Looking for Sterile Neutrinos with NOvA

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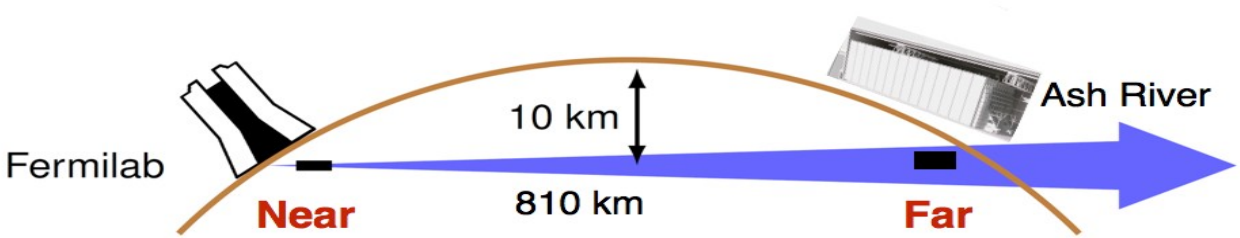
The NOvA Experiment

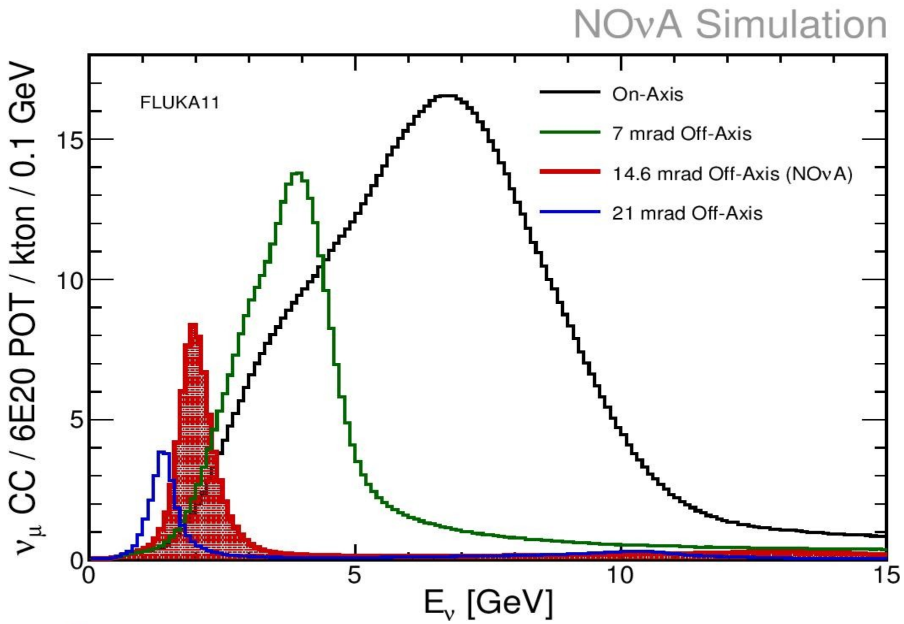
NOvA (NuMI Off-Axis ν_e Appearance)

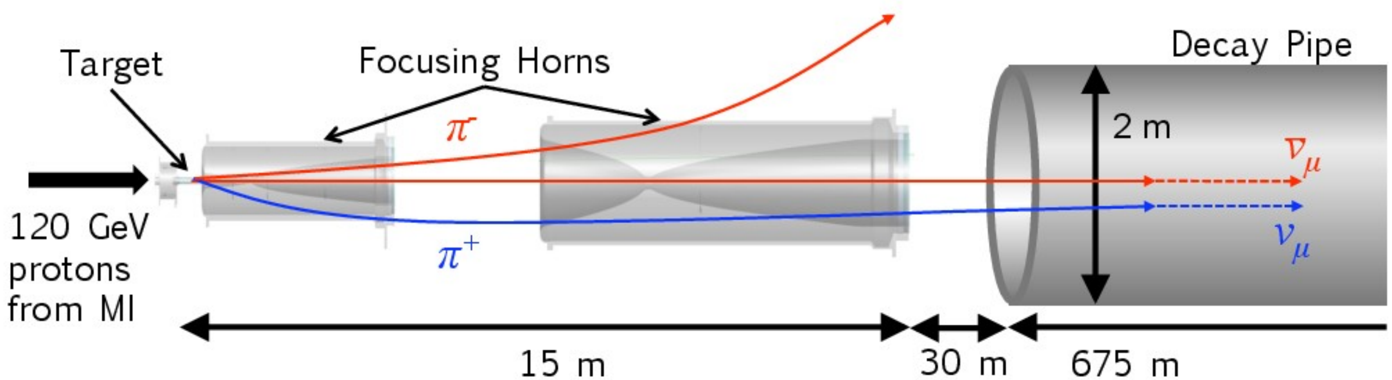
- A second generation long-baseline experiment designed to detect neutrinos in the Fermilab's *NuMI (Neutrinos at the Main Injector)* beam.
- An upgrade of the NuMI beam power from 400 kW to 700 kW.
- A 14 kt “totally active” tracking liquid scintillator calorimeter sited 14 mrad off the NuMI beam axis at a distance of 810 km in Ash River, Minnesota.
- A 300 ton near detector functionally identical to the far detector sited under ground at a distance of 1 km from the NuMI beam origin at Fermilab.



Beam Production and Detectors Location

- Direct a beam of 120 GeV protons from Fermilab's Main Injector onto a primary target.
- Interactions of the proton beam in the target produces secondary mesons, primarily pions and kaons.
- The mesons then decay to muons and neutrinos during their flight through a long decay tunnel of 675m.
- Off-axis location produces a large neutrino flux peaked at 2 GeV, the energy where oscillation to electron neutrinos is expected to be maximum.





NOvA Physics

$$P(\nu_\mu \to \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\text{sol}}}|^2$$
$$= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} \left(\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta\right)$$

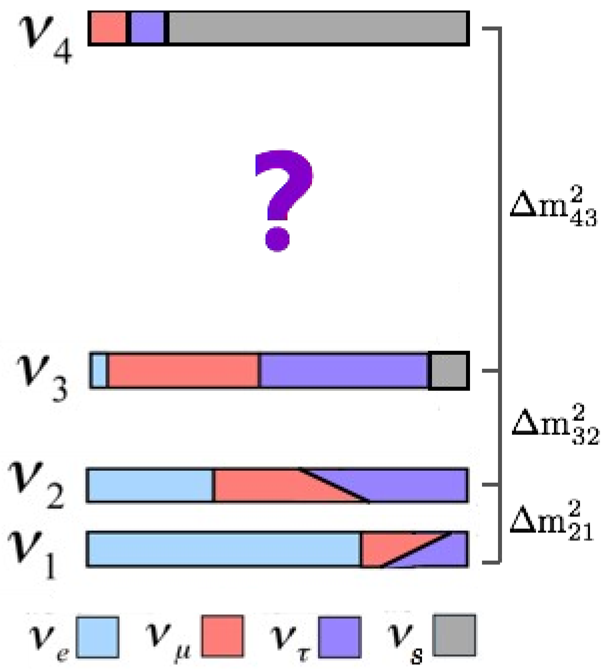
$$\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \Delta_{31}$$

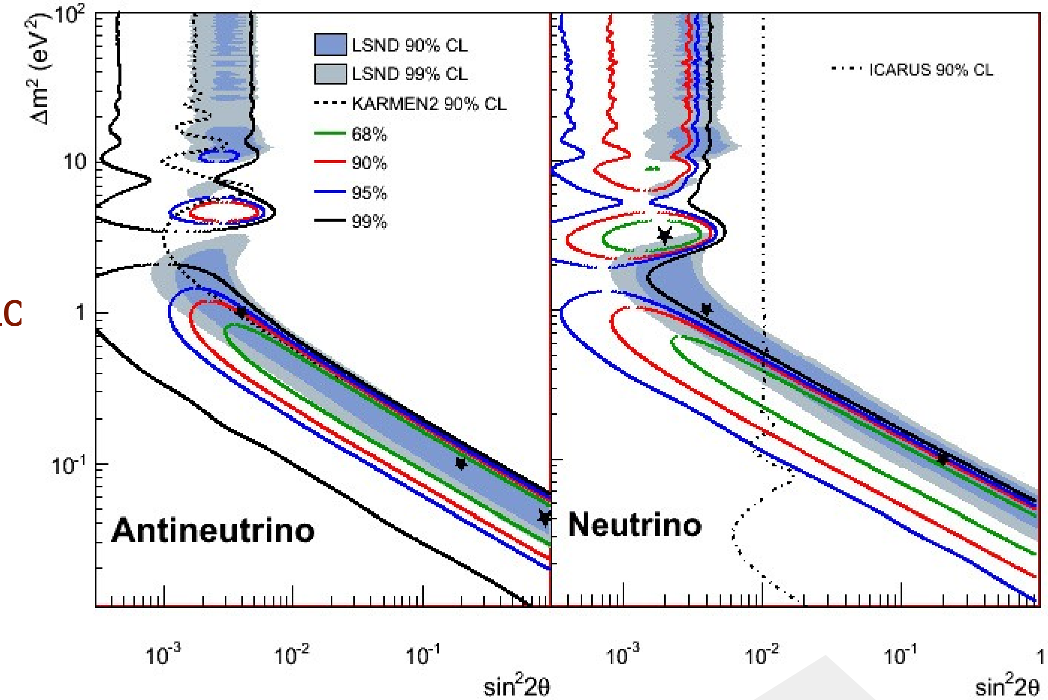
- *Value of θ_{13}?*
- *Value of θ_{23}(45 degrees)?*
- *Neutrino mass hierarchy problem*
- *Do neutrino oscillations violate CP ?*

- Are there more than three active neutrinos? – This talk

Sterile Neutrinos

- Hints from Short-baseline Experiments for extra flavor(s):
  - → LSND and MiniBooNE
- Measurements of Z^o width at LEP
  - → only three light active neutrinos
- Additional flavor(s) has/have no weak interac
  - → Sterile Neutrino(s)





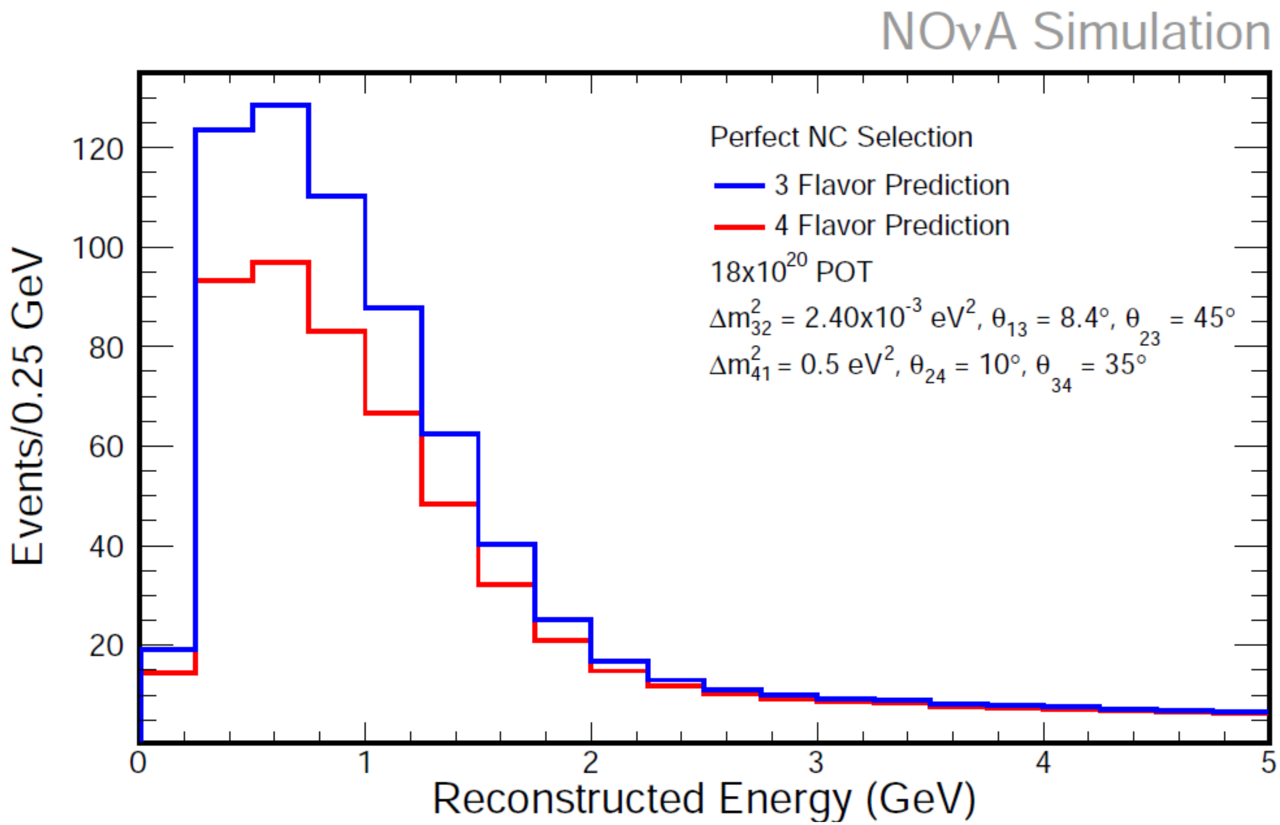
Phys. Rev. Lett.110, 161801

- Assuming a 3+1 model:
  - → One sterile neutrino mixing with the three known active neutrinos.
- New Parameters:
  - → Δm^2_{41}, θ_{14}, θ_{24}, θ_{34}

Looking for sterile neutrinos in NOvA

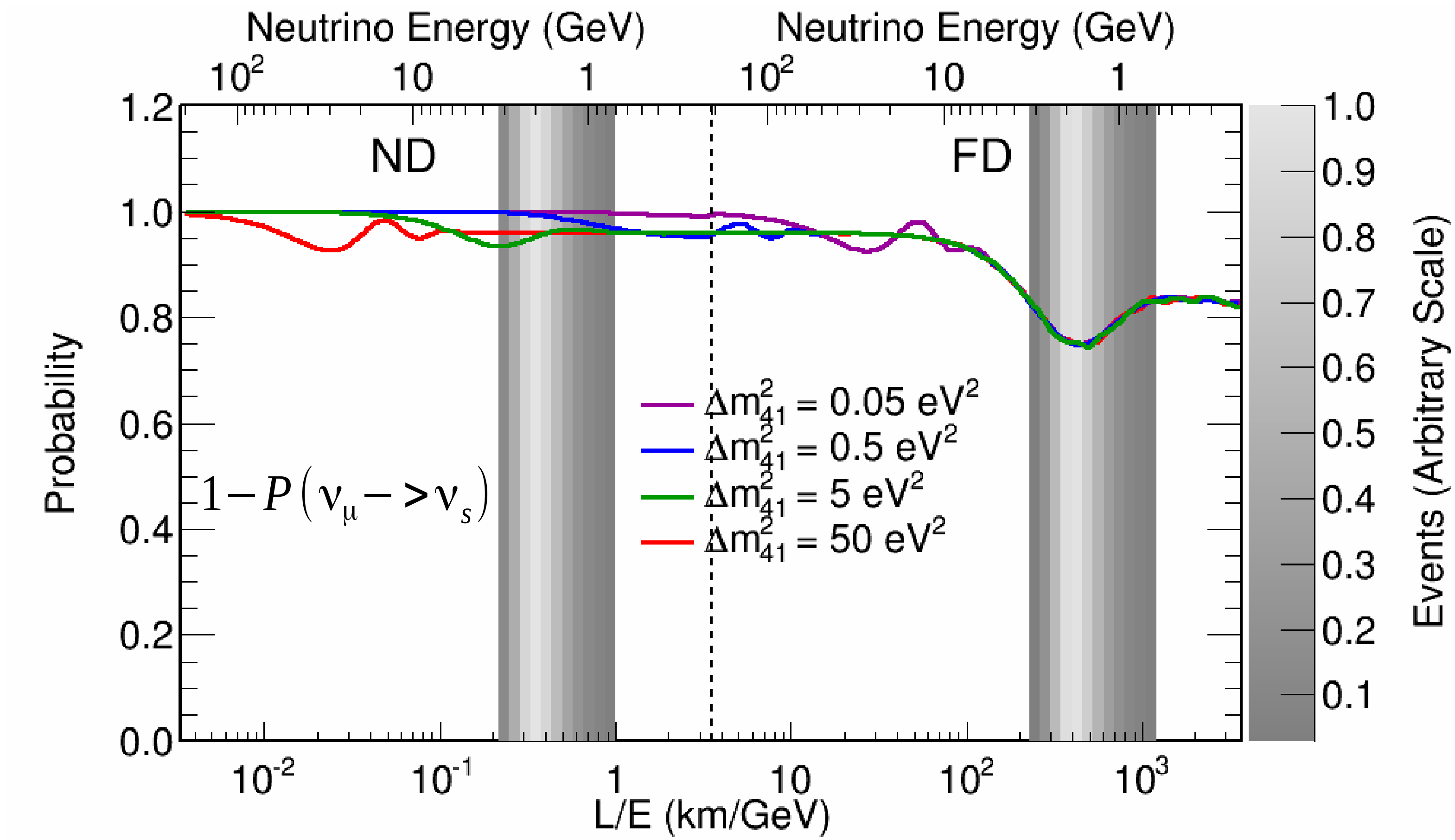
- Long-baseline experiments such as NOvA provide an excellent opportunity to test sterile neutrinos by comparing the observed interaction rates in the Near and Far detectors.

- Unlike charged-current (CC) interactions, neutral-current (NC) interactions are not affected by 3 flavor oscillations.



- $\nu_\mu \rightarrow \nu_s$ oscillation would reduce NC interaction as sterile neutrino would not interact in the detector.

Looking for sterile neutrinos in NOvA



- *An energy dependent reduction of the number of NC interactions in the FD with respect to the ND would be a clear evidence of oscillations into sterile neutrinos.*
- *Using Δm^2_{41} = 0.5 eV², so that we have no oscillations at the ND, but we have rapid oscillations at the FD*

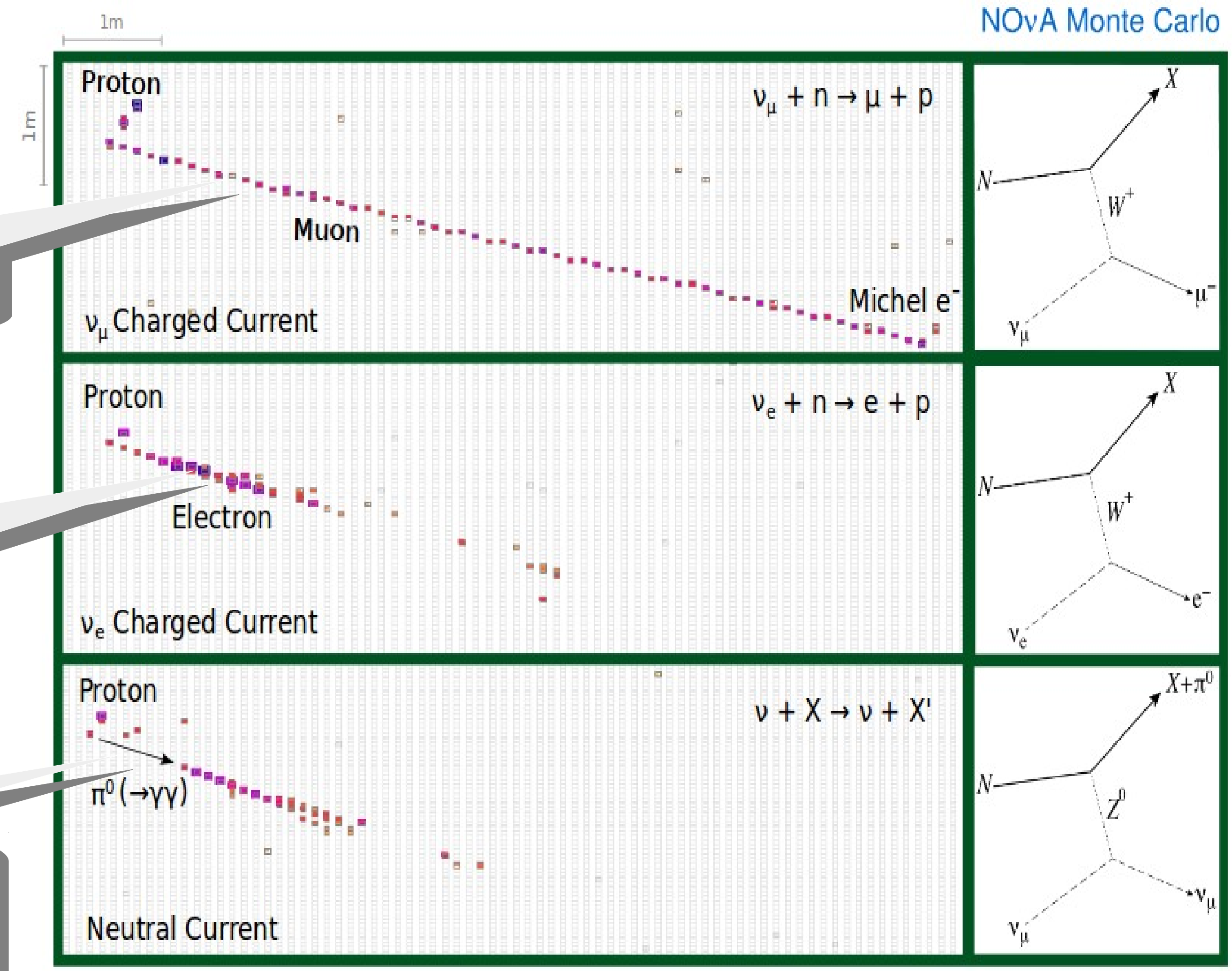
NOvA Event Samples

NOvA signal/background separation achieved via cuts on topological variables

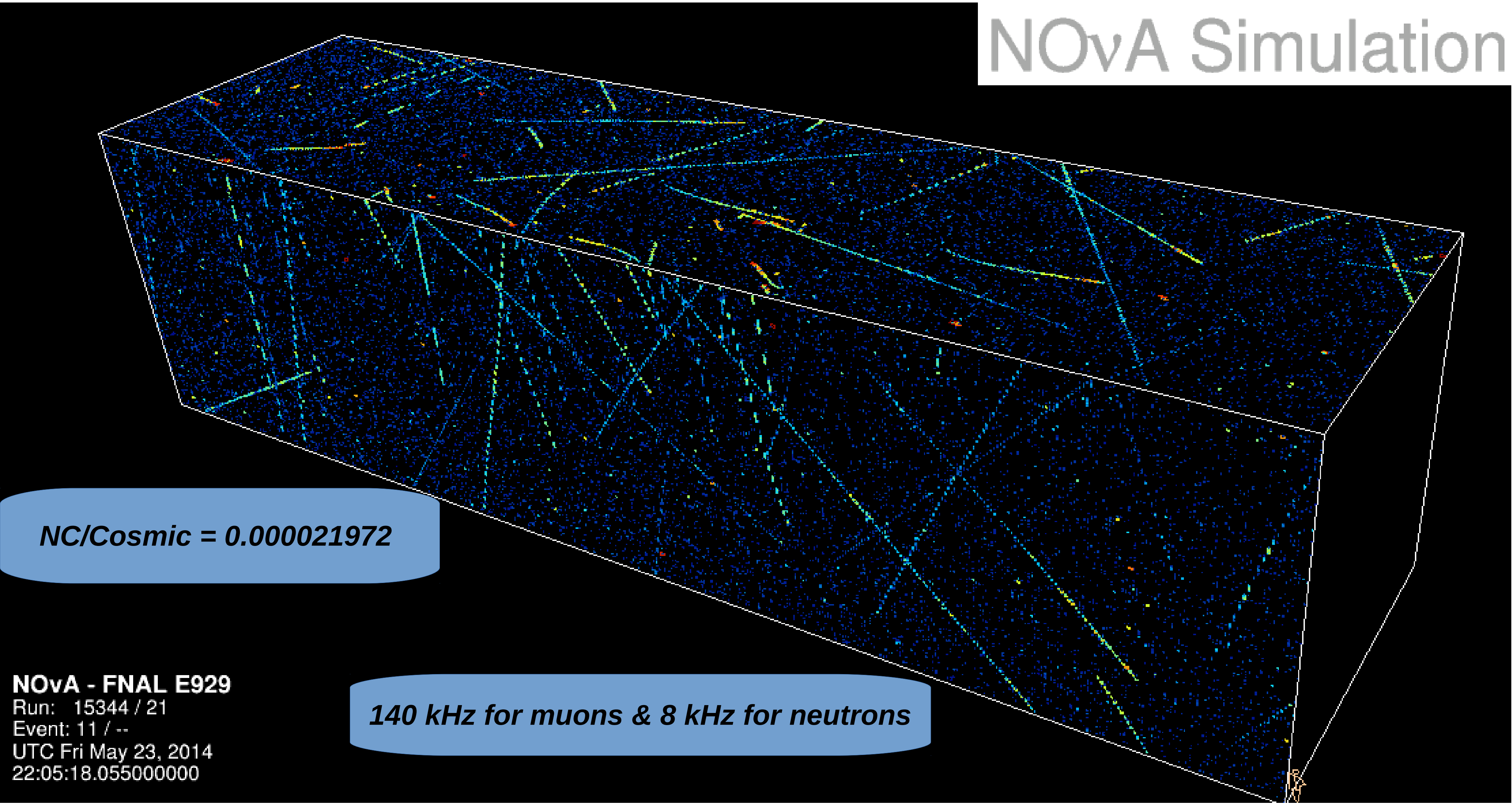
Long Muon track

Electromagnetic shower

Gap between vertex and gamma conversion



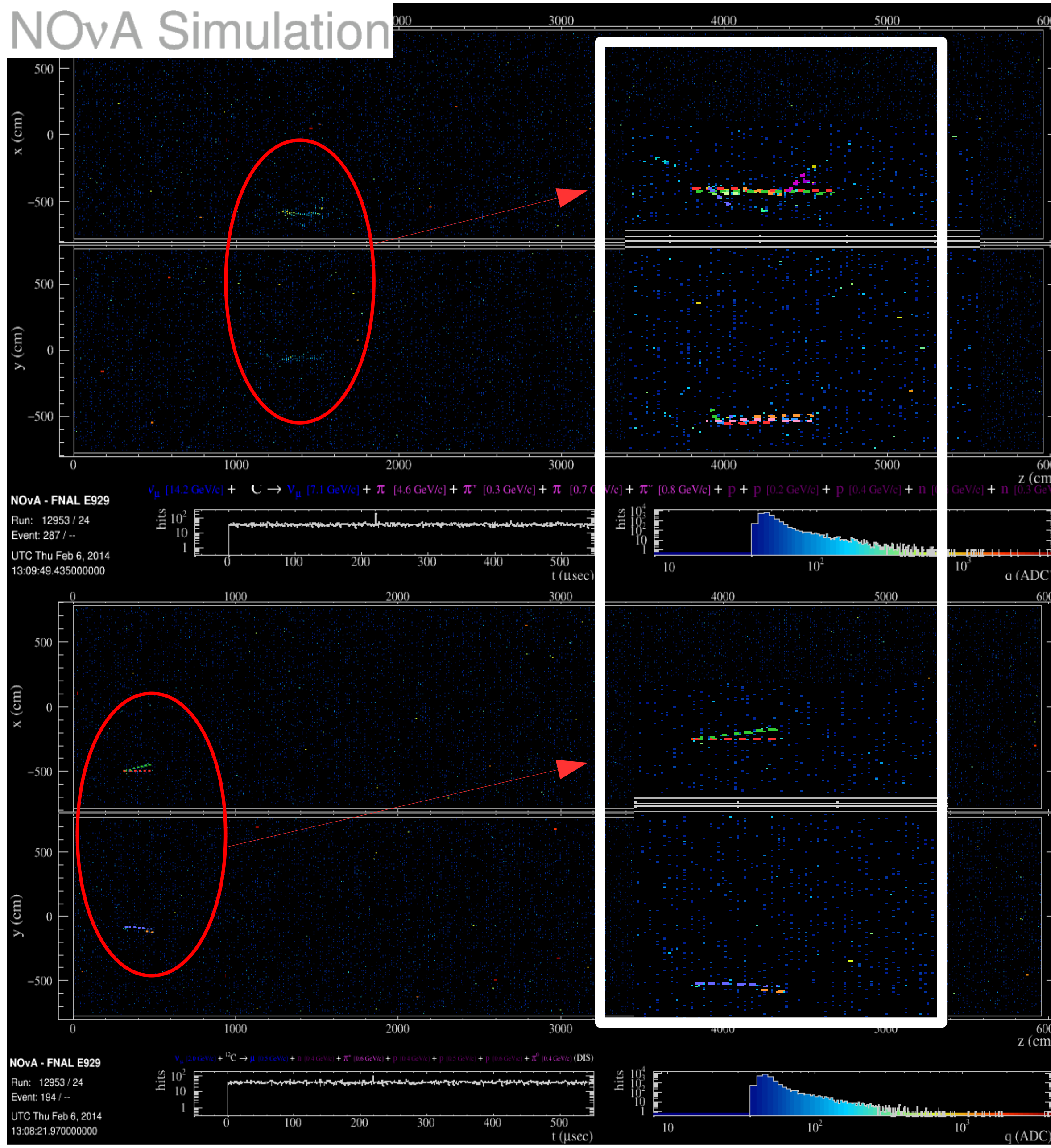
NOvA Cosmic Event Display



NC Signal Selection Challenges

- NC Signal:

  Hadronic Cascade



- *νμ CC Event:*

  Highly Inelastic

  event without long

  muon track

NC Signal Selection Challenges

- ν_e CC:

  not easy to distinguish

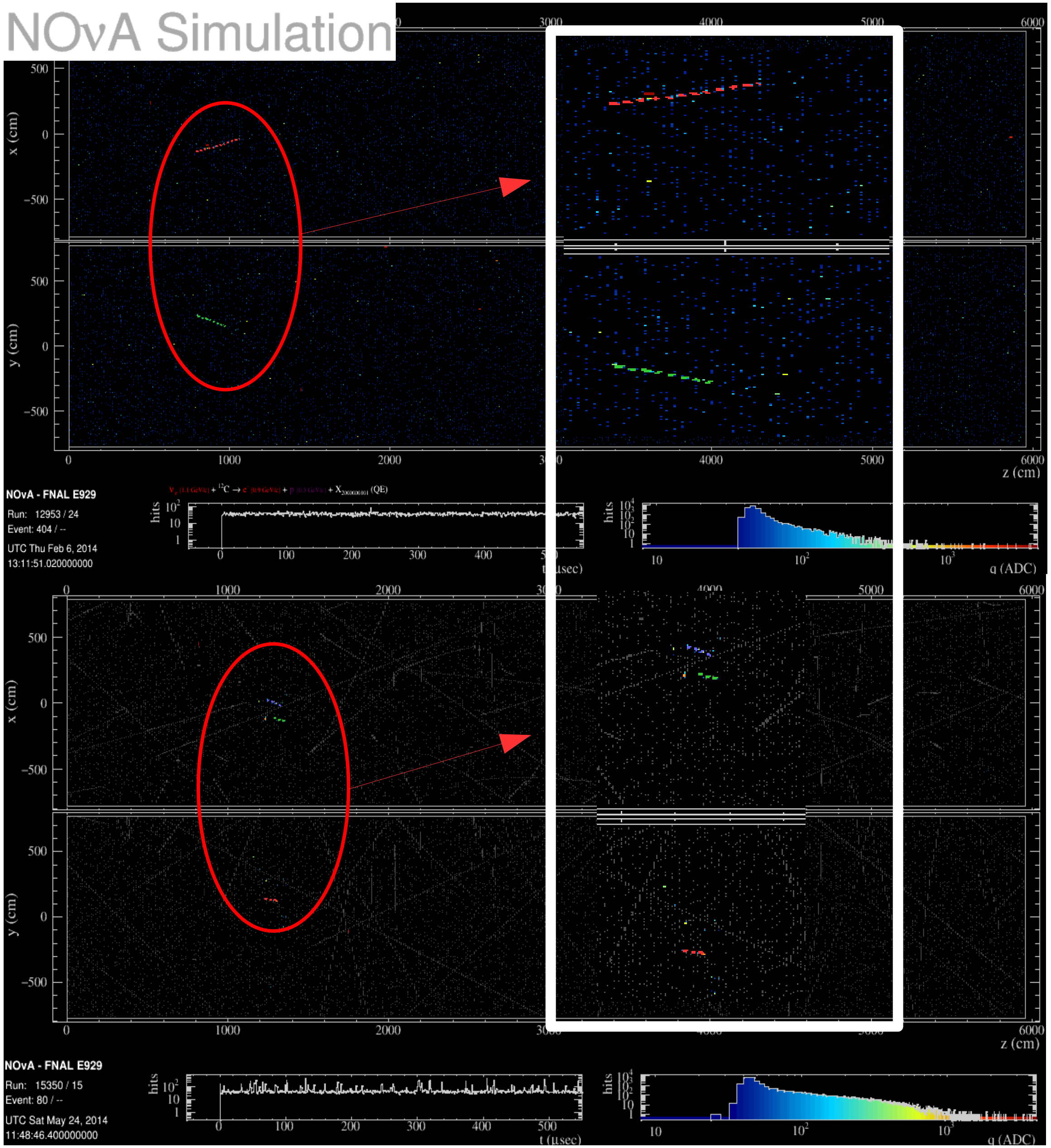
  from NC π° interactions,

  especially for the ND.

- Cosmic Event:

  numerous events,

  especially for the FD



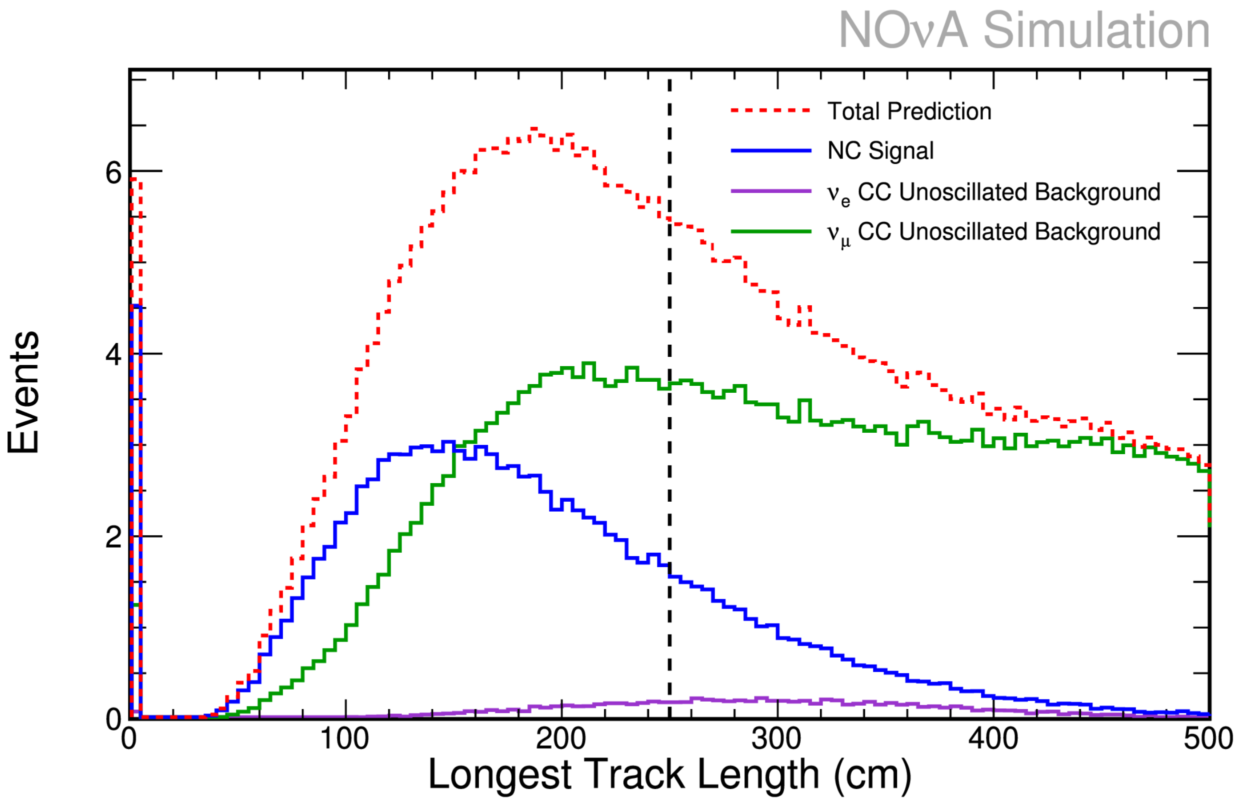
NC Selection Method

- *Data Quality:*

  To remove some detector issues, such as FEB Flash, or reconstruction failures.

- *Fiducial Volume:*

  To make sure the energy of the selected event can be correctly reconstructed.



- *Containment:*

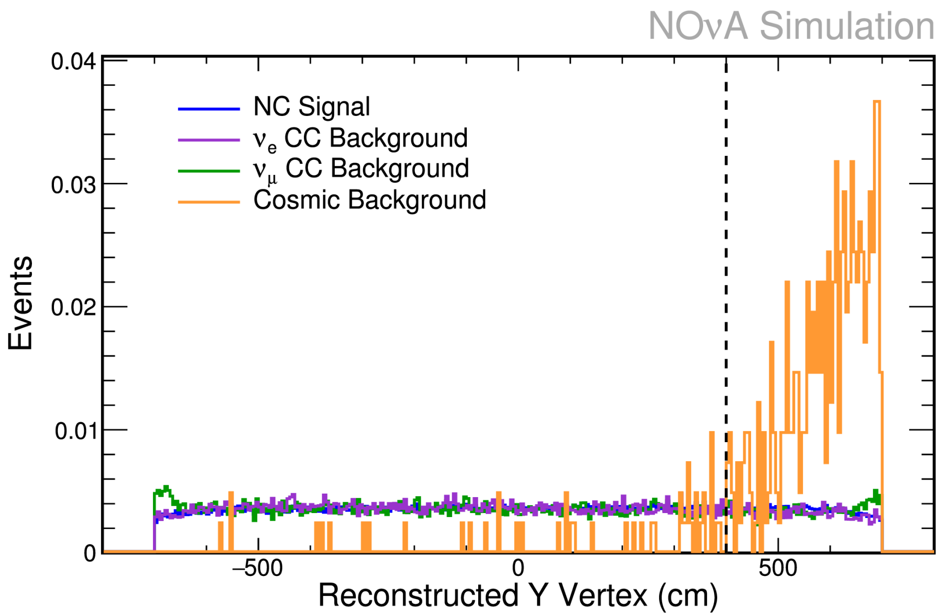
  To reject events which are partially outside the detector.

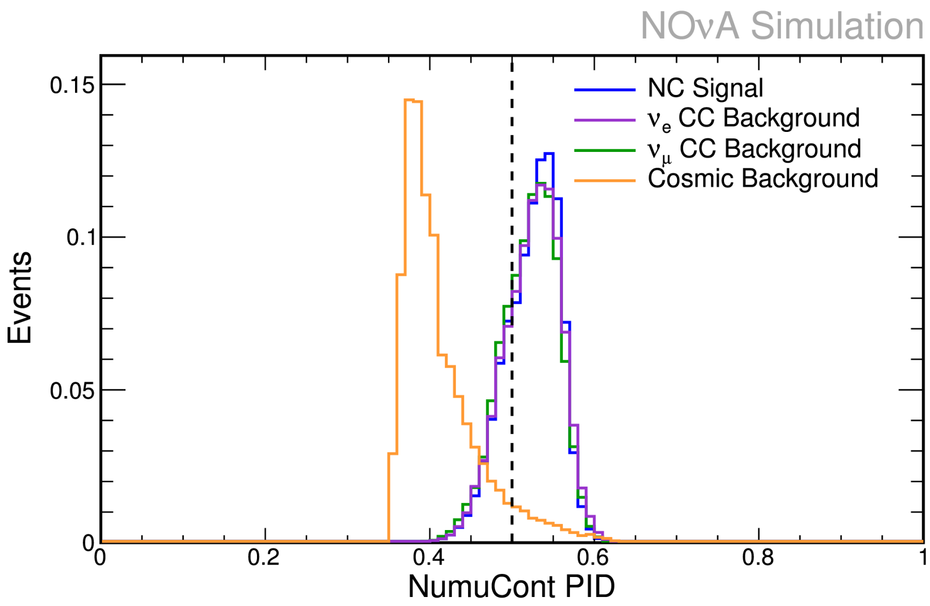
- *NC/CC Separation*

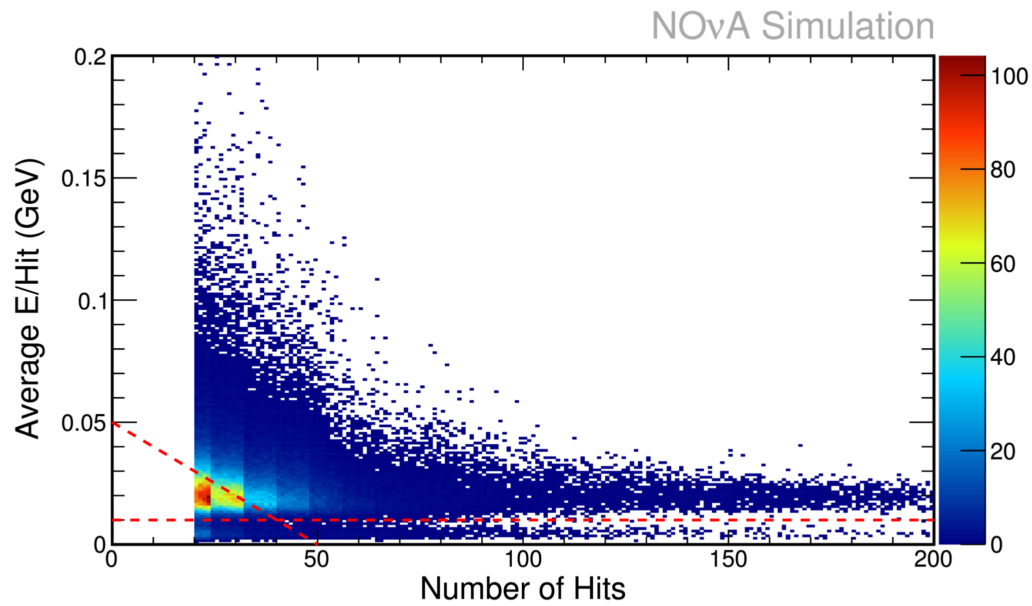
  To select NC signal from CC backgrounds.

NC Selection Method

- *Cosmic Background Rejection:*







First NC Selection Cut Flow (POT =6e20)

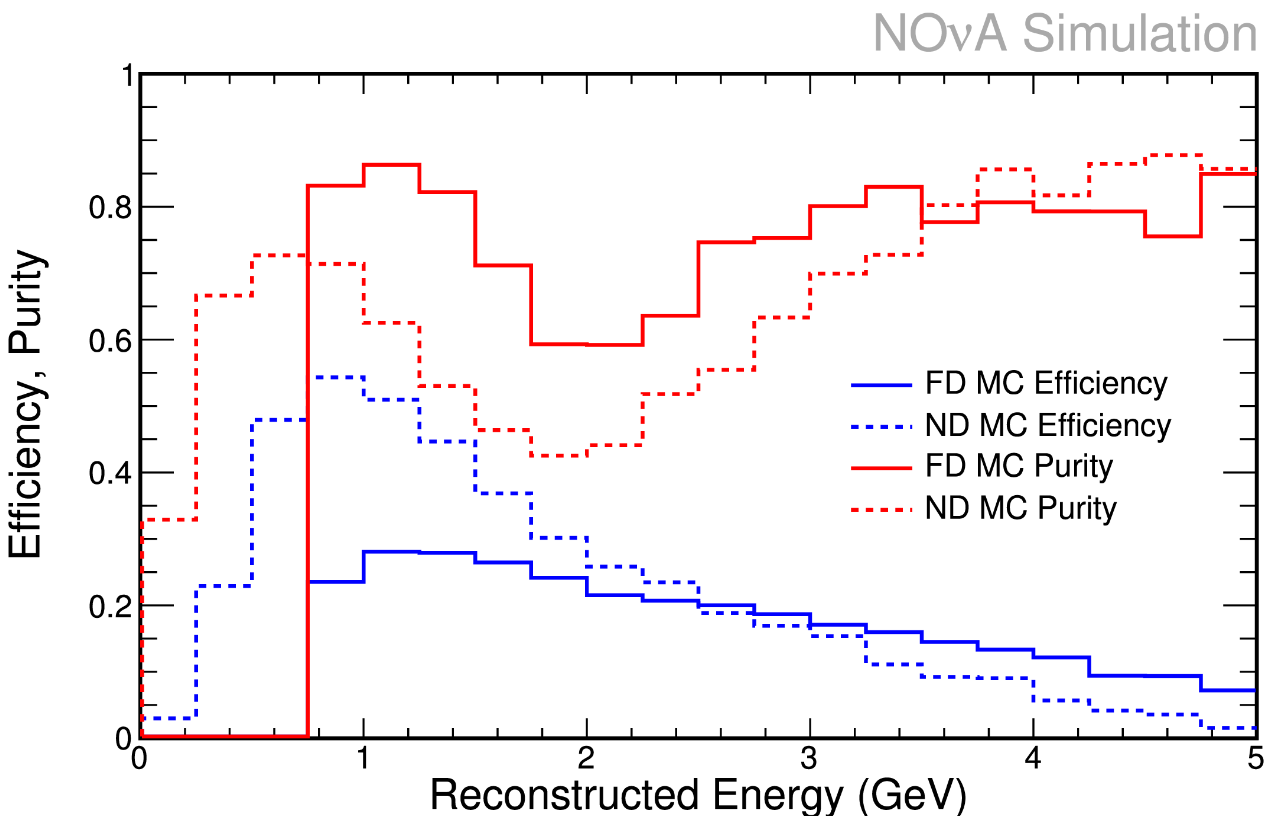
- Near Detector :

Cut	NC	CC Numu	CC Nue
No Cut	13.3×10^6	87.9×10^6	1.1×10^6
+DQ	9.8×10^6	78.8×10^6	0.77×10^6
+Fiducial	1.8×10^6	6.3×10^6	0.08×10^6
+Containment	718×10^3	814×10^3	26×10^3
+NHit, Track L	645×10^3	480×10^3	13×10^3
+PIDs	590×10^3	334×10^3	7×10^3

- Far Detector :

Cut	NC	Numu	Nue	Cosmic
No Cut	384.6	265.8	60.6	13.4×10^6
+DQ	362.1	262.0	59.1	13.0×10^6
+Fiducial	270.2	184.6	45.7	1.67×10^6
+Containment	145.8	49.3	41.2	42.9×10^3
+NHit, Track L	115.6	16.8	24.9	7.74×10^3
+PIDs	101.9	10.9	8.8	6.36×10^3
+Cos Rej	37.9	3.3	4.0	3.4

Efficiency and Purity



- Near Detector :
  - → Overall Purity = 63.4%
  - → Efficiency (All cuts/DQ+Fid)

    = 32.2%

- Far Detector:
  - → Overall Purity = 69.3% or 83.6% without considering cosmic events
  - → Efficiency (All cuts/DQ+Fid) = 13.5%

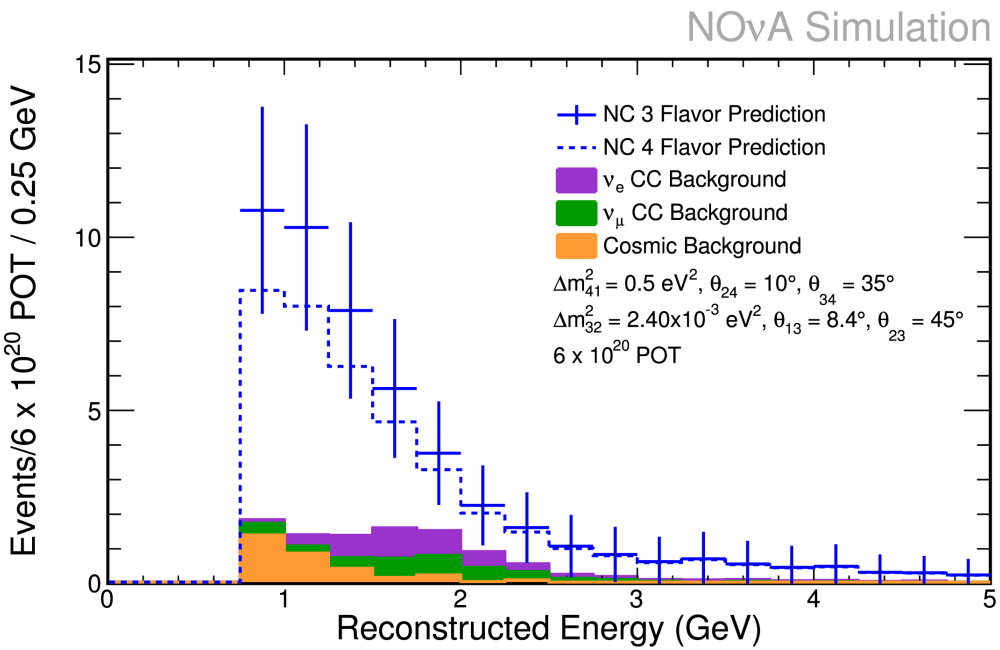
Far/Near Extrapolation

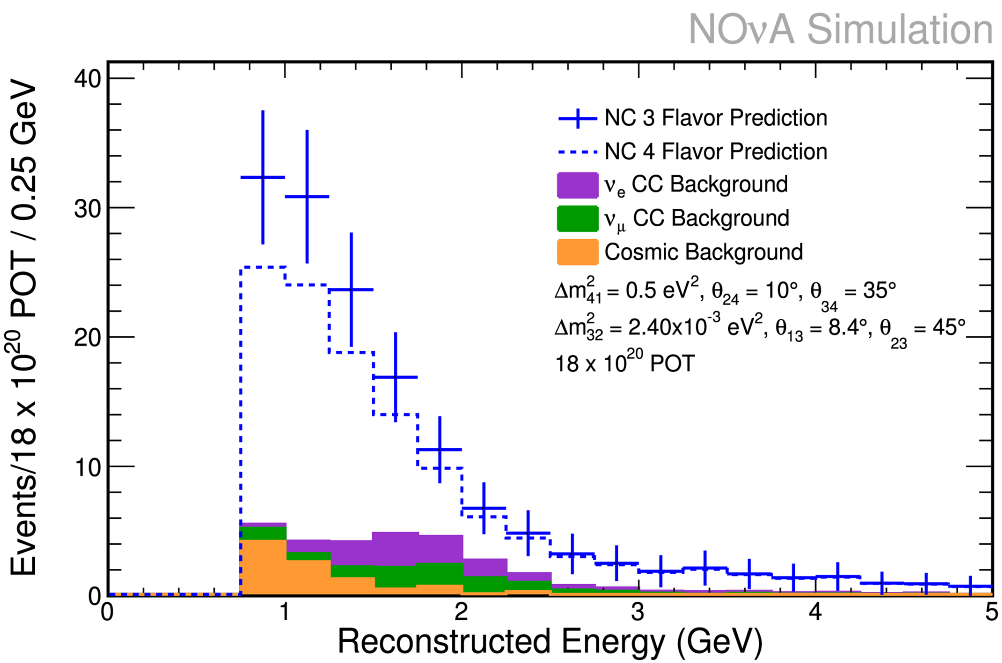
- The "fake" Near Detector energy spectrum is used to predict the Far Detector spectrum via the Far/Near Ratio method.

$$\boxed{FD_i^{predicted} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{Fake\ Data}}$$

- Correct each energy bin in the FD MC using the ND fake data/MC differences as a scale factor .

Energy Spectra

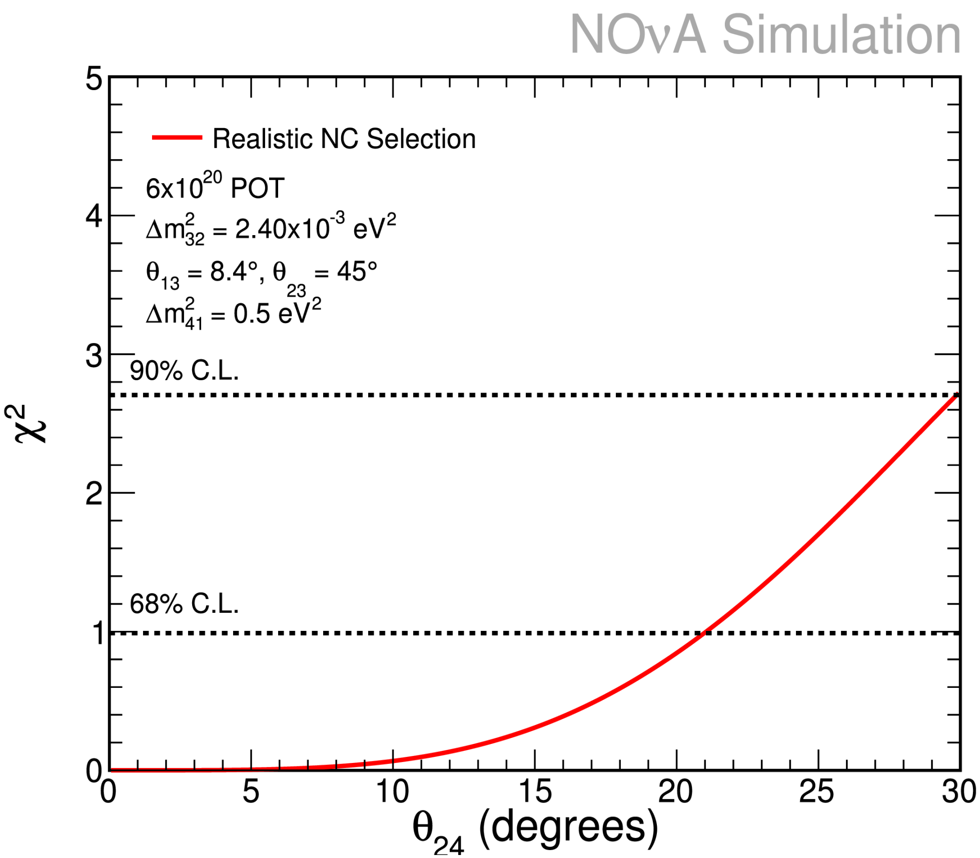


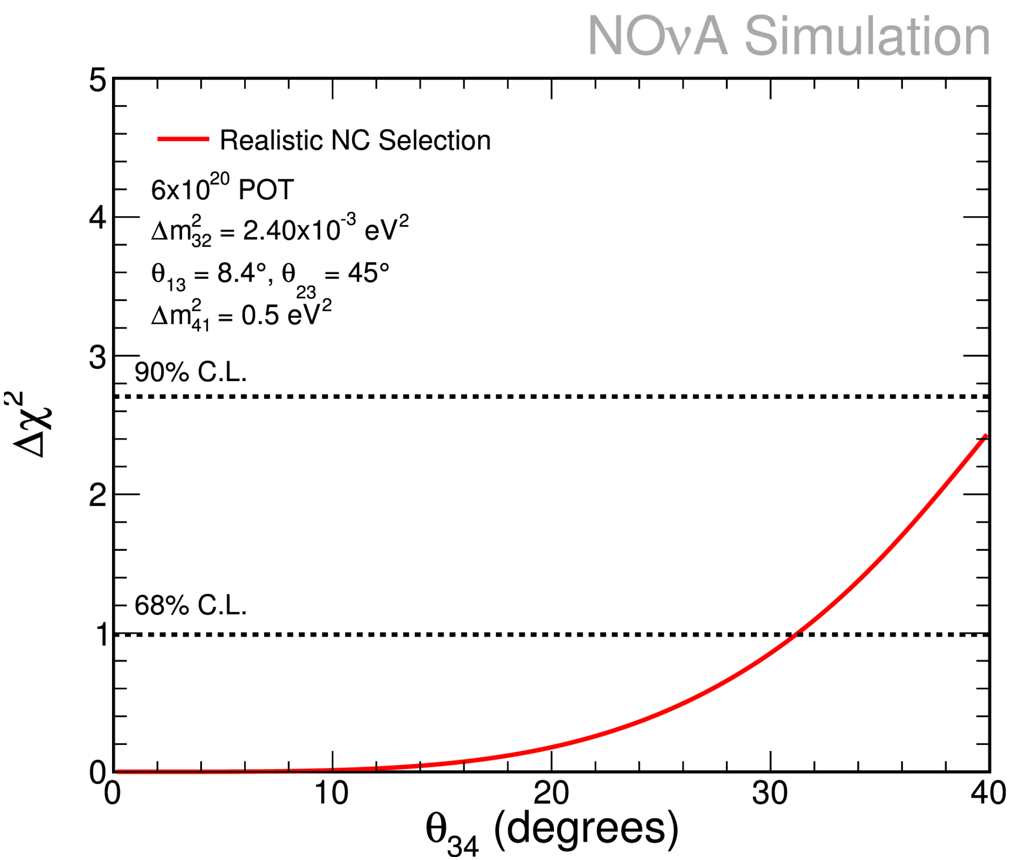


1 year data, POT =6e20

3 year data, POT =18e20

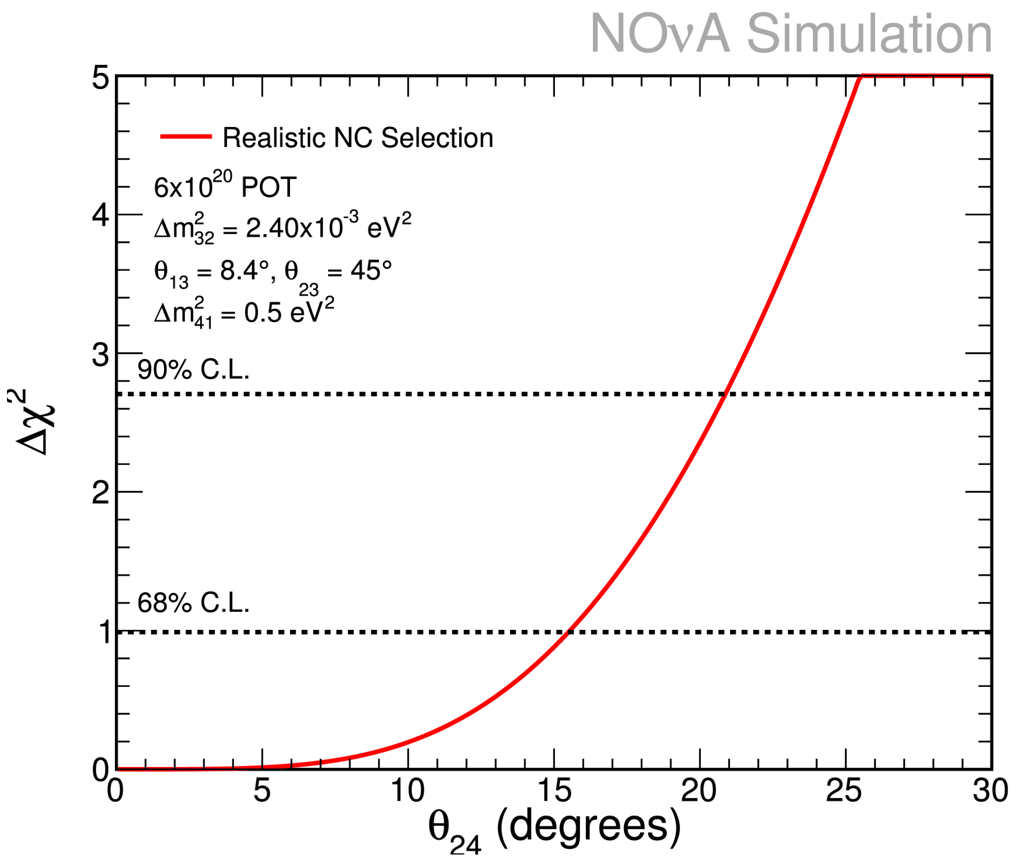
1 year data limits on sterile angles

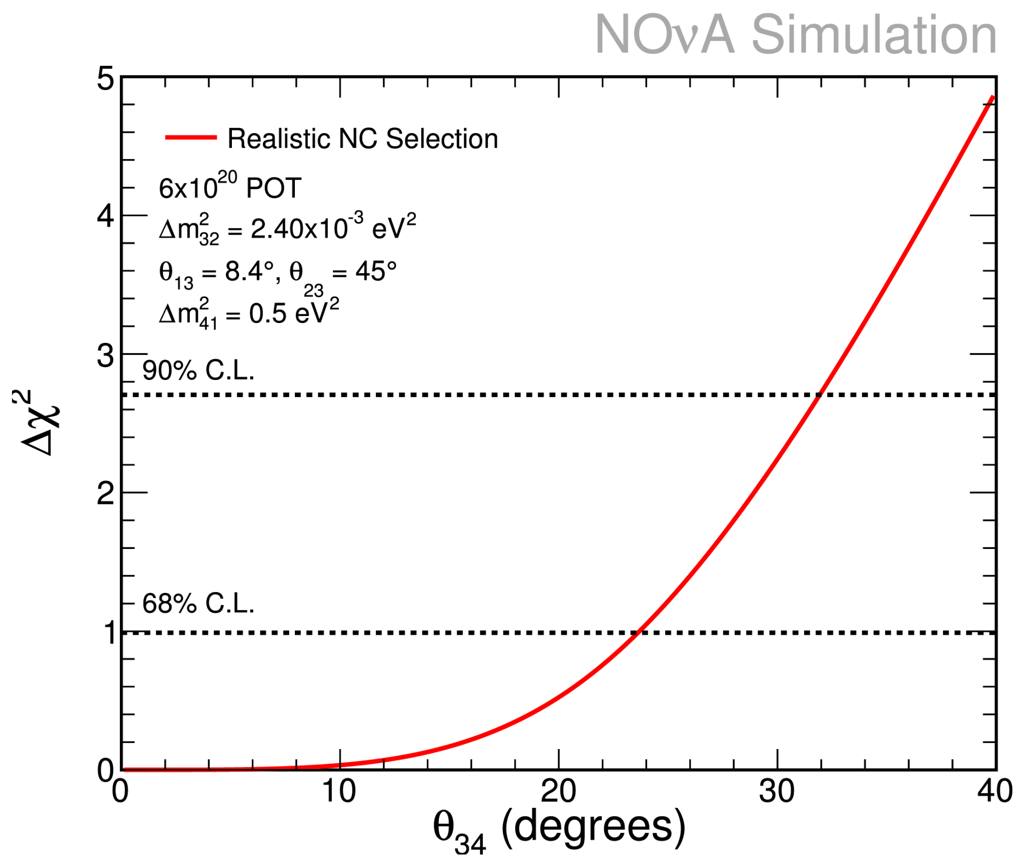




Realistic selection

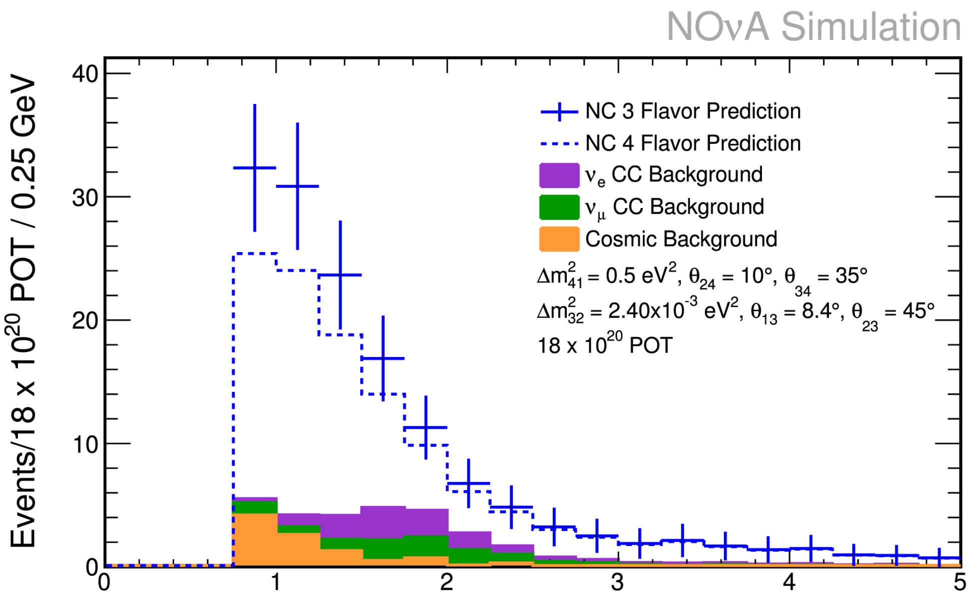
3 year data limits on sterile angles

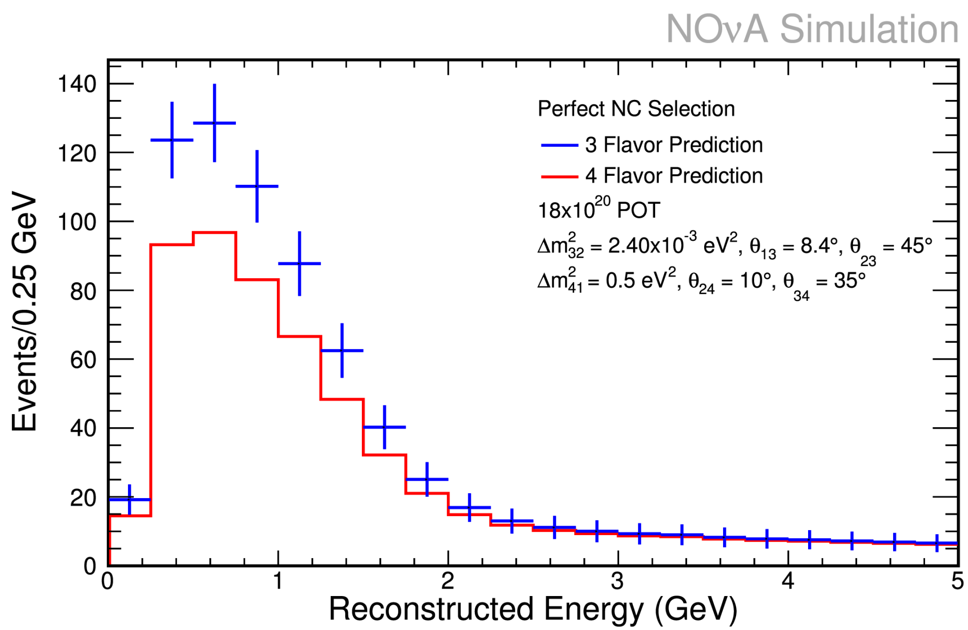


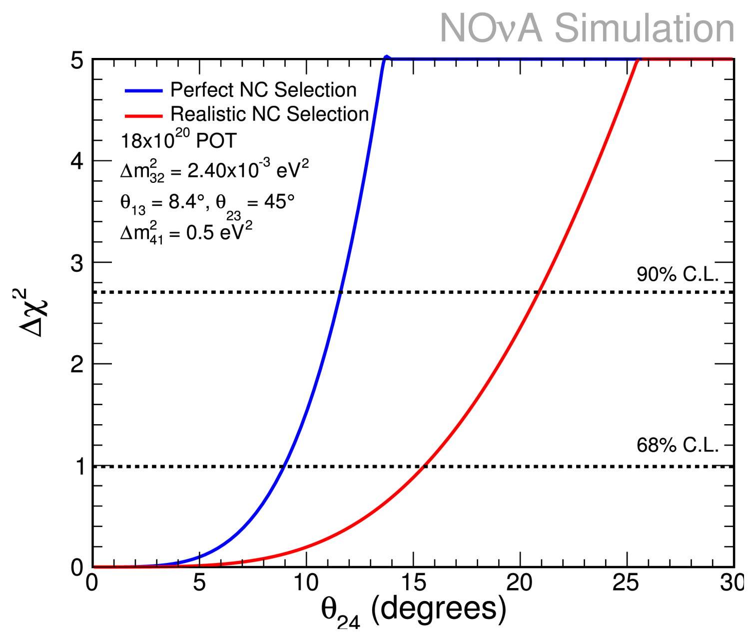


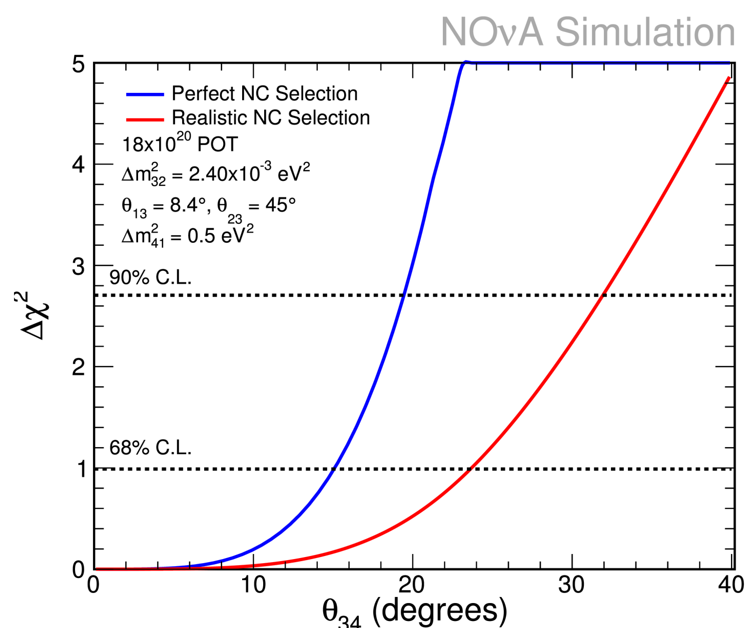
Realistic selection

Realistic/Perfect results Comparison



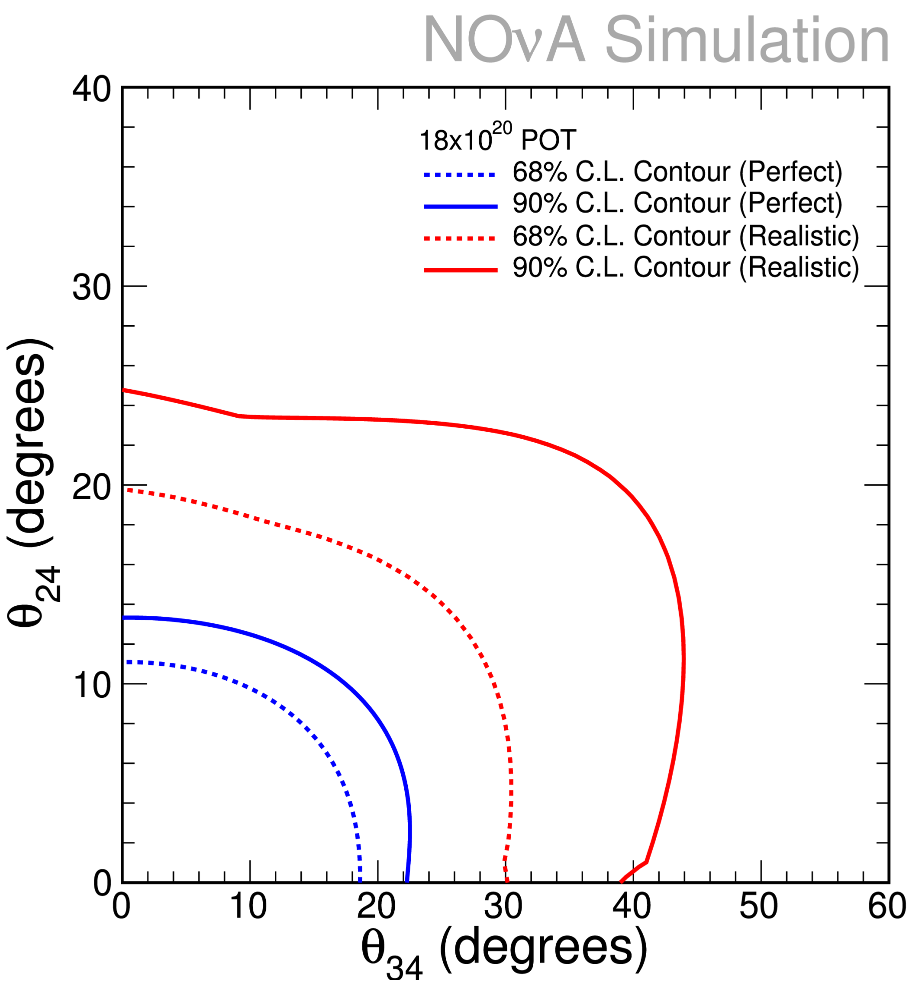


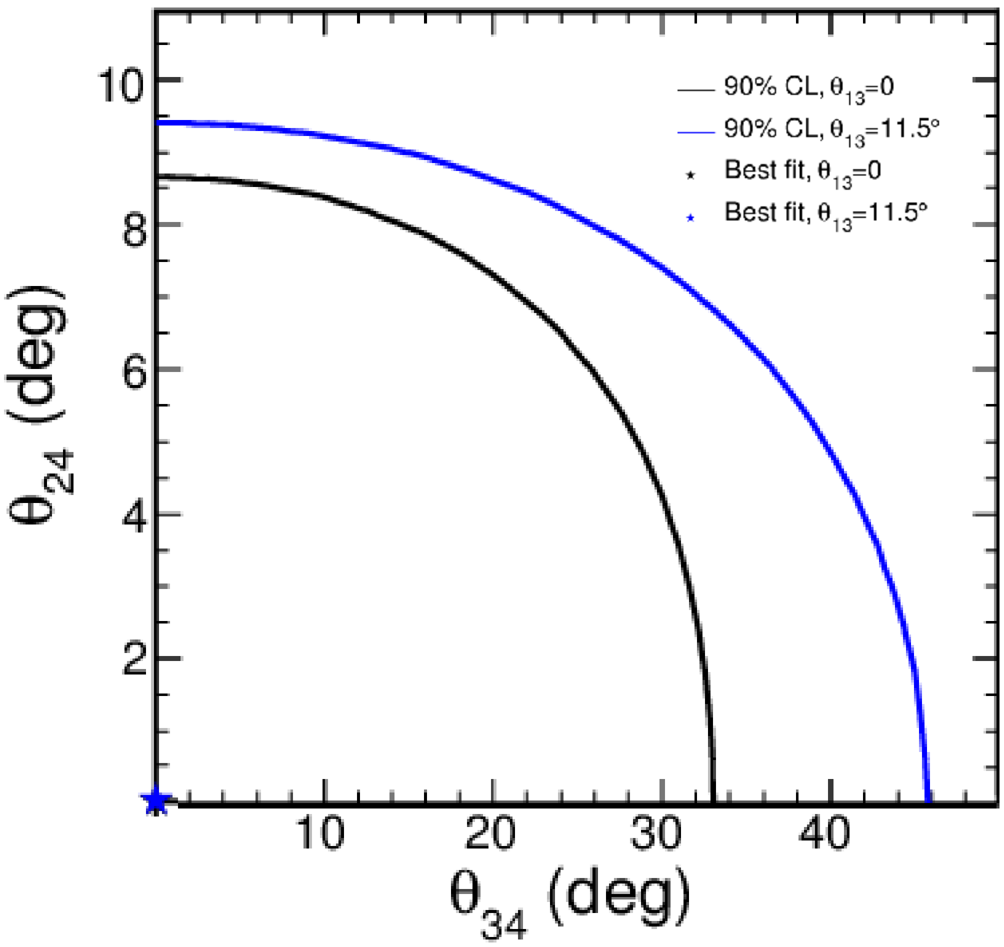




3-year data 2D sterile angles limits comparison

MINOS: Phys. Rev. Lett. 107, 011802





Conclusion

- NOvA can make important contributions to the body of knowledge of sterile neutrinos.
- There is room for improvement of the NC selection method and rejection of cosmic backgrounds.
- With preliminary selection, expect to improve on MINOS constraints on θ_{34}, if no evidence for sterile neutrino mixing is found.
- Stay tuned for results soon!


THANK YOU


PHYSICS

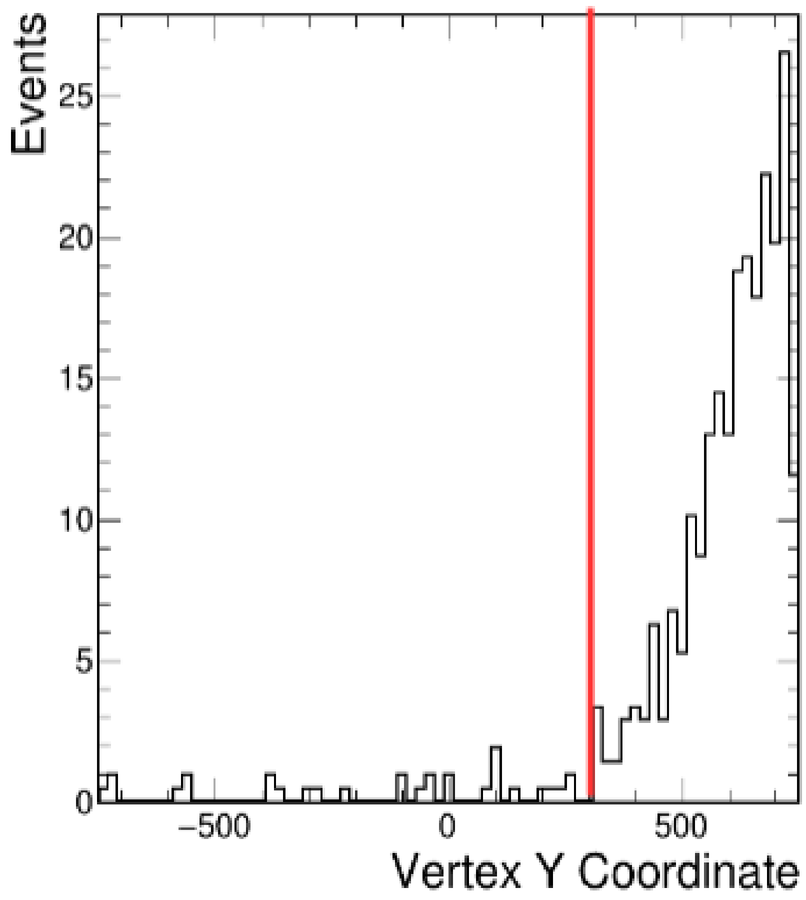

BACKUP

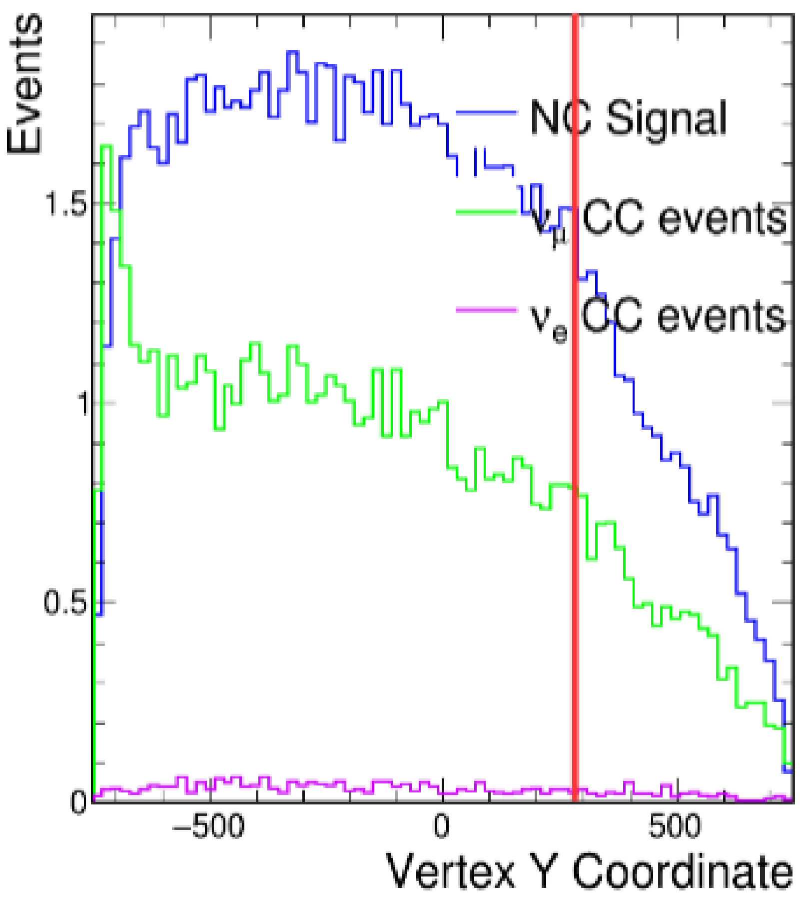
- 1. Additional neutrino species would belong to a singlet representation with respect to the strong interaction and the weak interaction, having zero electric charge, zero weak hypercharge, zero weak isospin, and, as with the other leptons, no color, although they do have a B-L of - 1. That means they would not interact electromagnetically, weakly, or strongly, making them extremely difficult to detect, that is why we call it sterile neutrinos.
- 2. They would have Yukawa interactions with ordinary leptons and Higgs bosons, which via the Higgs mechanism lead to mixing with ordinary neutrinos. That would allow them to mix with three active neutrinos!

- 3. They would also interact gravitationally due to their mass, however, and if they are heavy enough, they could explain cold dark matter or warm dark matter.
- 4. The number of sterile neutrino types is unknown. This is in contrast to the number of active neutrino types, which has to equal that of charged leptons and quark generations to ensure the anomaly freedom of the electroweak interaction.
- 5. There are no mass terms for neutrinos under the Standard Model: the model only contains a left-handed neutrino and its antiparticle, a right-handed antineutrino, for each generation, produced in weak eigenstates during weak interactions.
- 5. Sterile neutrinos allow the introduction of a Dirac mass term as usual. This can yield the observed neutrino mass, but it requires that the strength of the Yukawa coupling be much weaker for the electron neutrino than the electron, without explanation.

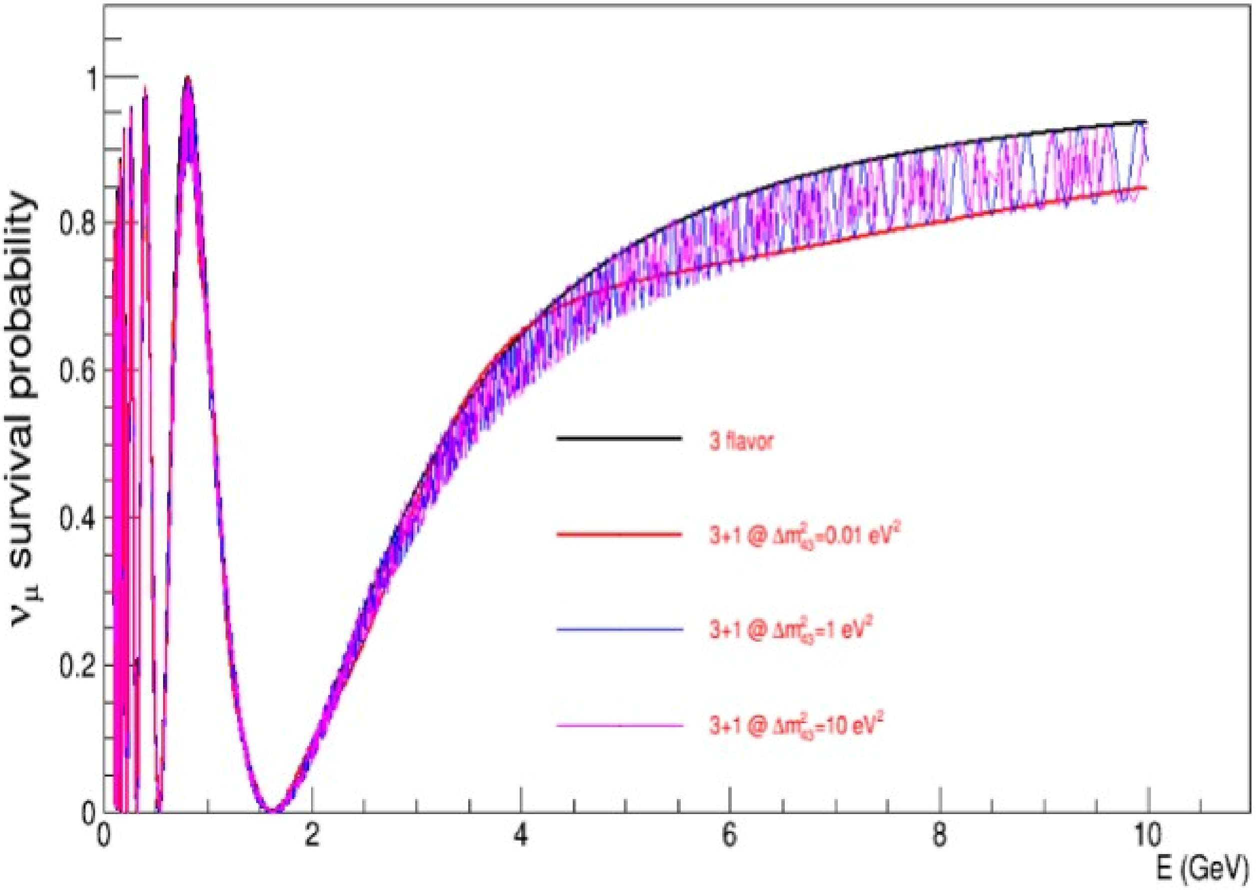
- 6.Unlike for the left-handed neutrino, a Majorana mass term can be added for a sterile neutrino without violating local symmetries (weak isospin and weak hypercharge) since it has no weak charge. However, this would still violate total lepton number.
- 7.It is possible to include both Dirac and Majorana terms: this is done in the seesaw mechanism. In addition to satisfying the Majorana equation, if the neutrino were also its own antiparticle, then it would be the first Majorana fermion. In this case, it could annihilate with another neutrino, allowing neutrinoless double beta decay. The contrasting case is a Dirac fermion, which is not its own antiparticle.

Y-Vertex


Events
25
20
15
10
5
0
−500
0
500
Vertex Y Coordinate


Events
1.5
1
0.5
0
−500
0
500
Vertex Y Coordinate
NC Signal
ν_μ CC events
ν_e CC events

Far Detector Oscillation



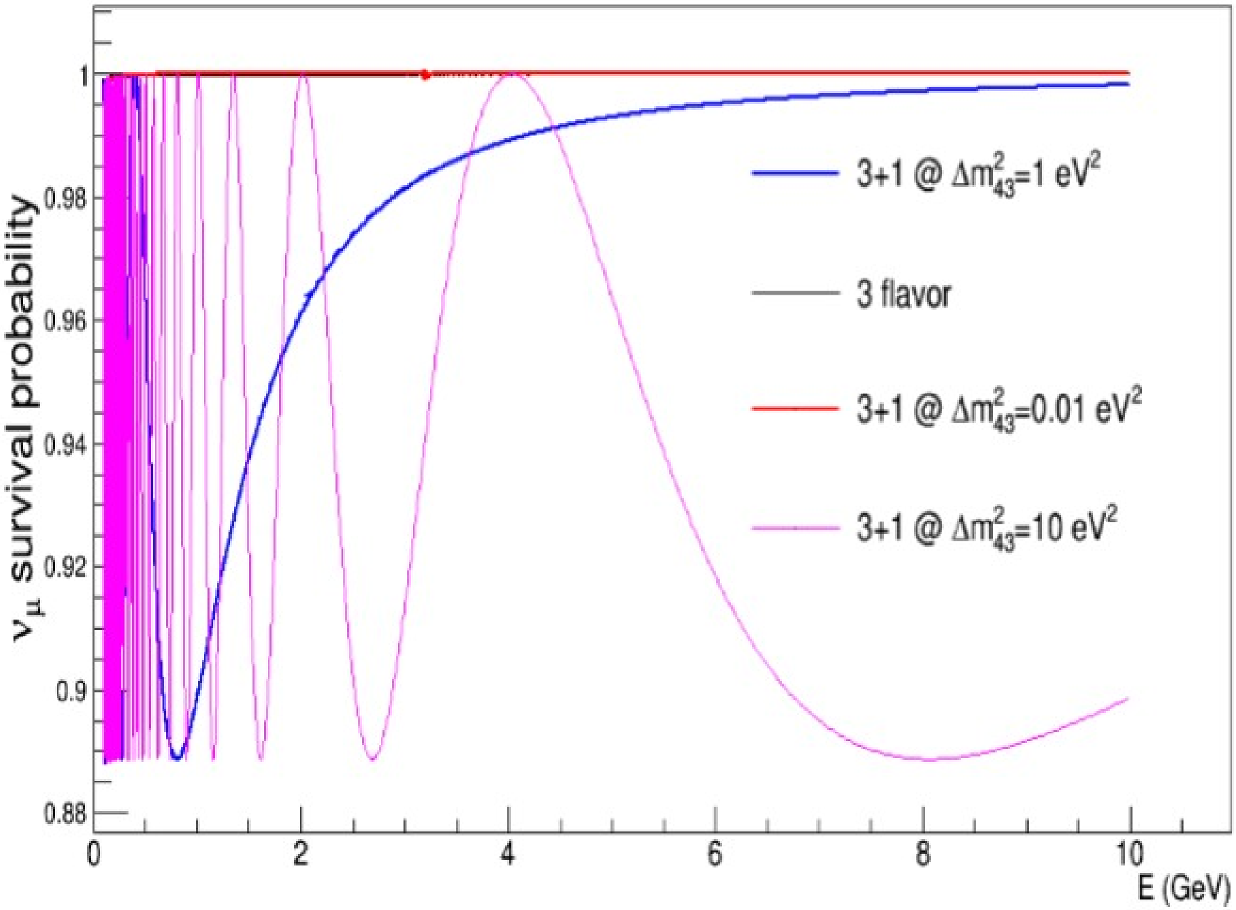
$\theta_{24}=10^o$

$\theta_{34}=35^o$

L=810 km

11

Near Detector Oscillation

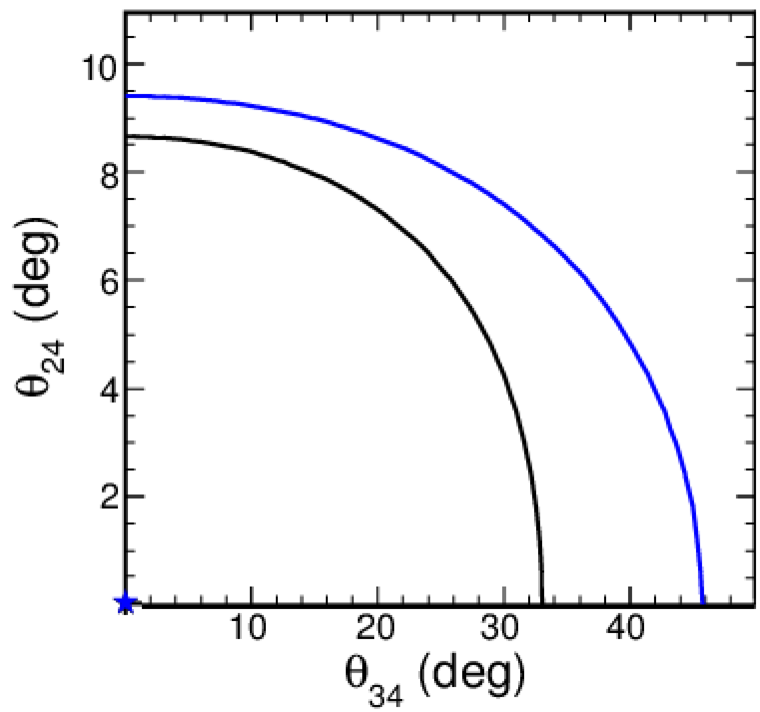


$\theta_{24}=10^o$

$\theta_{34}=35^o$

L=1 km

12


10
8
6
4
2
θ24 (deg)
10
20
30
40
θ34 (deg)