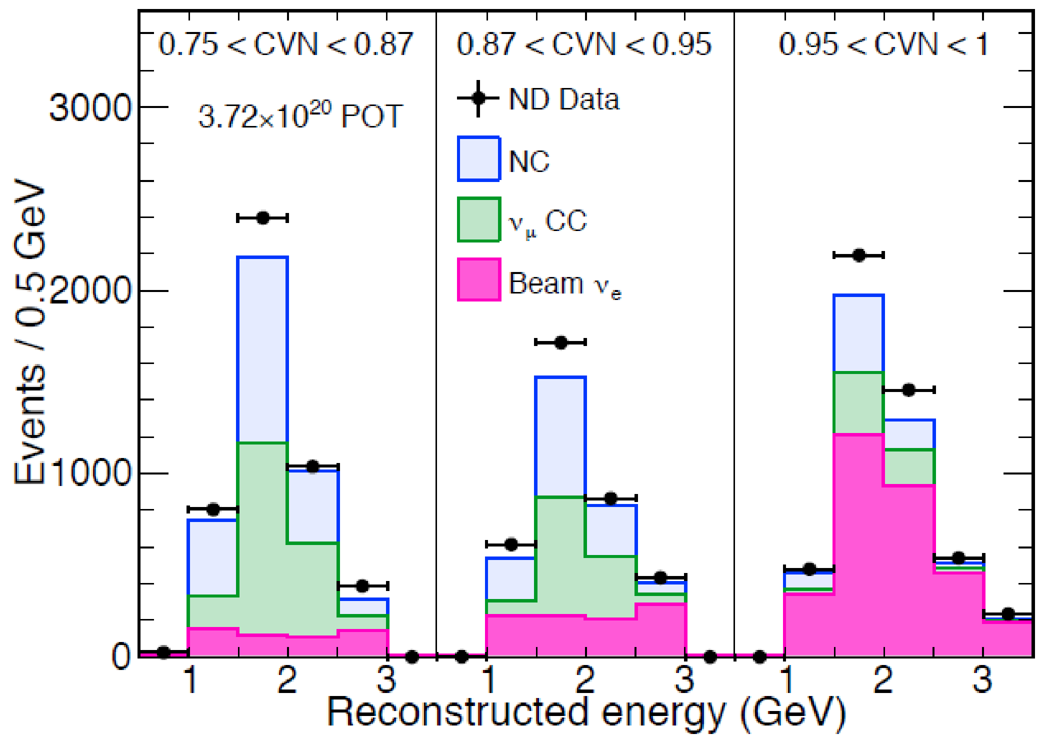




- 73% ν_e CC selection efficiency, 76% purity with CVN classifier
- Good ND Data/MC agreement
- CVN provides better cosmic rejection and similar systematics to 2015 classifiers

Data driven background correction

- ν_e CC selection in the ND picks out FD backgrounds
  - beam ν_e CC
  - ν_μ CC
  - NC
- ~10% excess of data over MC in the ND
- Extrapolate data/MC differences to adjust FD prediction
- Each component oscillates differently
- Must decompose the data into constituent components

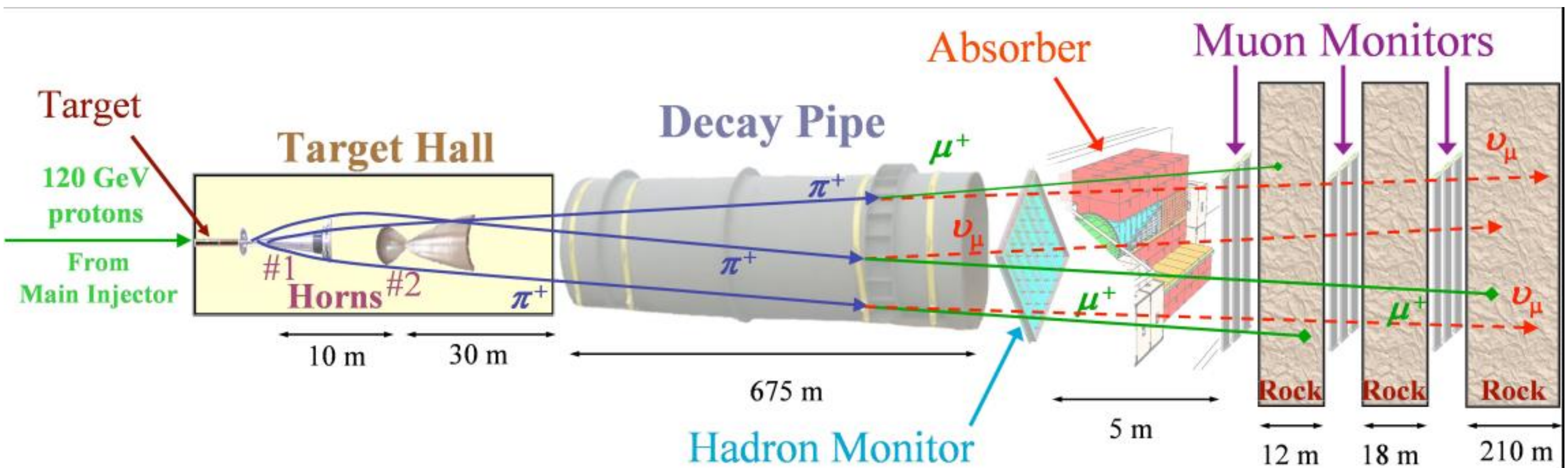


NOvA Experiment

How to make a neutrino beam

NuMI Off-axis ν_e Appearance

- NuMI - Neutrinos at the Main Injector, both ν_μ and $\bar{\nu}_\mu$
- Series of upgrades - 10 μs beam spill every 1.3 s
- Beam back from Sept 4, 2013 (300 -> 700 kW)
- 700 kW limit reached after Booster RF system upgrade
- 4.9×10^{13} POT/pulse – 6×10^{20} POT/year



NOvA physics goals

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$\overset{(+)}{-}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$
$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \qquad \Delta = \Delta m^2_{31} L/(4E) \qquad A = \overset{(-)}{+} G_f n_e L/(\sqrt{2}\Delta)$$

mixing angle θ_{13}

mass hierarchy

CP violation

θ_{23} octant

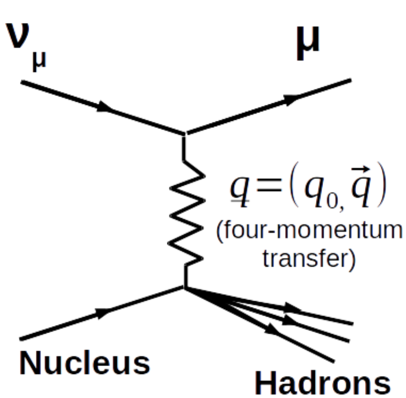
$\sin^2(2\theta_{13})$ has been measured at short-baseline and can be accessed in long-baseline search for ν_e events, which allows us to make measurements of δ_{CP} (CP violation phase parameter). We can gain information about the θ_{23} octant since $\sin^2(\theta_{23})$ is a coefficient on the leading-order term.

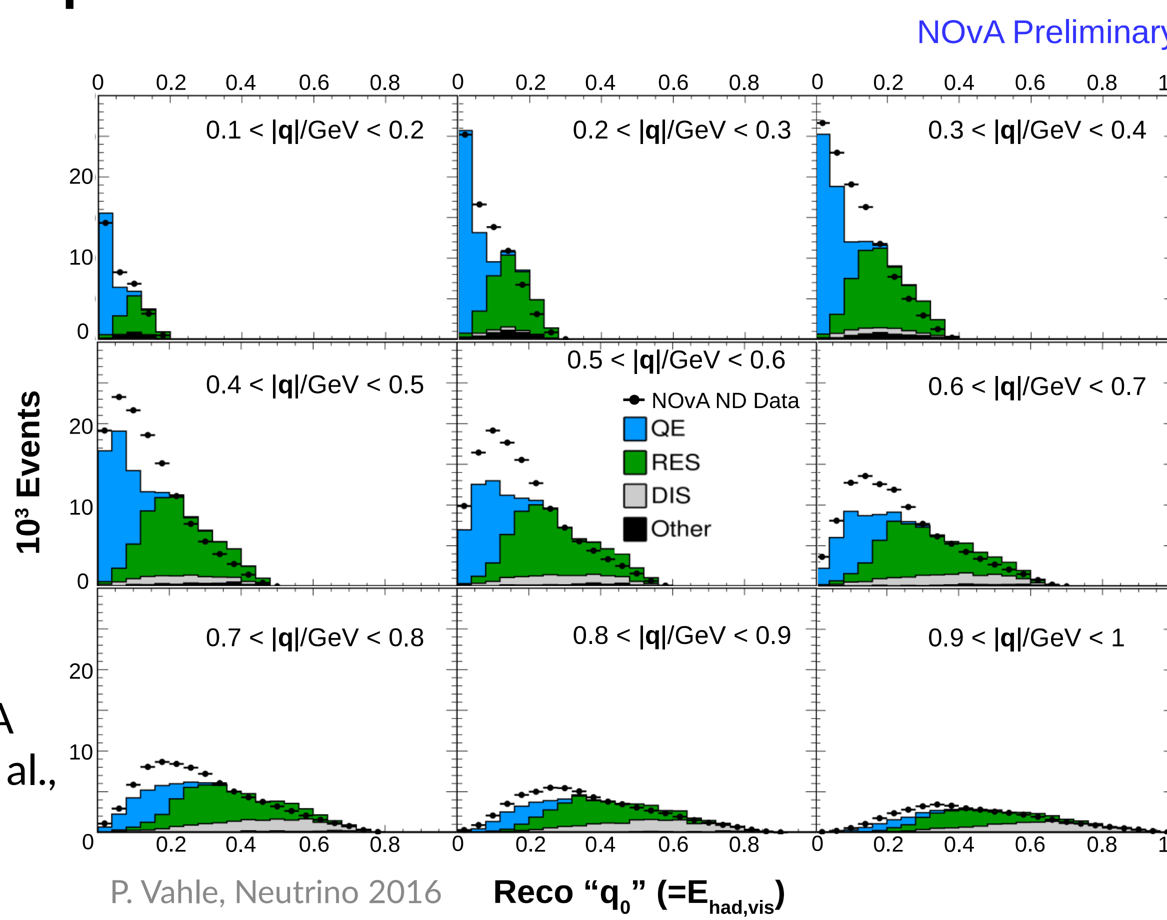
Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy - the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs. anti-neutrino running.

Plus much more non-oscillation topics (cross-sections, sterile neutrinos, monopoles, supernovae, NSI…).

Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production

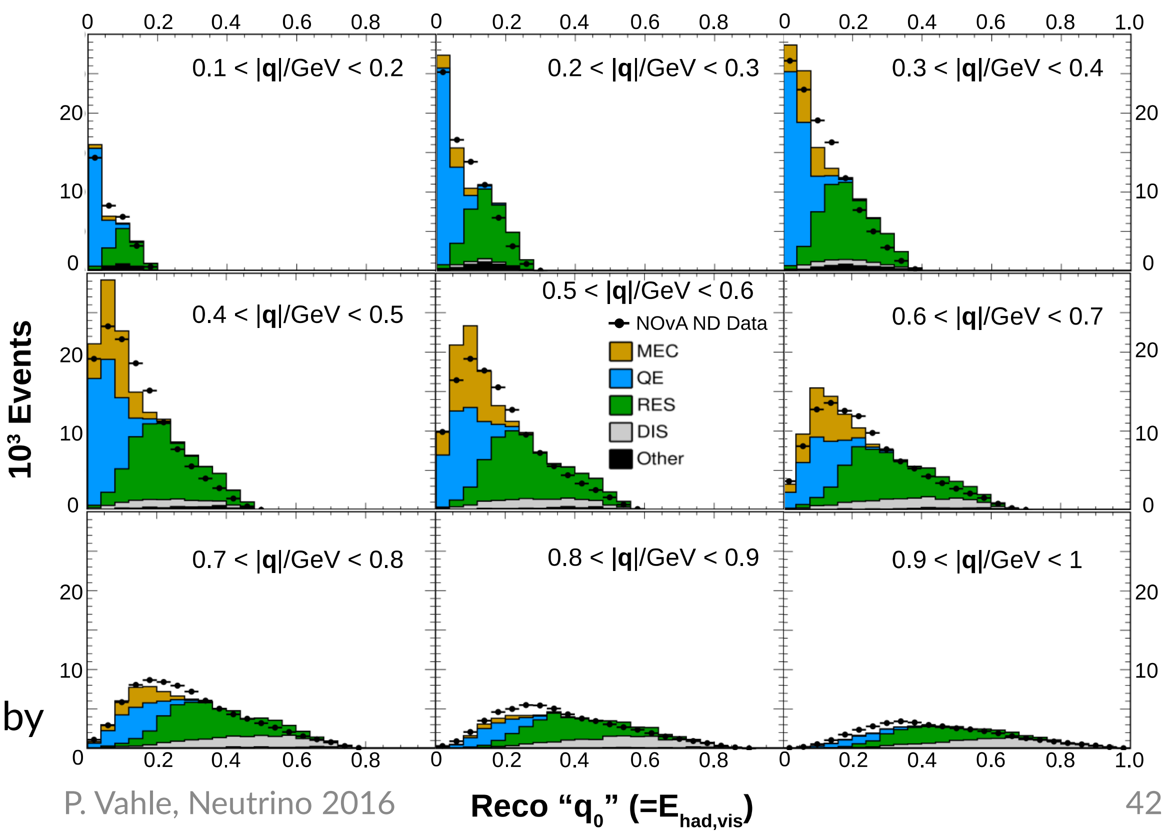




Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Scattering in a Nuclear Environment

- Enable GENIE empirical Meson Exchange Current Model
- Reweight to match NOvA excess as a function of 3-momentum transfer



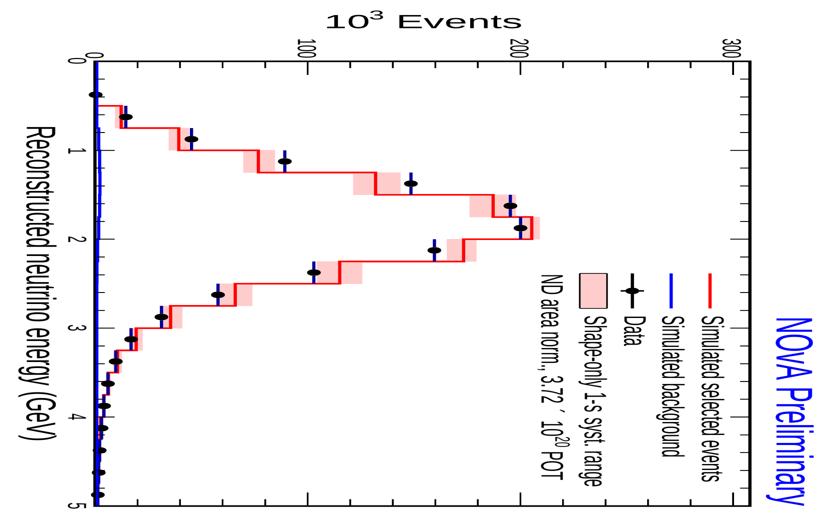
- 50% systematic uncertainty on MEC component
- Reduces largest systematics
  - hadronic energy scale
  - QE cross section modeling
- Reduce single non-resonant pion production by 50%

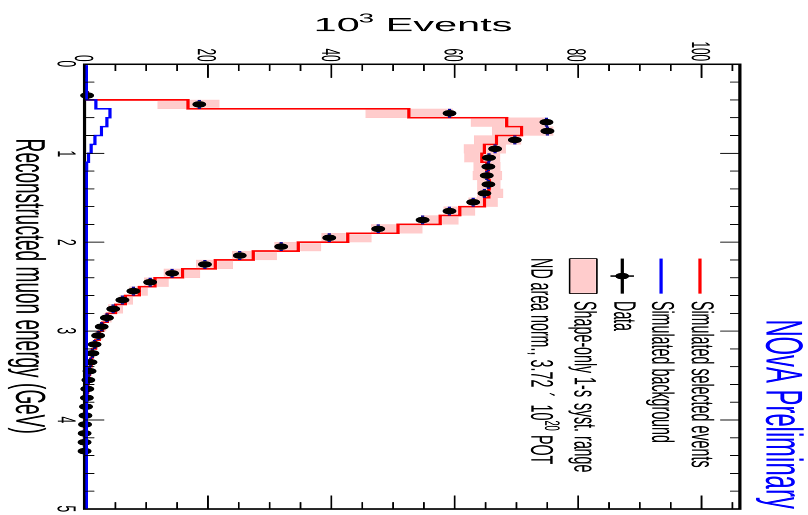
(P.A. Rodrigues et al, arXiv:1601.01888.)

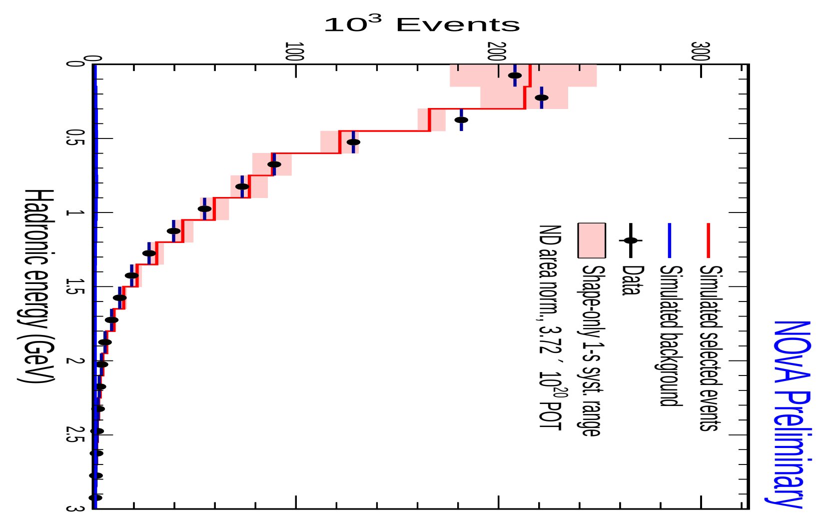
MEC model by S. Dytman, inspired by J. W. Lightbody, J. S. O'Connell, Computers in Physics 2 (1988) 57.

Muon Neutrino ND data

- Addition of MEC events substantially improves simulated hadronic energy distribution
  - hadronic energy scale uncertainty reduced (14% to 5%)
- Reconstructed neutrino energy unfolded, true Far/Near ratio used to extrapolate ND data for a FD prediction







Systematic uncertainties

- Various sources of systematic uncertainty considered
- Propagate the effect of each though the extrapolation with specially modified MC samples
- Include as pull terms in fit
- Table shows increase in quadrature of measurement uncertainty

Systematic	Effect on $\sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**


Di-Block: 01
Position: 06


GP:180
BLK:07 PLN:12 POS:02