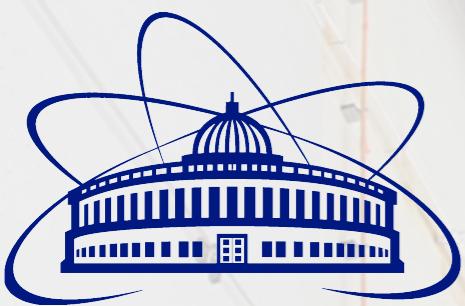


Cross-checks for the particle-identification algorithm in ν_e analysis by the means of muon removal procedure at the NOvA experiment

Liudmila Kolupaeva
for the NOvA collaboration



Neutrino Oscillations

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

OSCILLATION PARAMETERS AND HOW
PRECISELY DO WE KNOW THEM:

$$\theta_{12} \approx 34^\circ \quad (4.4\%)$$

$$\theta_{23} \approx 49^\circ \quad (5.2\%)$$

$$\theta_{13} \approx 9^\circ \quad (3.8\%)$$

$$\Delta m_{21}^2 \approx 7.4 \times 10^{-5} \text{ eV}^2 \quad (2.2\%)$$

$$\Delta m_{32}^2 \approx +2.5 \times 10^{-3} \text{ eV}^2 \quad (1.4\%)$$

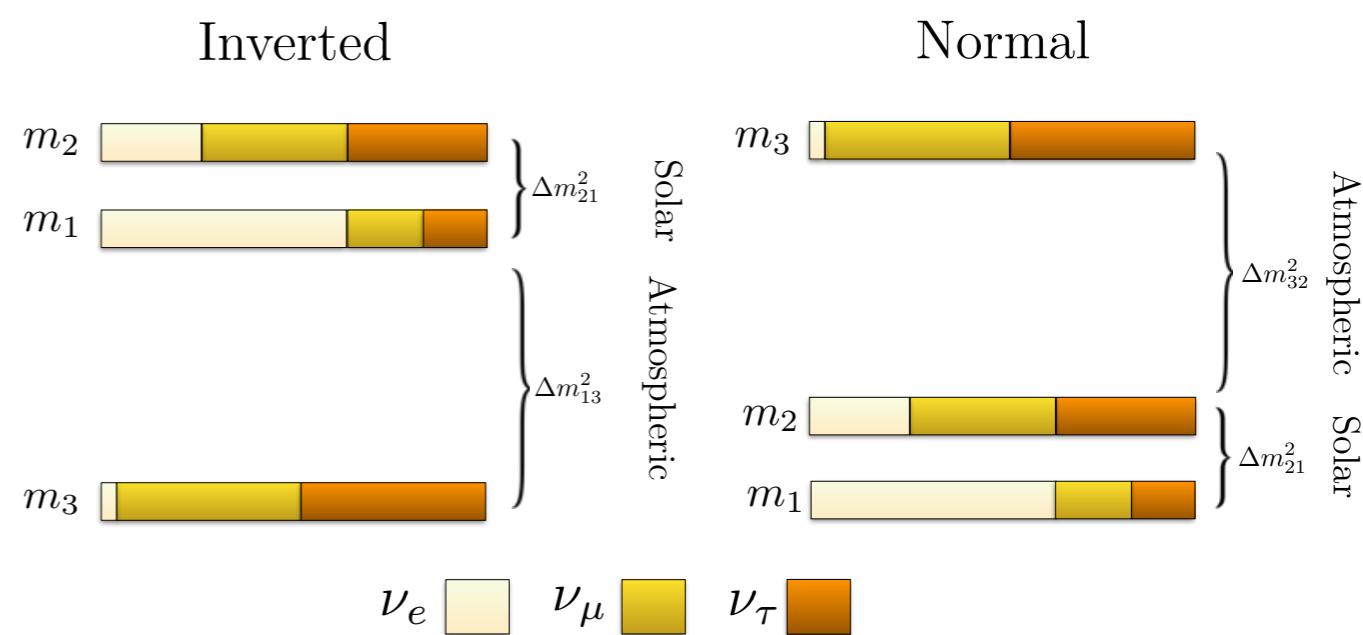


OPENED QUESTIONS:

Is $\theta_{23} 45^\circ$?

Is there CP violation in lepton sector?

Neutrino mass hierarchy is Normal or Inverted?



The NOvA Experiment

The NuMI Off-Axis ν_e Appearance Experiment

Experiment goals:

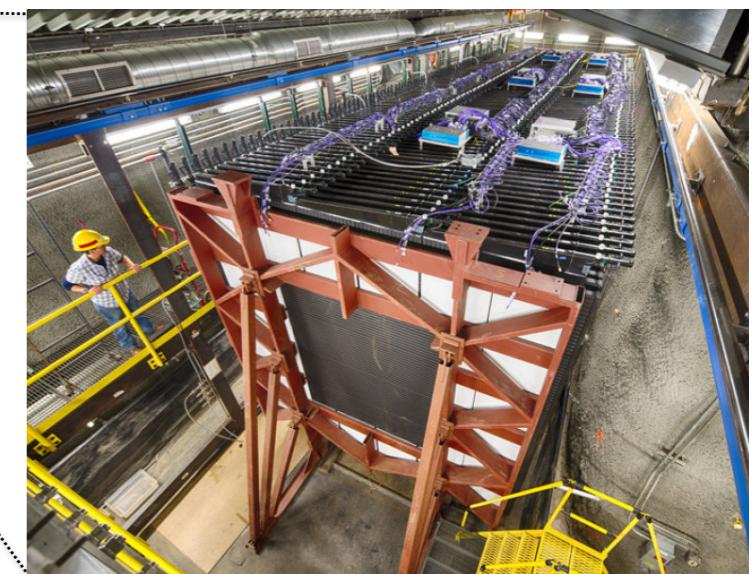
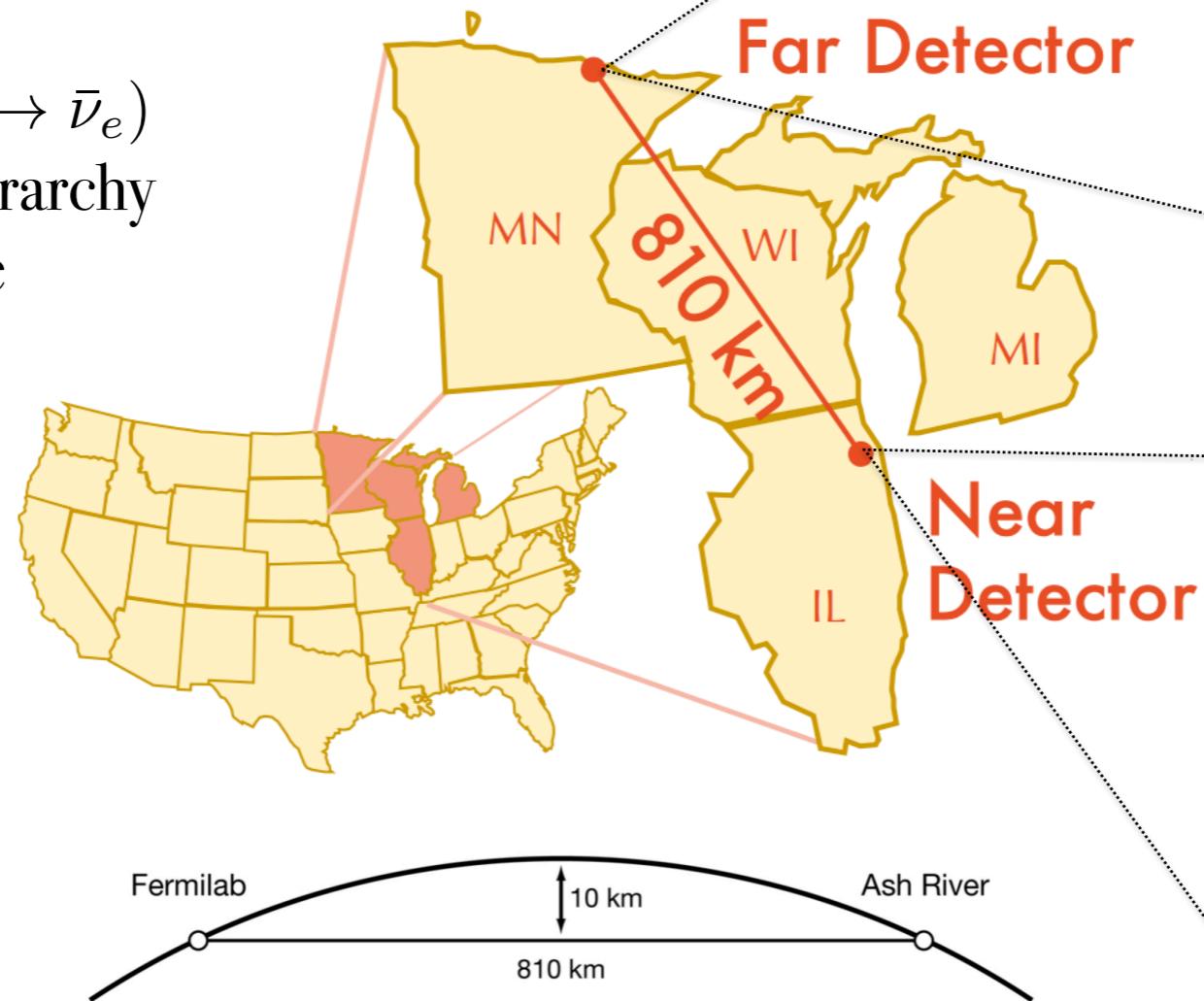
Using $\nu_\mu \rightarrow \nu_\mu$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

- * Precise measurement Δm_{32}^2
- * Mixing angle θ_{23}

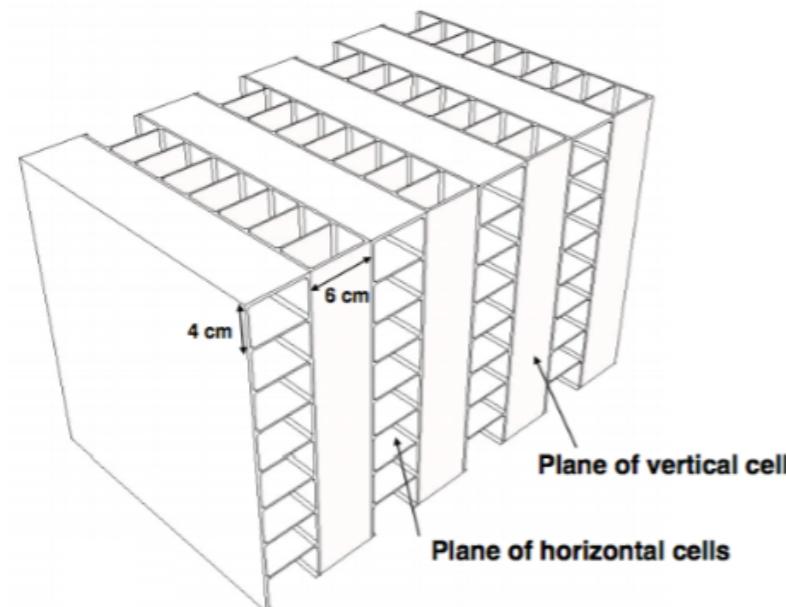
Using $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

- * Neutrino mass hierarchy
- * CP violating phase
- * Mixing angle θ_{23}

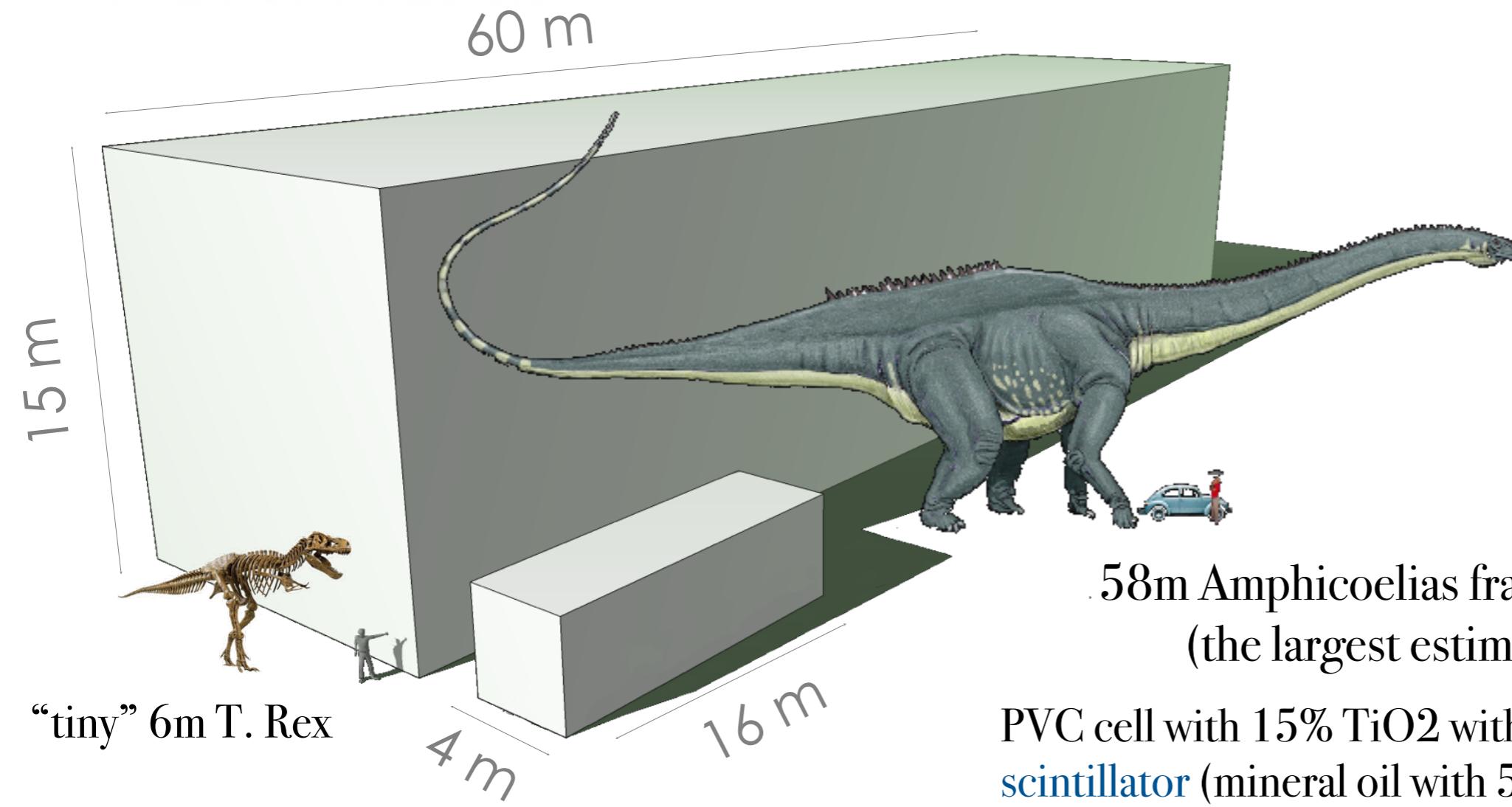
Long-baseline,
beam from Fermilab,
two detectors sit at
14 mrad off-axis



Detectors

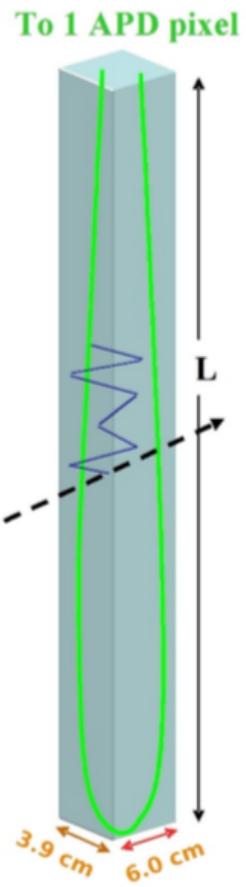


FD: 344 064 cells
ND: 20 192 cells

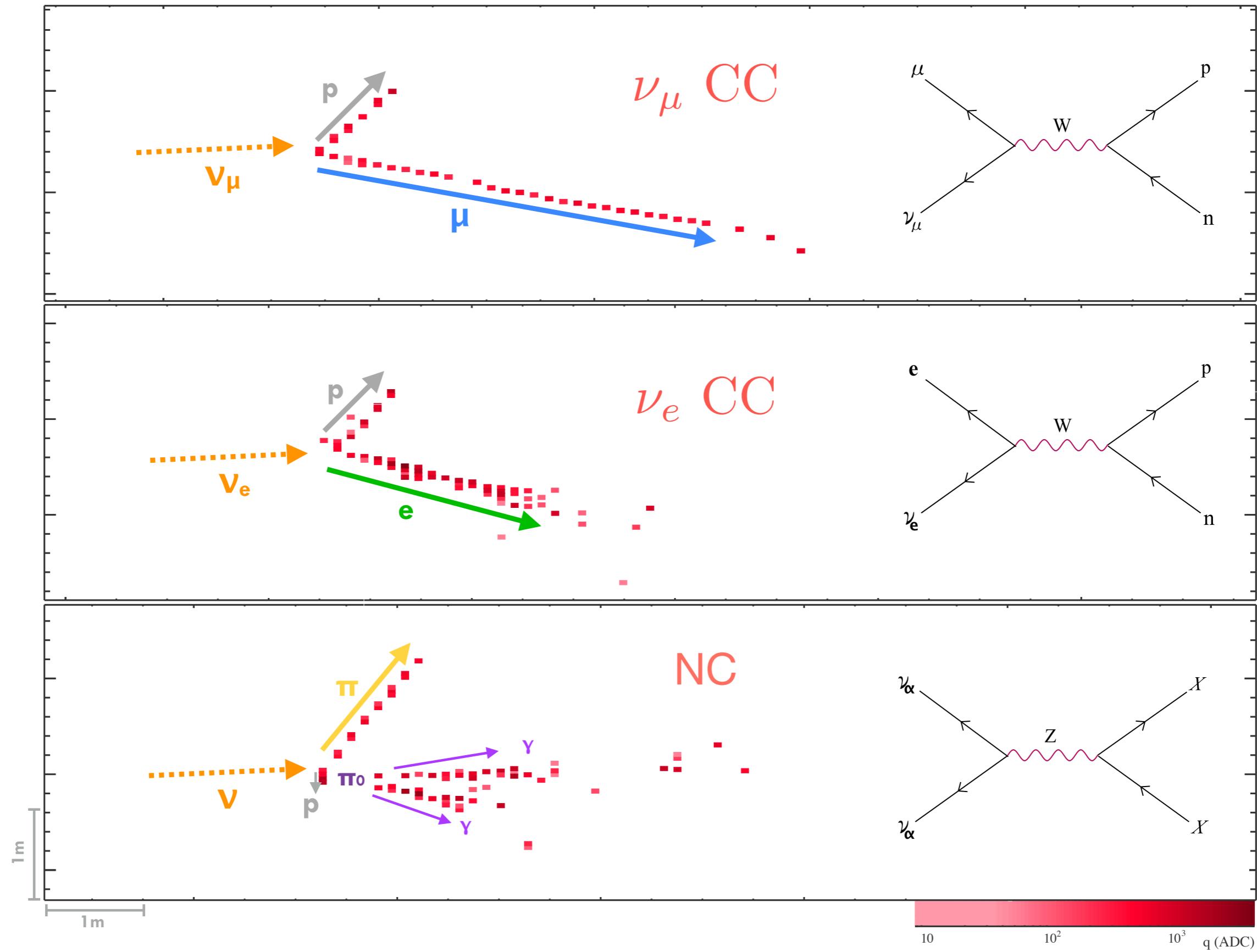


58m *Amphicoelias fragillimus*
(the largest estimate)

PVC cell with 15% TiO₂ with liquid scintillator (mineral oil with 5% pseudocumene)

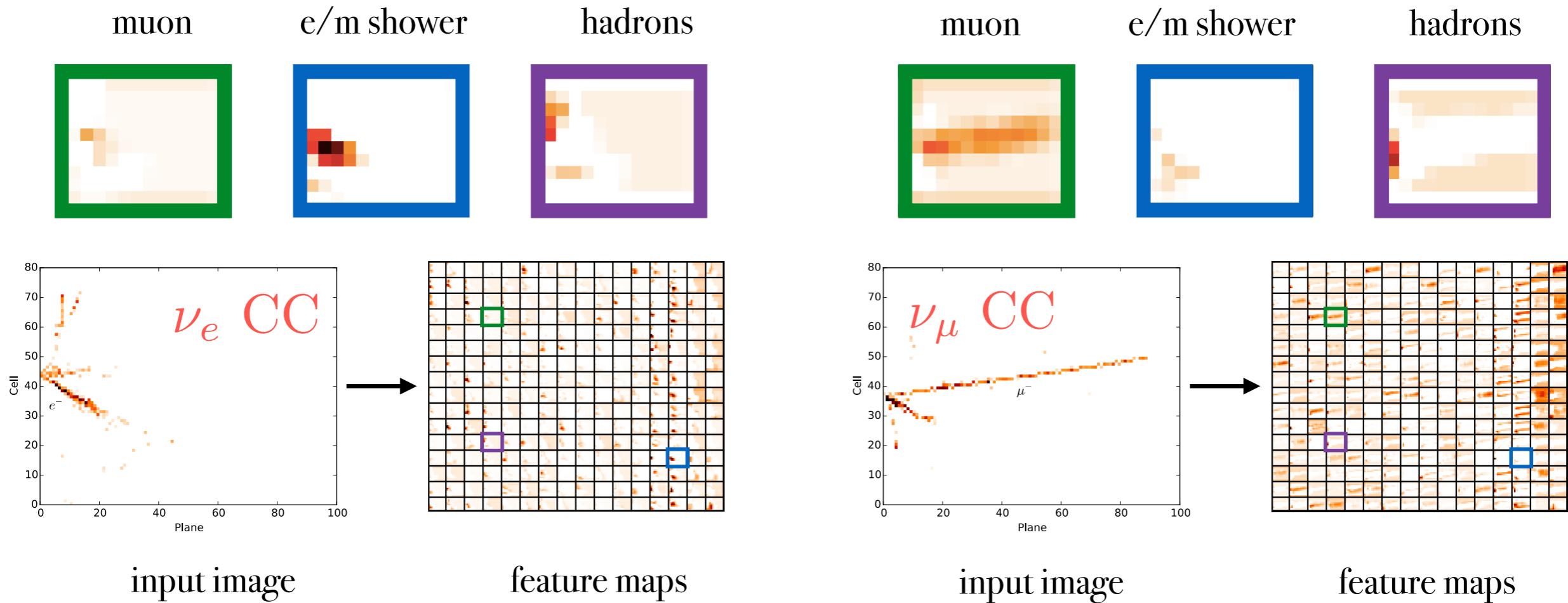


Event topologies



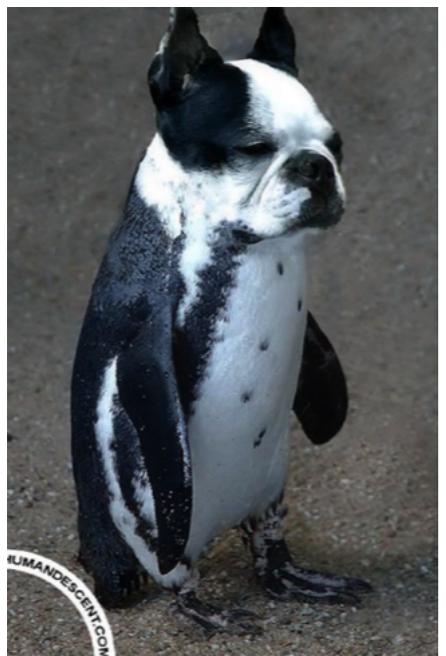
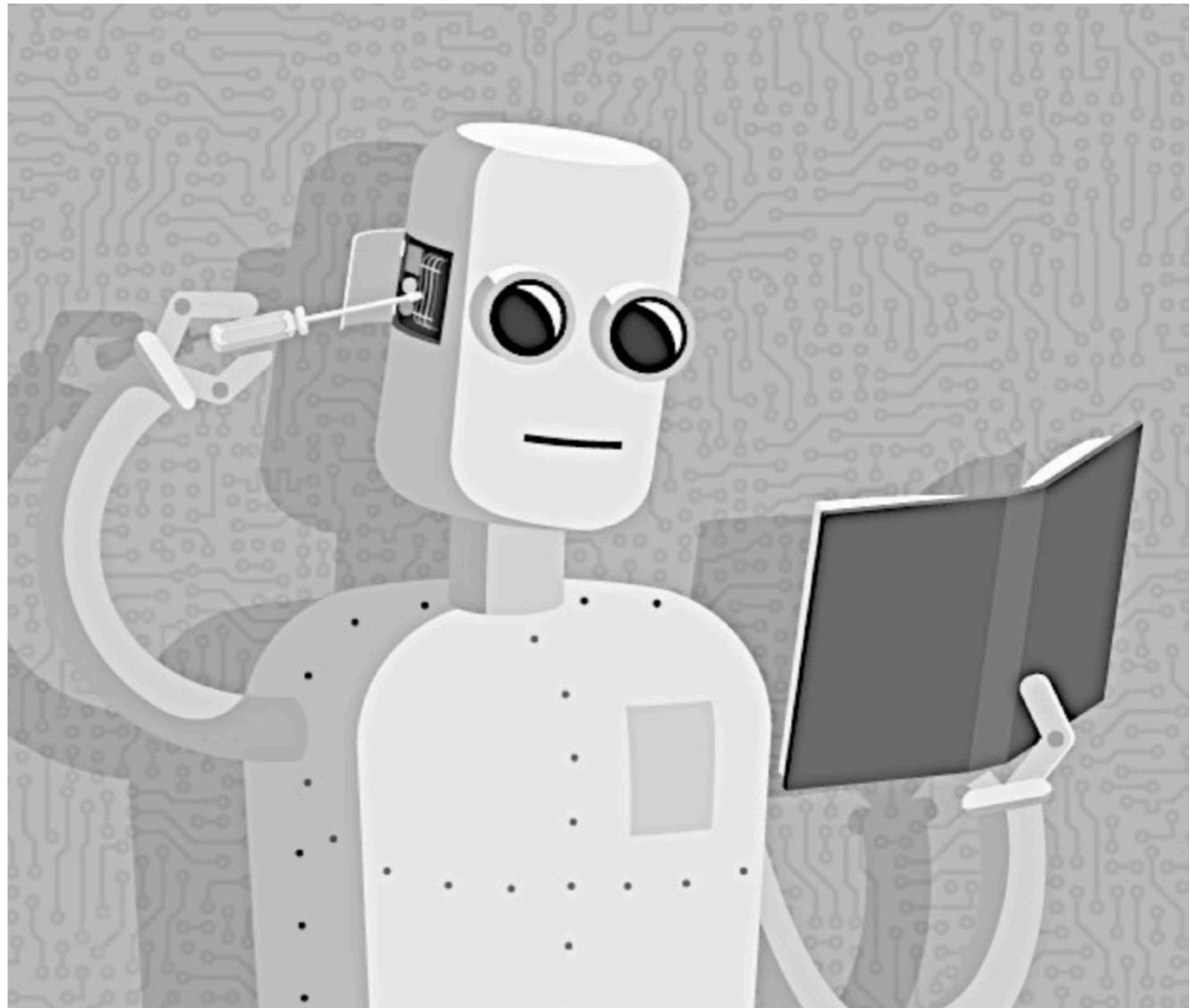
ν_e/ν_μ event selection

- * Events for analysis pass various cuts: data quality, fiducial volume, BDT cosmic rejection etc. and neutrino flavor identification PID.



- * We use convolution neural network called **CVN** (Convolutional Visual Network).
- * Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- * Multi-label classifier – the same network used in multiple analyses: can classify ν_e , ν_μ , ν_τ , NC and cosmic.

Challenge when applying machine learning



You know this is not like animals look in nature

How do we find the biases we have introduced in our training?

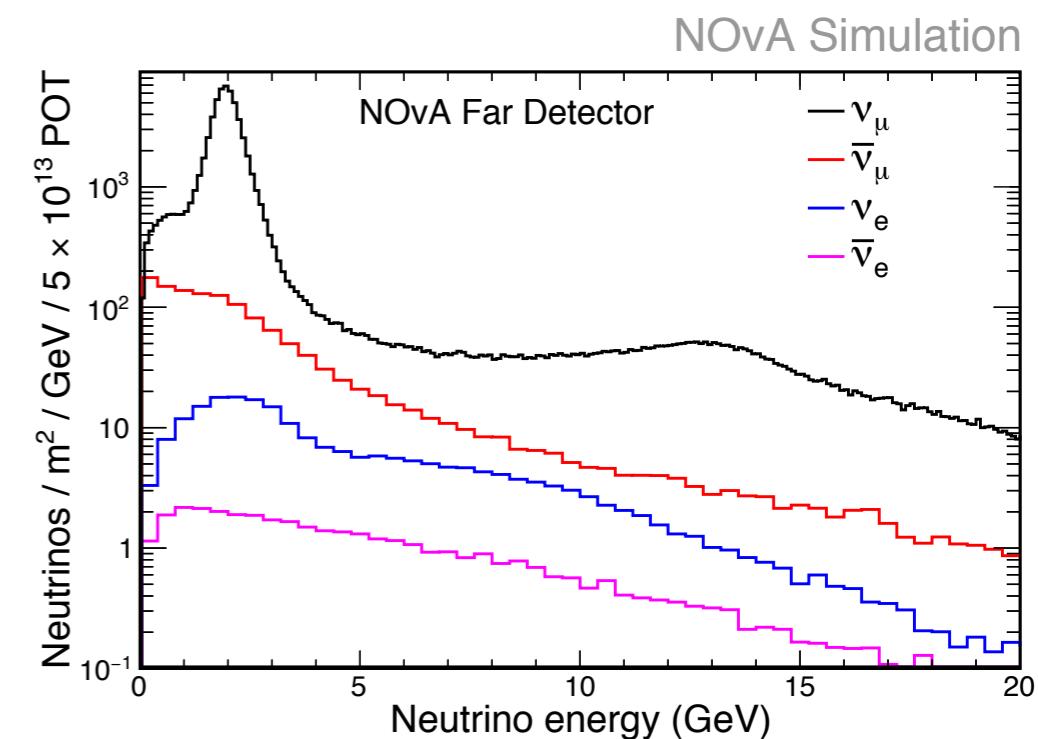
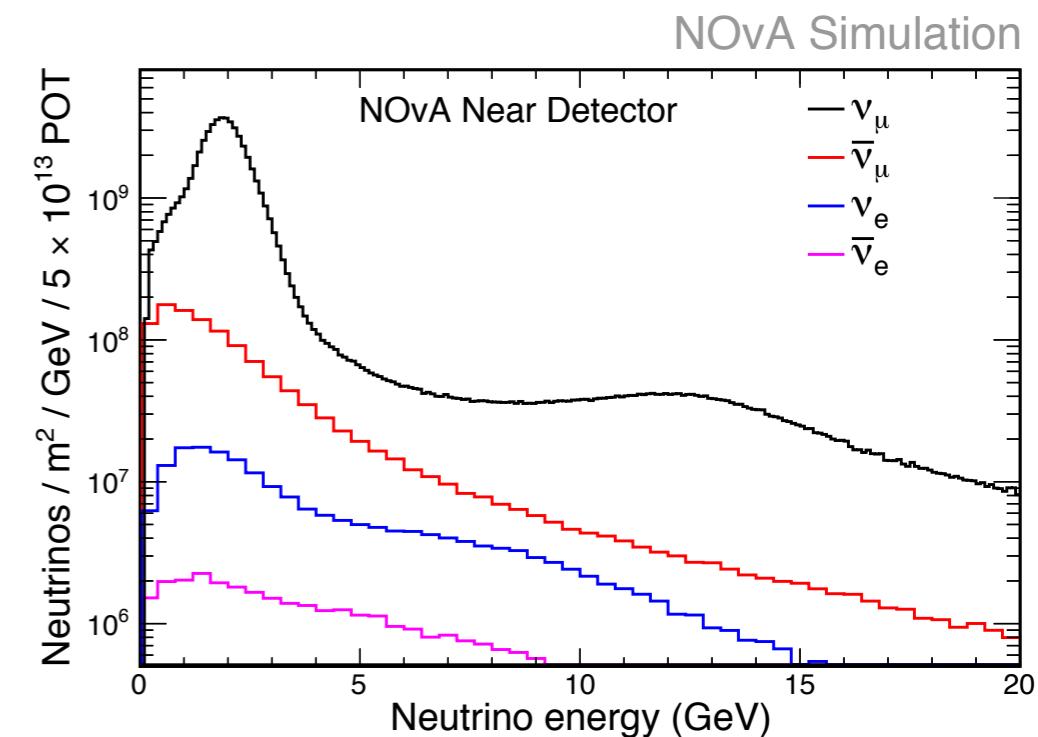
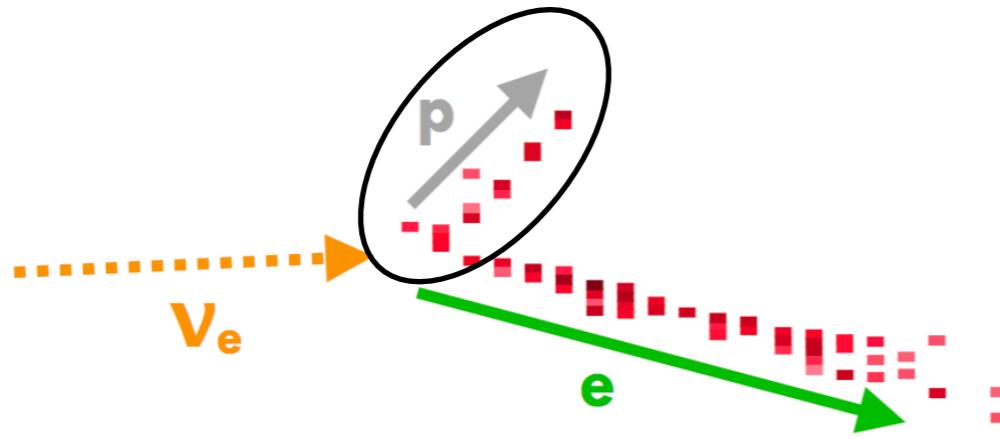
ν_e selection cross-checks

Perform various cross checks especially using ND, since there is $\times 10^6$ more statistics

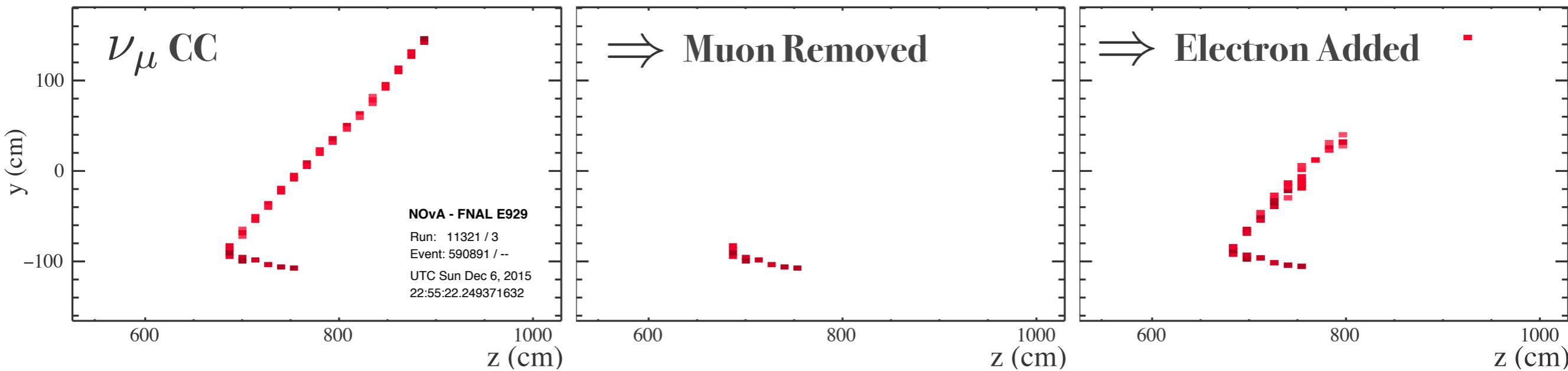
The ND data consist mainly of ν_μ and offers little information about what may be expected of the ν_e events.

The low number of ν_e events makes the cross-checks challenging

Muon-Removed Electron-Added (MRE) is a unique data-driven technique for performing the cross-check of hadronic component modeling that uses the large statistics of the ν_μ CC data events in the ND data sample



Muon Removed Electron added cross-check

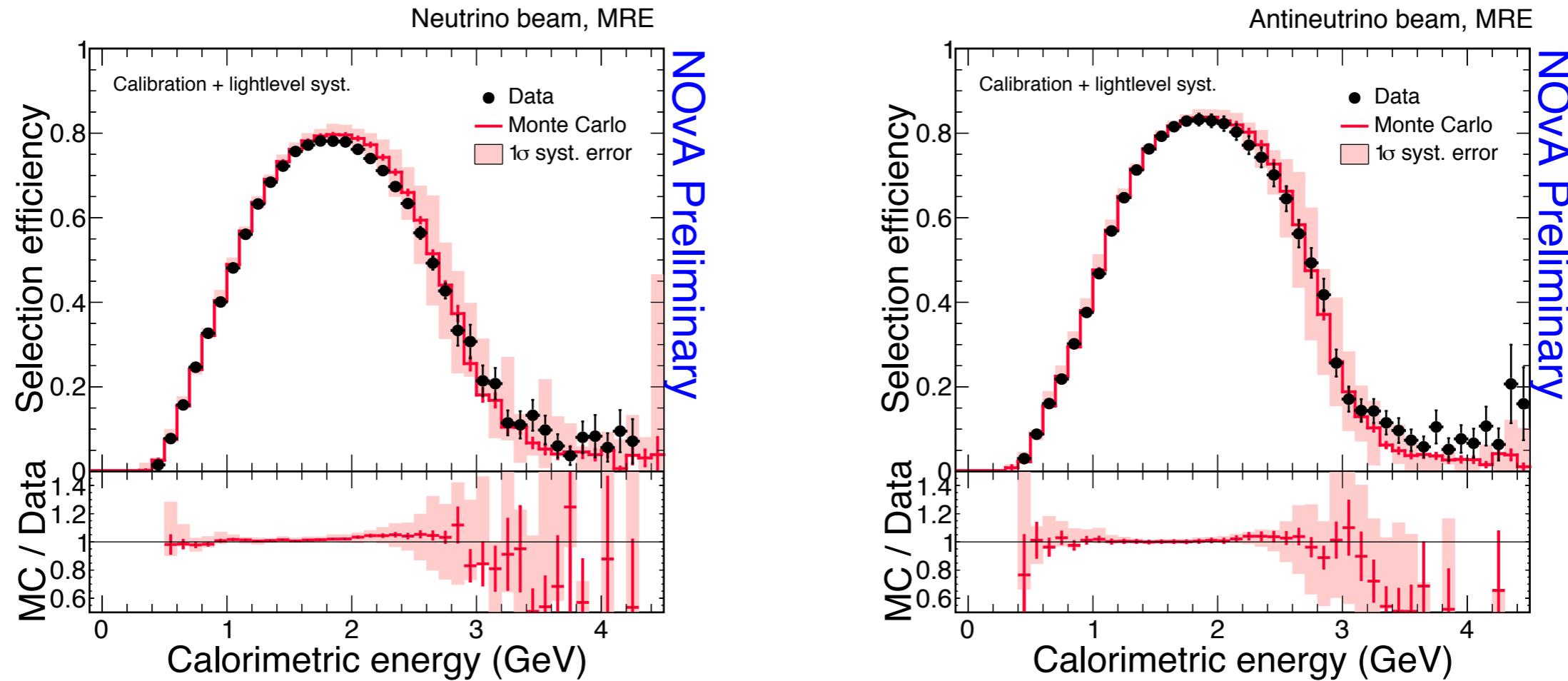


- * Select a muon neutrino interaction.
- * Remove the muon hits and replace with a simulated electron of the same energy preserving the nuclear/hadronic portion of the interaction.

Can perform on both data and simulation to compare selection algorithms.

These hybrid Data/Monte Carlo events allows us to study the impact of any mis-modeling of the hadronic shower on the ν_e selection efficiency by PID.

Muon Removed Electron added cross-check



		PRESELECTION	FULL SELECTION	EFFICIENCY	DIFFERENCE
Neutrino beam 6.77×10^{20} POT	Data MC	486083 511287	316009 341119	0.650 0.667	-2.56%
Antineutrino beam 3.29×10^{20} POT	Data MC	115400 123741	78133 84825	0.677 0.686	-1.23%

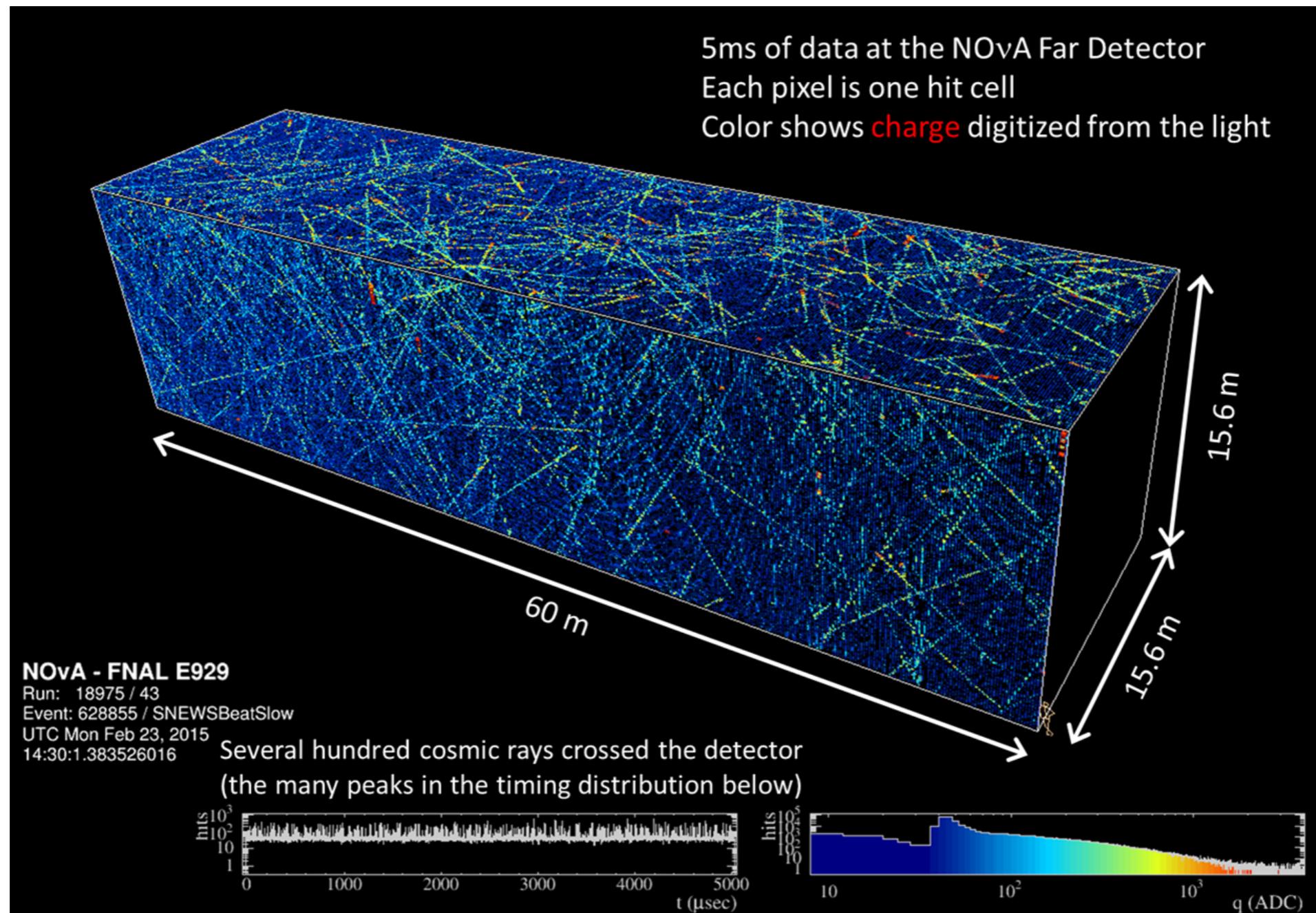
The overall PID selection efficiency agrees between data and MC at the **2% level** for MRE events both in neutrino and antineutrino beams.

CVN selection efficiency = events selected by PID / events before PID

Cosmic Muon Removed Bremsstrahlung showers

The FD operates on the surface with modest shielding resulting abundant cosmic ray muons entering the detector (at a rate of ~ 130 kHz)

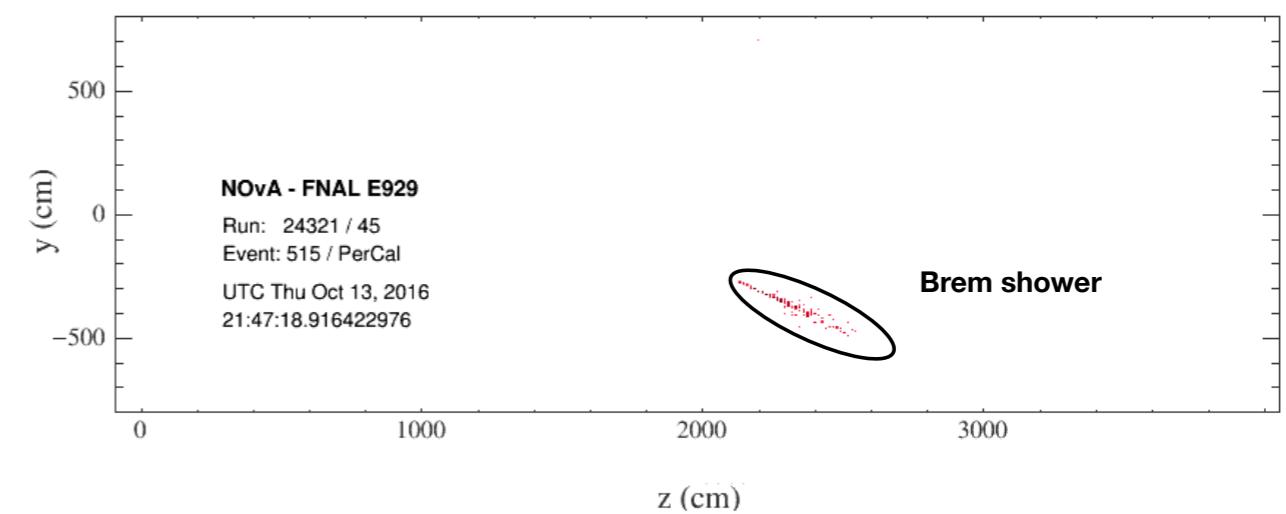
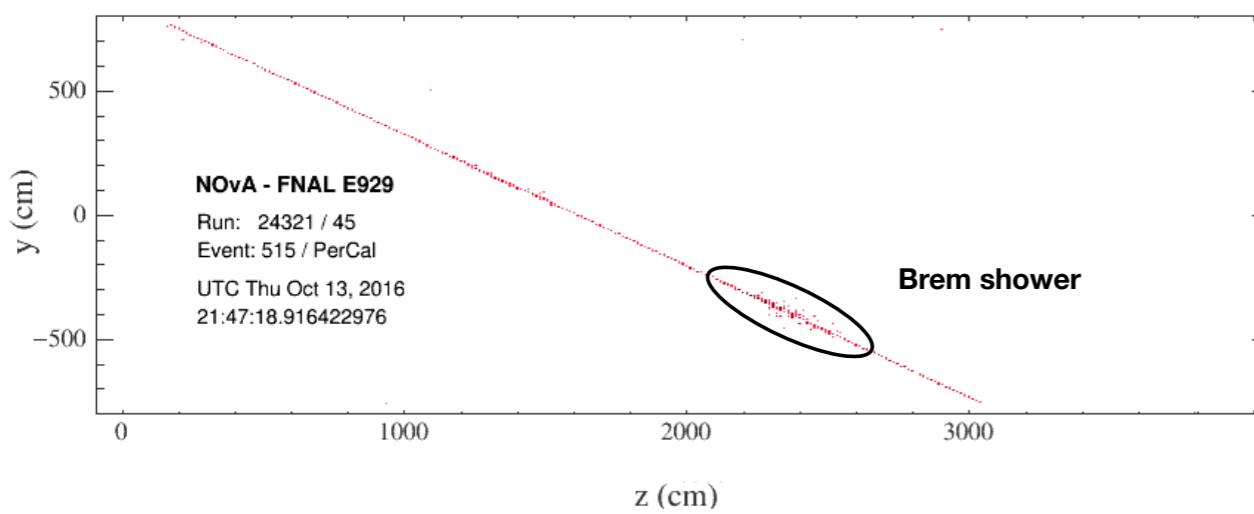
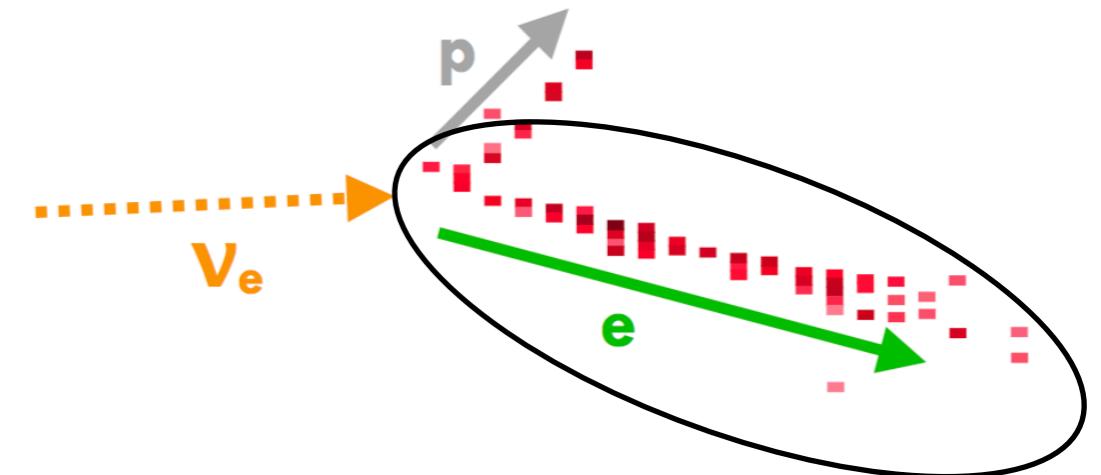
These muons can induce EM showers through bremsstrahlung radiation providing abundant EM showers in a few-GeV energy region.



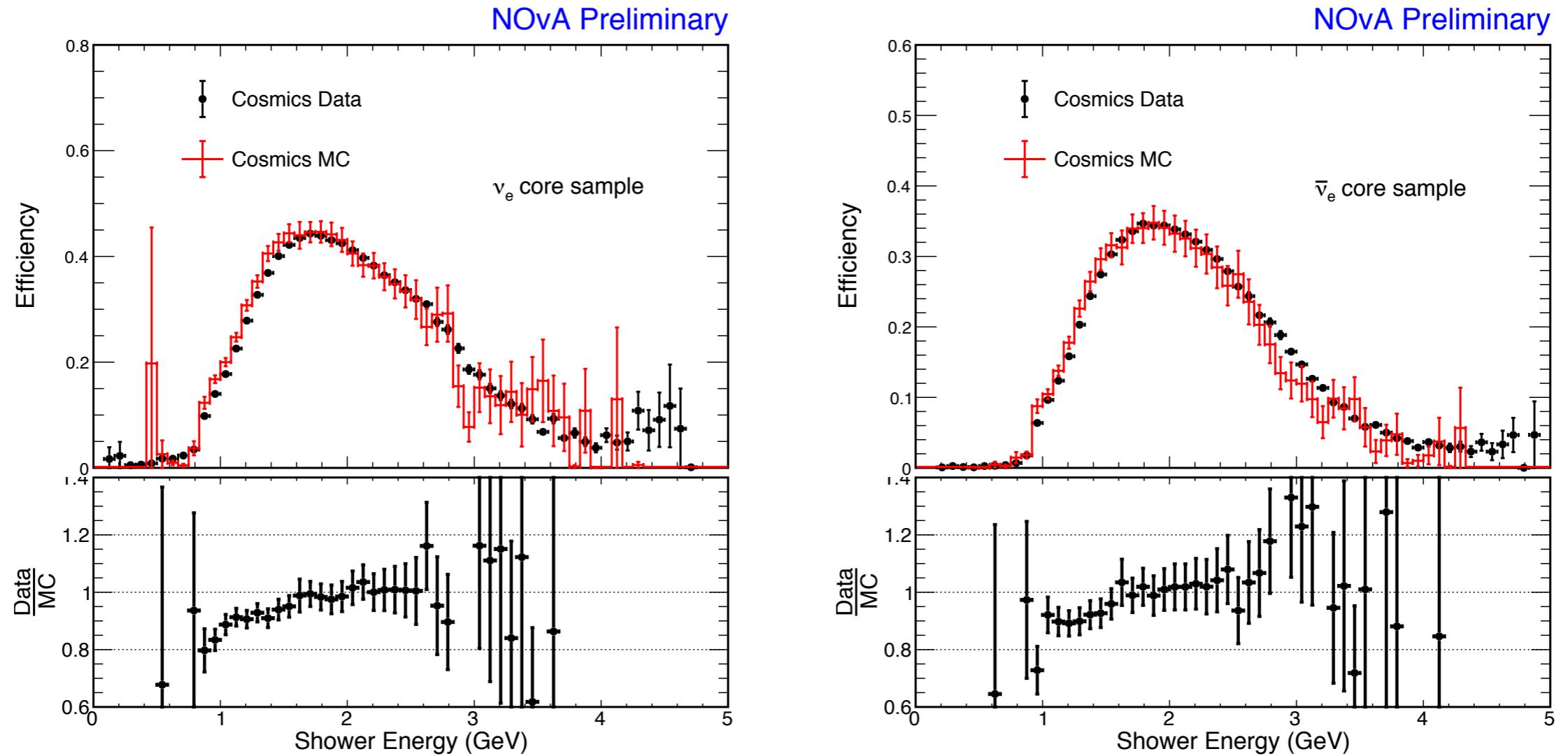
Cosmic Muon Removed Bremsstrahlung showers

In **Muon-Removed Bremsstrahlung** (MRBrem), we remove the muon from data & simulated FD cosmic muon rays, resulting in a pure selection of electromagnetic showers.

This sample can be used to characterise the EM signature and provide valuable cross-checks of the MC simulation, reconstruction, performance of CVN algorithms at FD



Cosmic Muon Removed Bremsstrahlung showers



EM shower selection efficiency of data and simulated brem showers agrees [within systematics](#) for neutrino and antineutrino CVN.

Conclusions

- * NOvA uses neural networks for particle identification.
- * Given the crucial role of PID for oscillation analysis, we carefully check its performance.
- * Among the cross checks there is a **Muon Removal Technique**.
- * Discussed two applications of **Muon Removal Technique** for checking neural network selection efficiency:
 - * Muon Removed Electron,
 - * Muon Removed Bremsstrahlung.
- * The resulting PID selection efficiency between data and MC show agreement at the few-percent level.
- * Further studies underway with actual spectrum correction by applying ND selection efficiency ratio to the FD predictions.