Impact of High Energy ν_e ($\bar{\nu}_e$) Events on NOvA Oscillation Sensitivities

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On behalf of the NOvA Collaboration

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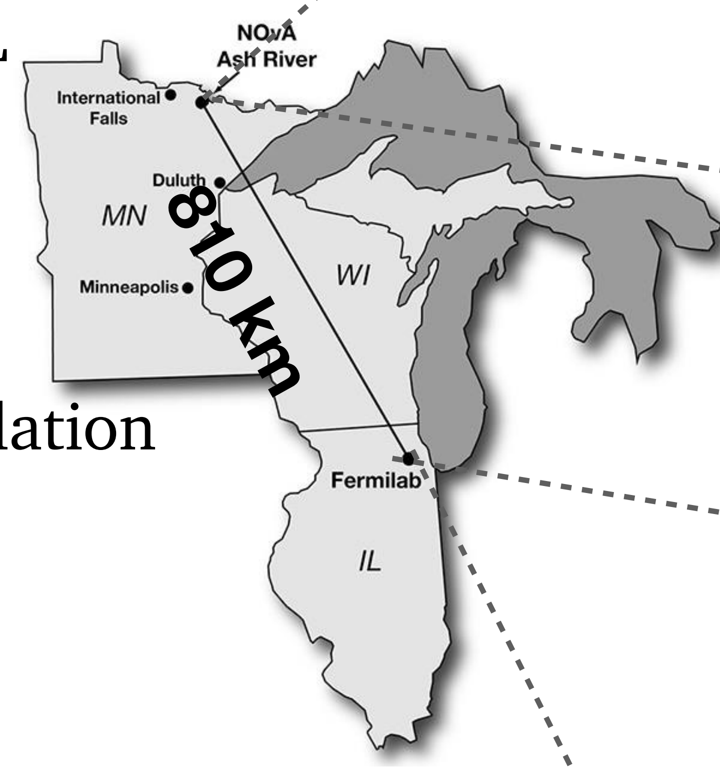
Introduction : The NOvA Experiment

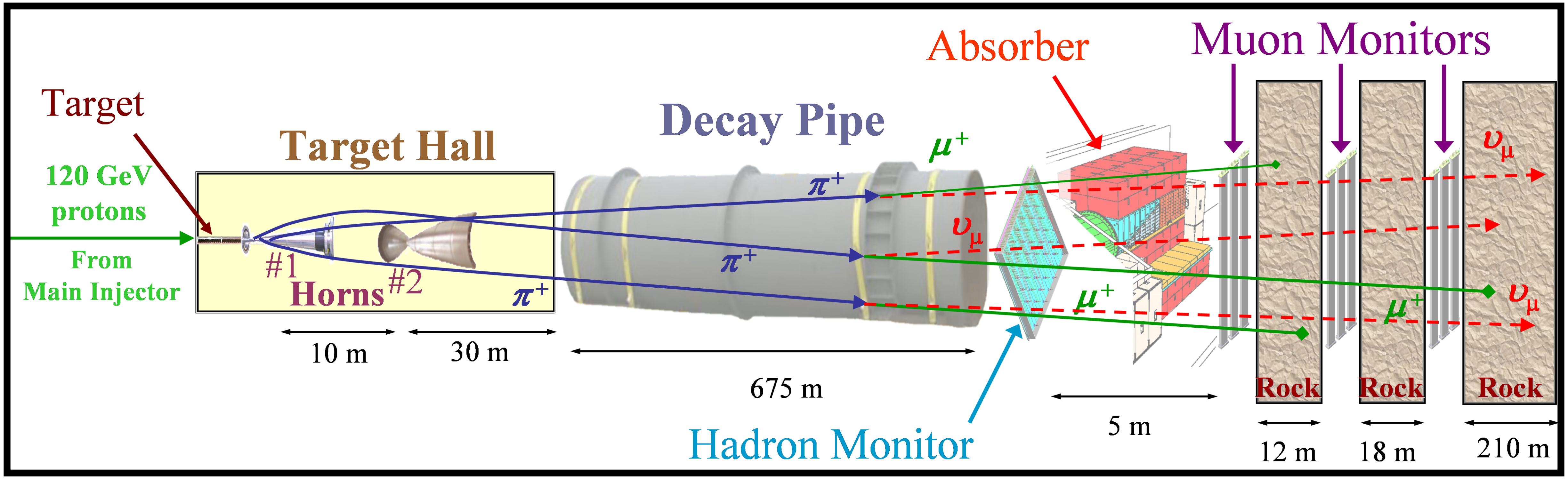
- A long-baseline neutrino oscillation experiment
- Functionally equivalent, segmented, mineral oil based liquid scintillator detectors
  - **FD** : 14 kton, On surface, Ash River
  - **ND :** 300 tons, Underground, FNAL
  - Situated 809 km apart
  - 14.6 milli-radians Off-axis
- Primary Goals :
  - To constrain 3-flavor neutrino oscillation parameters
  - Resolve ν Mass Hierarchy Problem
  - Resolve Octant Degeneracy
  - Matter- Antimatter Asymmetry
- Oscillation Channels:
  - ν_μ $(\bar{\nu}_\mu)$ **disapperance**
  - ν_e $(\bar{\nu}_e)$ **appearance**



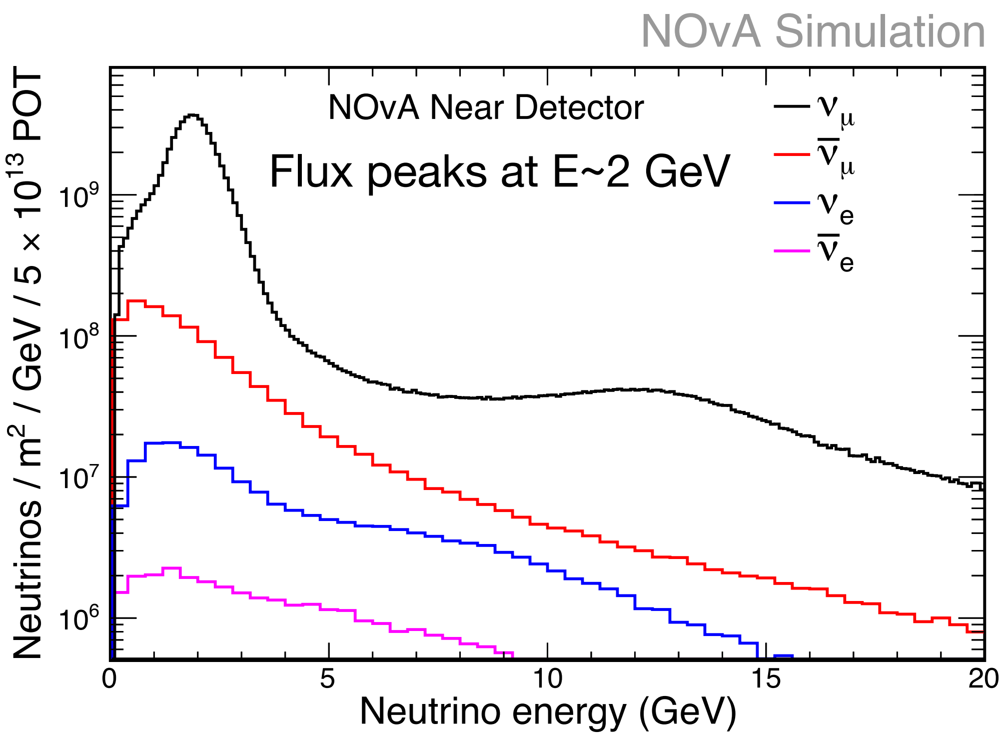
FD

ND

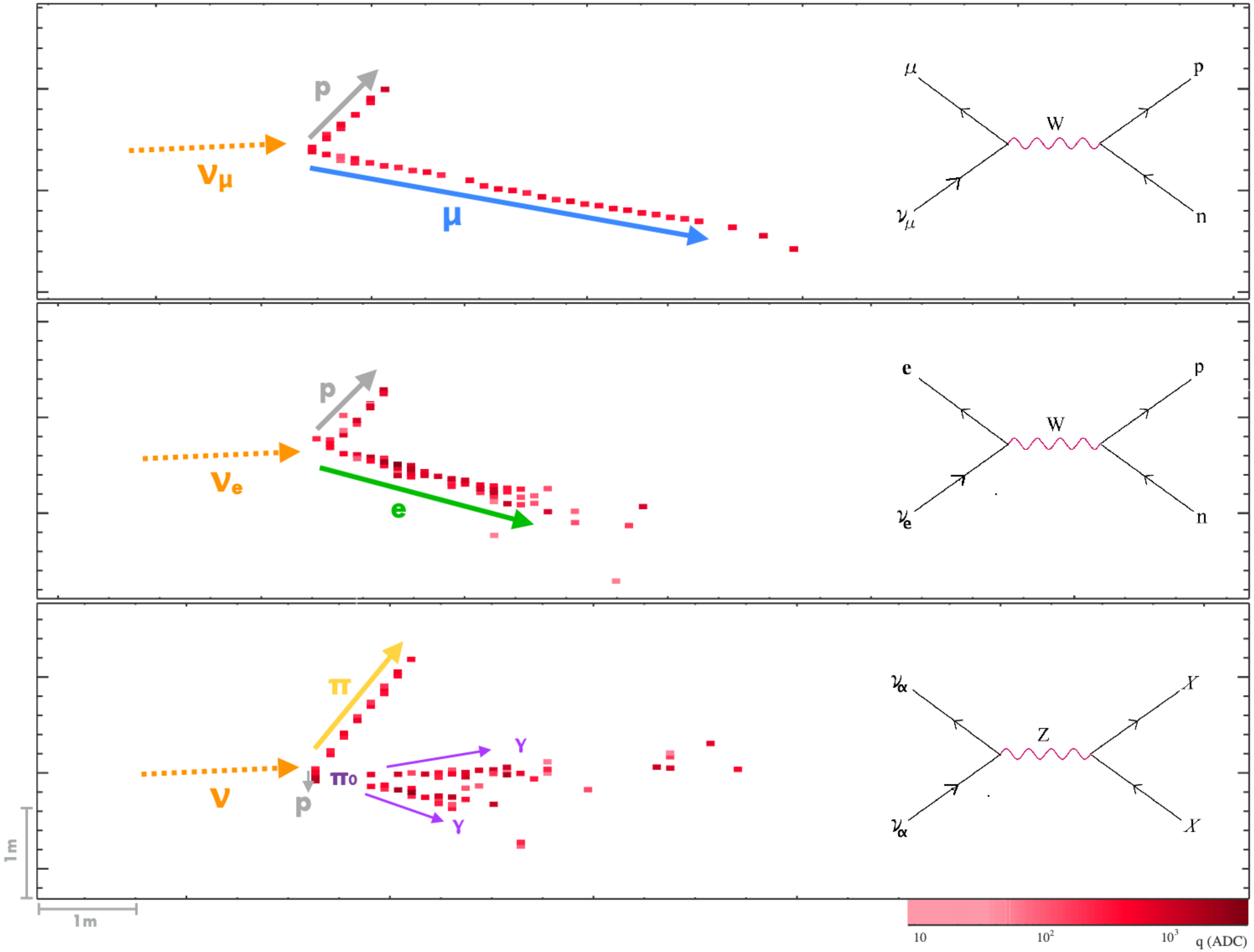
The NuMI Beam



- ✳ 120 GeV protons from the Main Injector (MI) strike a segmented, fixed, graphite target (~0.95m long, $\sim 1.8\lambda$), which produces Pions and Kaons
- ✳ A set of two magnetic horns focuses the produced mesons. These horns can be configured to focus either the positively or the negatively charged mesons
- ✳ These mesons decay in a decay pipe to produce neutrino beams



Event Topologies

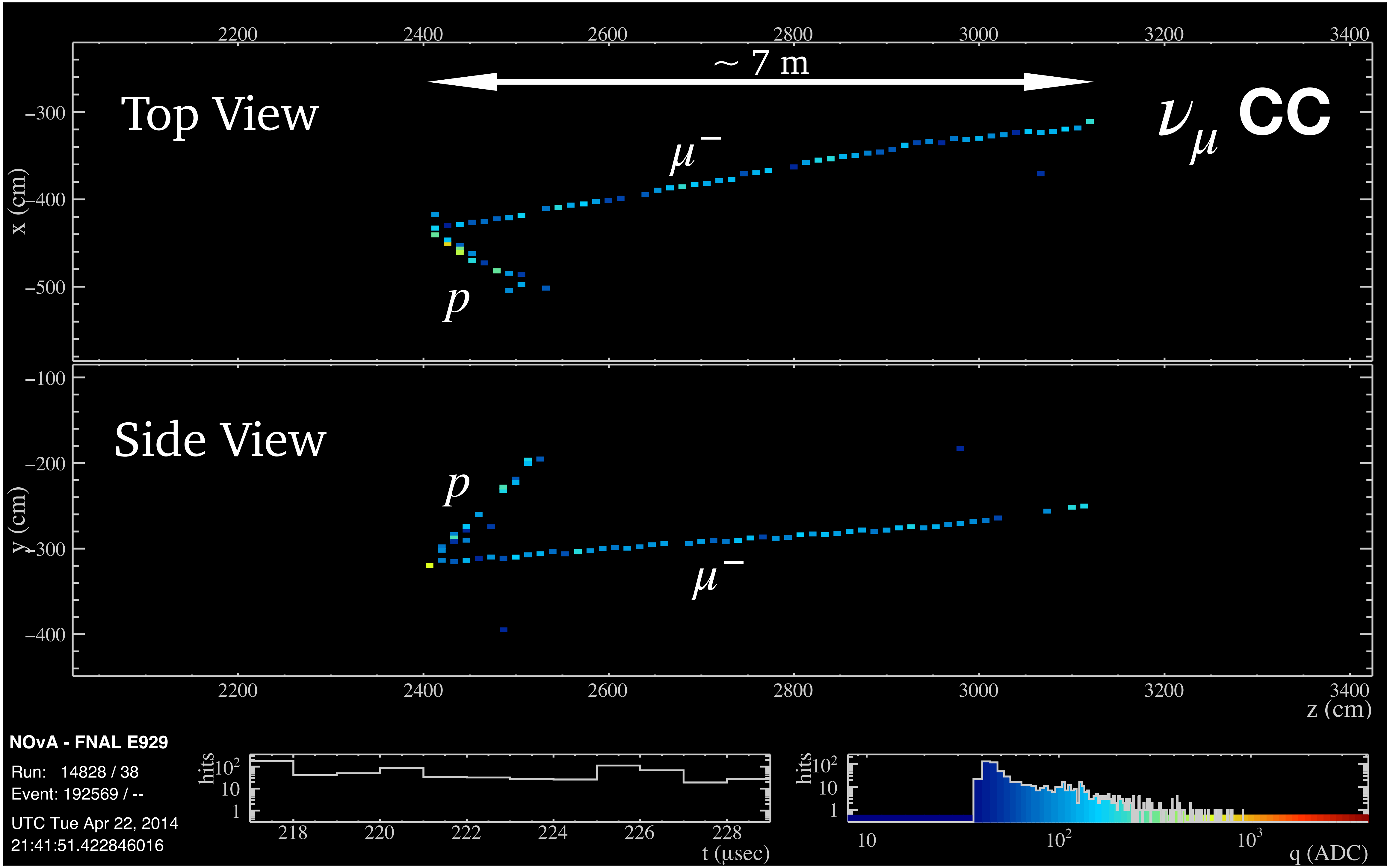


ν_μ **CC**

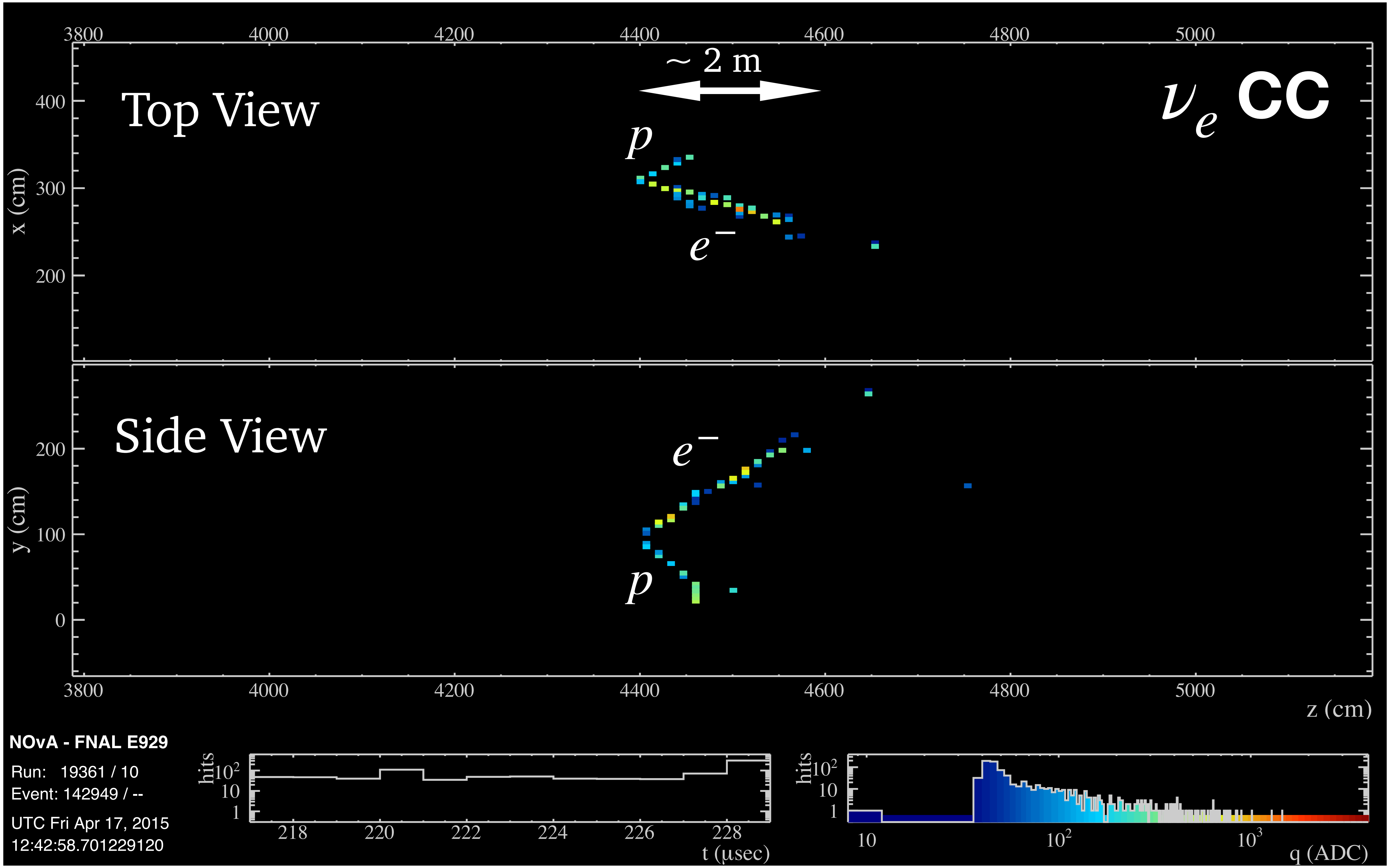
ν_e **CC**

NC

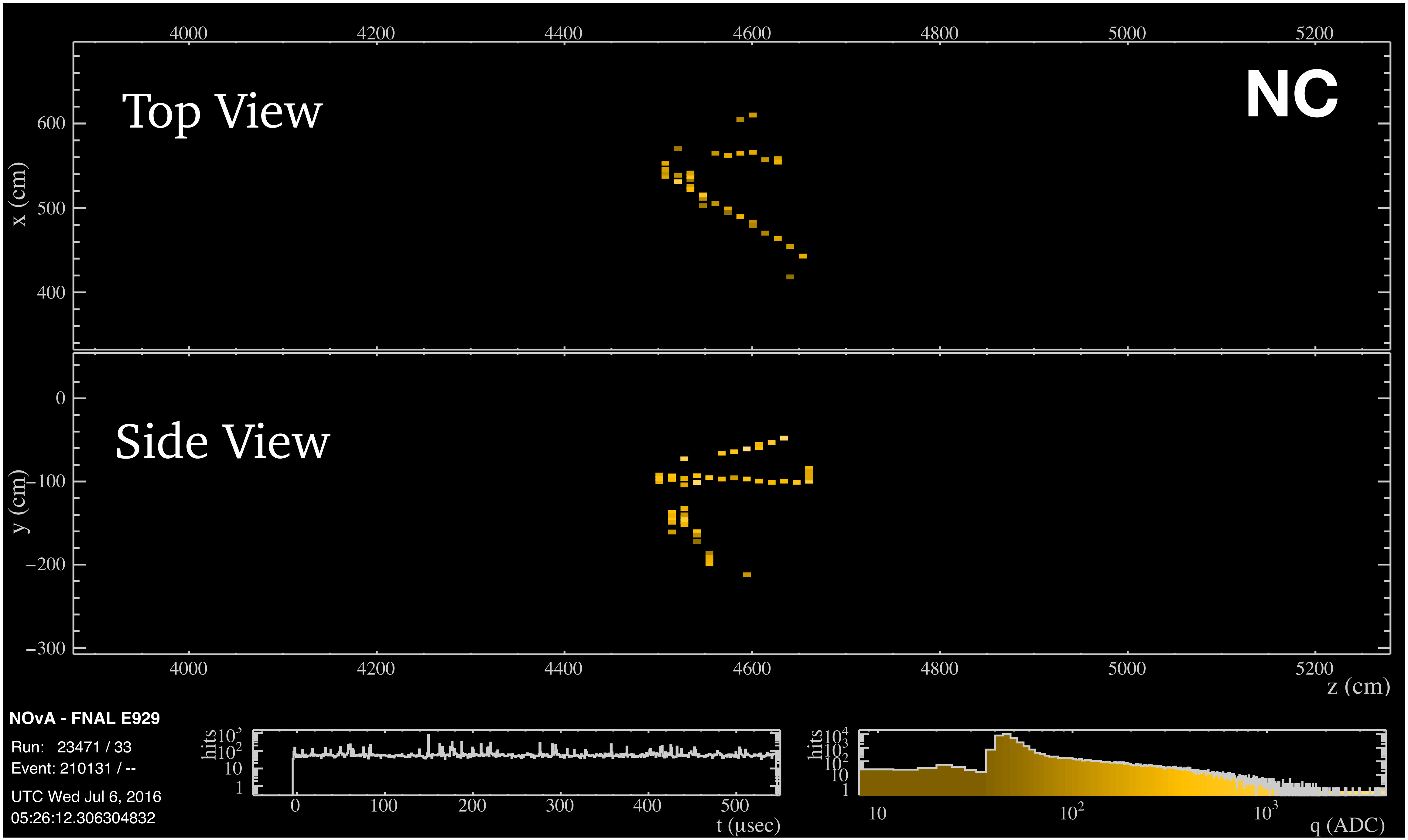
Real Event Display



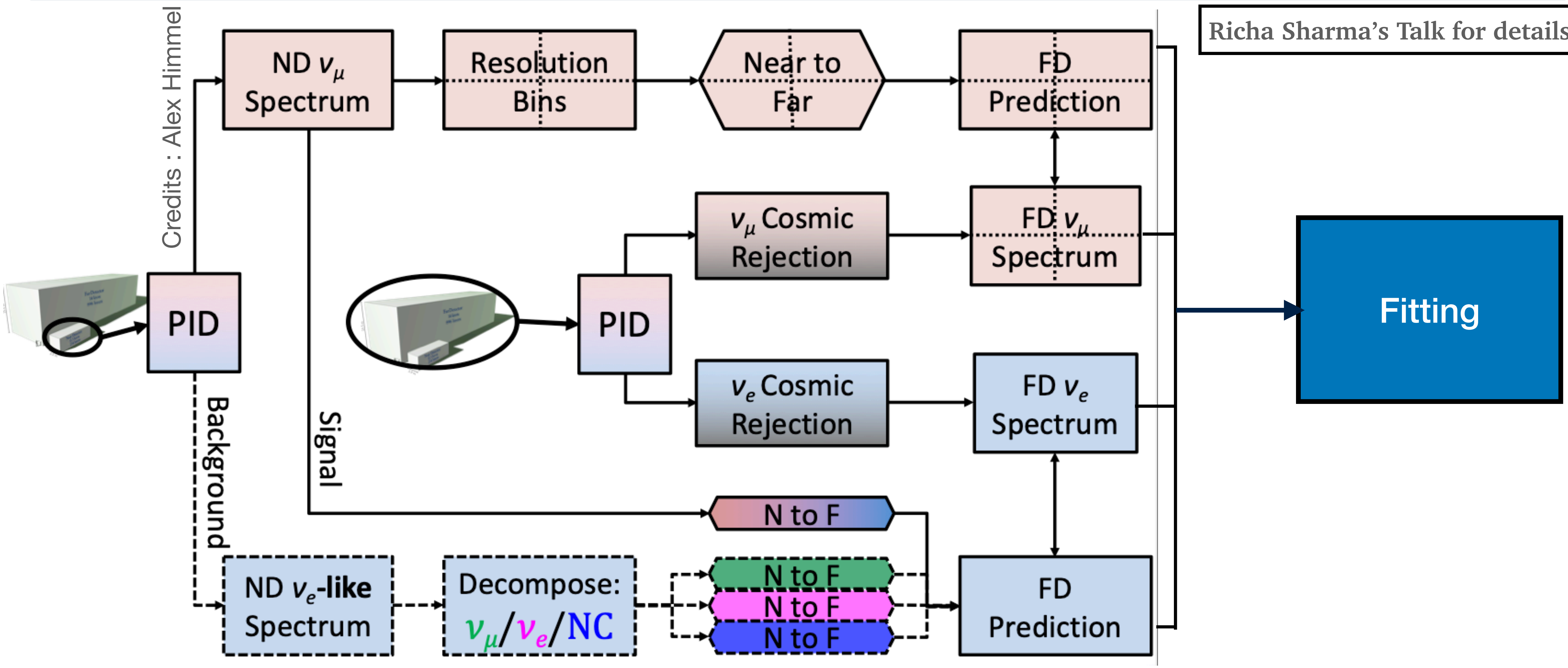
Real Event Display



Real Event Display



3-Flavor Analysis Strategy



- ✴ The **ND/FD** observes the **un-oscillated/oscillated** spectrum
- ✴ The FD simulated events are corrected using the ND data/MC
- ✴ The FD data and corrected predictions are compared to constrain the oscillation parameters

Including High Energy ν_e ($\bar{\nu}_e$) Events

- NOvA uses ν_e ($\bar{\nu}_e$) events in the energy range $1 < E_{\nu_e} < 4$ GeV for constraining the oscillation parameters

- The idea is to investigate if an additional power to constrain the oscillation parameters can be obtained by adding higher energy samples in the analysis

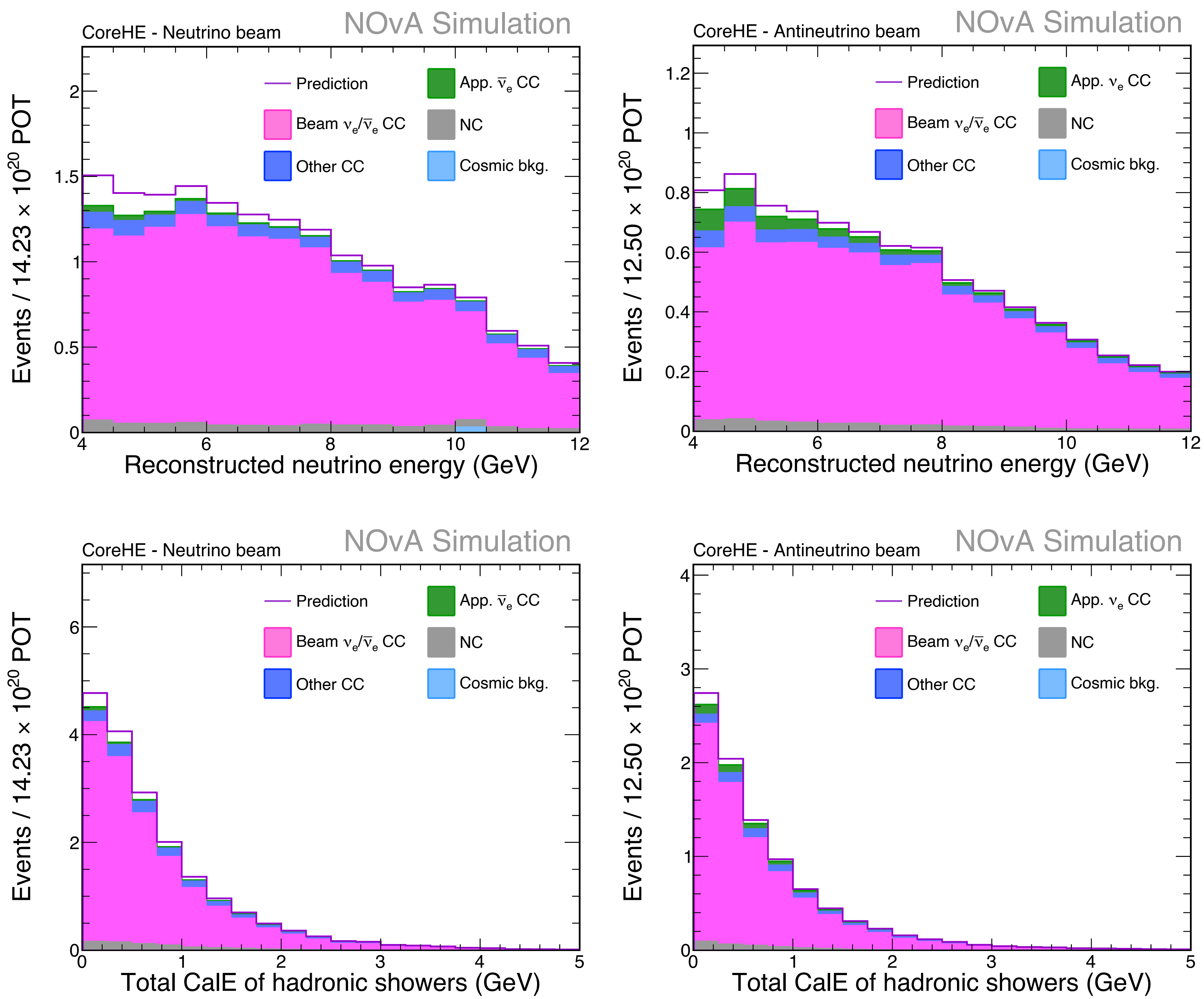
- One such sample is with energies $E_{\nu_e} > 4$ GeV

- Previously, $4 \leq E_{\nu_e} \leq 12$ GeV events sample was separately used to see if our MC predictions are reasonable or not

- In this study, ν_e ($\bar{\nu}_e$) events with energies $4 \leq E_{\nu_e} \leq 12$ GeV has been included in Far Detector predictions

High Energy ν_e ($\bar{\nu}_e$) Distributions

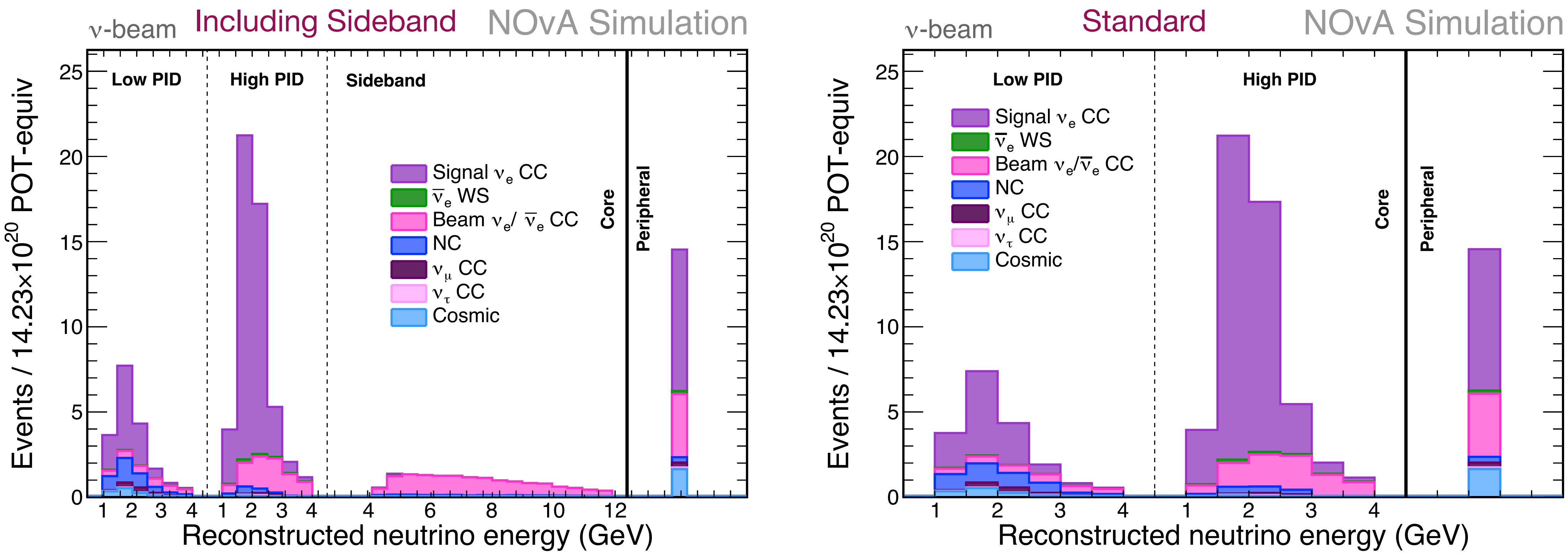
- FD ν_e spectra outside the signal region i.e. $E_\nu > 4.0$ GeV
- Previously used as a cross-check to ensure data quality
- Data/MC comparison outside the signal region provides confidence in the analysis
- The high energy electron neutrino sample is dominated heavily by the intrinsic beam ν_e ($\bar{\nu}_e$) background



CalE = Total Hadronic Energy

FD ν_e Predictions with Systematics

- Comparison of FD ν_e predictions with systematics including high energy events with standard 3-flavor predictions

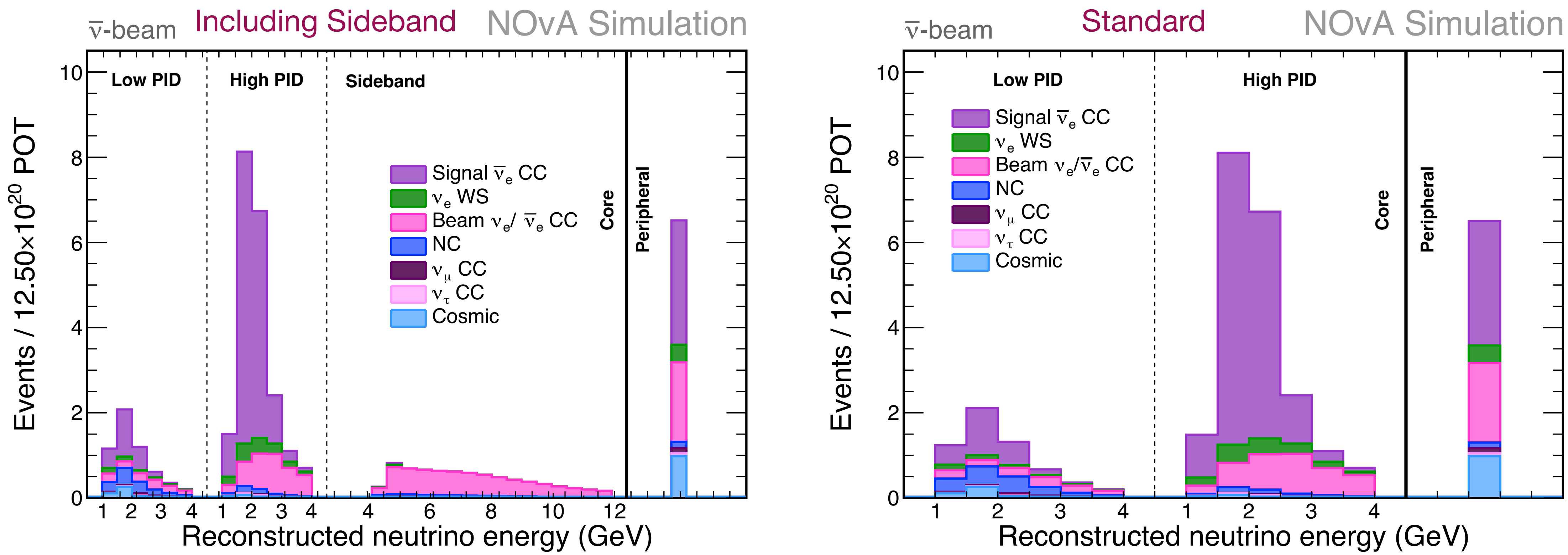


	Signal Events	Beam Events	WS Events	NC Events	ν_μ Events	ν_τ Events	Cosmic Bkg. Events
New	59.43	26.76	1.04	6.07	1.69	0.86	3.22
Standard	59.25	13.91	1.01	5.29	1.36	0.52	3.13

- High energy events originate mostly from beam background

FD $\bar{\nu}_e$ Predictions with Systematics

- Comparison of FD $\bar{\nu}_e$ predictions with systematics including high energy events with standard 3-flavor predictions



	Signal Events	Beam Events	WS Events	NC Events	ν_μ Events	ν_τ Events	Cosmic Bkg. Events
New	19.94	12.96	2.38	2.25	0.47	0.49	1.57
Standard	19.88	6.59	2.30	1.99	0.33	0.32	1.55

- High energy events originate mostly from beam background

Fitting Method

- The Poisson log-likelihood is minimized to get the best fit values of the oscillation parameters
- For the joint fit, separate $\Delta\chi^2$ values are calculated for ν_e, $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$ spectra
- Individual contributions are summed to get the final $\Delta\chi^2$ value

$$\ln \lambda(\vec{\theta}, \vec{\delta}) = -2 \sum_{i=1}^{N} \left[\nu_i(\vec{\theta}, \vec{\delta}) - n_i + n_i \ln \frac{n_i}{\nu_i(\vec{\theta}, \vec{\delta})} \right] + \sum_{i=1}^{M} \frac{\delta_i^2}{\sigma_i^2}$$

$\nu_i =$ Predicted neutrino events

$n_i =$ Observed neutrino events

$\vec{\theta} =$ Oscillation parameters

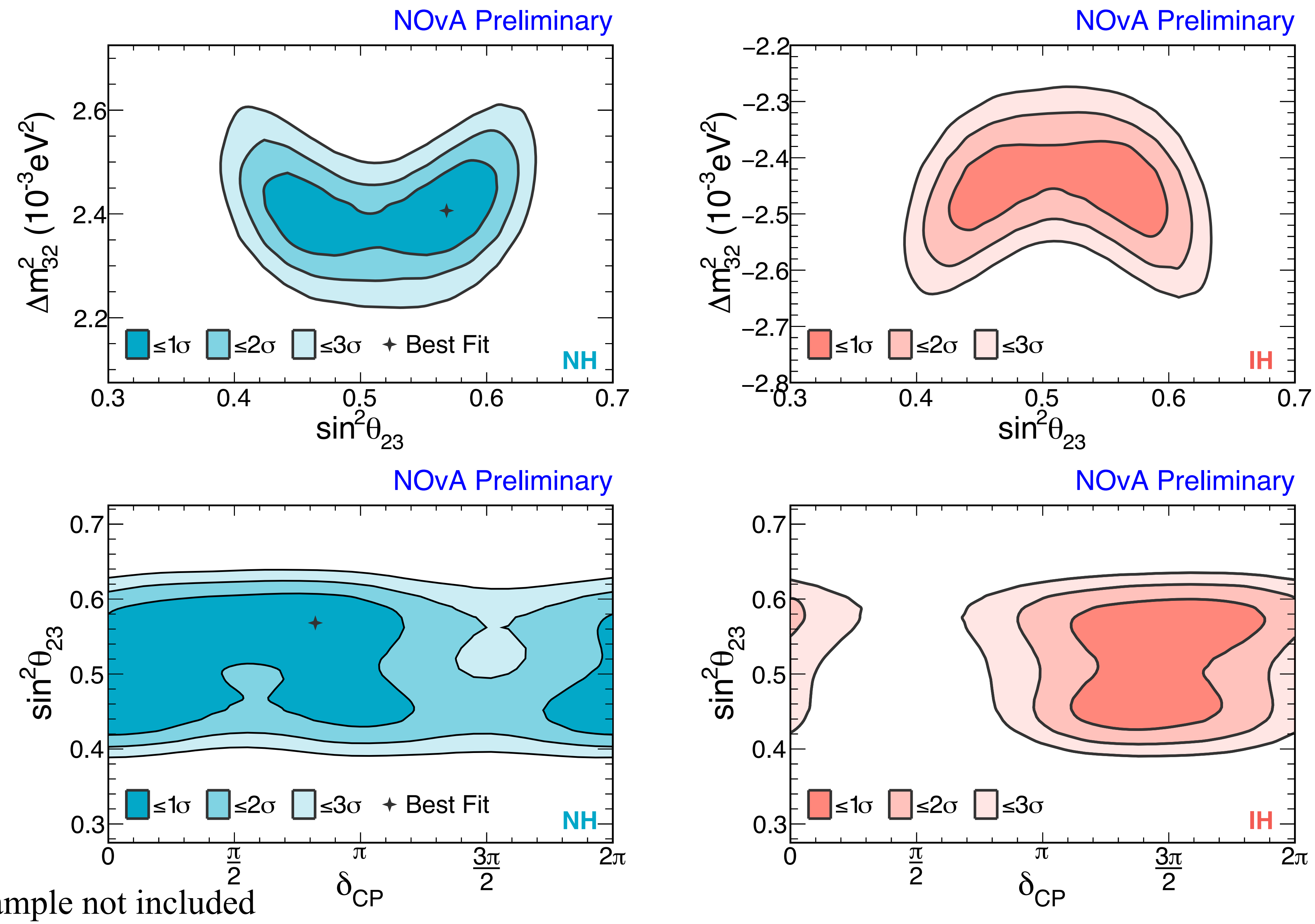
$\vec{\delta} =$ Systematic nuisance parameters

- The fits are profiled over the oscillation parameters in different combinations to generate physics sensitivities
- In this study, the FD predictions including the high energy event sample was used instead of the standard 3-flavor predictions

➡Addition of high energy ν_e ($\bar{\nu}_e$) events to FD predictions had no impact on NOvA oscillation sensitivities

NOvA Oscillation Sensitivities

- NOvA latest 3-flavor neutrino oscillation sensitivities, using only the core energy samples[1]



[1]High energy sample not included

Conclusions

- NOvA is a long-baseline neutrino oscillation experiment situated at Fermilab that imposes good constraints on the oscillation parameters
- High energy sample is heavily dominated by beam background
- Minimal gain in signal events from high energy sample
- Minimal impact on standard 3-flavor oscillation sensitivities

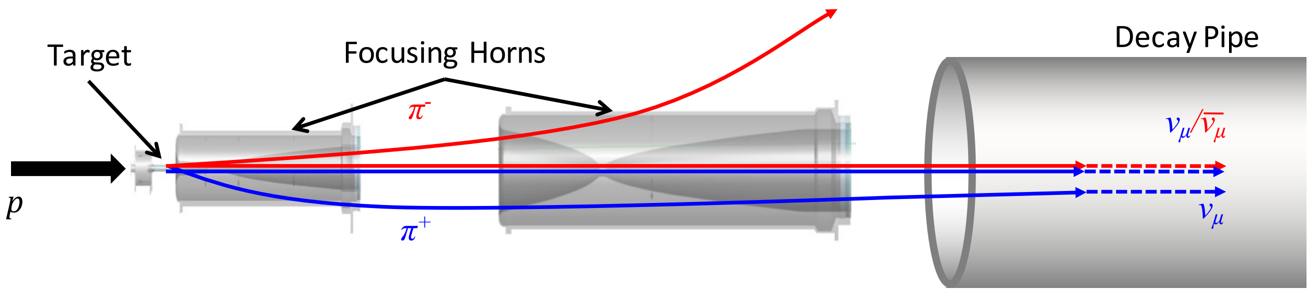
- High energy ν_e ($\bar{\nu}_e$) sample could be effective in :
  - Constraining beam background coming from $K^{\pm}$ and K^0 decays
  - Constraining background as NOvA considers moving to a direct two detector (ND + FD) fit
  - Investigating impacts on NOvA's improved sensitivities to non-standard interactions

The NOvA Collaboration

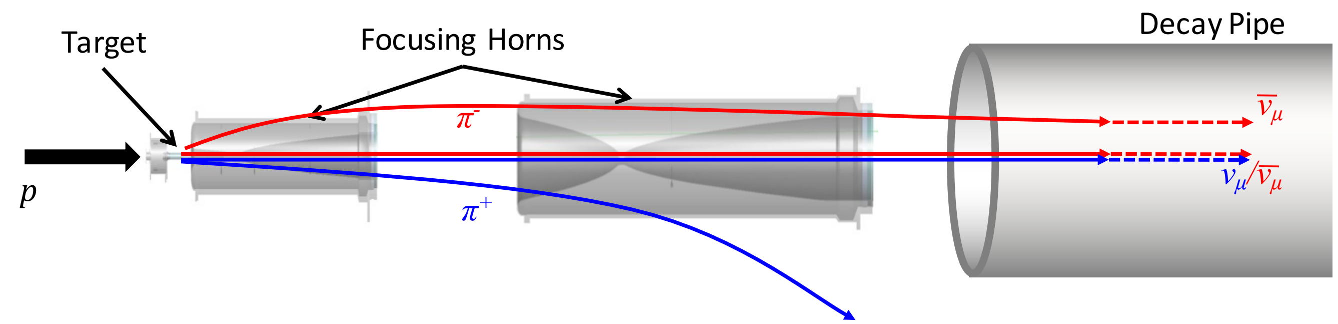
http://novaexperiment.fnal.gov

Back Up

Horn Current Configurations



Forward Horn Current (FHC) Configuration



Reverse Horn Current (RHC) Configuration

- Magnetic horns configuration for making $\nu_\mu/\bar{\nu}_\mu$ beam is called the Forward/Reverse Horn Current (FHC/RHC) configuration
- Depending upon the current configuration, either the positively charged mesons (π^+/K^+) or the negatively charged mesons (π^-/K^-) are focussed
- The focussed mesons decay in flight to give a highly pure $\nu_\mu/\bar{\nu}_\mu$ beam with a small amount of wrong-sign $\bar{\nu}_\mu/\nu_\mu$ contamination

Components	ν_μ	$\bar{\nu}_\mu$	$\nu_e+\bar{\nu}_e$
FHC Beam	~95%	~4%	~1%

Components	$\bar{\nu}_\mu$	ν_μ	$\nu_e+\bar{\nu}_e$
RHC Beam	~93%	~6%	~1%

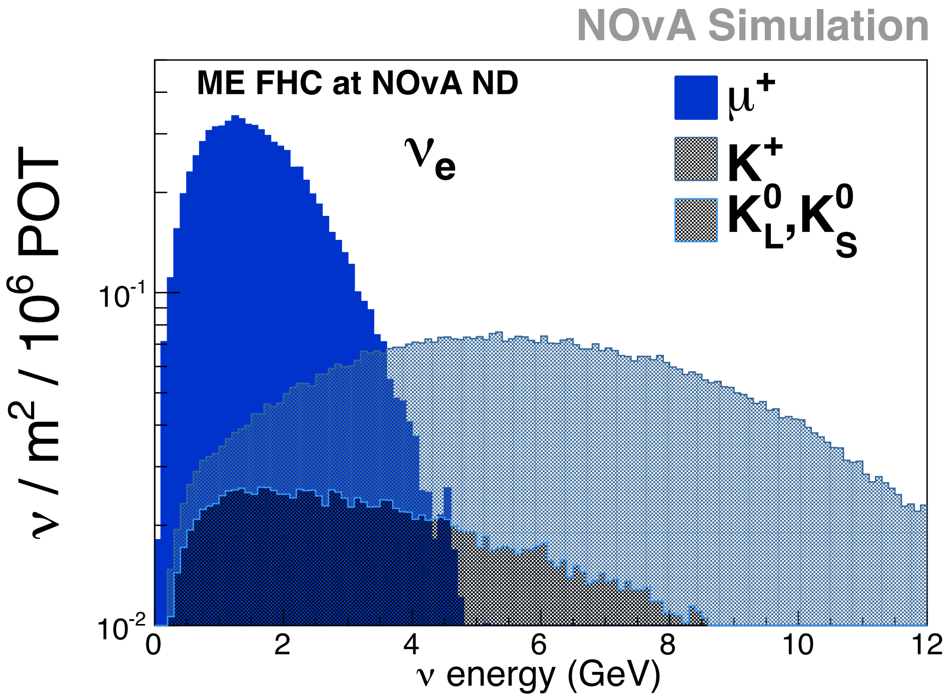
Intrinsic Beam Background

- $\pi^{\pm}$, $K^{\pm}$ and K^0 present in the ν-beam decays to produce ν_e ($\bar{\nu}_e$)

$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_e(\bar{\nu}_e)$$

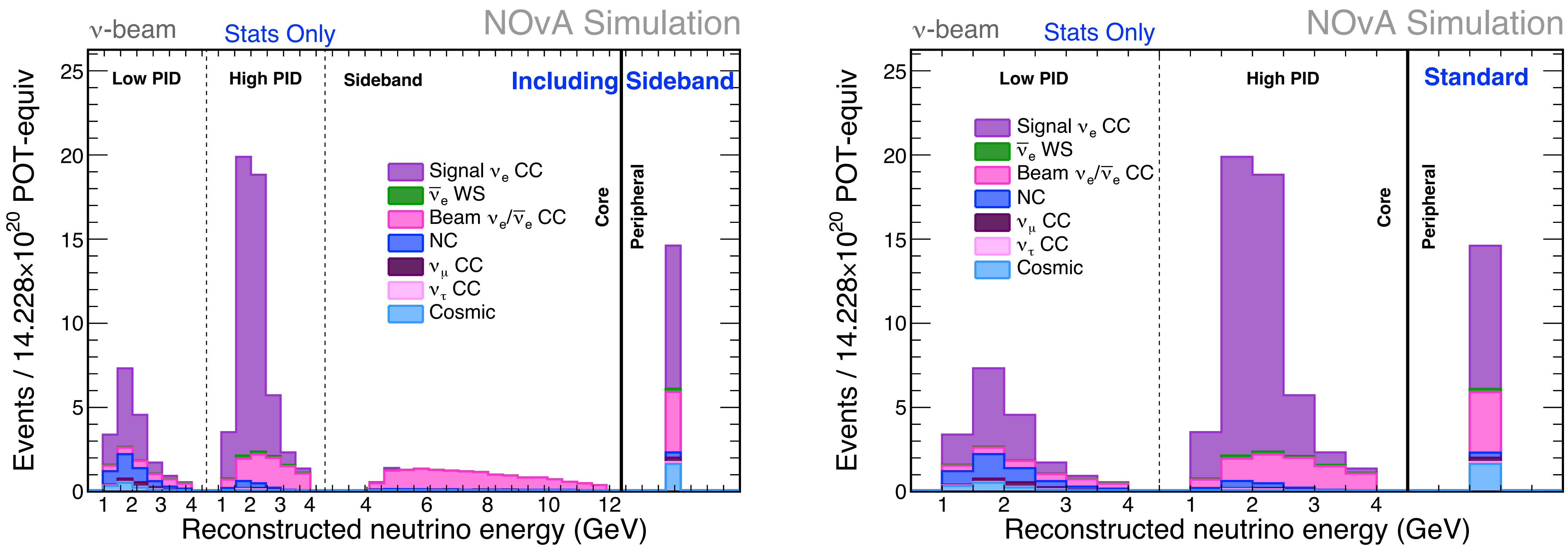
$$K^{\pm} \rightarrow \pi^0 + e^{\pm} + \overset{(-)}{\nu}_e$$



- These ν_e ($\bar{\nu}_e$) events make intrinsic beam background as they mimic ν_e appearance signal in the FD
- The majority of low-energy ν_e's come from $\mu^{\pm}$ decay
- Most of the high energy ν_e's come from $K^{\pm}$ and K^0 decay
- Both ν_{μ} CC and ν_e CC events share the same ancestors ($\pi^{\pm}$)
- ν_e CC events are corrected using ND ν_{μ} Data/MC ratios
- Different corrections are applied for the low and the high energy region

FD ν_e Predictions - Stats Only

- Comparison of FD ν_e statistics only predictions including high energy events with standard 3-flavor predictions

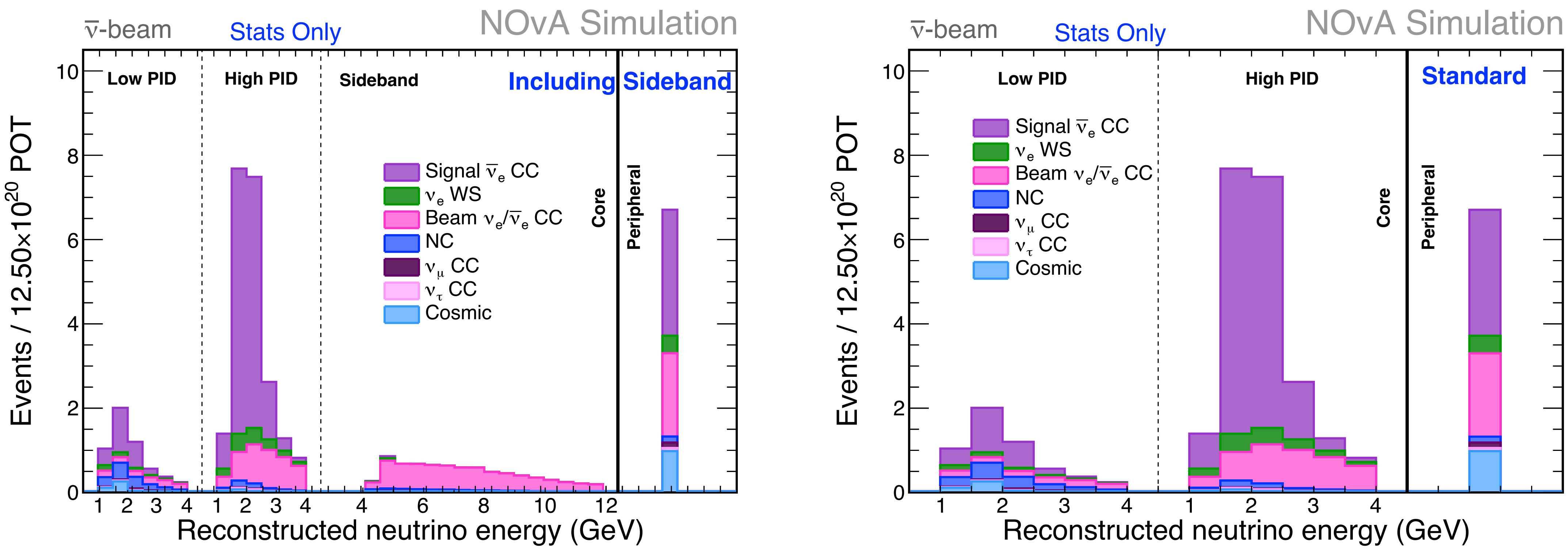


	Signal	Beam	WS	NC	Numu	Nutau	Cosmics
New	60.23	26.85	1.08	6.05	1.39	0.94	3.22
Standard	60.11	13.64	1.04	5.08	1.17	0.58	3.13

- High energy events originate mostly from beam background

FD $\bar{\nu}_e$ Predictions - Stats Only

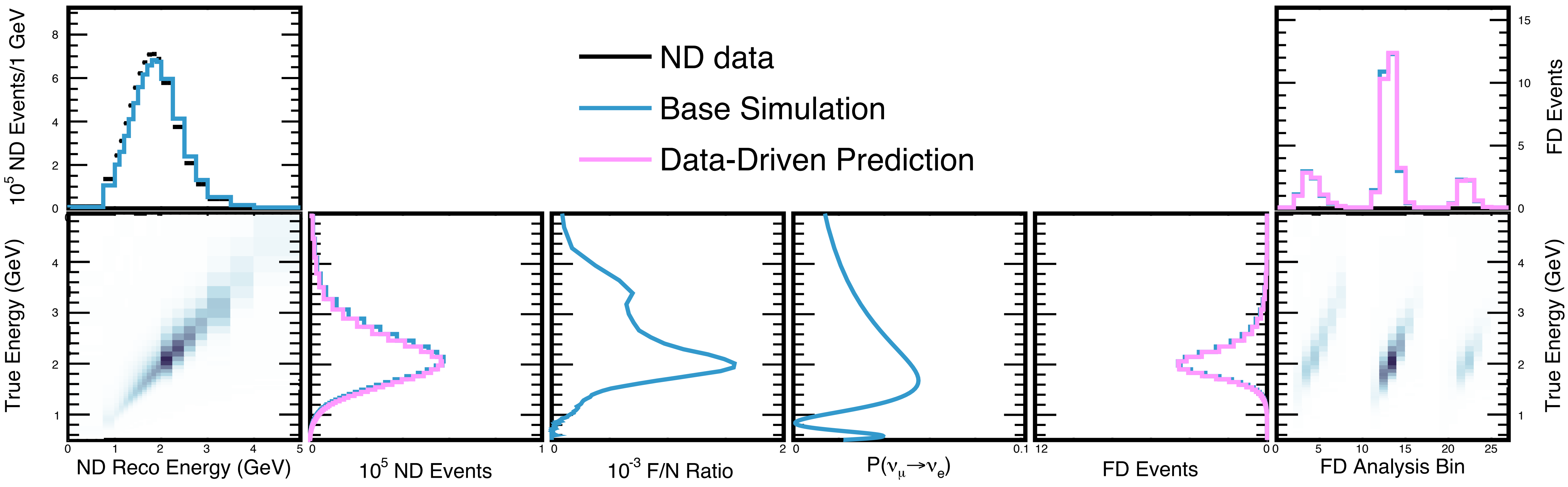
- Comparison of FD $\bar{\nu}_e$ statistics only predictions including high energy events with standard 3-flavor predictions



	Signal	Beam	WS	NC	Numu	Nutau	Cosmics
New	20.14	13.60	2.43	2.22	0.40	0.54	1.57
Standard	20.12	6.99	2.36	1.76	0.32	0.35	1.55

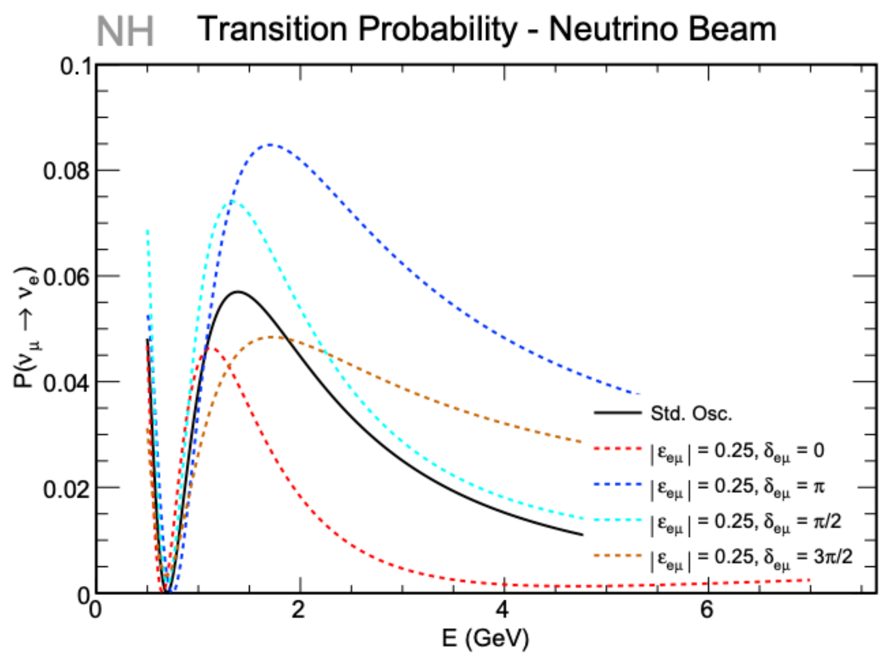
- High energy events originate mostly from beam background

Near to Far Extrapolation

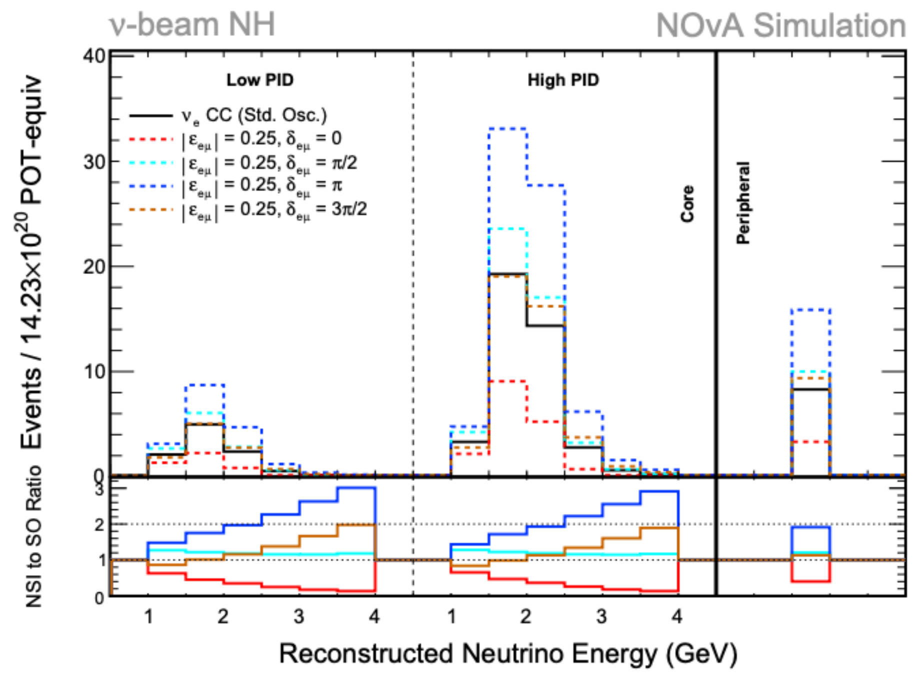


- The Far Detector simulated events are corrected using the Near Detector data

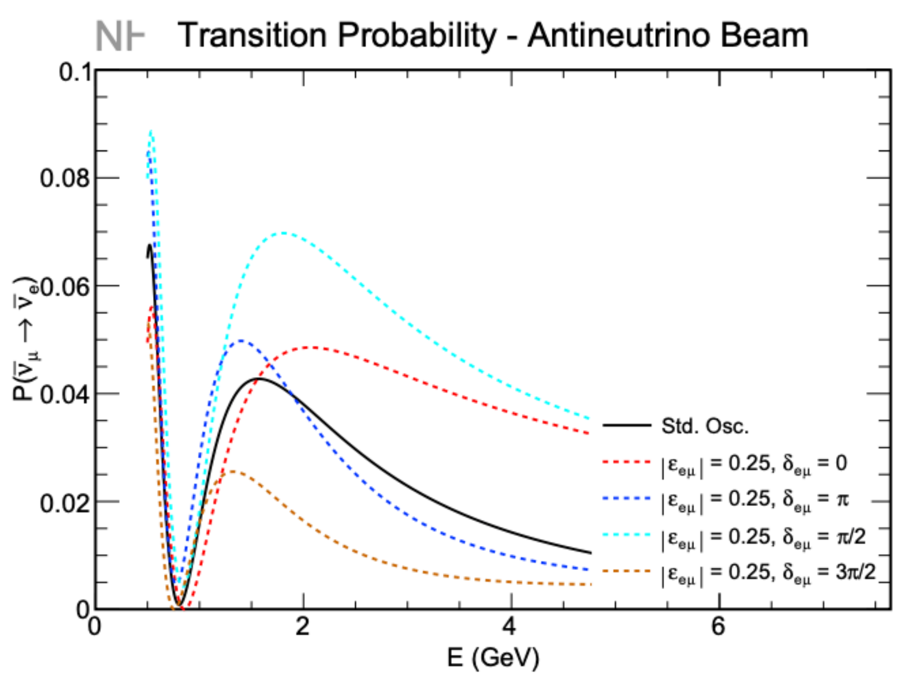
NSI - Probabilities and Predictions



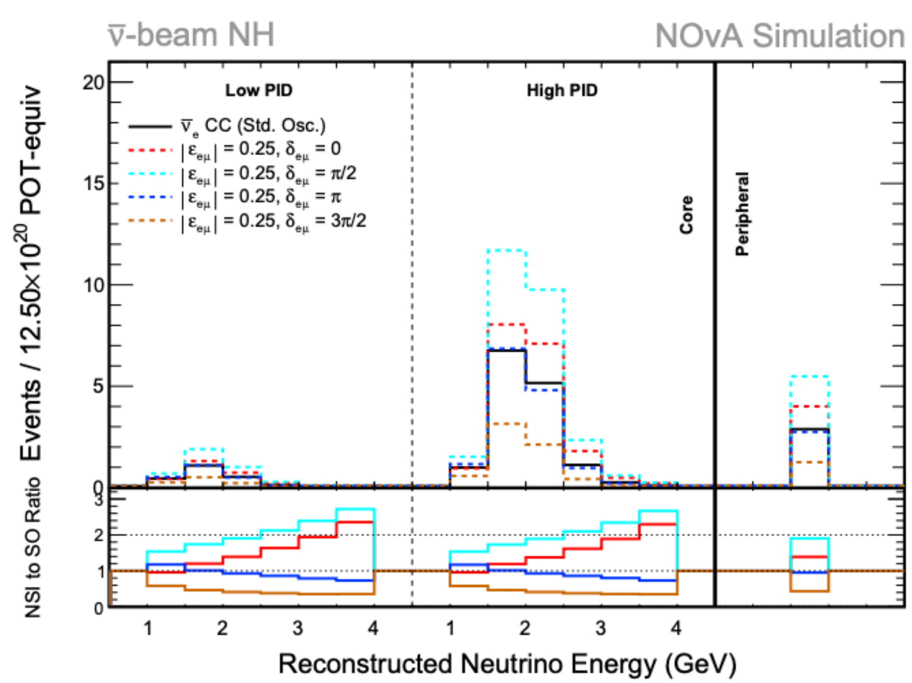
(a) $\varepsilon_{e\mu}$: $\nu_\mu \to \nu_e$



(b) $\varepsilon_{e\mu}$: ν_e CC events



(c) $\varepsilon_{e\mu}$: $\bar{\nu}_\mu \to \bar{\nu}_e$



(d) $\varepsilon_{e\mu}$: $\bar{\nu}_e$ CC events

Systematics

- Systematic uncertainties are taken into account by allowing corresponding parameters to float freely in our fits
- The likelihood is minimised simultaneously wrt to all of the parameters
- For each systematic, the entire analysis is re-performed, changing every simulation step necessary for the systematic shift to determine the **likelihood** as a function of the systematic parameters

CCQE z-exp EV shift 1
CCQE z-exp EV shift 2
CCQE z-exp EV shift 3
CCQE z-exp EV shift 4
MaCCRES
MvCCRES
ZNormCCQE
RPA shape: high-Q^2 enh
RPA shape: low-Q^2 supp
RES low-Q^2 suppression
DIS vnCC1pi
hN FSI mean free path
hN FSI fate fraction EV
MEC E_ν shape, ν
MEC E_ν shape, $\bar{\nu}$
MEC $(q_0, |\vec{q}|)$ response, ν
MEC $(q_0, |\vec{q}|)$ response, $\bar{\nu}$
MEC IS np fraction, ν
MEC IS np fraction, $\bar{\nu}$
Radiative corrections for ν_e
Radiative corrections for $\bar{\nu}_e$
Second class currents
Genie PC 0
Genie PC 1
Genie PC 2
Genie PC 3
Genie PC 4
ν_τ Scale

Flux Component 00
Flux Component 01
Flux Component 02
Flux Component 03
Flux Component 04
AbsCalib
RelCalib
CalibShape
CalibDrift
Lightlevel
Cherenkov
Uncorr ND Mu Energy Scale
Uncorr MuCat Mu Energy
Neutron Pile-up
Corr Mu Energy Scale
Neutron response
Acceptance Sig

Statistics Vs. Systematics Event Counts

	Signal		Beam		WS		NC		Numu		Nutau		Cosmics	
	Stats	Syst	Stats	Syst	Stats	Syst	Stats	Syst	Stats	Syst	Stats	Syst	Stats	Syst
Sideband	60.23	59.43	26.85	26.76	1.08	1.04	6.05	6.07	1.39	1.69	0.94	0.86	3.22	3.22
Standard	60.11	59.25	13.64	13.91	1.04	1.01	5.08	5.29	1.17	1.36	0.58	0.52	3.13	3.13

FD ν_e Event Counts

	Signal		Beam		WS		NC		Numu		Nutau		Cosmics	
	Stats	Syst	Stats	Syst	Stats	Syst	Stats	Syst	Stats	Syst	Stats	Syst	Stats	Syst
Sideband	20.14	19.94	13.60	12.96	2.43	2.38	2.22	2.25	0.40	0.47	0.54	0.49	1.57	1.57
Standard	20.12	19.88	6.99	6.59	2.36	2.30	1.76	1.99	0.32	0.33	0.35	0.32	1.55	1.55

FD $\bar{\nu}_e$ Event Counts