Event selection for the ν_e analysis in the NOvA experiment

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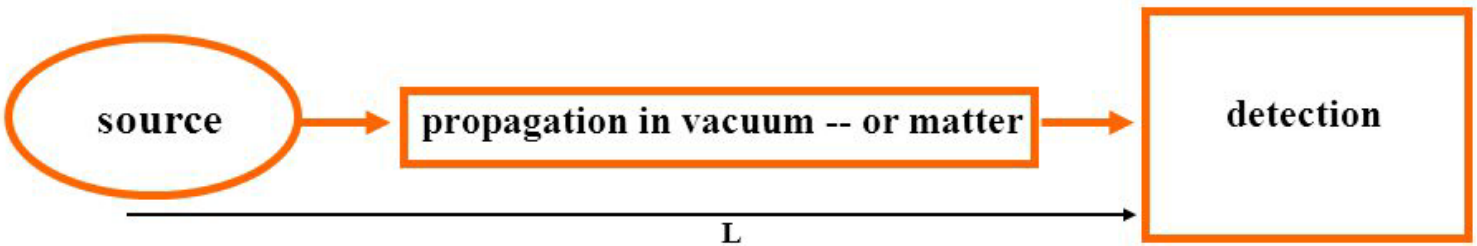
Theory of neutrino oscillations

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

$\|\Delta m^2_{32}\| = \|m^2_3 - m^2_2\|$ $\simeq 2.5 \times 10^{-3}$ eV^2	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} = \|m^2_2 - m^2_1\|$ $\simeq 7.5 \times 10^{-5}$ eV^2
$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$	$\nu_e \to \nu_e$
$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$	$\nu_e \to \nu_\mu, \nu_\tau$
atmospheric, long-baseline	reactor and long-baseline	solar and reactor

Oscillation parameters: $\theta_{12}, \theta_{23}, \theta_{13}$, CP phase δ, $|\Delta m^2_{13}|$, Δm^2_{12}



The NuMI Off-Axis ν_e Appearance Experiment. Goals

NOvA experiment goals :

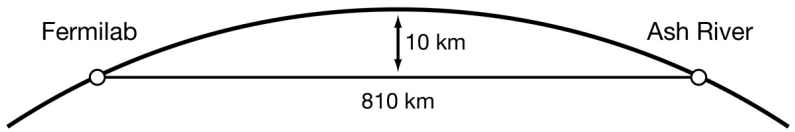
Using $\nu_\mu \to \nu_e$ $(\overline{\nu}_\mu \to \overline{\nu}_e)$

- neutrino mass hierarchy
- CP violating phase

Using $\nu_\mu \to \nu_\mu$ $(\overline{\nu}_\mu \to \overline{\nu}_\mu)$

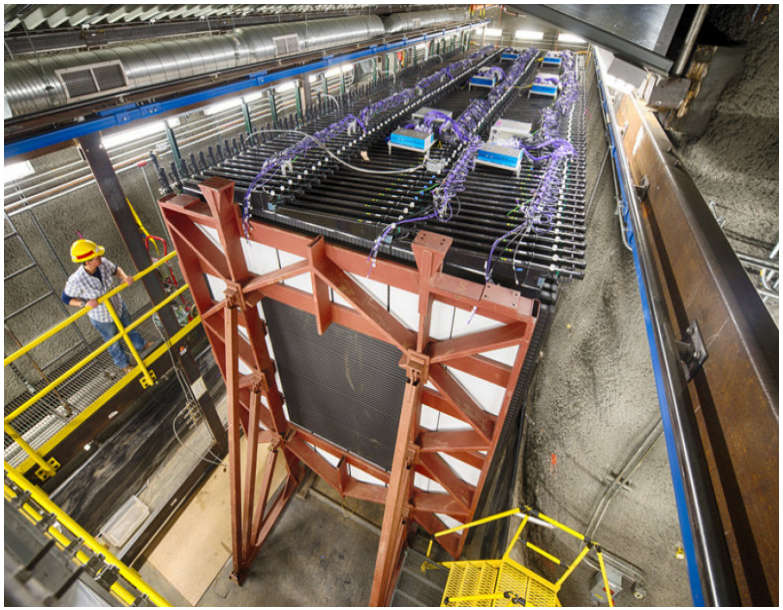
- precise measurement Δm^2_{32}
- mixing angle θ_{23} octant (more than $45°$ or less).

Also:
sterile neutrino searches (via deficit of NC events), supernova, neutrino cross-section measurements in the Near Det., monopoles, cosmic ray physics, and many other interesting phenomena.



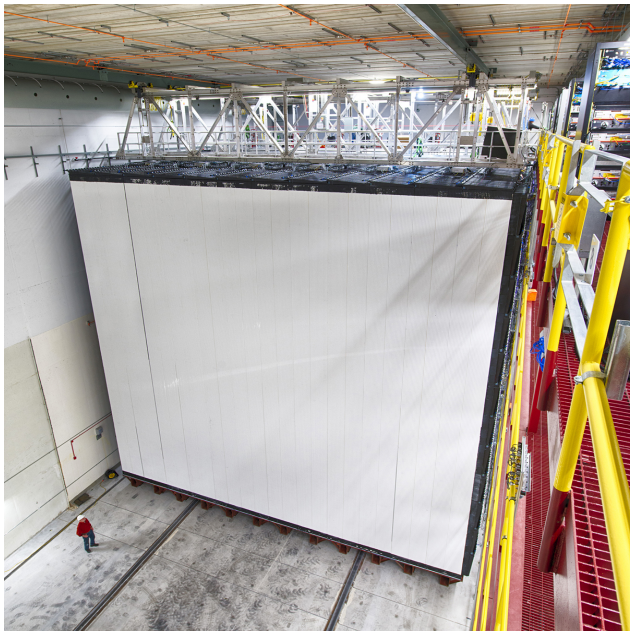
14 mrad off beam axis

Two detector scheme



Near Detector (ND):

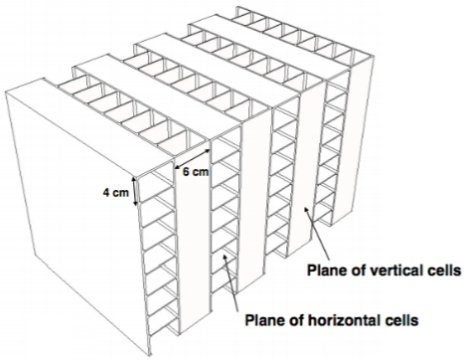
- 1 km after target, weight 300 t
- measure flux composition before oscillations
- ND data used for prediction in FD (extrapolation procedure)



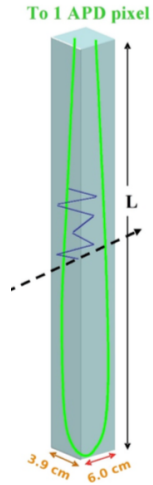
Far Detector (FD):

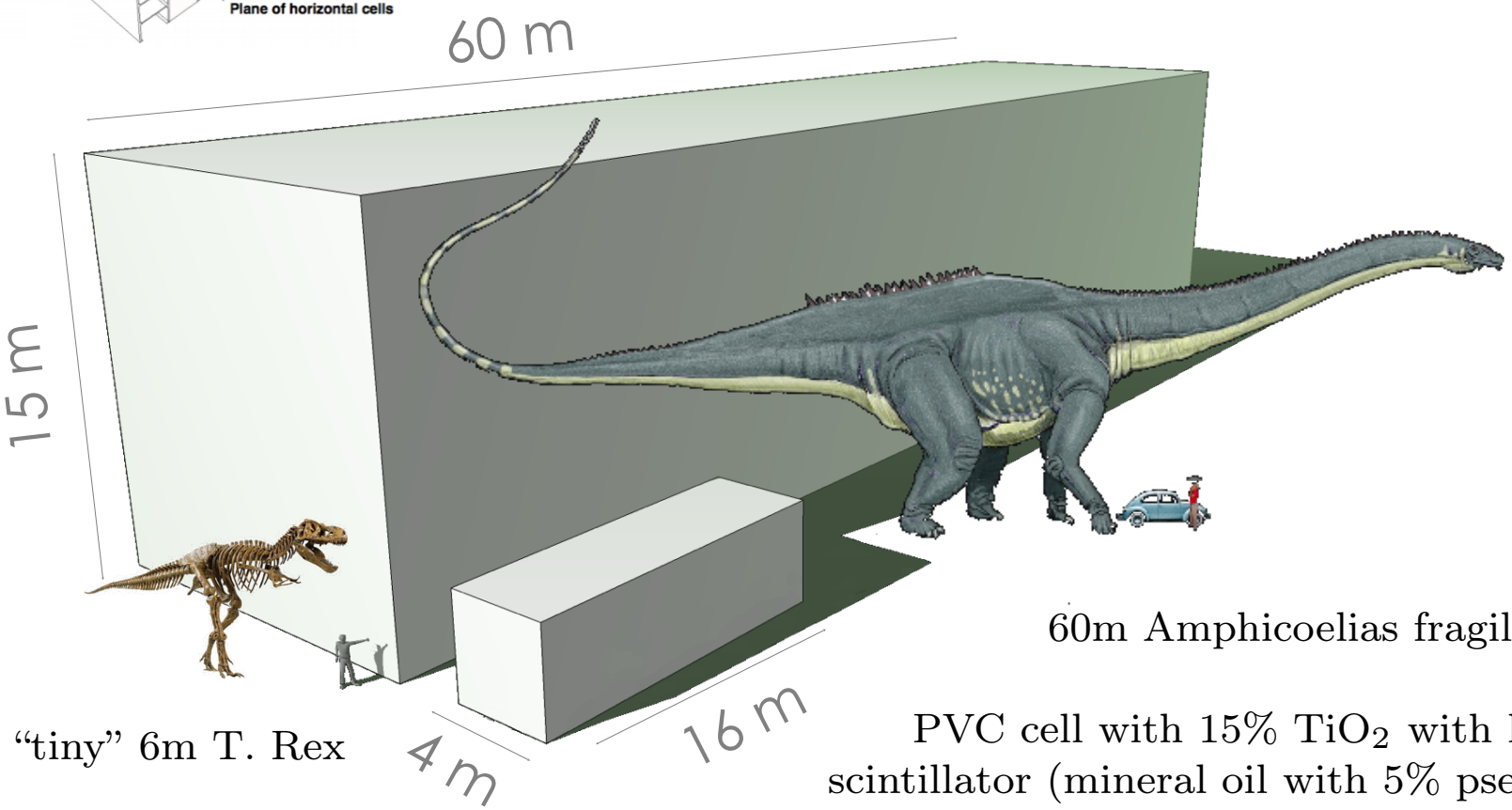
- 810 km after target, weight 14 kt
- measure neutrino flux after oscillations
- extrapolation cancels most systematics
- FD identical to ND

Two NOvA detectors - huge tracking calorimeters



FD: 344 064 cells
ND: 20 193 cells

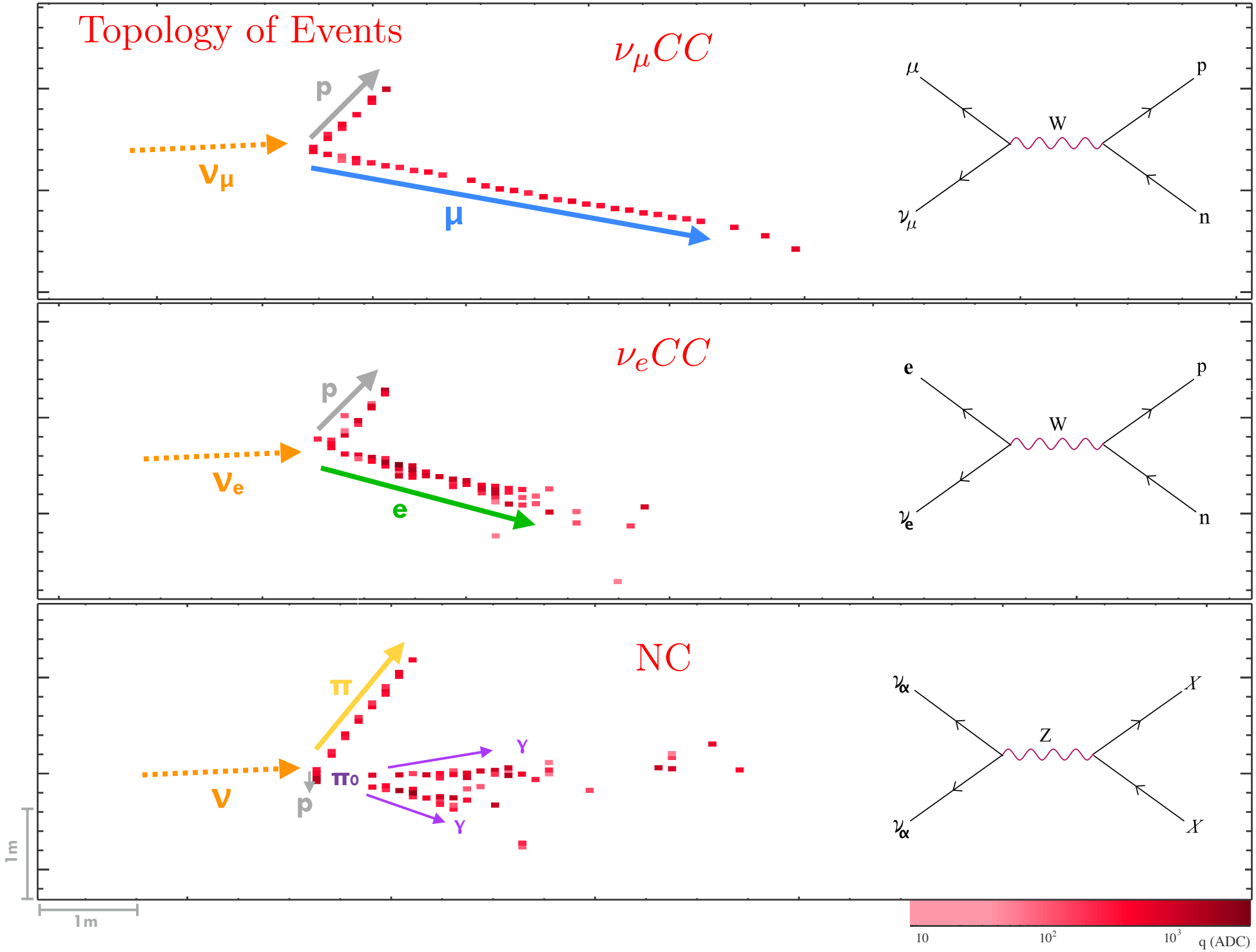




"tiny" 6m T. Rex

60m Amphicoelias fragillimus

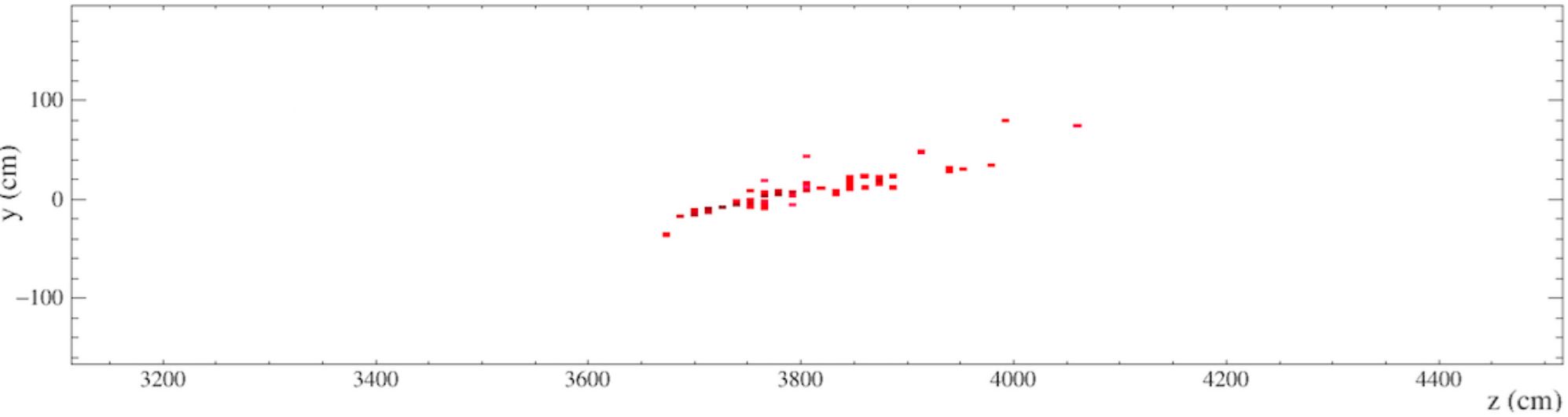
PVC cell with 15% TiO_2 with liquid scintillator (mineral oil with 5% pseudocumene)


Topology of Events
$\nu_\mu CC$
p
ν_μ
μ
μ
W
p
ν_μ
n
$\nu_e CC$
p
ν_e
e
e
W
p
ν_e
n
NC
π
γ
π_0
ν
p
γ
ν_α
Z
X
ν_α
X
1 m
1 m
10
10^2
10^3
q (ADC)

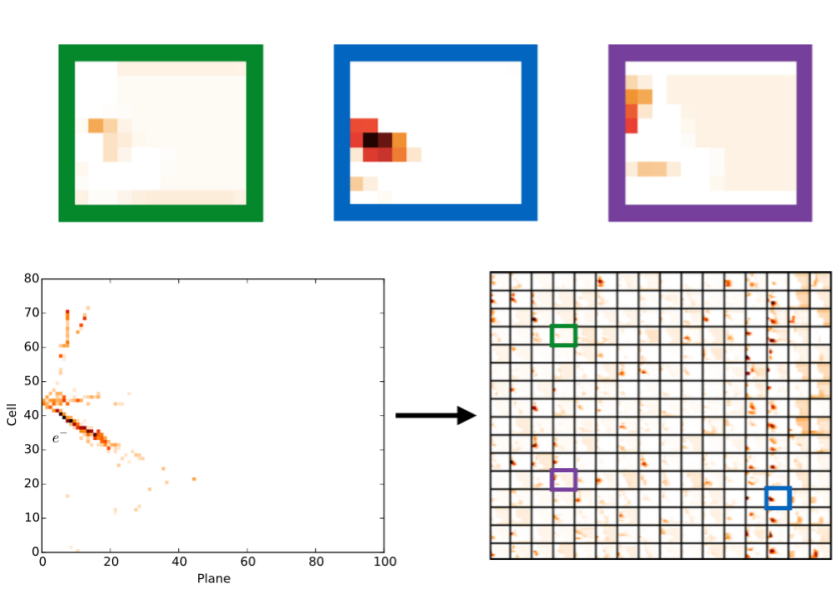
ν_e Appearance Mode

- Identify ν_e CC candidates in the FD.
- Use ND events to predict beam backgrounds in the FD.
- The excess over the background is a signal.

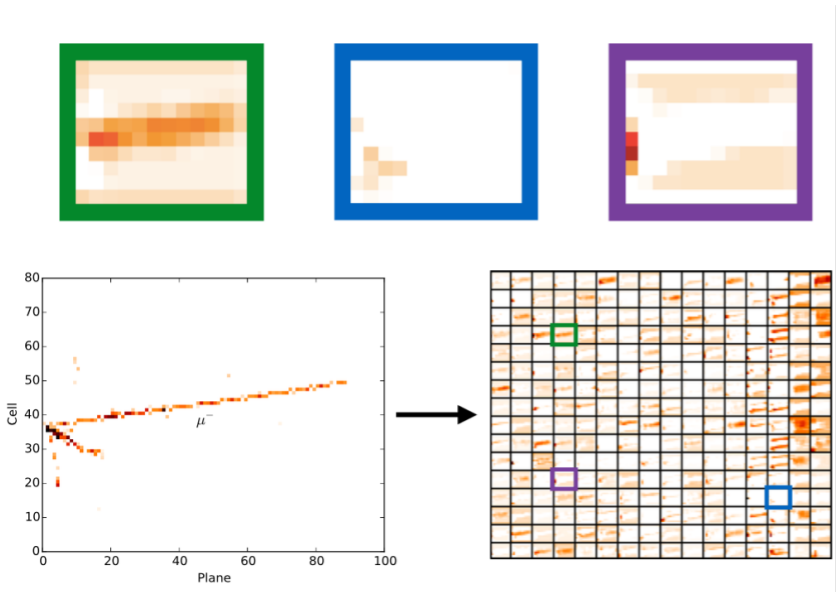
- Currenly have 8.85×10^{20} POT (Proton on target) statistics (50% more than in 2016 analysis)
- Many significant improvements for 2017 analysis: revised detector resoponce and cross section models, new data based flux prediction, analysis techniques (selection and binning).



Particle identification technique



ν_e event

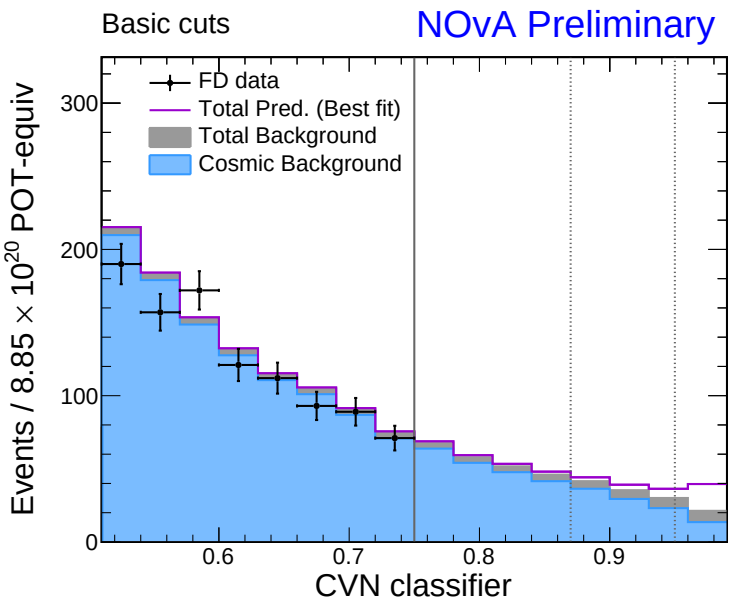


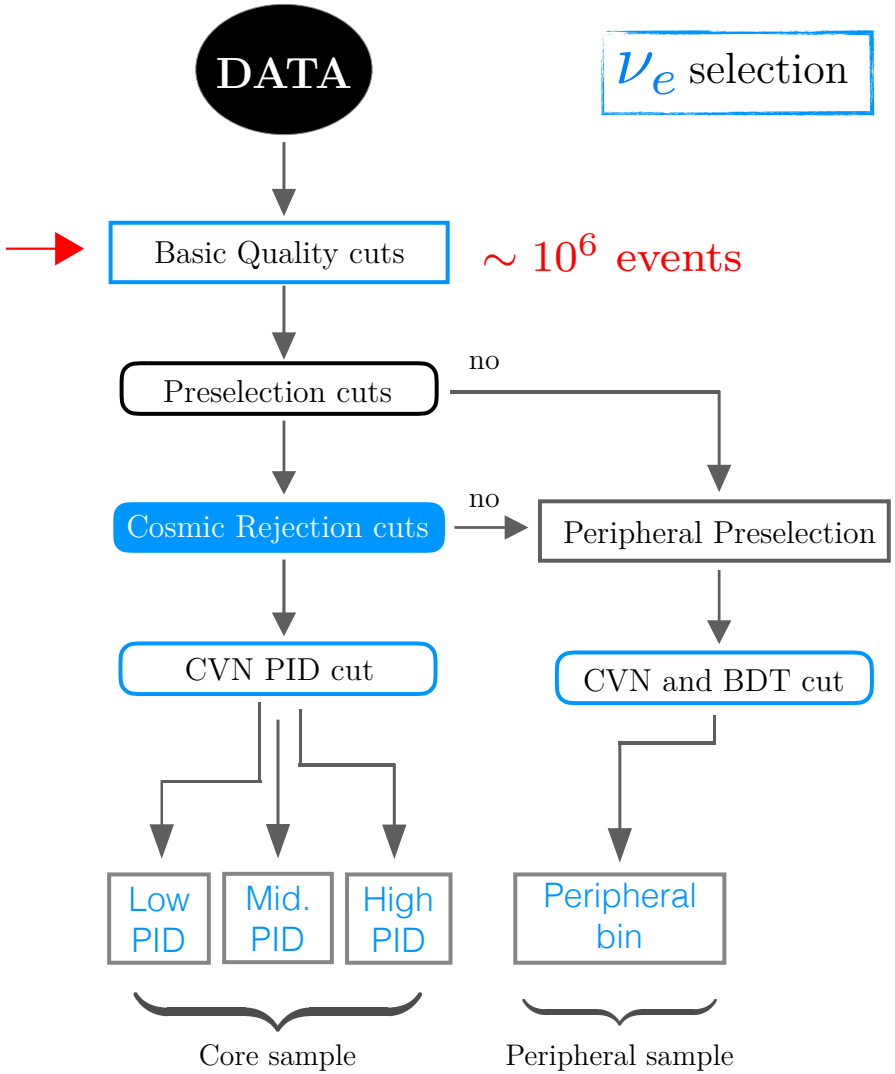
ν_μ event

- We keep using "Convolutional Visual Network" (CVN) - particle identification technique based on ideas from computer vision and deep learning.
- Input: Calibrated hit maps; Image processing transformations $\rightarrow$ abstract features
- Network decides important features + correlations; Output: event classifier
- Use in ν_μ and ν_e analysis the same event selection technique.

Improved ν_e selection for 2017 analysis

- This cartoon illustrates the selection flow in ν_e analysis.
- Cosmic bkg is one of the largest in the NOvA FD.
- We introduced two samples for 2017 analysis - Core and Peripheral.





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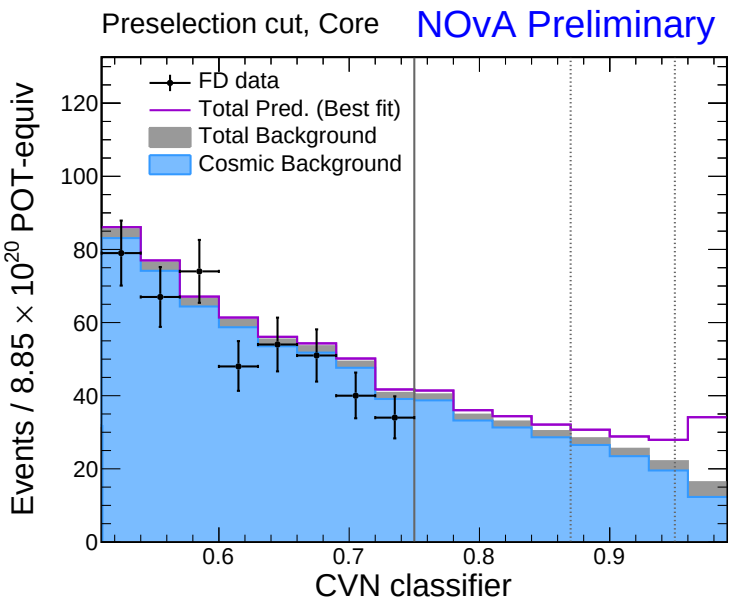

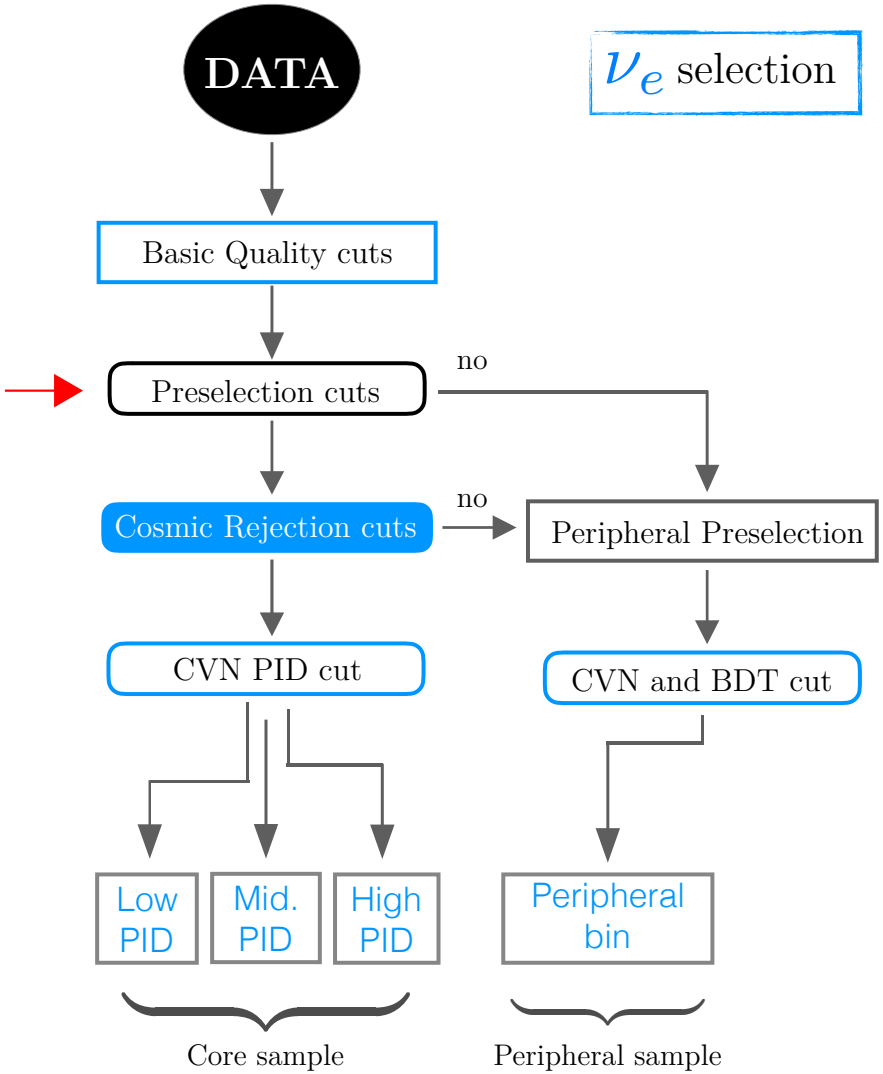

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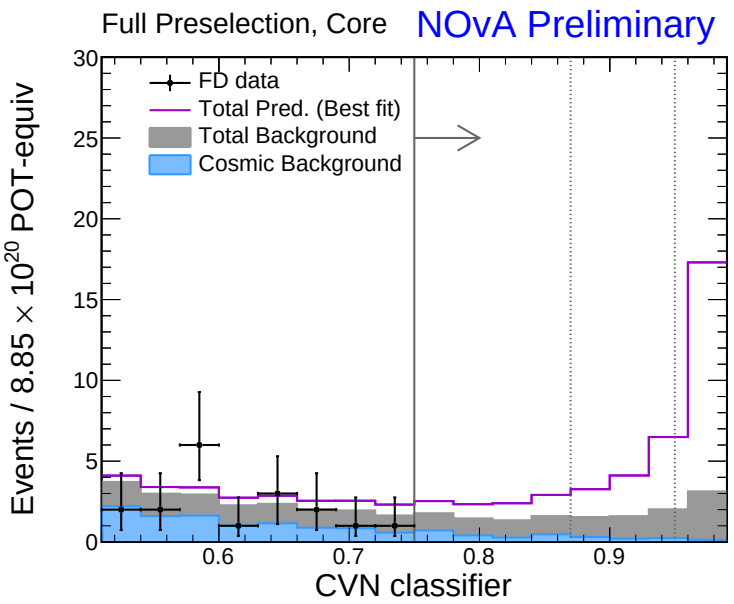

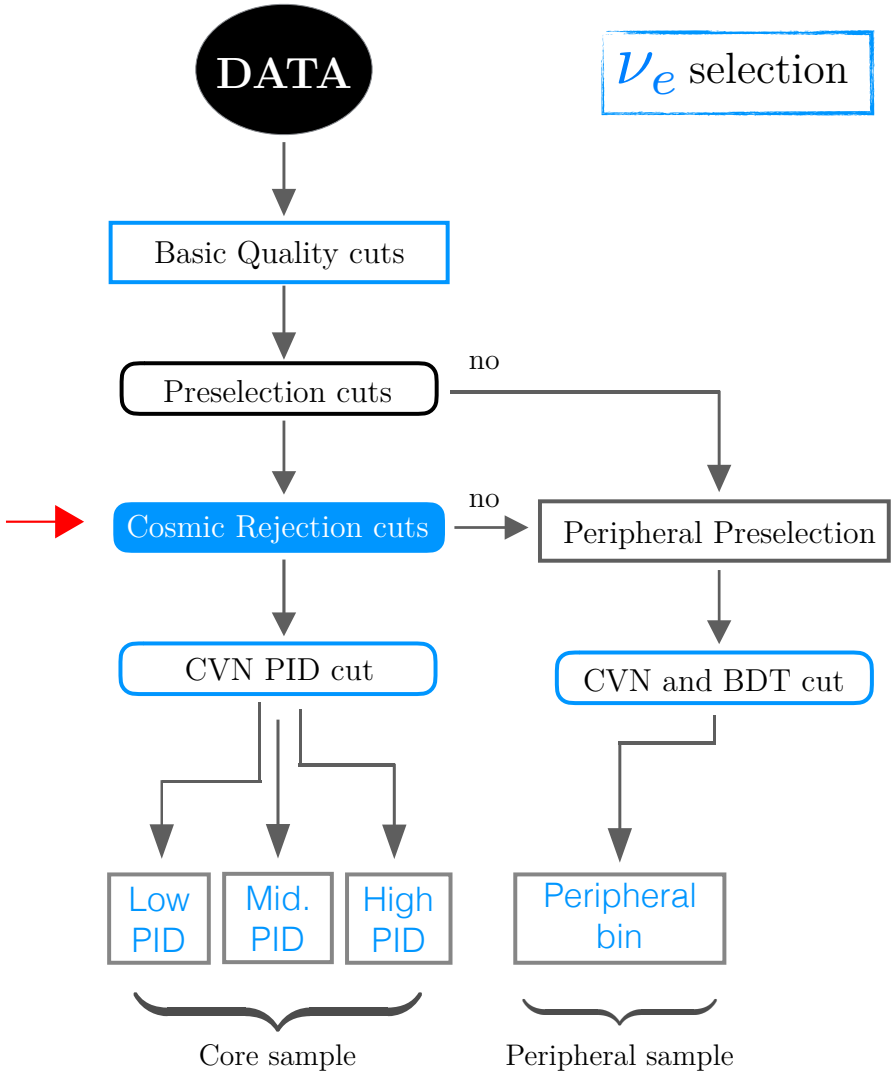

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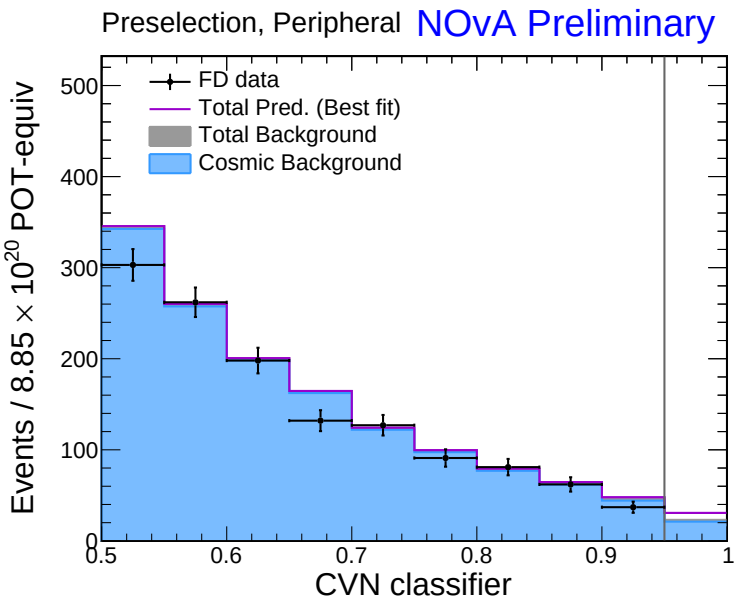

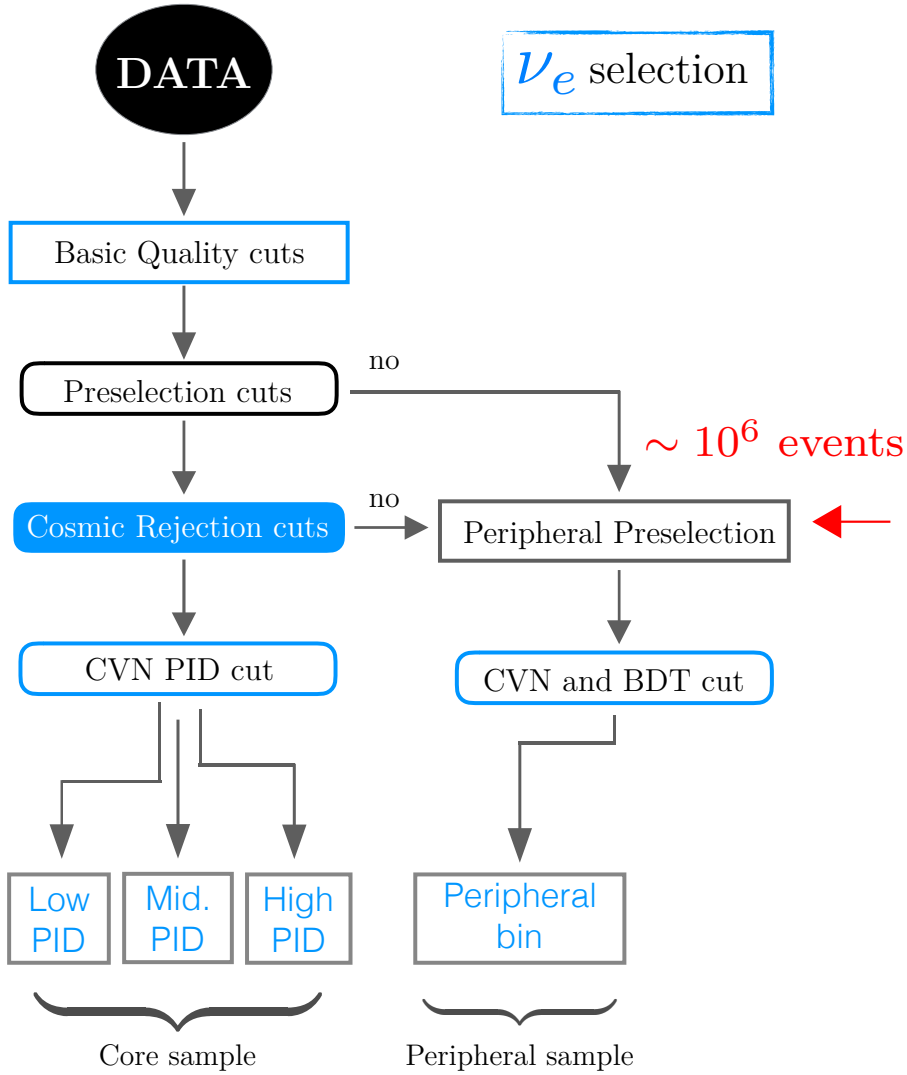

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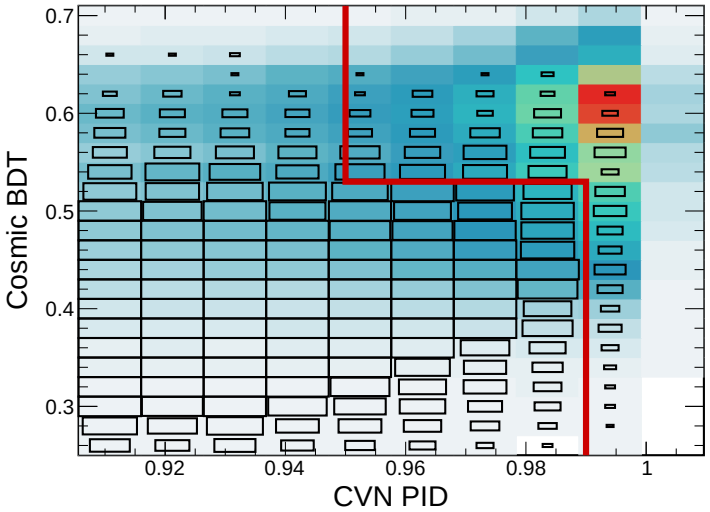

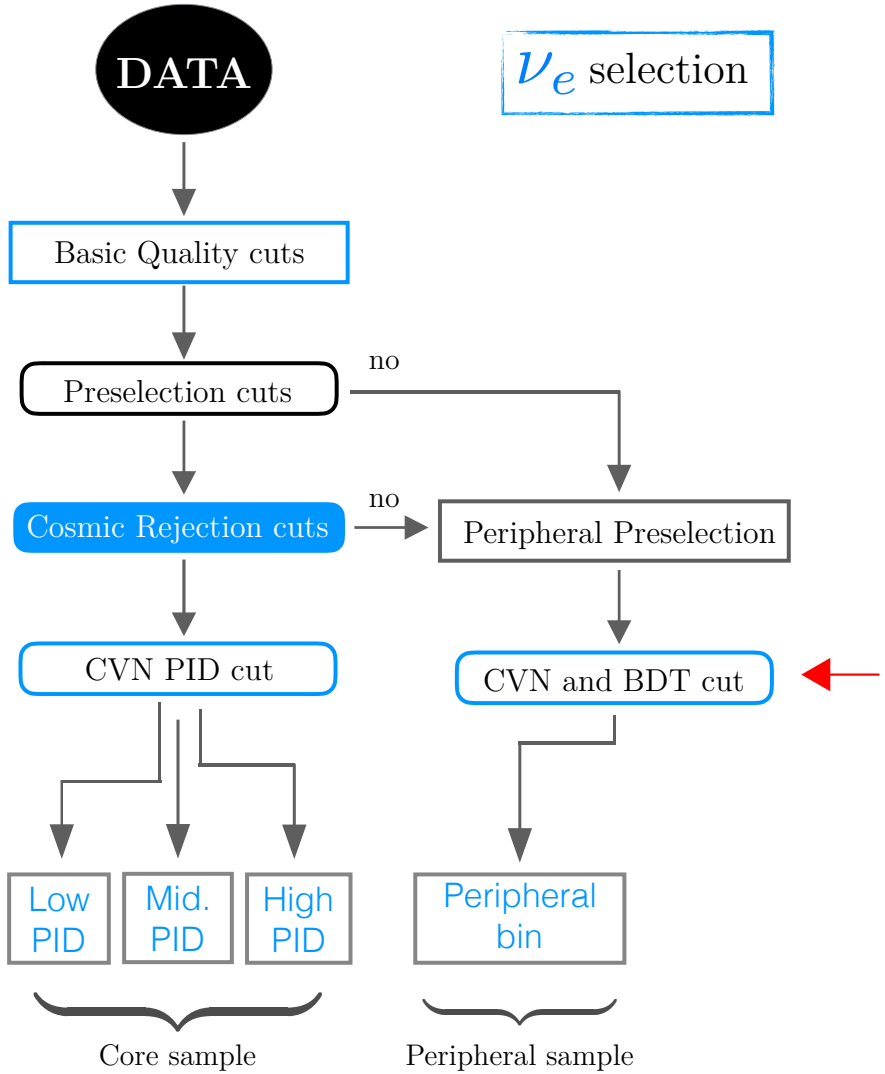

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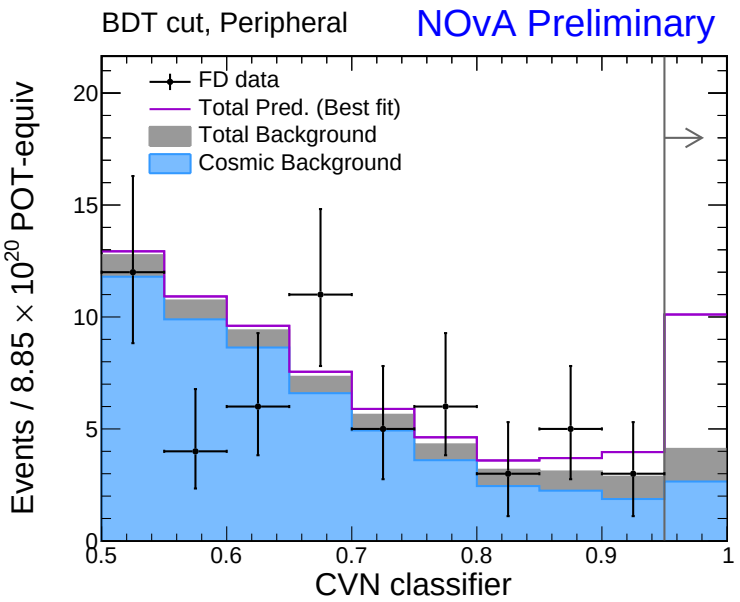
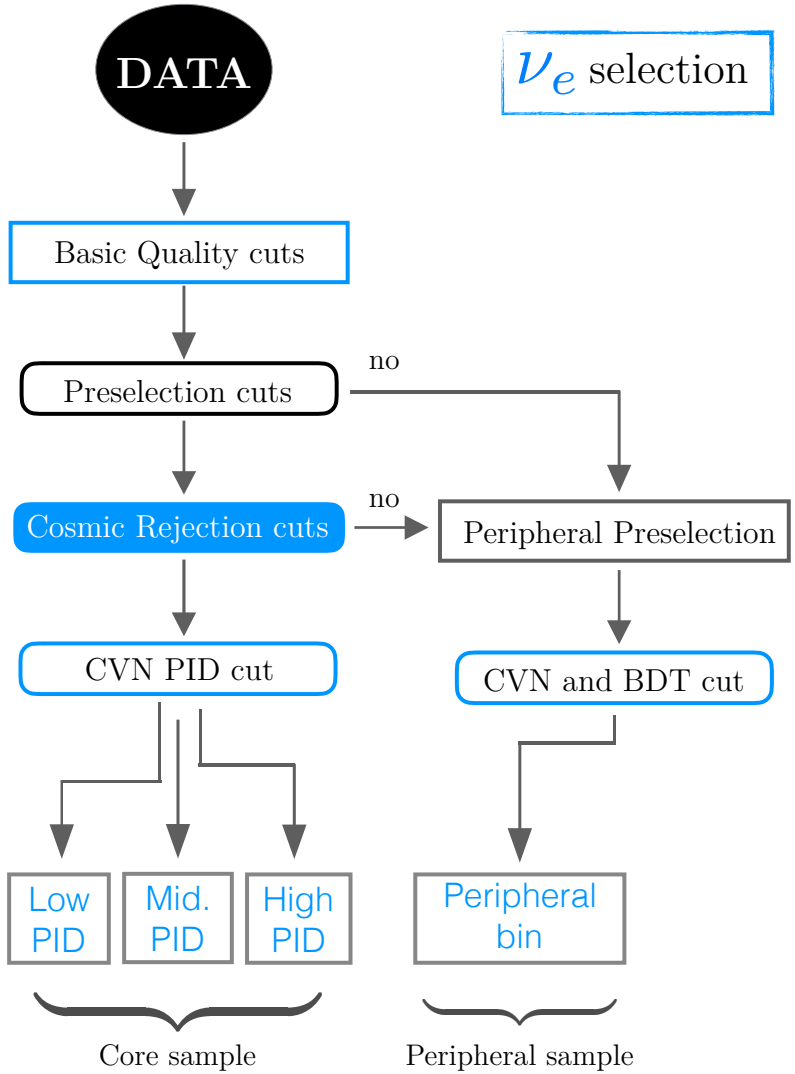
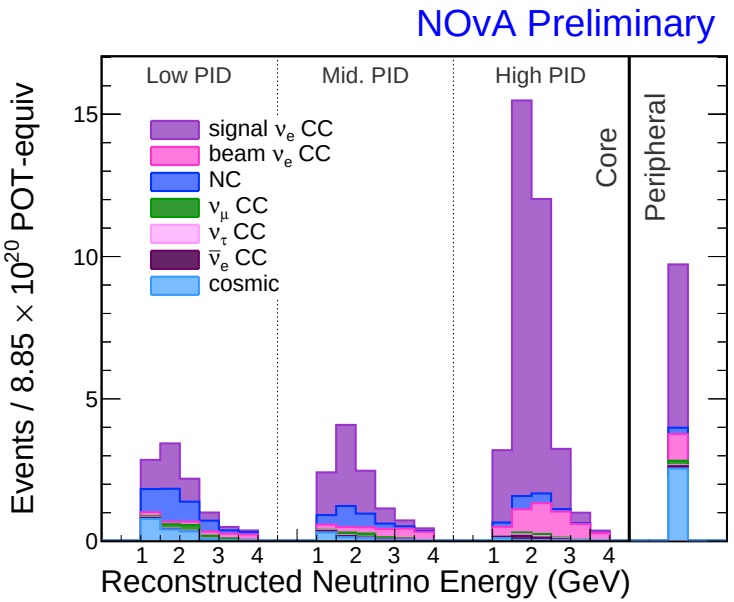
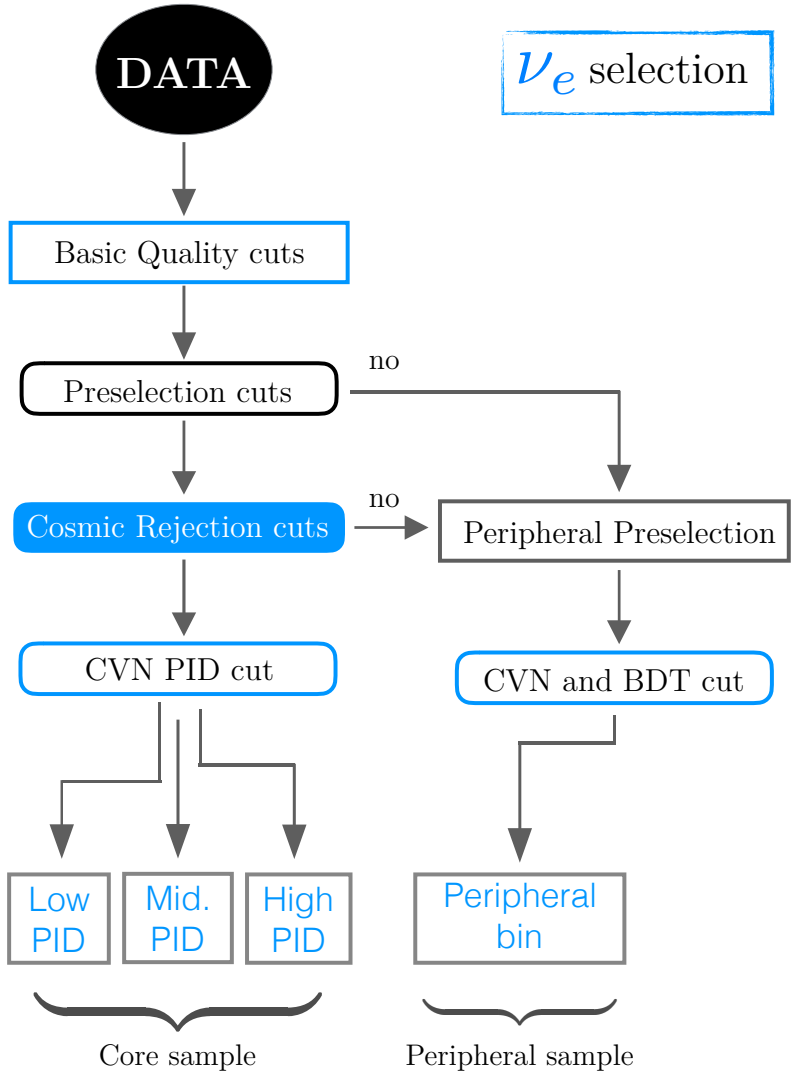




Improved ν_e selection for 2017 analysis

- As a result of this flow we have 4 spectra for different CVN PID binning and Peripheral sample separately.

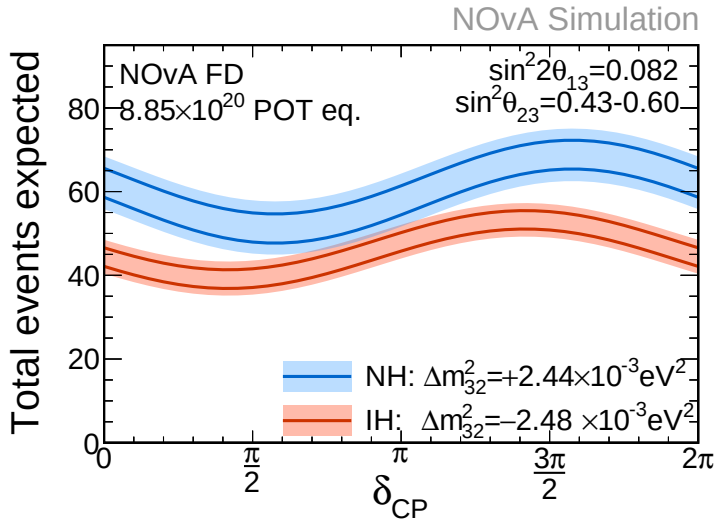




Far Detector Signal and Background Expectations

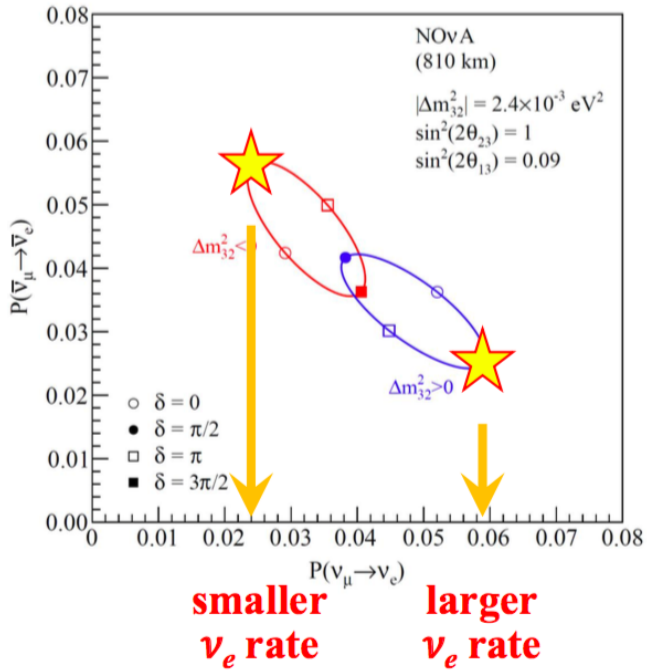
- Signal depends on oscillation parameters

IH, $\delta_{CP} = \pi/2$	NH, $\delta_{CP} = 3\pi/2$
20	48



- Expect about 20.5 background events.
- Dominated by Beam ν_e and NC events.
- Background has small variation with oscillation parameters.

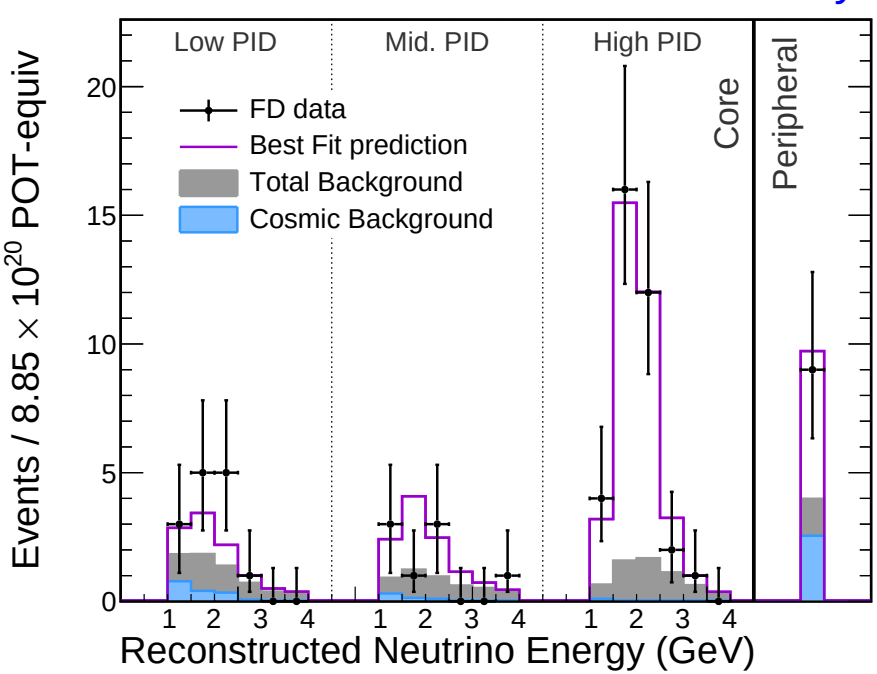
Total bkg.	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic
20.5	7.1	6.6	1.1	0.3	4.9

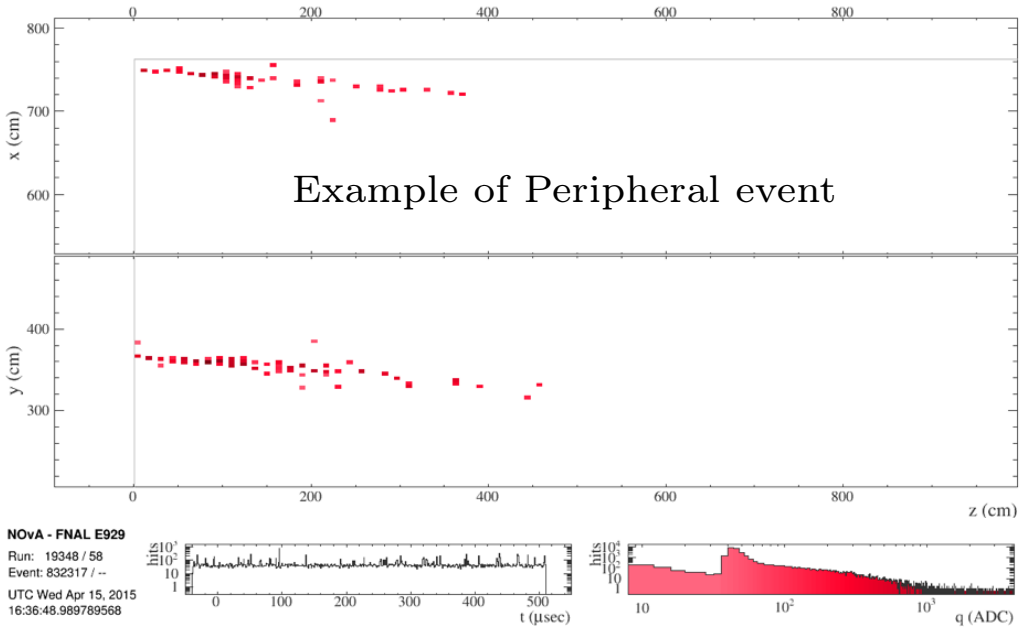


ν_e Far Detector spectrum

Observed 66 events in the FD, with background expectation 20.5±2.5.
9 events in the peripheral sample.

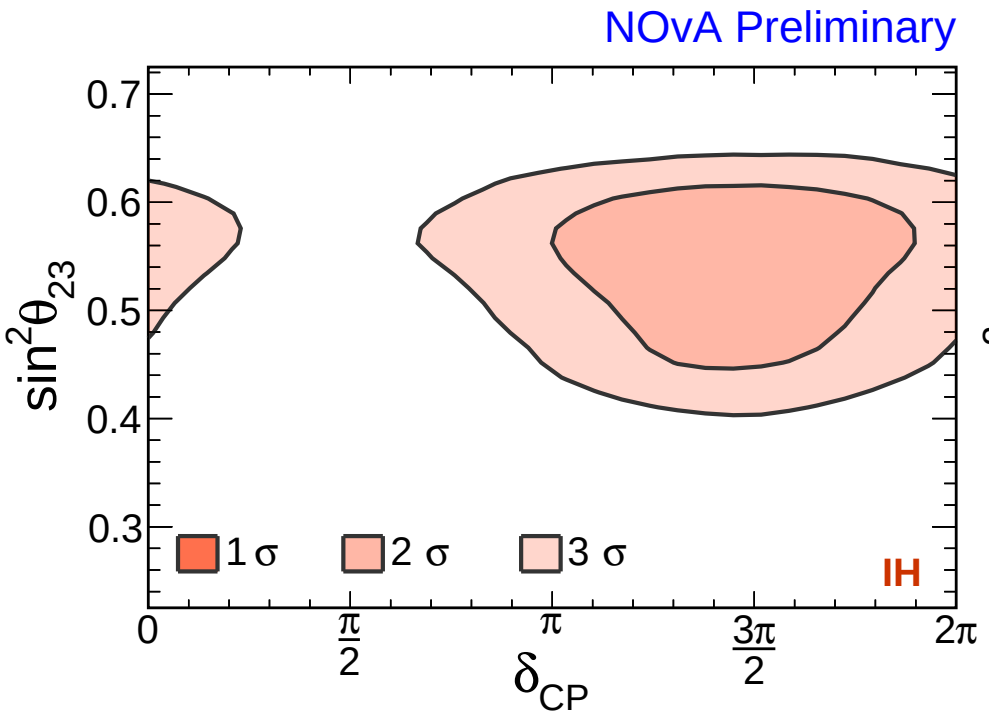
In 2016 analysis we had 33 events, thus with just +50% of exposure and improvement in selection techniques we ×2 the analysis sample.

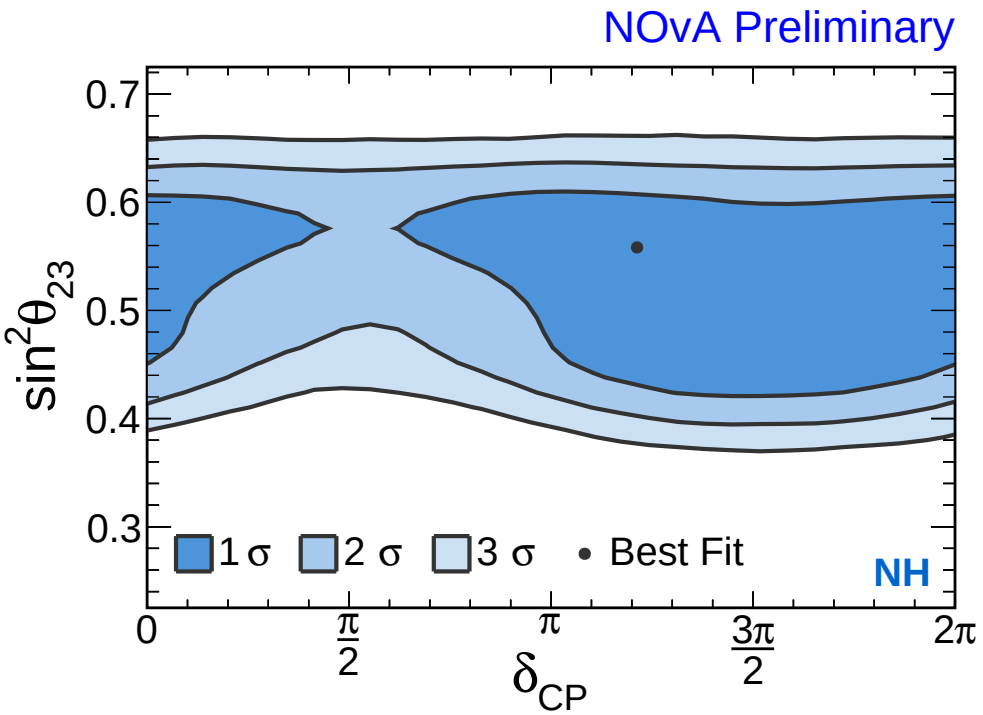




NOvA fit results

With 66 events in the FD we have obtained the next results:





- Best Fit: $\delta_{CP} = 1.21\pi$, Upper Octant, Normal Hierarchy.
- Upper octant is prefered at 0.2σ.
- Exclude $\delta_{CP} = \pi/2$ region in the IH at $> 3\sigma$.
- Approaching IH rejection at 2σ.

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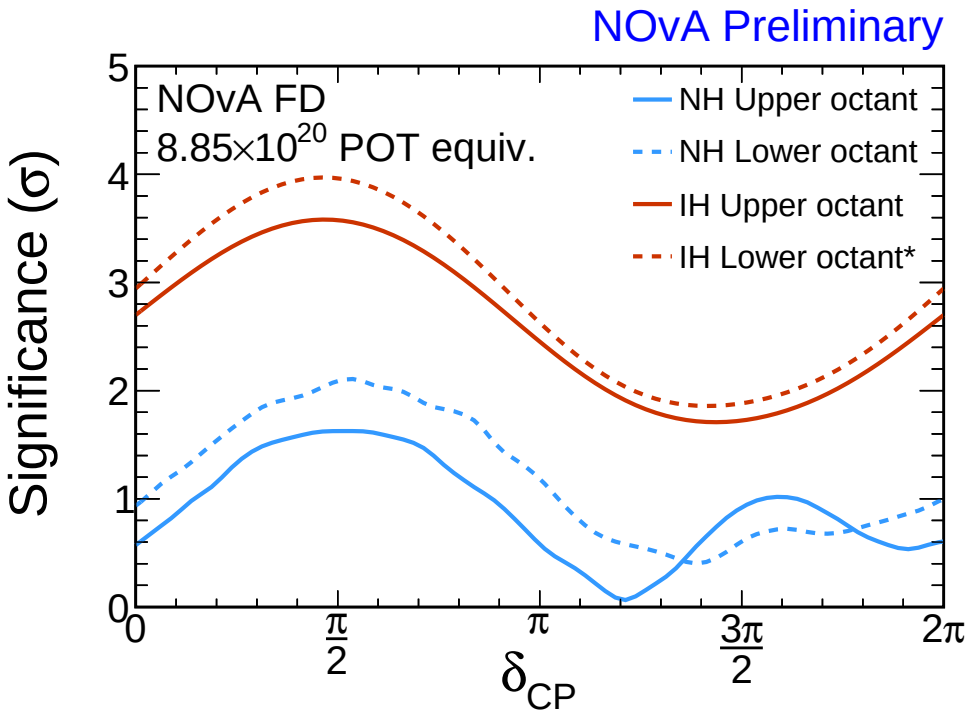

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Summary

With 8.85×10^{20} POT and significant improvements in our analysis tools and simulation, NOvA obtained the next results:

- We doubled our analysis sample with just +50% more exposure.
  - Found 66 ν_e CC events in the FD (33 events were in the previous analysis)
- Inverted Hierarchy, $\delta_{CP} = \pi/2$ is disfavored at greater than 3σ.
  - Approaching 2σ IH rejection for all values of δ_{CP}.
- We're running with antineutrino beam right now.
  First result with $\nu + \bar{\nu}$ data later this year