NOνA Experiment – Recent Status

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Outline

- Neutrino oscillations, oscillation parameters
- 2016 NOvA results
- NOvA experiment
  - Layout, main features of NOvA experiment
  - Fermilab accelerator complex, neutrino beam
  - NOvA detectors
  - ν_e event selection (CVN)
- Future outlook
- Summary

Neutrino mixing

atmospheric ν **Mixed Term** **solar ν**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Main atmospheric neutrino oscillation channels (NOνA, T2K, MINOS+, IceCube etc.)
$\nu_\mu \to \nu_\mu$ **(disappearance):**

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

$\nu_\mu \to \nu_e$ **(appearance with matter effect):**

$$\begin{aligned} P(\nu_\mu \to \nu_e) &= \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2\left[\left(\frac{V}{2} - \frac{\Delta m^2}{4E}\right) L\right]}{\left(\frac{2EV}{\Delta m^2} - 1\right)^2} + \\ &+ a \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\left(\frac{\Delta m^2}{4E} L - \delta\right) \frac{\sin\left(\frac{V}{2} L\right)}{\frac{2EV}{\Delta m^2}} \frac{\sin\left[\left(\frac{V}{2} - \frac{\Delta m^2}{4E}\right) L\right]}{1 - \frac{2EV}{\Delta m^2}} \\ &+ a^2 \sin^2 2\theta_{12} \cos^2\theta_{13} \cos^2\theta_{23} \frac{\sin^2\frac{V}{2} L}{\left(\frac{2EV}{\Delta m^2}\right)^2} \end{aligned} \tag{5.2}$$

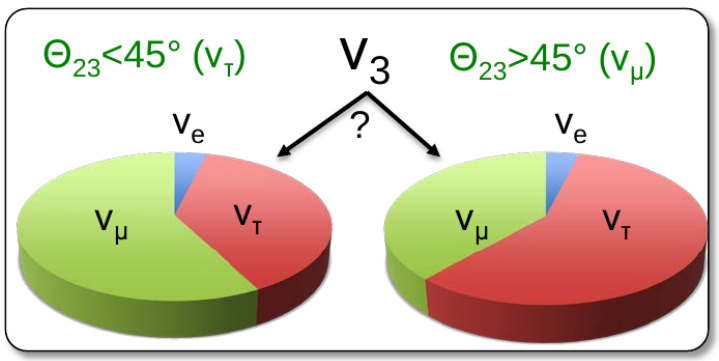
$$a = \Delta m^2_{21}/\Delta m^2 \qquad V \equiv \sqrt{2} G_F N_e$$

Neutrino oscillations (parameters) 3ν-model

- Neutrino mixing $\Rightarrow$ 9 parameters (3 angles, 3 masses, 3 phases)
- Neutrino oscillations $\Rightarrow$ 6 parameters: 3 angles, 2 squared-mass diffs., 1 CP phase
- $\Delta m^2 = m_3^2 - \frac{m_1^2 + m_2^2}{2} \approx \Delta m^2_{31} \approx \Delta m^2_{32} \approx 2.5 \times 10^{-3}\ \text{eV}^2 \gg \Delta m^2_{21}$

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	$6.93 - 7.97$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	$2.37 - 2.63$ $(2.33 - 2.60)$
$\sin^2\theta_{12}$	0.297	$0.250 - 0.354$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	$0.379 - 0.616$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	$0.383 - 0.637$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	$0.0185 - 0.0246$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	$0.0186 - 0.0248$
δ/π	1.35 (1.32)	$(0.92 - 1.99)$ $((0.83 - 1.99))$

C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001, 2016



Remaining "oscillation secrets"

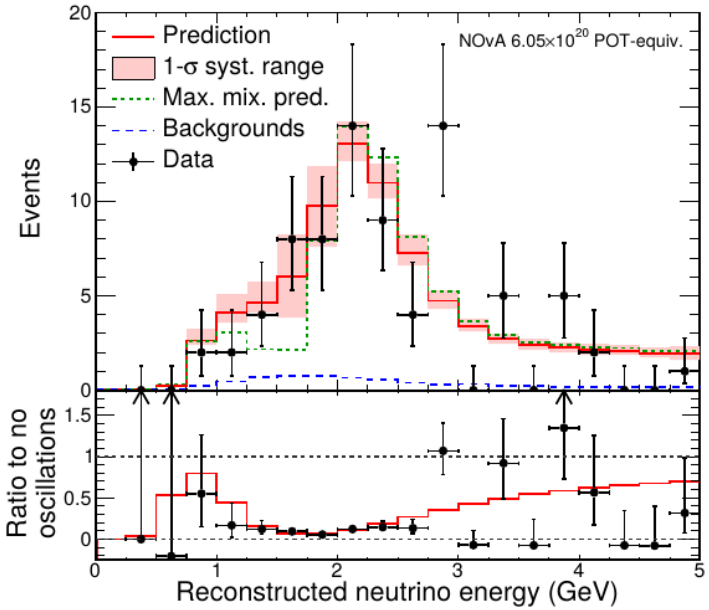
- What is the mass hierarchy, i.e. $\Delta m^2 >$ or < 0?
- Do oscillations violate CP? What is δ?
- Is 23-mixing (bi)maximal? If not, is $\theta_{23} >$ or $< 45°$?
- Beyond? (steriles, supernovae, monopoles etc.)

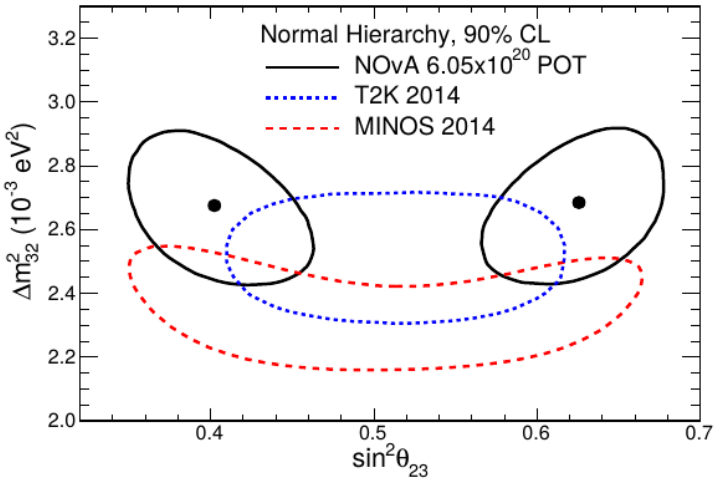
- $\nu_\mu \to \nu_\mu$ **channel:**
  1. $\sin^2 \theta_{23}$, bimaximal mixing
  2. $|\Delta m^2|$
- $\nu_\mu \to \nu_e$ **channel:**
  1. θ_{23} vs. δ contours

  + with future $\bar{\nu}$ data (from Feb 2017):
  2. θ_{23} octant, $>$ or $<$ 45°
  3. δ hyperplane, $\delta \in [0, \pi]$ or $[\pi, 2\pi]$
  4. hierarchy signatures
- $\nu_\mu \to \nu$**, i.e. NC channel:**
  1. ν_s existence (3+1 model with recent data)
  2. bounds on Δm^2_{41}, θ_{34}, θ_{24}
- **XSec, Exotics**

NOvA Results 2016

$\nu_\mu \rightarrow \nu_\mu$ analysis





P. Adamson et al. (NOνA Coll.), Phys. Rev. Lett. 118, 151802 (2017) – Published 10 April 2017, (arXiv: 1701.05891)

- Detected 78 ν_μ events in FD (bkg. 3.7 beam, 2.4 cosmics)
- Expected w/o oscillations: 473 ± 30

Oscillation parameters best estimates

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

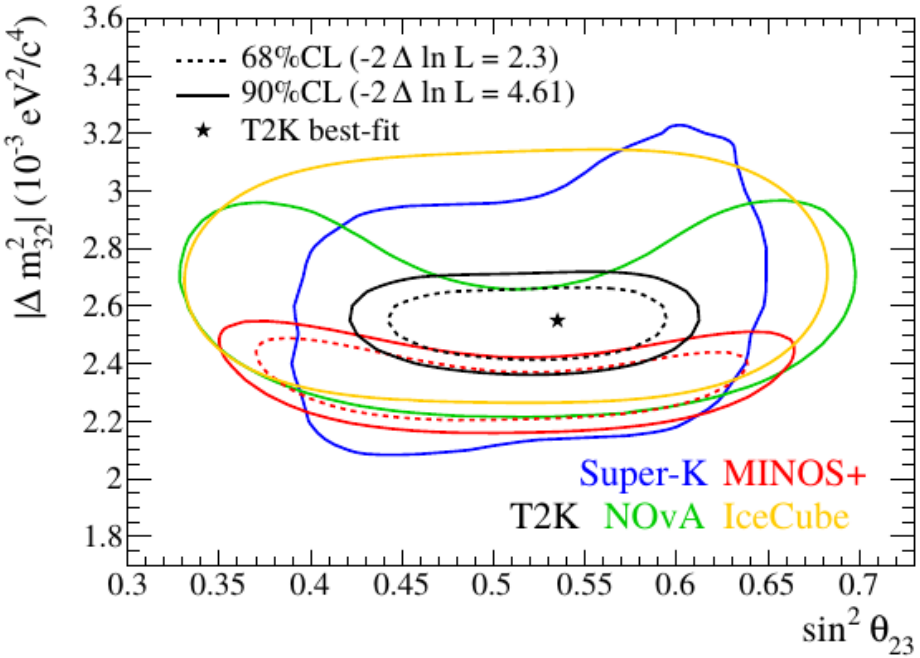
IH: $\Delta m^2_{32} = (-2.72 \pm 0.11) \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.398^{+0.030}_{-0.022}$ || $0.618^{+0.022}_{-0.030}$

$\sin^2\theta_{23} = 0.5$ excluded at 2.5σ

NOvA Results 2016 – NOvA vs T2K

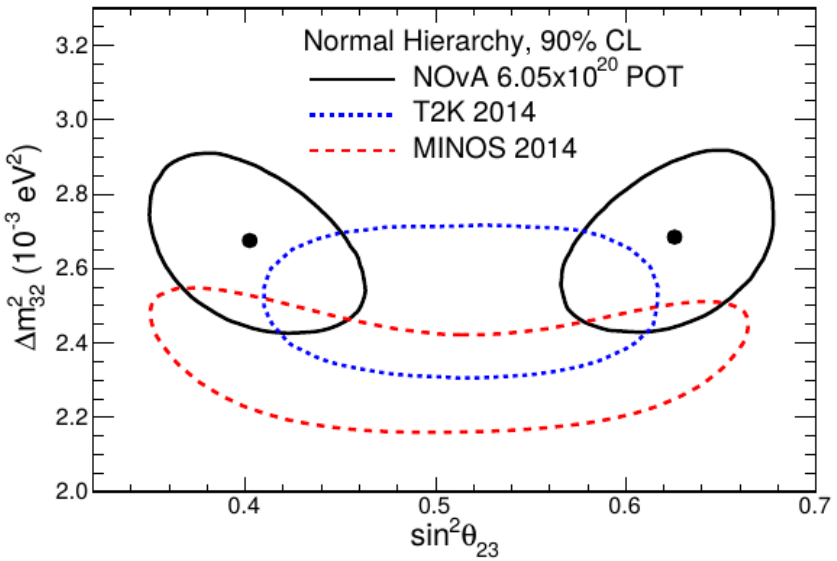
$\nu_\mu \rightarrow \nu_\mu$ analysis, bimaximal 23-mixing

T2K

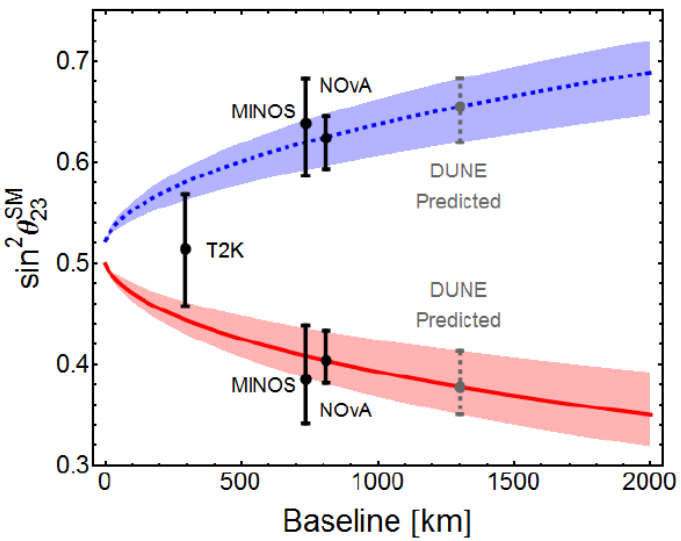


K. Abe et al. (T2K Collaboration) Phys. Rev. Lett. 118, 151801 (2017) – Published 10 April 2017 (arXiv: 1701.00432)

NOvA

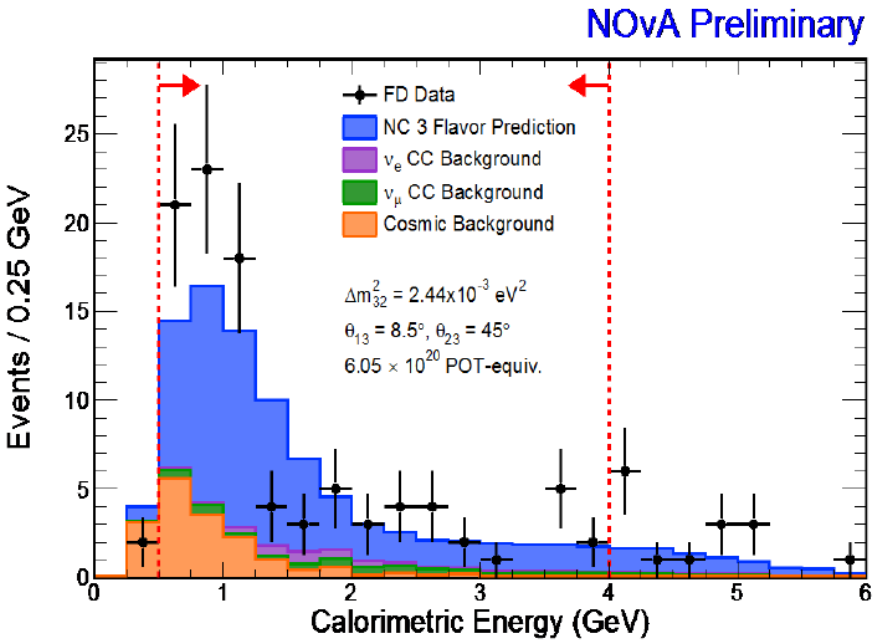


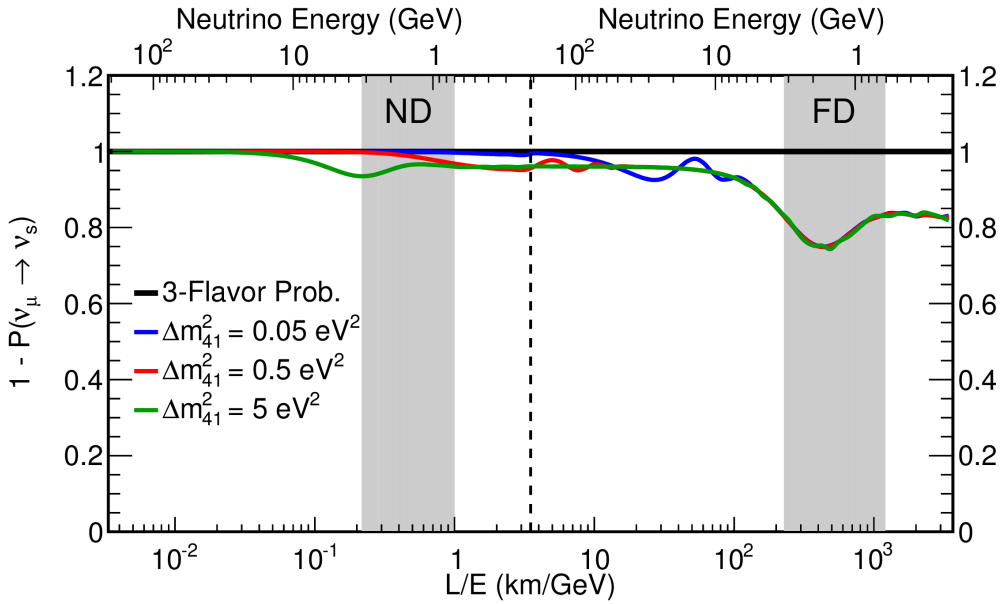
Neutrino decoherence



First explanations:

- **Nonstandard neutrino interactions (NSI):** J. Liao et al. Phys. Lett. B 767 : 350-353 (2017) (arXiv: 1609.01786)
- **Neutrino decoherence:** J. A. B. Coelho et al. arXiv: 1702.04738



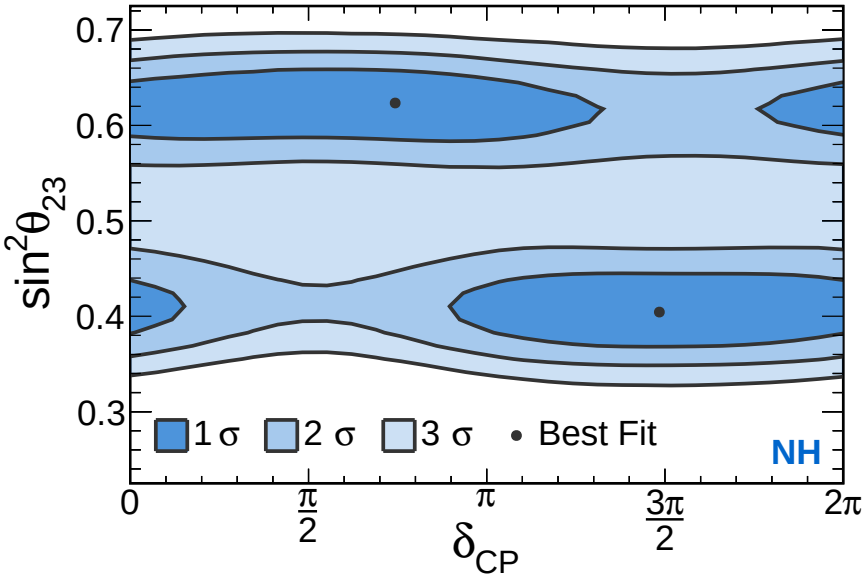


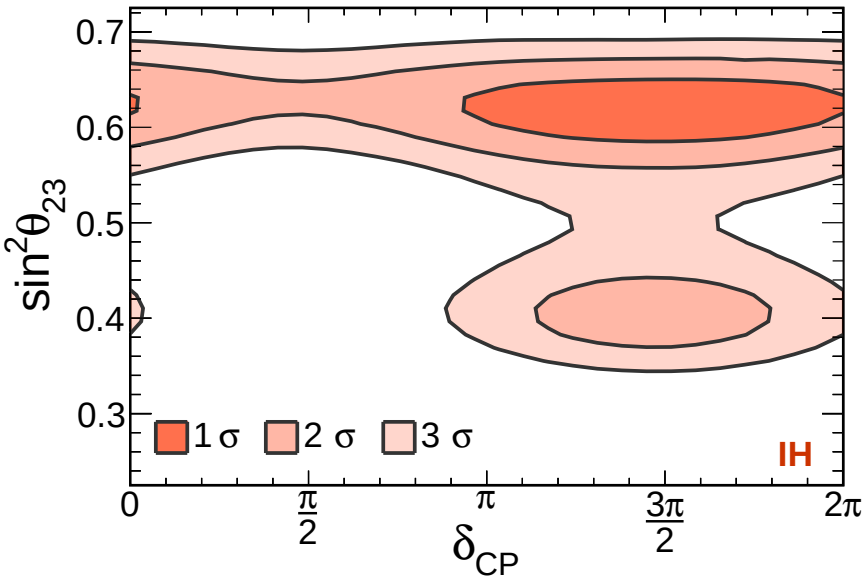
- First presented at ICHEP 2016
- Detected 95 NC events (effectivity 50%, purity 72%)
- No evidence of ν_s (minimal 3+1 model tested):

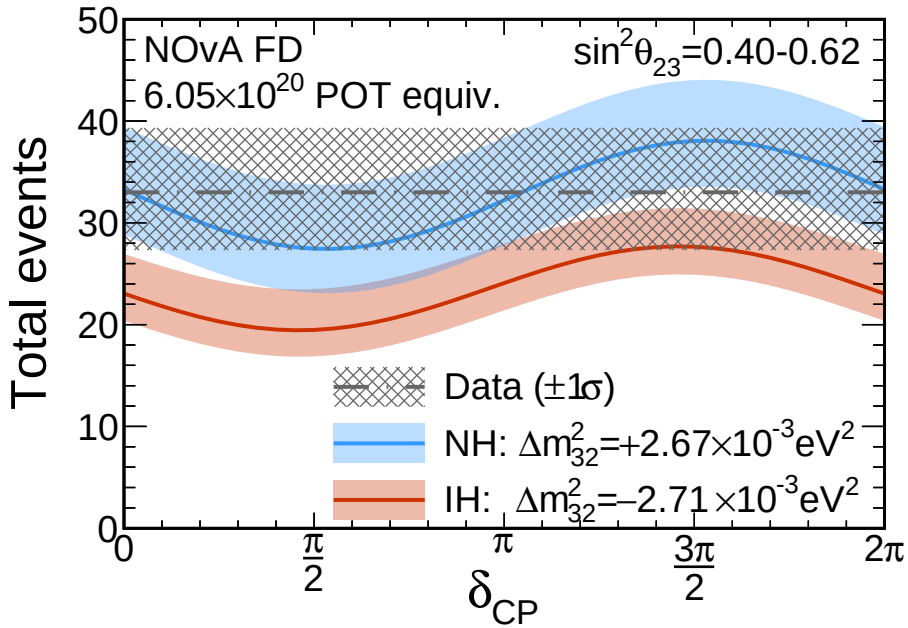
$$\text{For } 0.05 \text{ eV}^2 < \Delta m^2_{41} < 0.5 \text{ eV}^2$$
$$\theta_{34} < 35°, \theta_{24} < 21° \text{ (90\% C.L.)}$$

NOvA Results 2016

$\nu_\mu \to \nu_e$ analysis, $\nu_\mu \to \nu_\mu$ constrained, contours

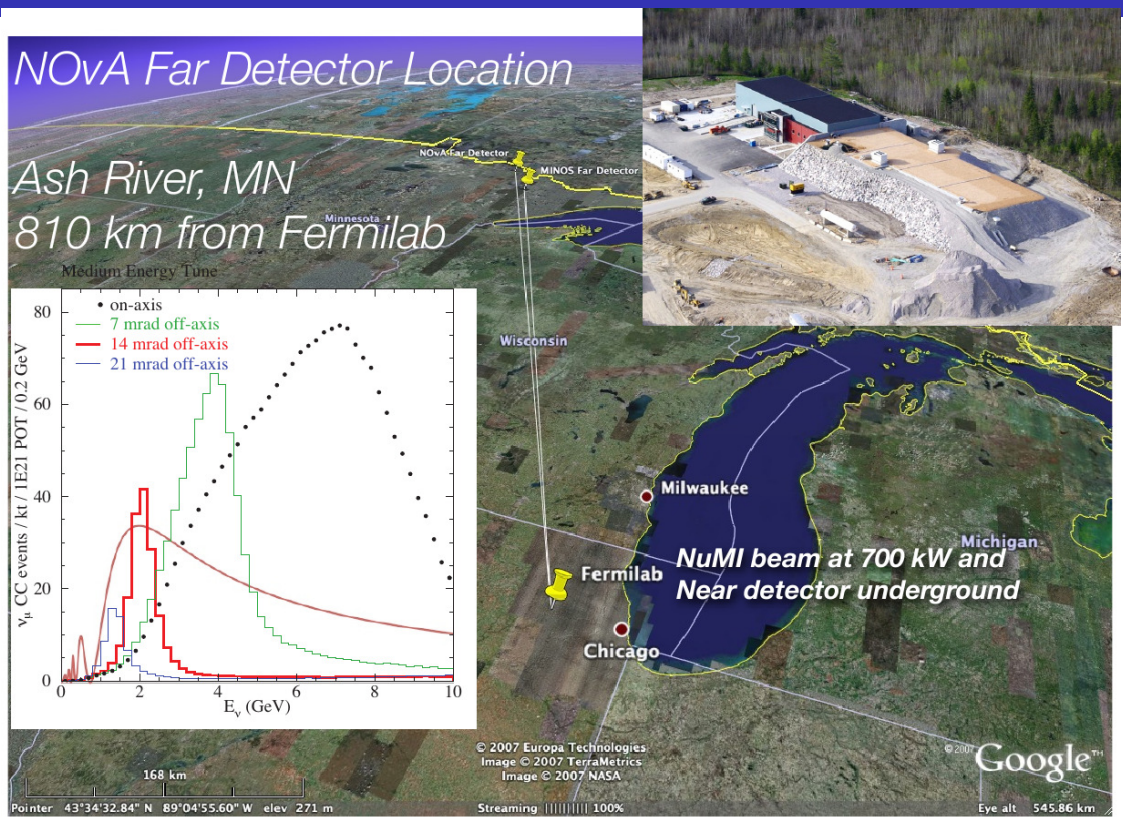






- arXiv: 1703.03328
- Detected 33 ν_e events (bkg. 8.2±0.8), i.e. $> 8\sigma$ ν_e appearance signal
- Best estimates:
  NH, $\delta = 1.49\pi, \sin^2\theta_{23} = 0.40$
- Degenerated estimates:
  NH, $\delta = 0.74\pi, \sin^2\theta_{23} = 0.62$
  IH, $\delta = 1.49\pi, \sin^2\theta_{23} = 0.62$
- IH, $\sin^2\theta_{23} < 0.5$ excluded at 93%
- $\bar{\nu}$ data will help resolve degeneracies

NOvA Experiment
NuMI Off-axis ν_e Appearance



$\nu_\mu \to \nu_\mu, \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu, \bar{\nu}_e$

Matter effect (modification of oscillation patterns when in matter)

Near and Far detector, calorimetric, tracking, 65% fiducially and 24/7 temporaly active

Off-axis detectors (ca 14 mrad)

NuMI beamline – from MINOS

$L = 810$ km, $E \simeq 2.0$ GeV

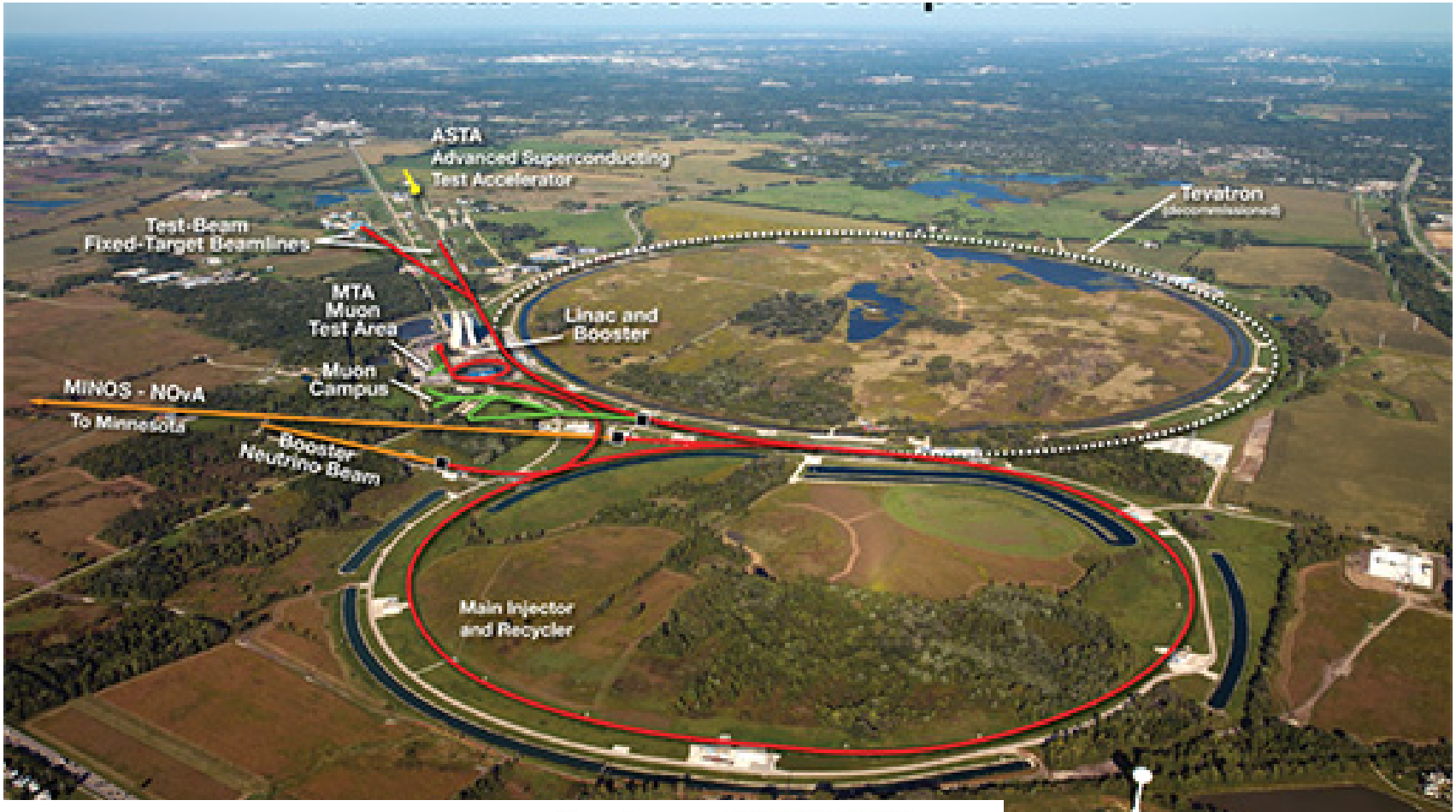
CVN (Convolutional Visual Network) effective event identification based on image processing

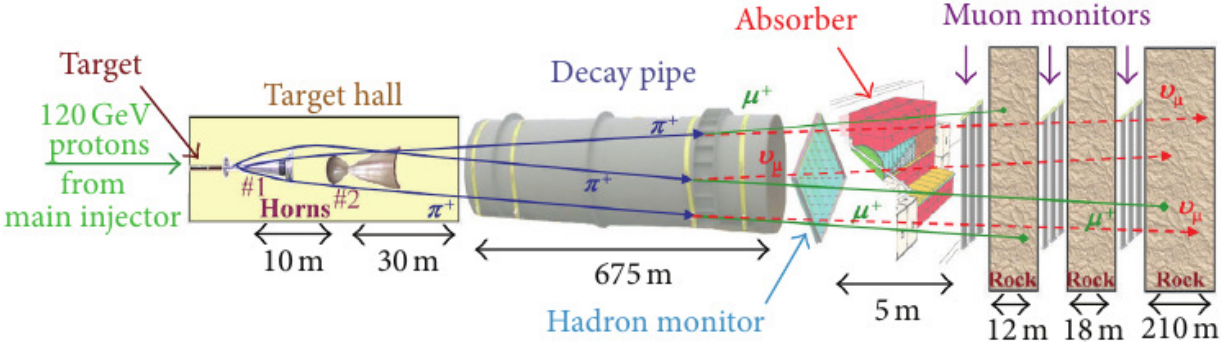
Physics goals

- $\nu_\mu \to \nu_\mu$: $\theta_{23}, |\Delta m^2|$
- $\nu_\mu \to \nu_e$: $\delta, \Delta m^2, \theta_{23}, (\theta_{13})$
- $\nu_\mu \to \nu$, NC: $?\nu_s?$ (minimal 3+1 model, recently)
- XSecs, magnetic moments, monopoles, supernovae, WIMPs and more!

FNAL Acc. Complex

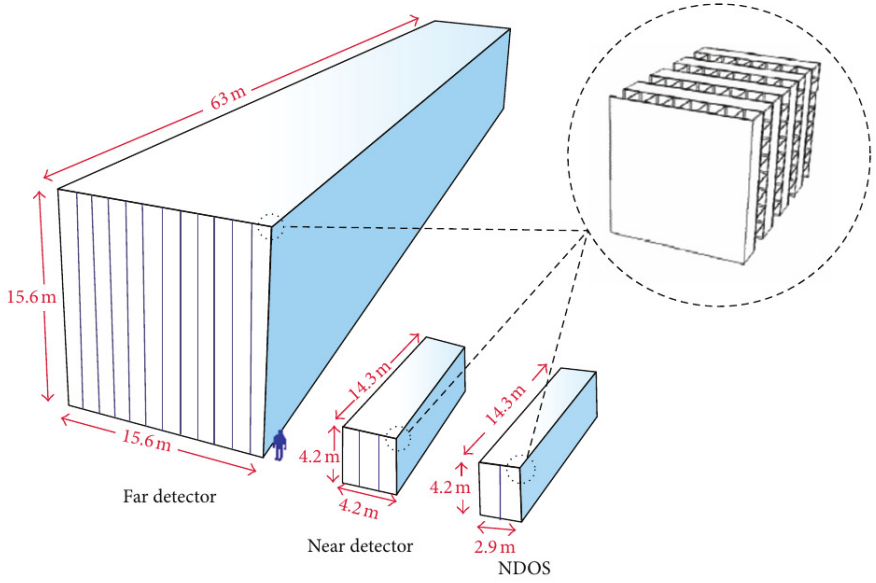
NuMI beam

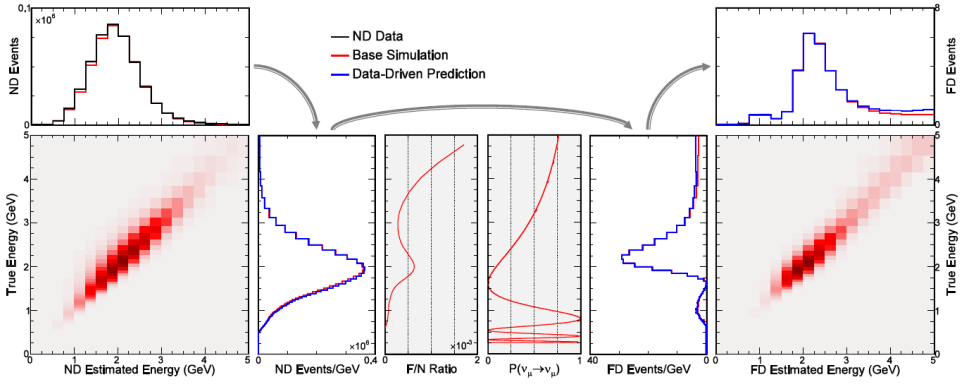




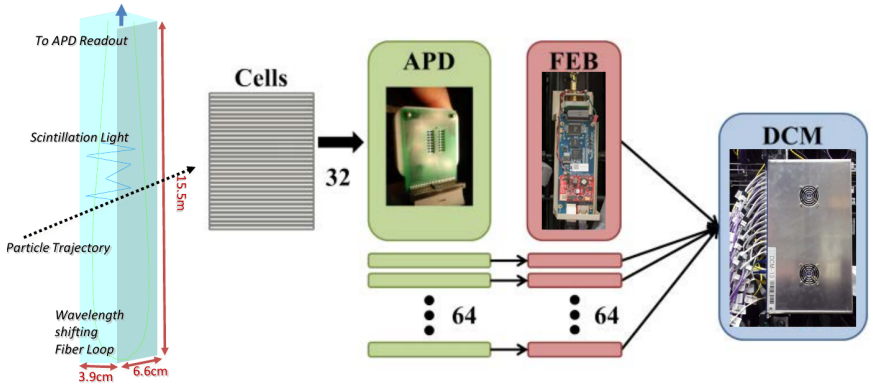
NuMI beamline (700 kW) used by a number of neutrino experiments incl. MINERvA or former MINOS

NOvA Detectors



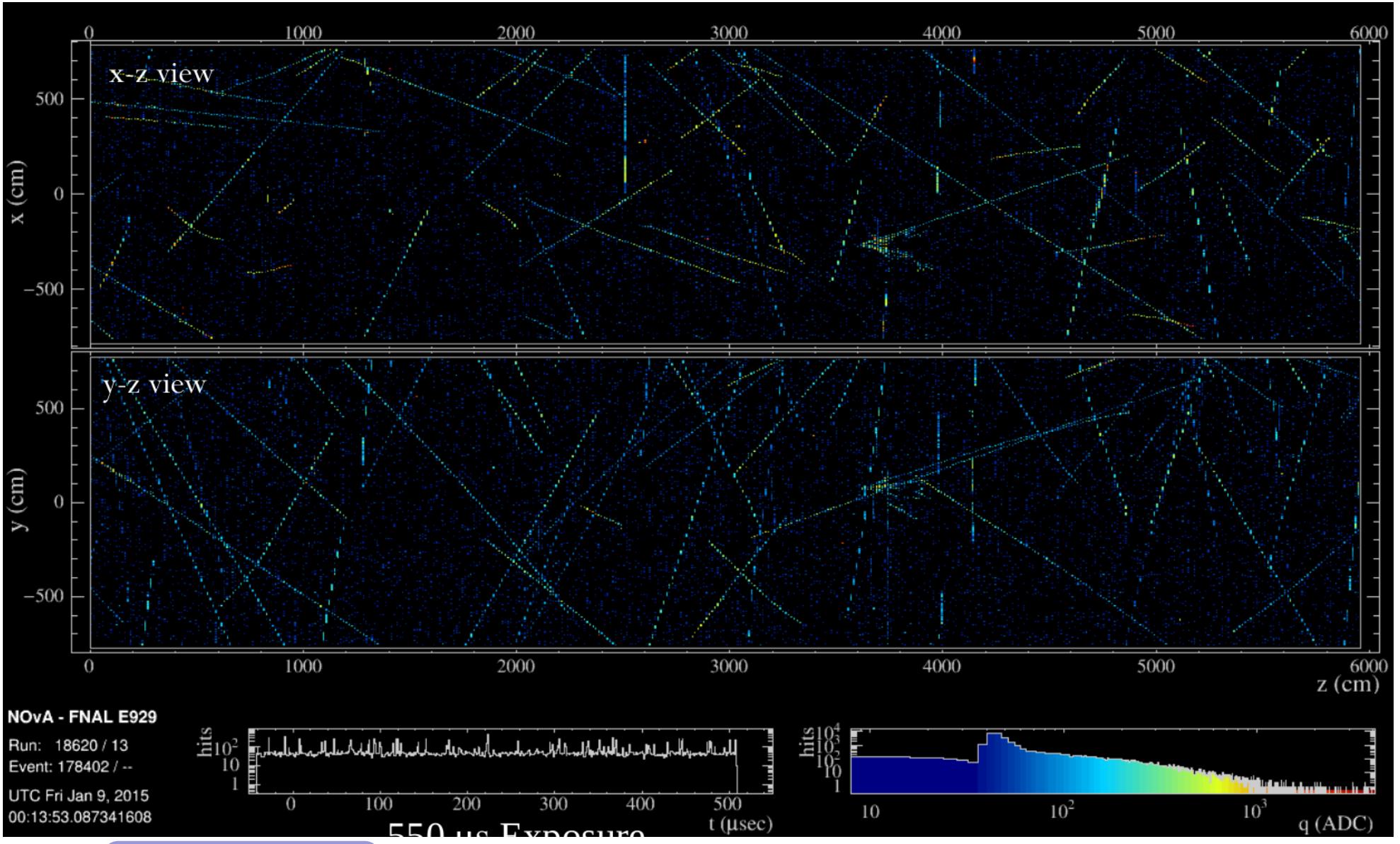


- Far (FD) and Near (ND) detectors
- Data-driven prediction of FD events
- FD – 14 kton (15.6x15.6x63 m), ND – 0.3 kton (4.2x4.2x14.3 m)
- 65 % active volume (9 kton of scintillator in FD), segmented:
  FD – 344 064 cells (pixels)
  ND – 18 000 cells (pixels)
- 3D event reconstruction
- Emmited light collected by wavelength-shifting fibers with both ends connected to one pixel of avalanche photodiode (APD, 32 pixels)



Event Visualization

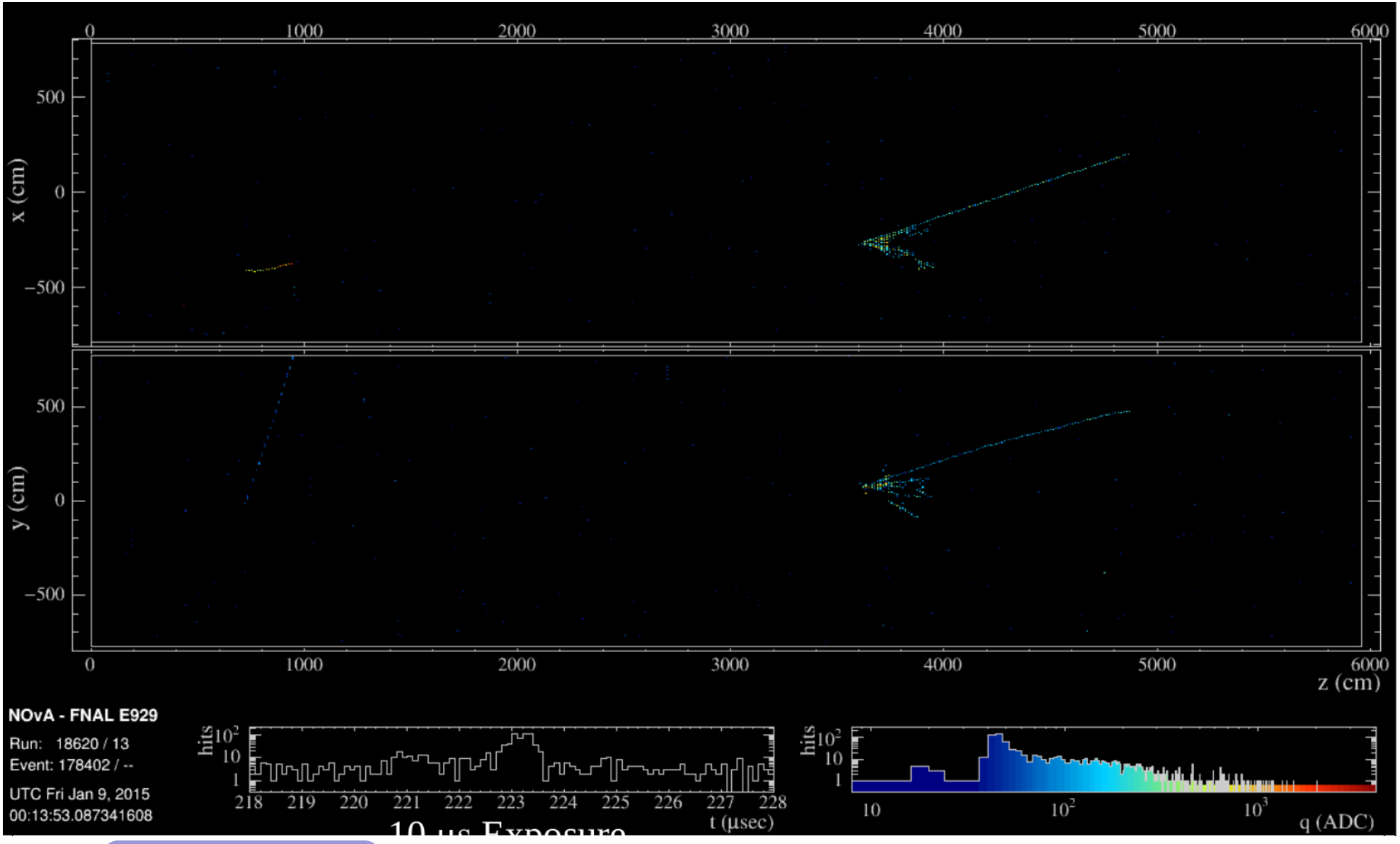
550 μs readout window



▸ LIVE DATA STREAMING

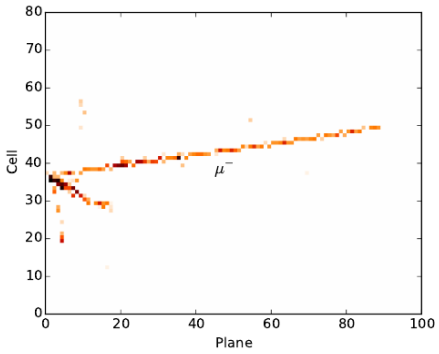
Event Visualization

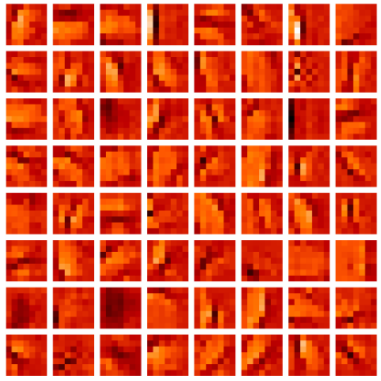
Beam spill time zoomed

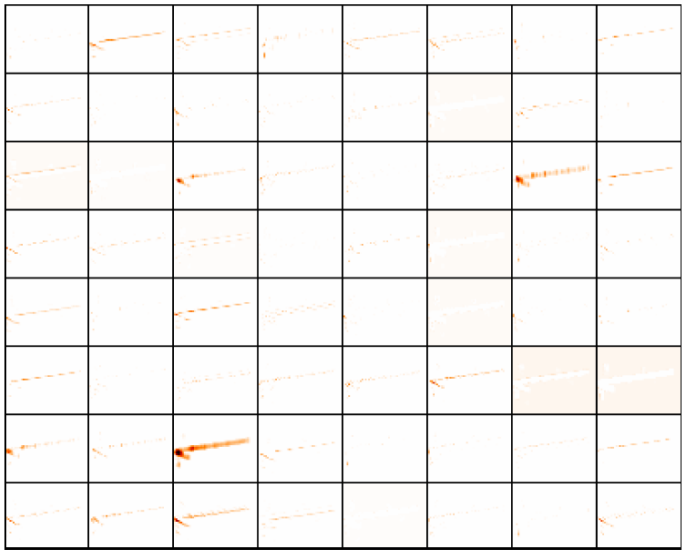


▶ LIVE DATA STREAMING

Event Selection (CVN)
Convolutional Visual Network

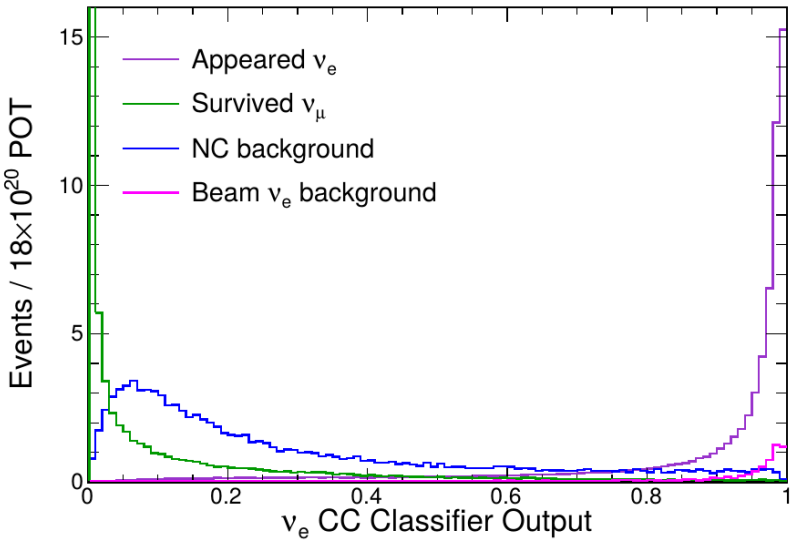


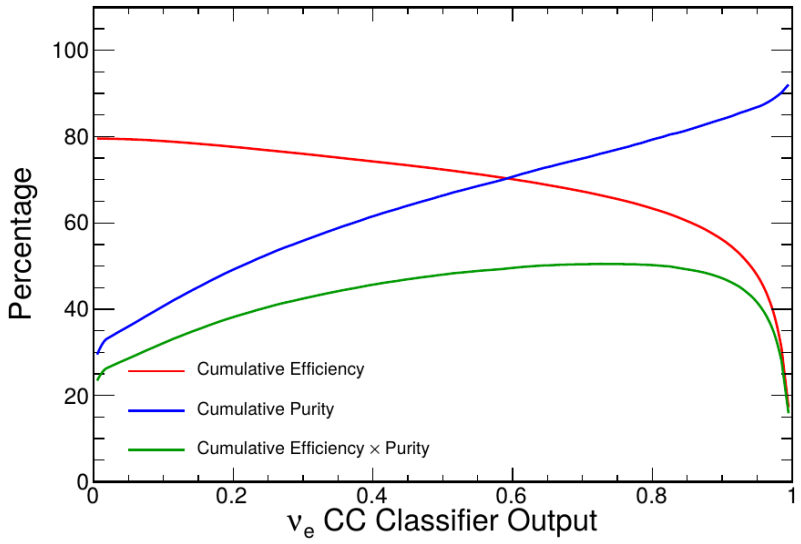


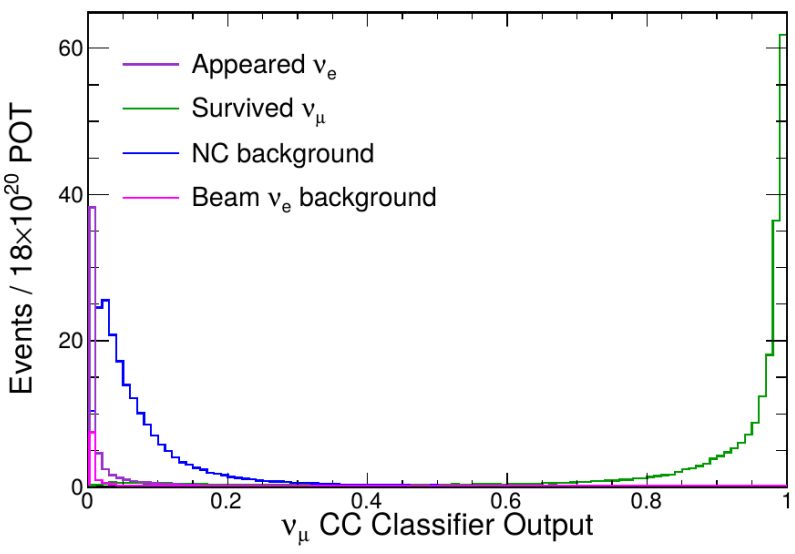


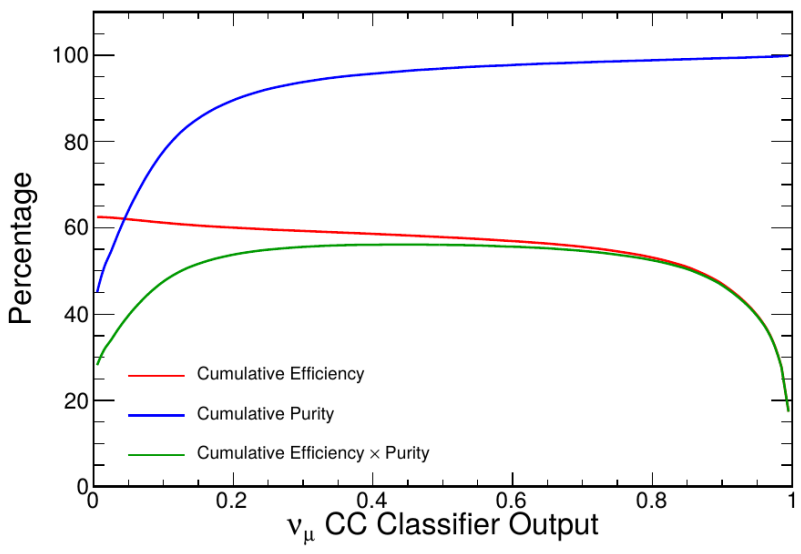
- CVN is a serie of image processing transformations (filters)
- Designed to identify and extract abstract features (patterns) from the sample
- Extracted features are used as input to conventional neural network to classify the event
- INPUT: calibrated hitmap!!, OUTPUT: "probability" of event corresponding to one of trained neutrino interactions: ν_e, ν_μ, ν_τ, NC
- CVN provides +30% exposure equivalent improvement of ν_e sensitivity in comparison to usual (former) selection techniques

Event Selection (CVN)
Convolutional Visual Network

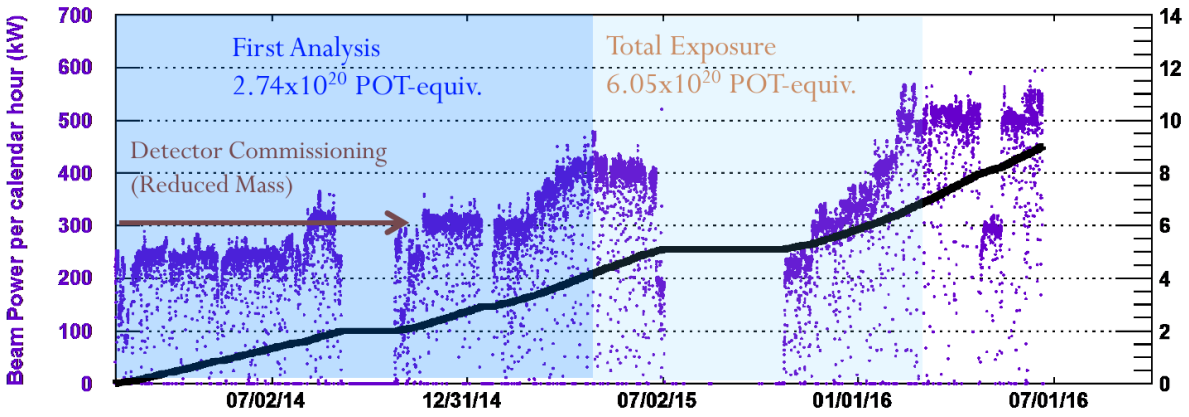


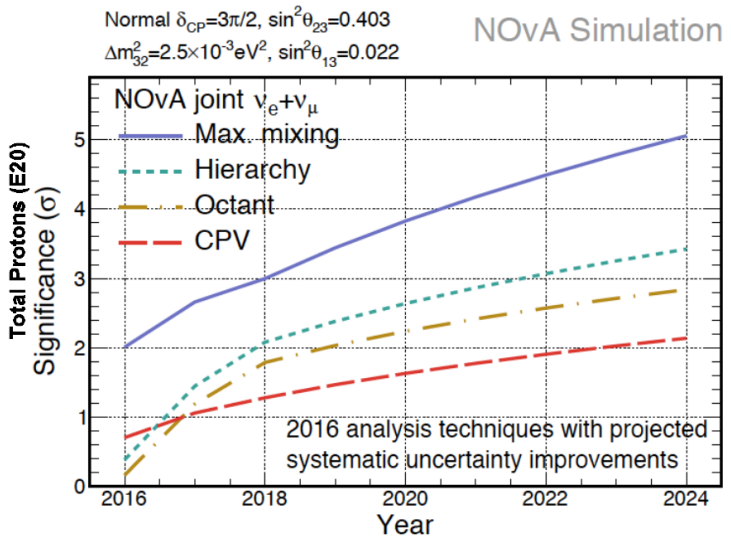






- NuMI power $\sim$ 640 kW (maximum over 700 kW, up to now 9-10$\times 10^{20}$ POT)
- Run plan until 2024
- Potential upgrade to $\sim$ 0.9-1.0 GW in 2020
- $\bar{\nu}$ beam from Feb 20, 2017 (9×10^{20} POT for ν and $\bar{\nu}$ until end of 2018)
- 3rd analysis starting now (expected 9×10^{20} POT of ν data)





Summary

- 2016 NOvA results on neutrino oscillations:
  - $\nu_\mu \rightarrow \nu_\mu$:

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

    IH: $\Delta m^2_{32} = (-2.72 \pm 0.11) \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.398^{+0.030}_{-0.022}$ || $0.618^{+0.022}_{-0.030}$

    $\sin^2\theta_{23} = 0.5$ excluded at 2.5σ
  - $\nu_\mu \rightarrow \nu_e$ with $\nu_\mu \rightarrow \nu_\mu$ constrains:

    $> 8\sigma$ ν_e appearance signal

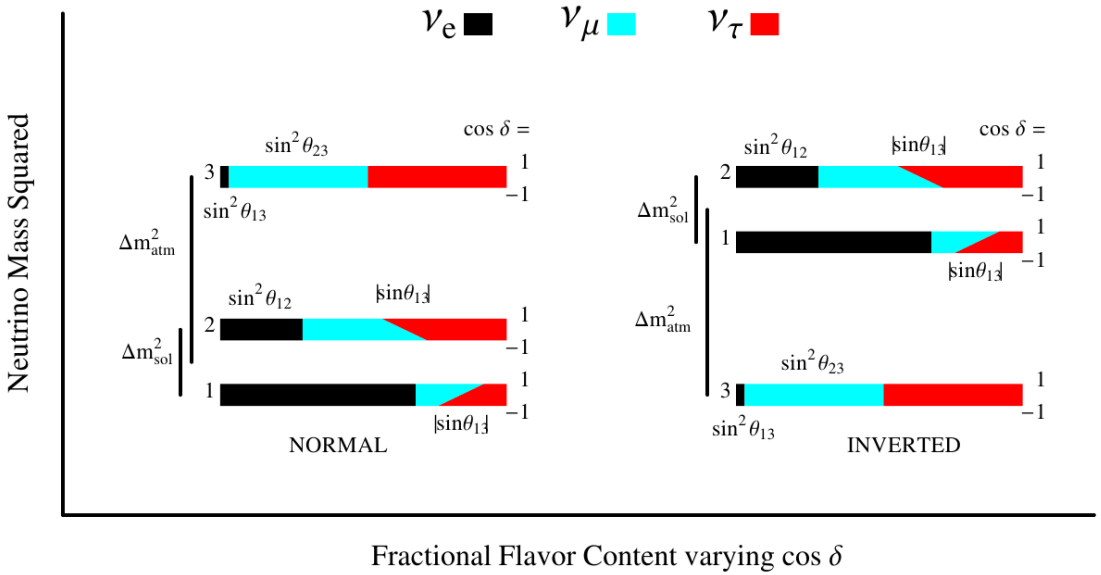
    IH, $\sin^2\theta_{23} < 0.5$ excluded at 93%

    NH and non-zero δ prefered at low significance
  - NC events:

    No evidence of ν_s

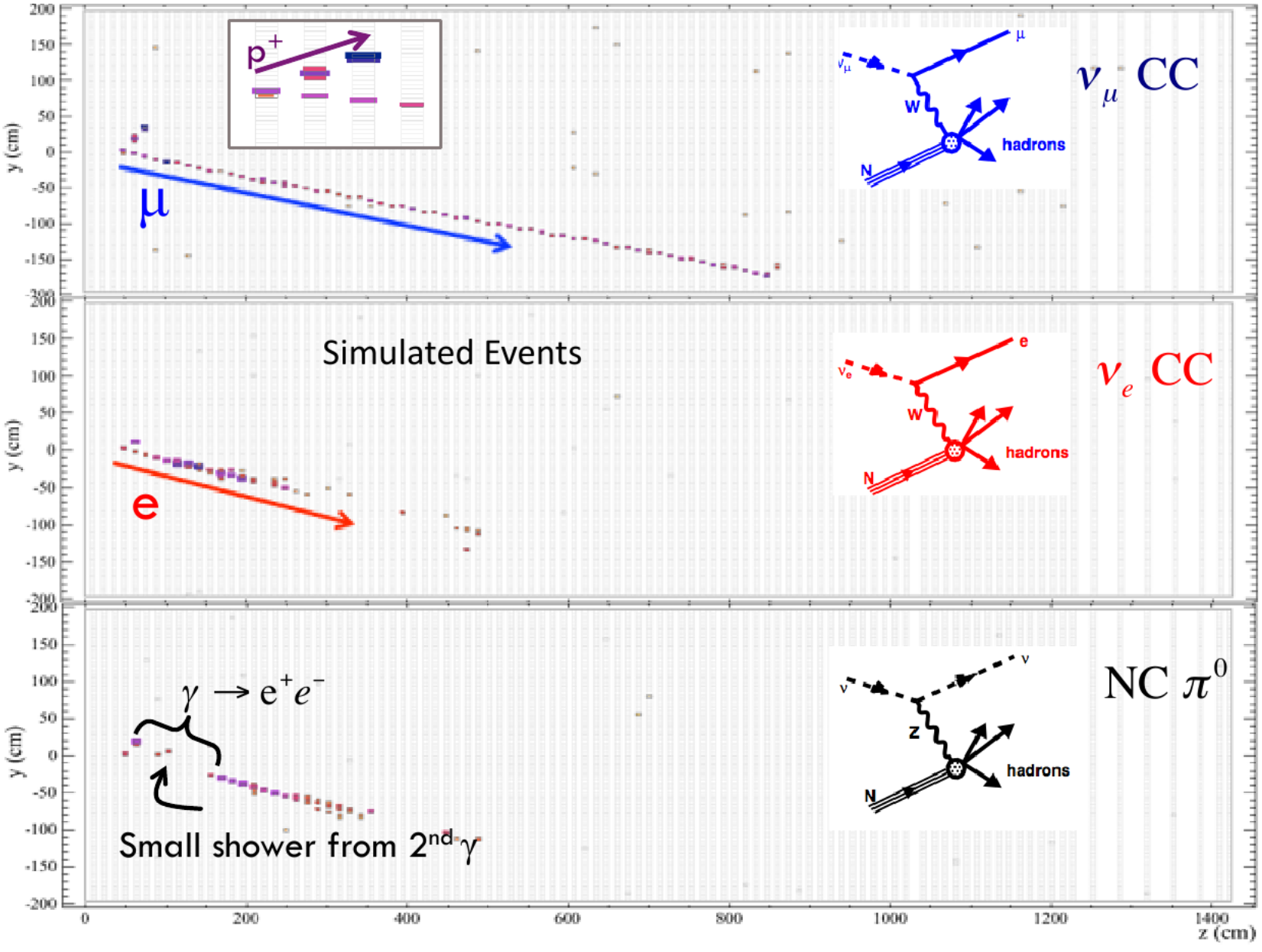
    Expecting stronger bounds on extra osc. parameters with further data
- ν run ended, taking $\bar{\nu}$ data since Feb 20, 2017, NuMI at $\sim$ 700 kW
- Expecting notable contribution of $\bar{\nu}$ data to ν_e analysis concerning θ_{23}, δ and hierarchy degenerations
- 3rd period of analysis in progress, i.e. 9×10^{20} POT-equiv. of ν data

Backups – Oscillations

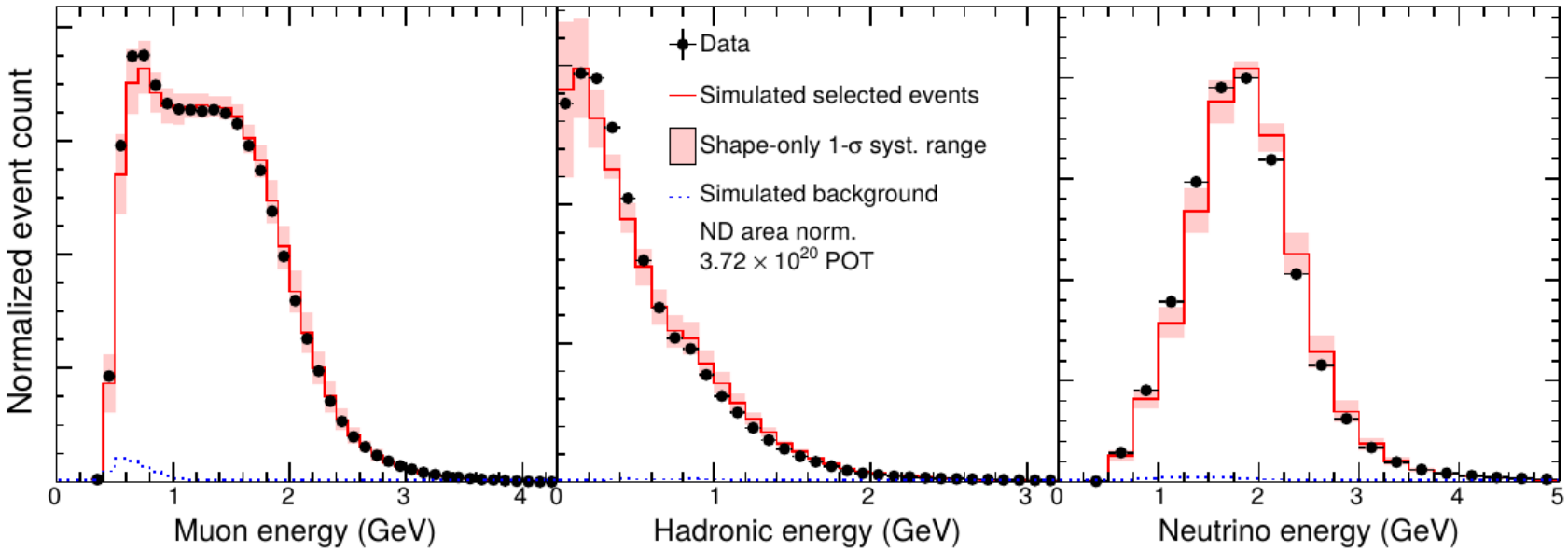


$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta; L, E) &= \left|\mathrm{Amp}(\nu_\alpha \to \nu_\beta; L, E)\right|^2 = \\
&= \left|\sum_{i=1}^{3} U^*_{\alpha i} U_{\beta i} \exp\left(-\mathrm{i}\frac{m_i^2}{2E} L\right)\right|^2 = \\
&= \sum_{i=1}^{3}\sum_{j=1}^{3} U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j} \exp\left(-\mathrm{i}\frac{\Delta m^2_{ij}}{2E} L\right)
\end{aligned}
$$

Backups – Event topologies



Backups – ν_μ analysis



Source of uncertainty	Uncertainty in $\sin^2\theta_{23}(\times 10^{-3})$	Uncertainty in Δm^2_{32} $(\times 10^{-6}$ eV$^2)$
Absolute muon energy scale [±2%]	+9 / -8	+3 / -10
Relative muon energy scale [±2%]	+9 / -9	+23 / -14
Absolute hadronic energy scale [±5%]	+5 / -5	+7 / -3
Relative hadronic energy scale [±5%]	+10 / -11	+29 / -19
Normalization [±5%]	+5 / -5	+4 / -8
Cross sections and final state interactions	+3 / -3	+12 / -15
Neutrino flux	+1 / -2	+4 / -7
Beam background normalization [±100%]	+3 / -6	+10 / -16
Scintillation model	+4 / -3	+2 / -5
δ_{CP} $[0 - 2\pi]$	+0.2 / -0.3	+10 / -9
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99

Backups – ν_e analysis