NOvA Short-Baseline Tau Neutrino Appearance Search

Rijeesh Keloth

Fermilab, USA / Cochin University of Science and Technology, INDIA

For The NOvA Collaboration

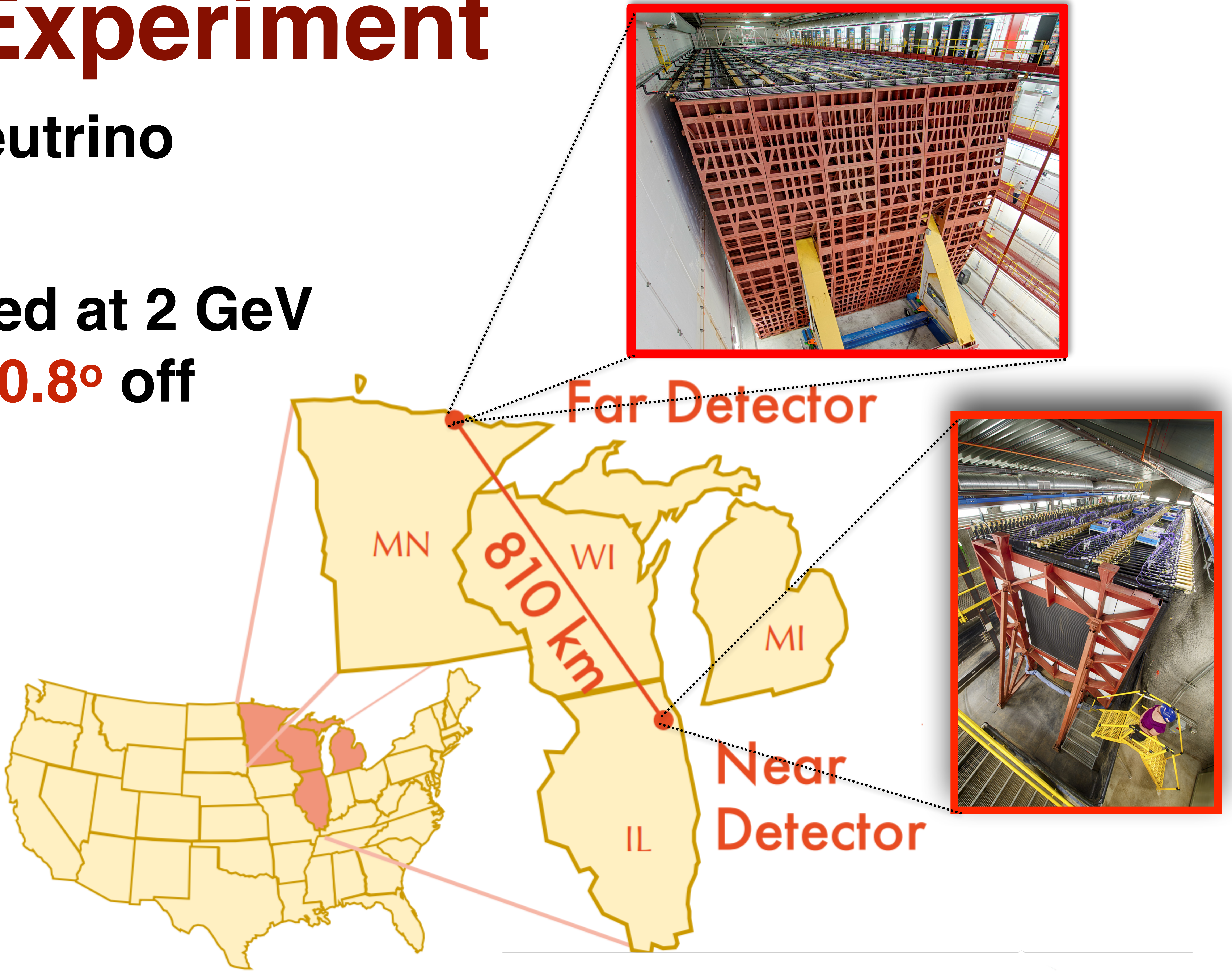
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY

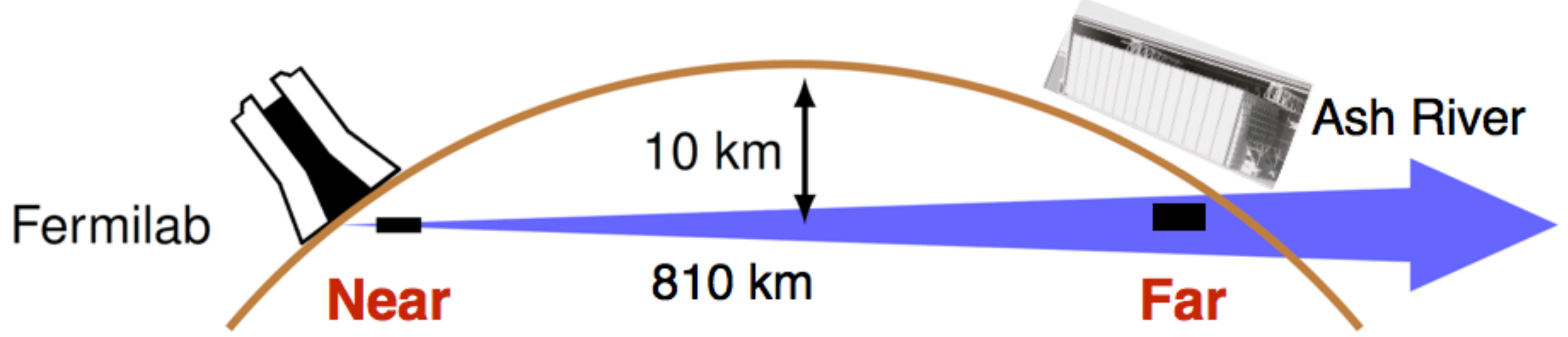
New Perspectives 2017

05 June 2017, Fermilab

NOvA Experiment

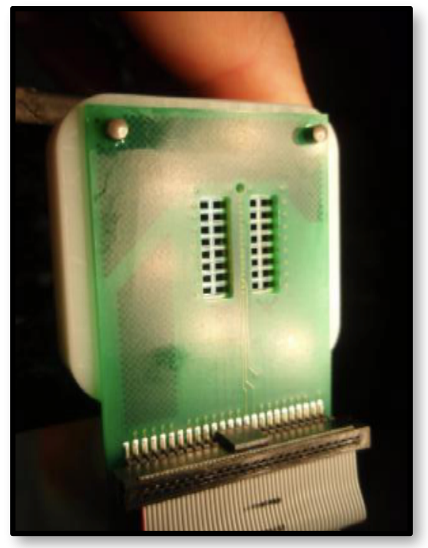
- **Off-axis long-baseline neutrino oscillation experiment**
- **Narrow-band beam peaked at 2 GeV as detectors are located 0.8° off NuMI beam axis**
- **Near Detector:**
  - 105 m underground
  - 1 km from target
  - 0.3 kton
- **Far Detector:**
  - Located on surface
  - 810 km from target
  - 14 kton





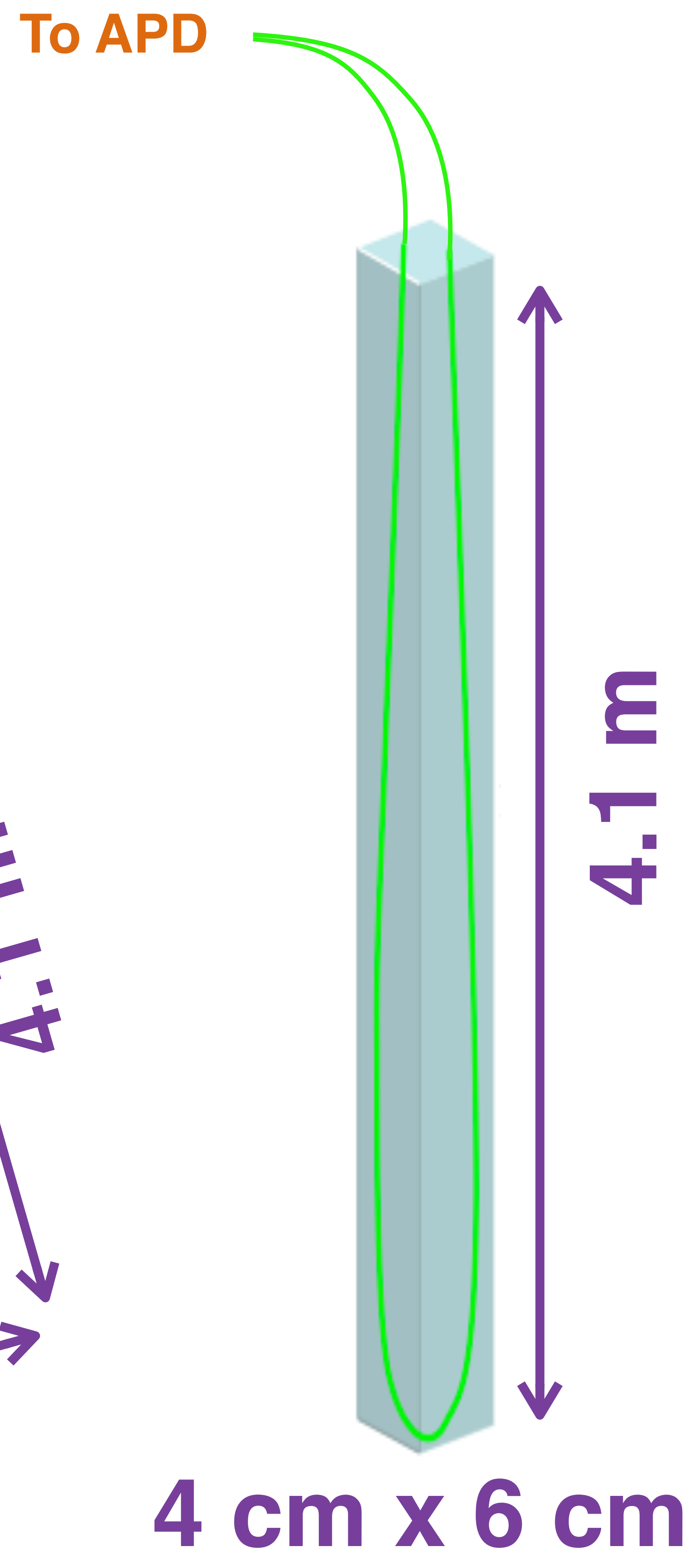
NOvA Detectors

- ✦ Functionally identical detectors made of planes of extruded PVC cells, alternating horizontal and vertical planes to provide 3D tracking.
- ✦ Each cell filled with liquid scintillator, light collected in wavelength shifting fibers and fed into avalanche photodiode.



32-pixel APD

A NOvA cell

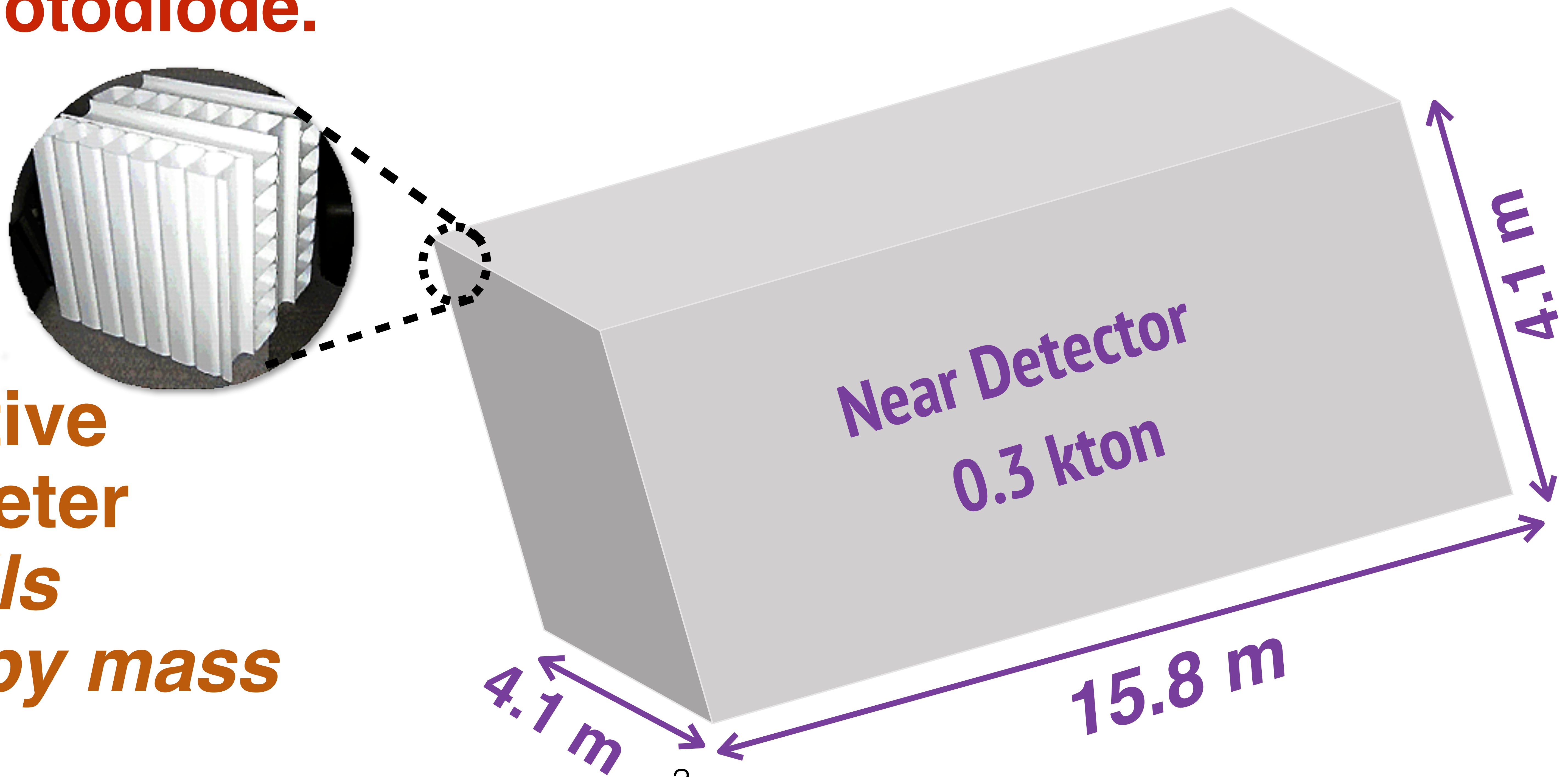


Near detector:

Fine-grained, low-*Z*, highly-active tracking calorimeter

→ *20k PVC cells*

→ *65% active by mass*



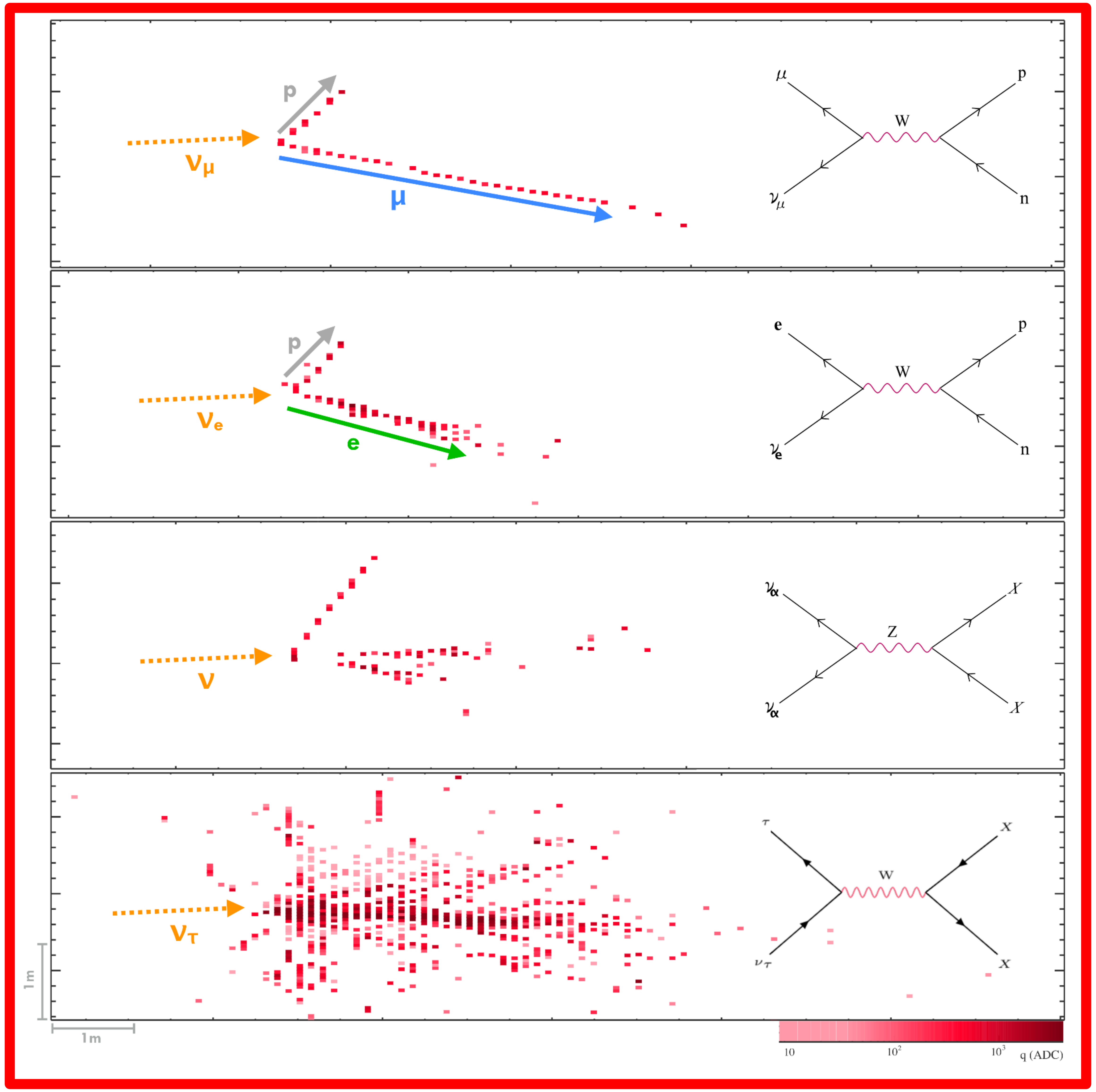
Neutrino Interactions in NOvA Detectors

ν_μ CC — Long muon track

ν_e CC — Electronic shower

NC — Hadrons

ν_τ CC — Tau decay

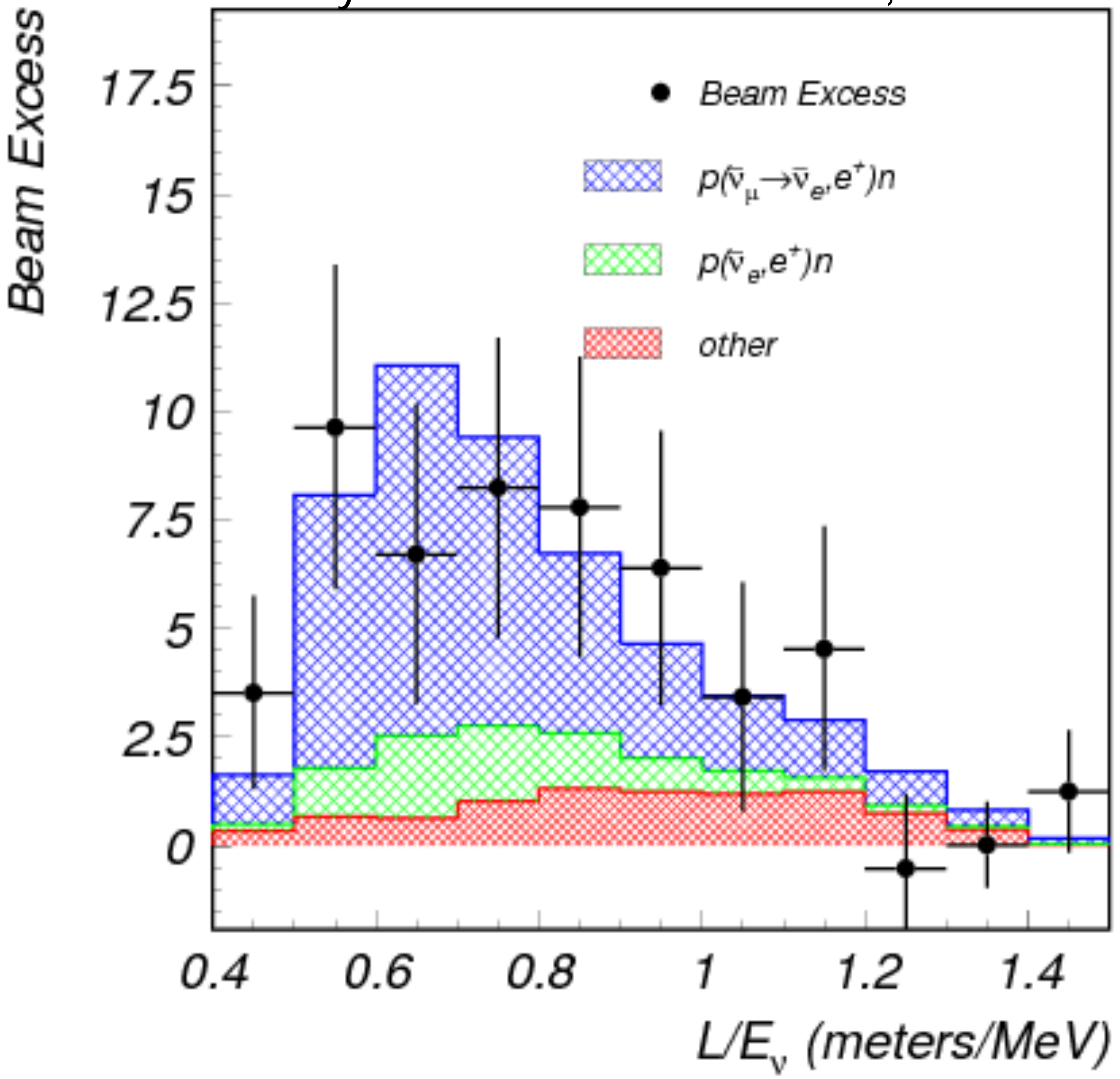


Short-Baseline Oscillations

Why we are interested in looking for sterile neutrinos?

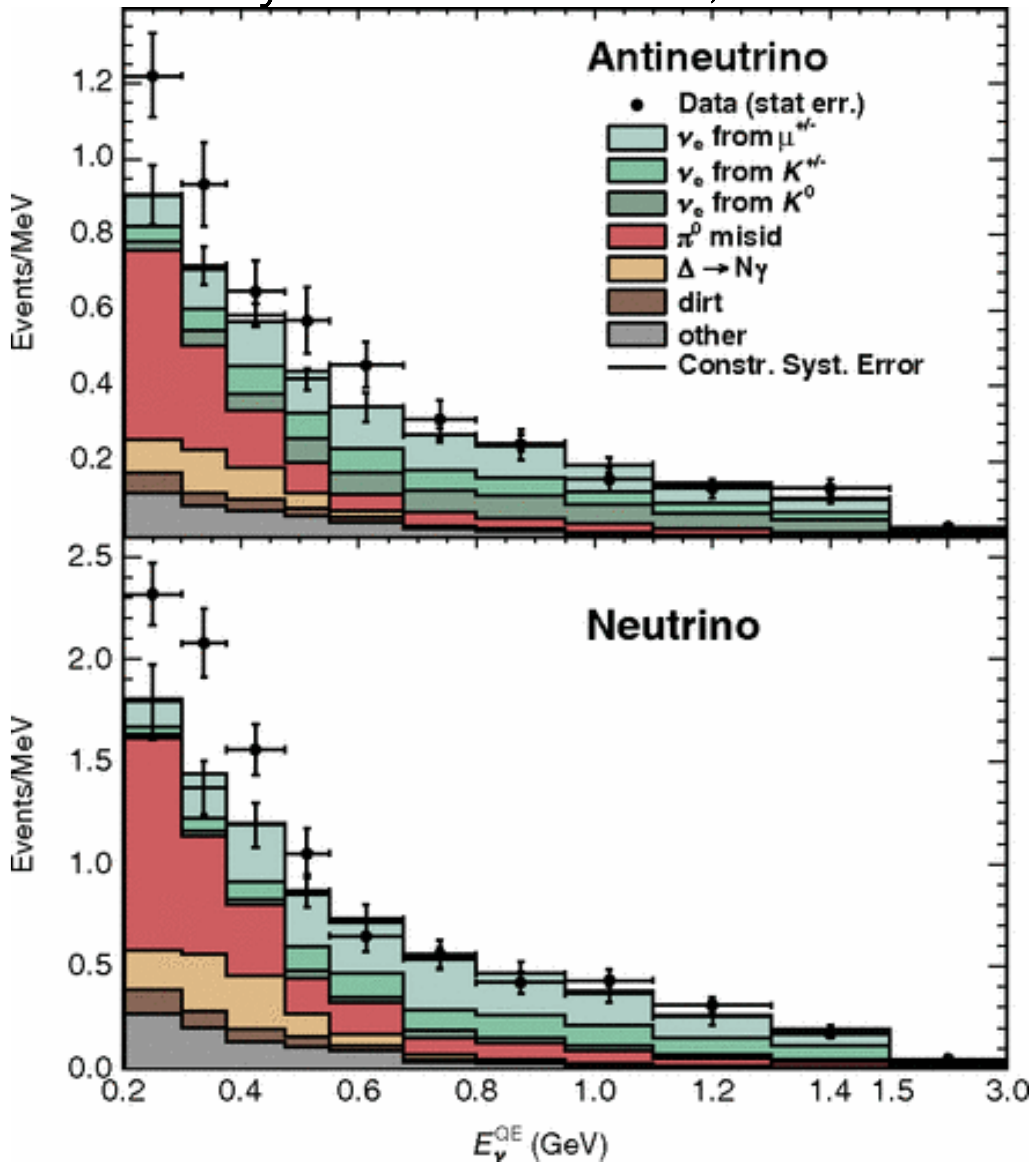
- LSND and miniBooNE reported a $\bar{\nu}_e$ excess in anti-neutrino mode
- Is this evidence that sterile neutrinos exist?

Phys.Rev.D64:112007,2001



LSND Beam Excess

Phys.Rev.Lett.110, 161801

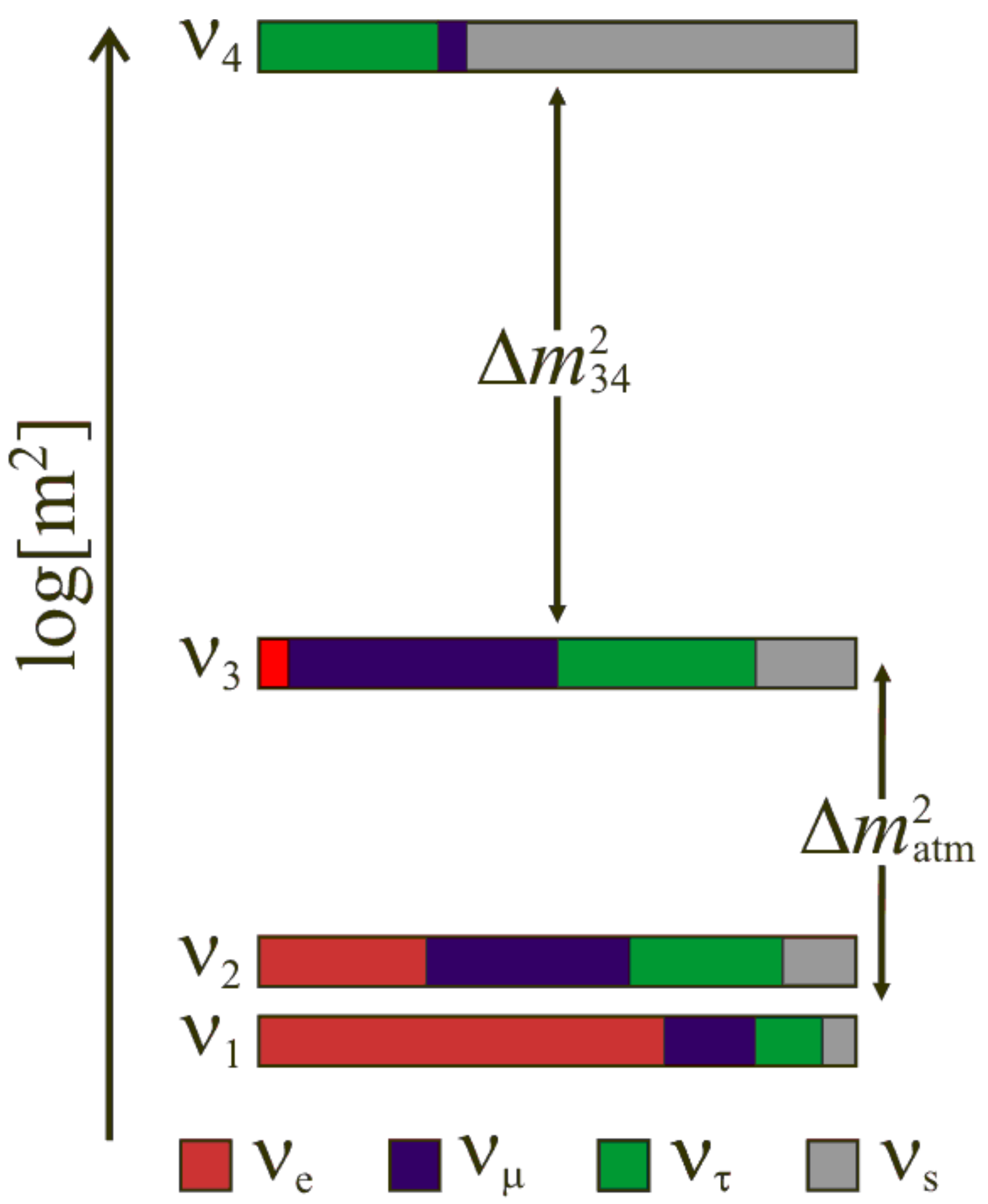


MiniBooNE Beam Excess

Sterile Neutrino Oscillations

3+1 Oscillation Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



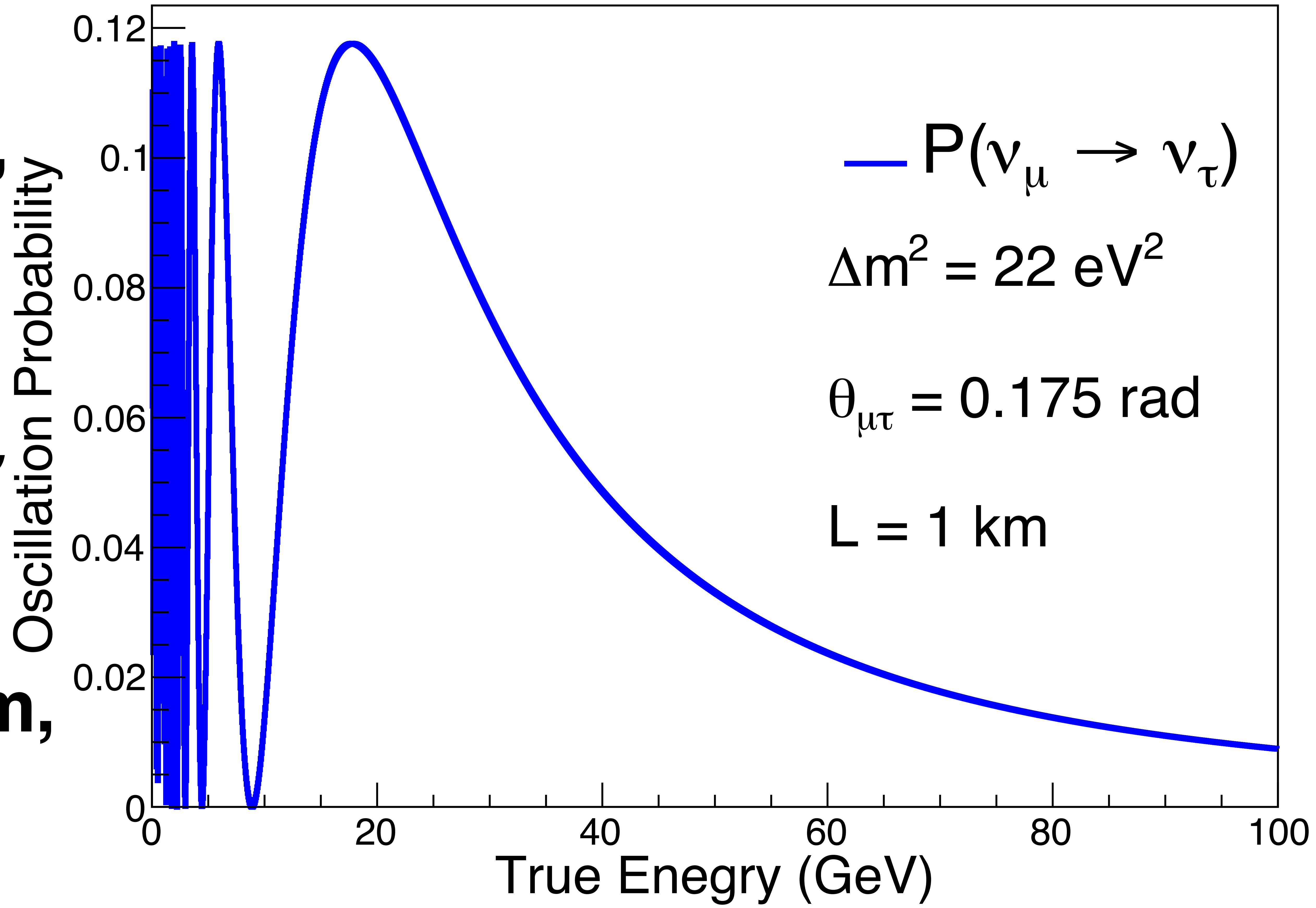
✦ **Looking for sterile neutrino oscillations using a two-flavor approximation of the 3+1 model, governed by a single large mass-squared splitting**

Two-flavor Oscillation Model

Two-Flavor $\nu_\mu \rightarrow \nu_\tau$ oscillations probability (SBL Approximation)

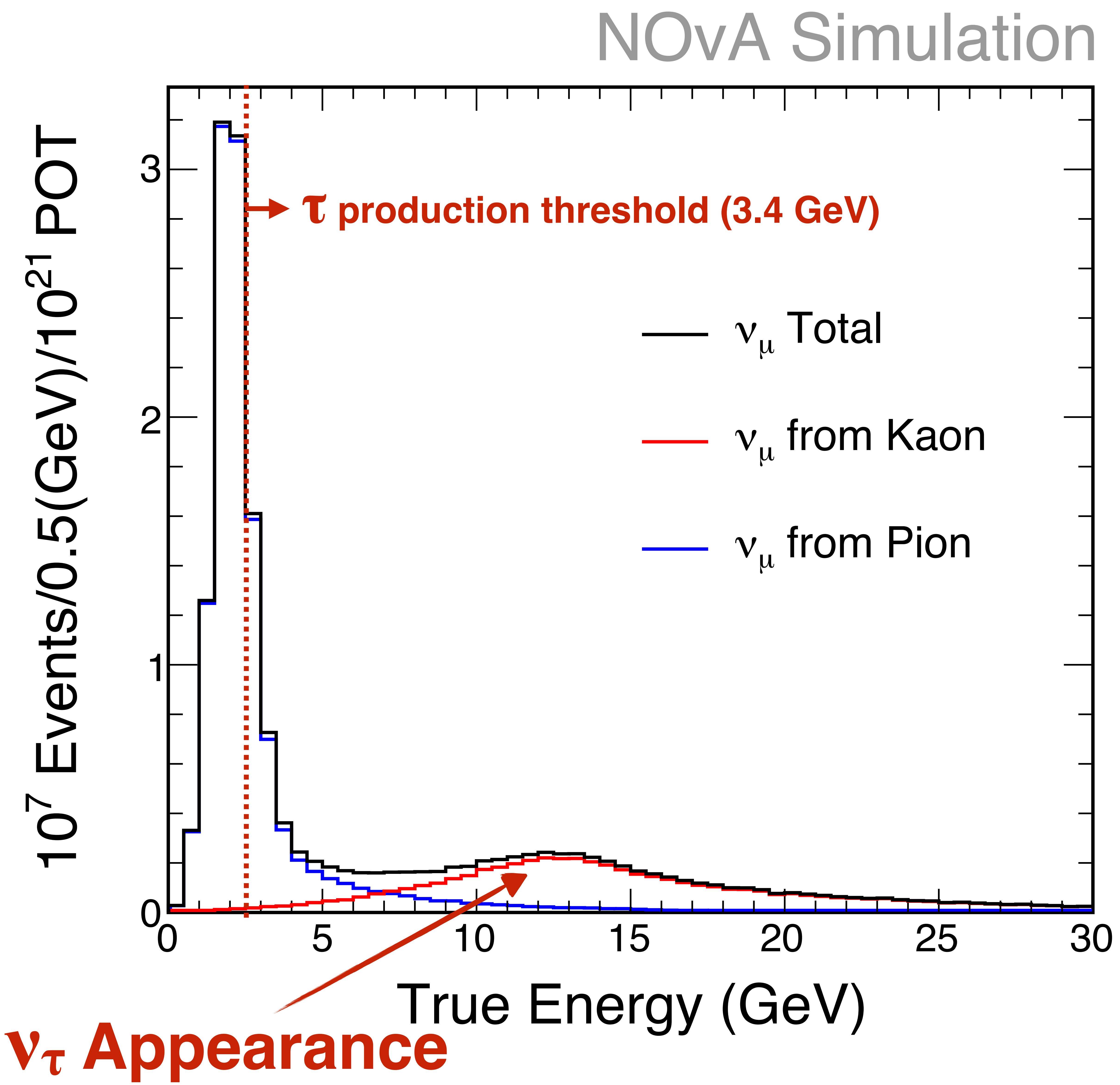
$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{\mu\tau} \sin^2(1.27 \Delta m^2 L/E_\nu)$$

- **Appearance of ν_τ at the NOvA ND, due to oscillations with mass squared difference between the active and sterile neutrino, Δm^2 ~ 10 -100 eV^2**
- **Oscillations while traveling ~ 1 km, from Source to Near Detector**



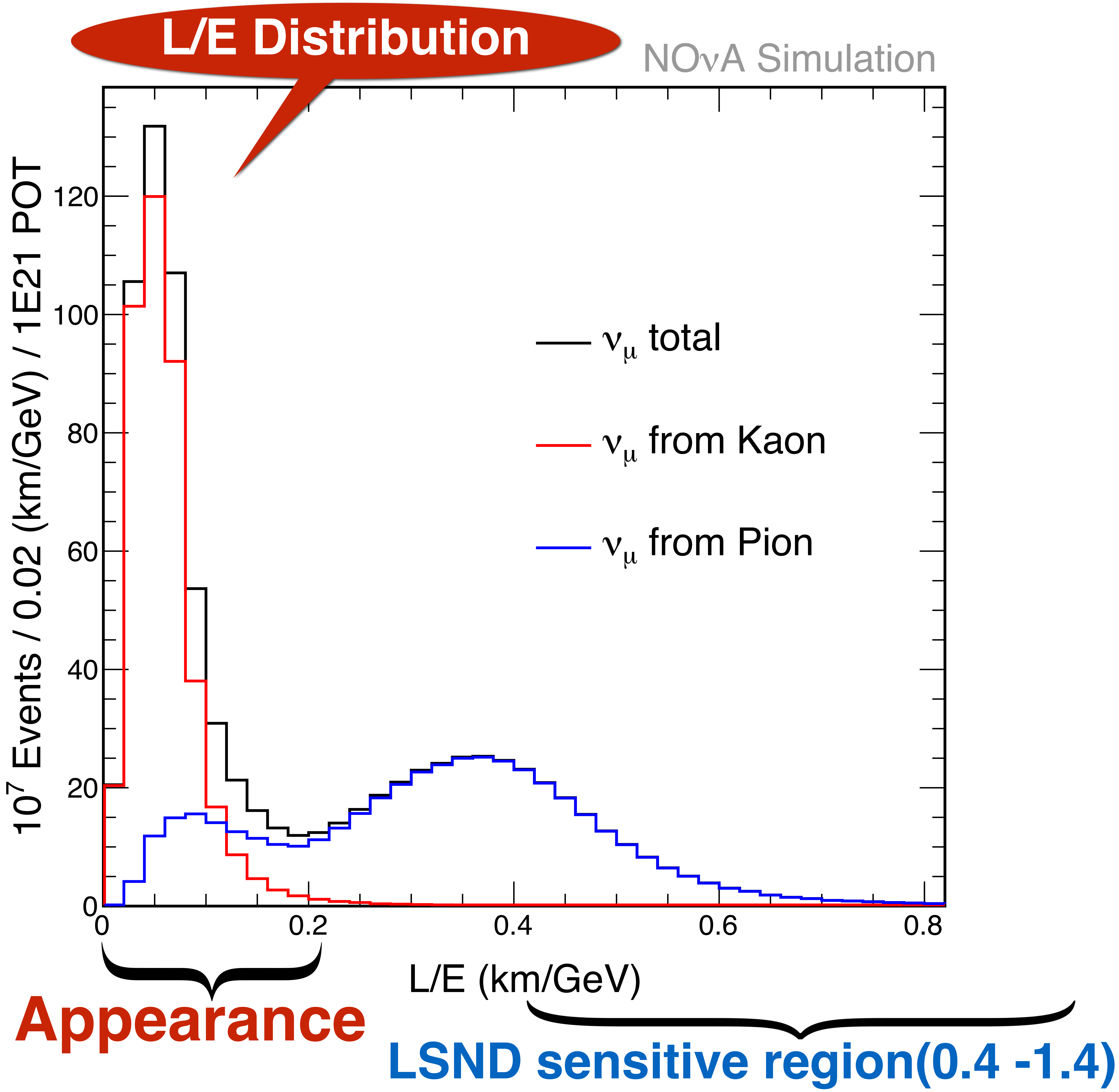
SBL ν_τ Appearance in NOvA

- **Neutrinos in narrow-band beam peaked at 2 GeV predominantly created by pion decays**
- **But τ production threshold is 3.4 GeV**
- **Focusing on high-energy neutrinos resulting from kaon decays to search for SBL $\nu_\mu \rightarrow \nu_\tau$ oscillations**



SBL ν_τ Appearance in NOvA

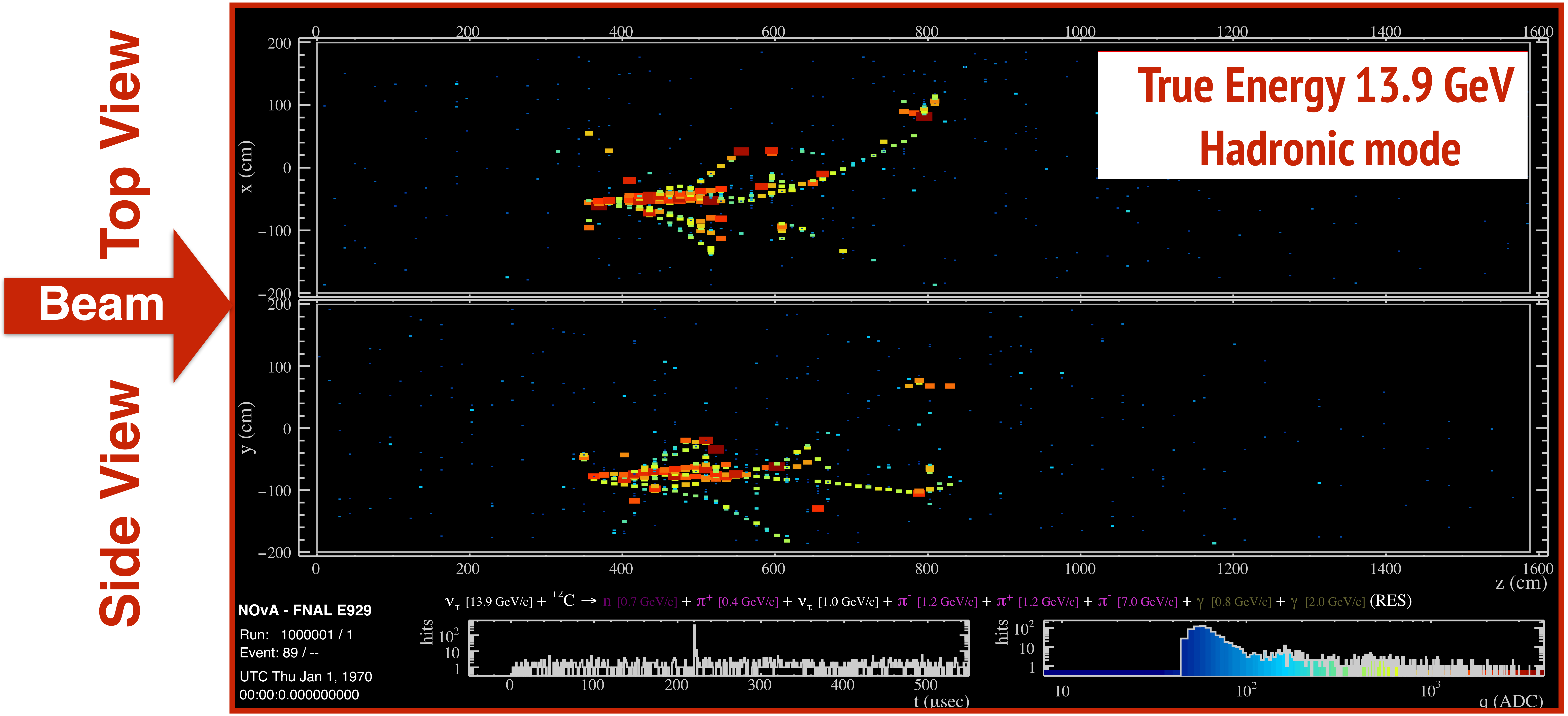
- ✦ Neutrinos in narrow-band beam peaked at 2 GeV predominantly created by pion decays
- ✦ But τ production threshold is 3.4 GeV
- ✦ Focusing on high-energy neutrinos resulting from kaon decays to search for SBL $\nu_\mu \to \nu_\tau$ oscillations



ν_τ Detection in NOvA Near Detector

- ν_τ CC interactions in the ND occur primarily at greater than ~ 5 GeV
- High-multiplicity hadronic systems originating from nuclear scattering.
- In addition we see the decay products of the outgoing τ lepton in the final state.
- Categorize ν_τ CC interaction using τ decay modes

Simulated ν_τ CC in NOvA Near Detector

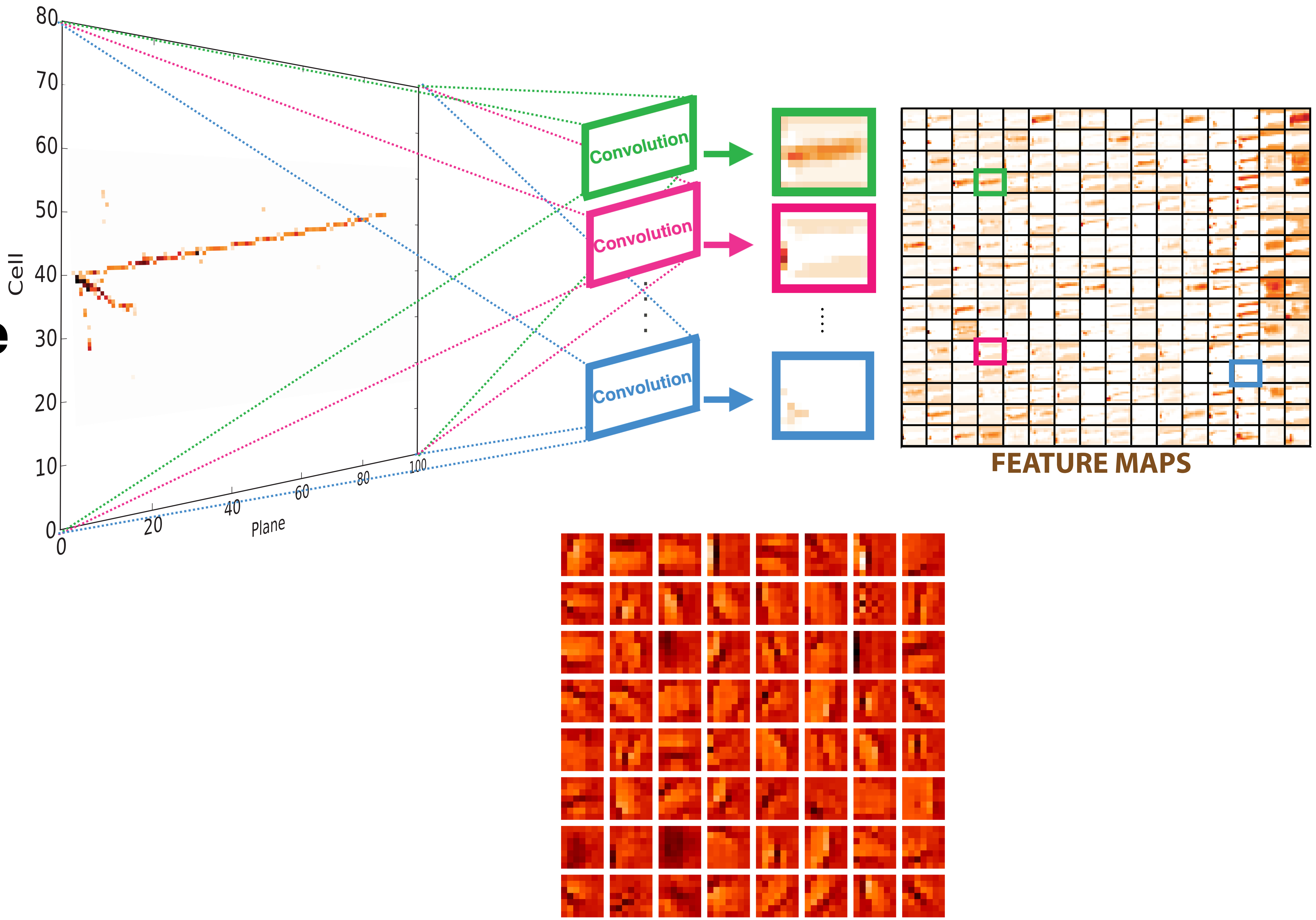


- **Hadronic**: one outgoing ν_τ and typically one or three pions
- **Leptonic**: two outgoing neutrinos and an electron or muon.

Convolutional Neural Network Based PID

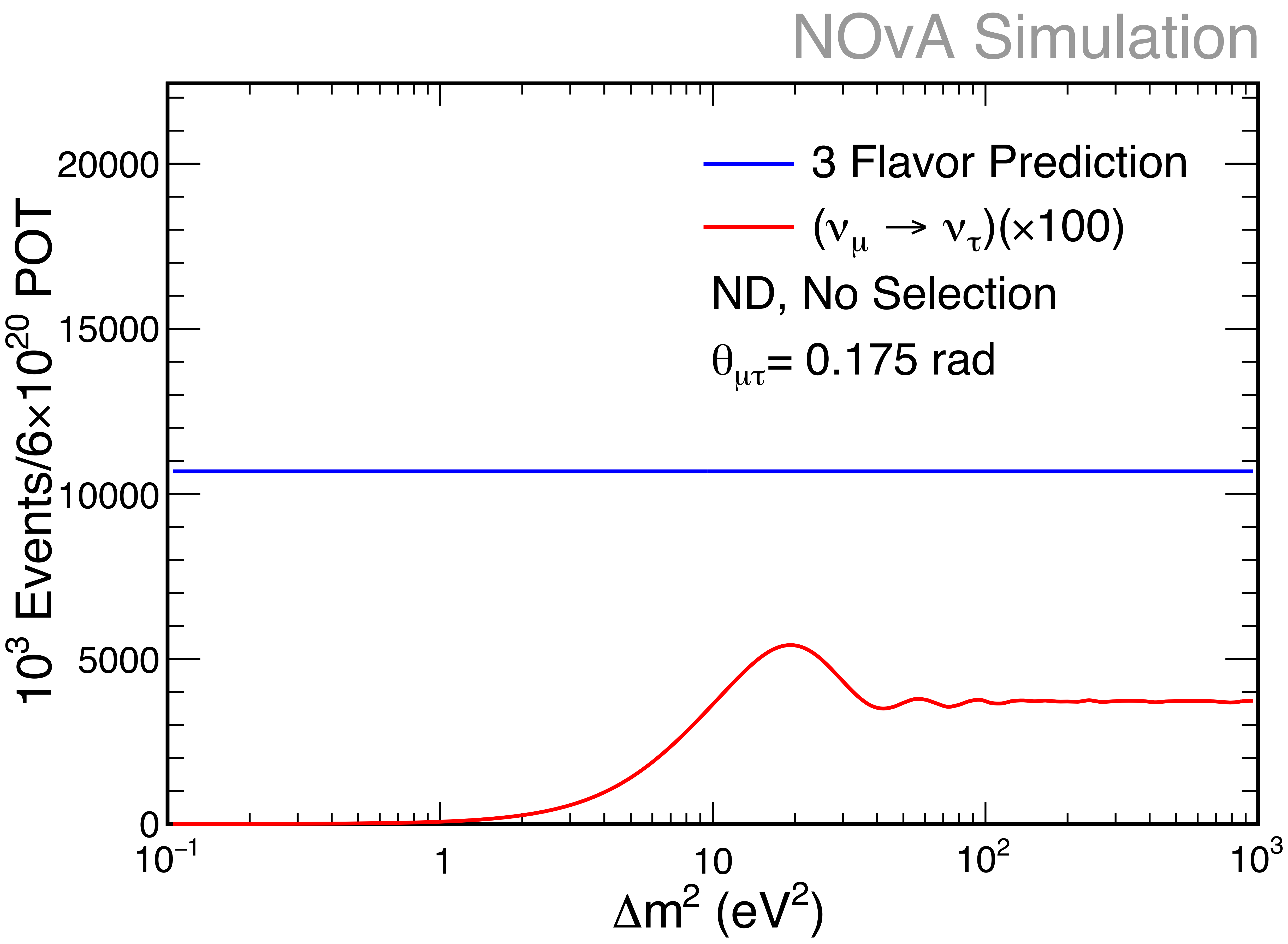
- Use the tools from the computer vision community to classify neutrino interactions.
- Convolutional Visual Network (CVN), based on the GoogLeNet convolutional neutral network (CNN) architecture.
- Treat each event as an image, and pass these images through layers of learned filters to extract the features.

A. Aurisano et al., 2016 JINST 11 P09001



Signal Selection

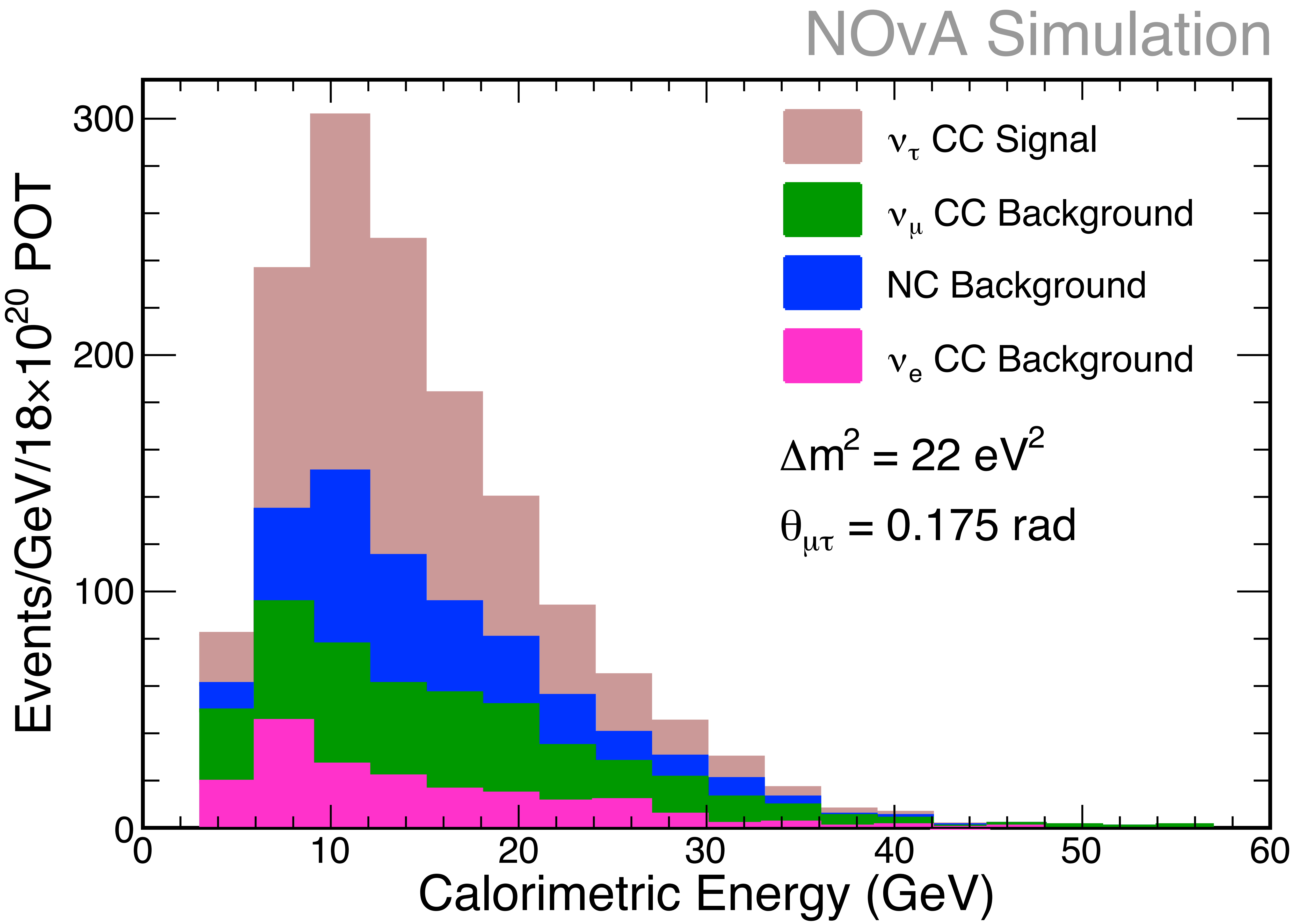
- ✦ **CVN is used as a primary selector**
- ✦ **Preselection: Cuts to remove the detector external activity**



The ν_τ CC signal is maximized for $\Delta m^2 = 22\ eV^2$ corresponding to small L/E for muon neutrinos originating from kaon decays.

ν_τ CC Signal Prediction

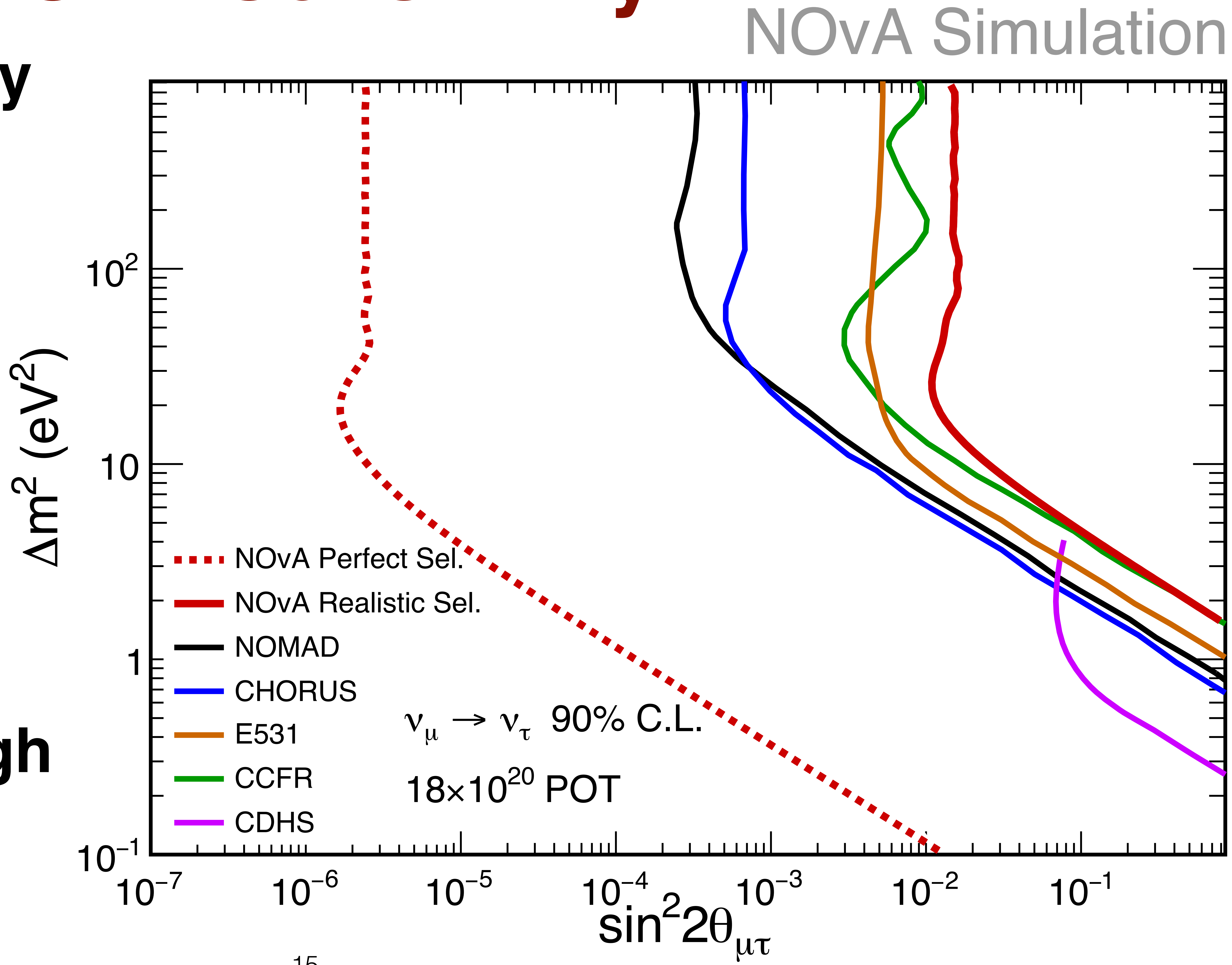
- Signal and Background predictions for three nominal years of NOvA running (18×10^{20} POT)



Calorimetric energy distribution of ν_τ CC signal and background stacked plot

NOvA Sensitivity

- Stats-only sensitivity plot
- NOvA sensitivity competitive with previous experimental limits
- Much room for improvement through optimization of τ selection



Summary

- Search for sterile neutrinos using $\nu_\mu \rightarrow \nu_\tau$ oscillations in NOvA is very promising.
- Preliminary sensitivity shows NOvA will be competitive with previous experiments after 3 years of running.
- Started assessing effects of systematic uncertainties
- Future work will include modifying the PID by categorizing ν_τ CC according to τ decay modes

Stay tuned for the upcoming results…

www-nova.fnal.gov

NOvA Collaboration

Backup

3+1 Oscillation Model

Sterile neutrino Oscillations(SBL Approximation)

- $\nu_\mu \rightarrow \nu_\tau$ oscillations using 3+1 model is sensitive to θ_{34} and θ_{24}

$$\sin^2 2\theta_{\mu\tau} = 4\,|U_{\mu 4}|^2 |U_{\tau 4}|^2$$

$$|U_{\tau 4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$$

$$|U_{\mu 4}|^2 = \cos^2\theta_{14}\sin^2\theta_{24}$$

$$\boxed{\sin^2 2\theta_{\mu\tau} = \cos^4\theta_{14}\sin^2 2\theta_{24}\sin^2\theta_{34}}$$

3+1 Oscillation Model

Sterile neutrino Oscillations(SBL Approximation)

(3+1) Model ν_e Appearance Probability[2]

$$P^{\text{SBL},3+1}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Where

$$\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}|^2 |U_{e4}|^2$$

and

$$\sin^2 2\theta_{\mu e} = \sin^2 \theta_{24} \sin^2 2\theta_{14}$$

(3+1) Model ν_μ Disappearance Probability

$$P^{\text{SBL},3+1}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu} = 1 - 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) \sin^2 \frac{\Delta m^2_{41} L}{4E} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Where

$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$$

and

$$\sin^2 2\theta_{\mu\mu} = cos^2\theta_{14} sin^2\theta_{24}$$

---

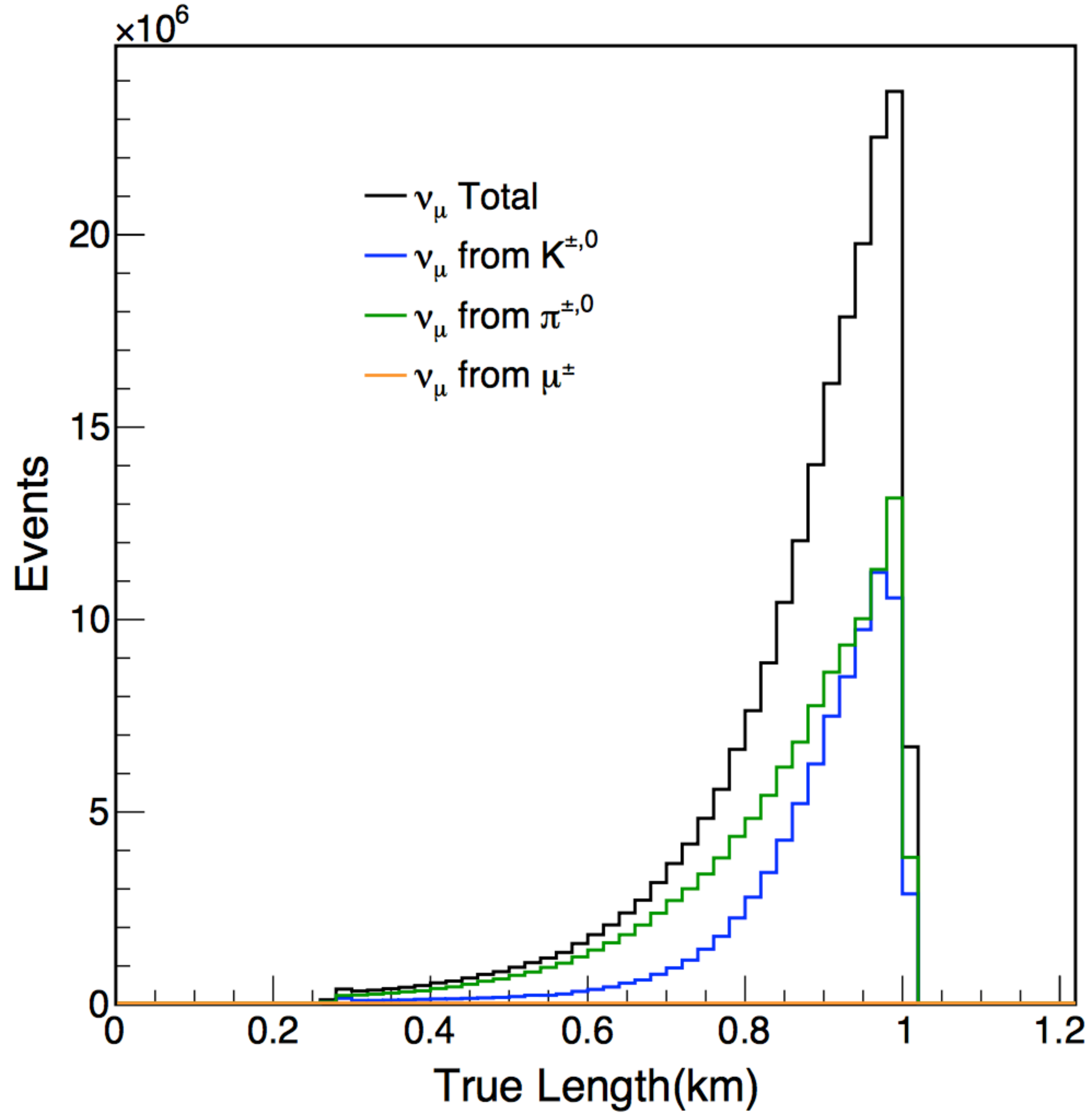
[2] Sterile Neutrino Oscillations:The Global Picture, arXiv: 1303.3011

Other Sterile Neutrino Searches in NOvA

- **Short-Baseline ν_μ dissappearance and ν_e appearace search**
  - ✦ **Disappearance in muon neutrinos and appearance in electron neutrinos at the NOvA ND, due to oscillations with mass squared difference between the active and sterile neutrino, $\Delta m^2_{41} > 1eV^2$**

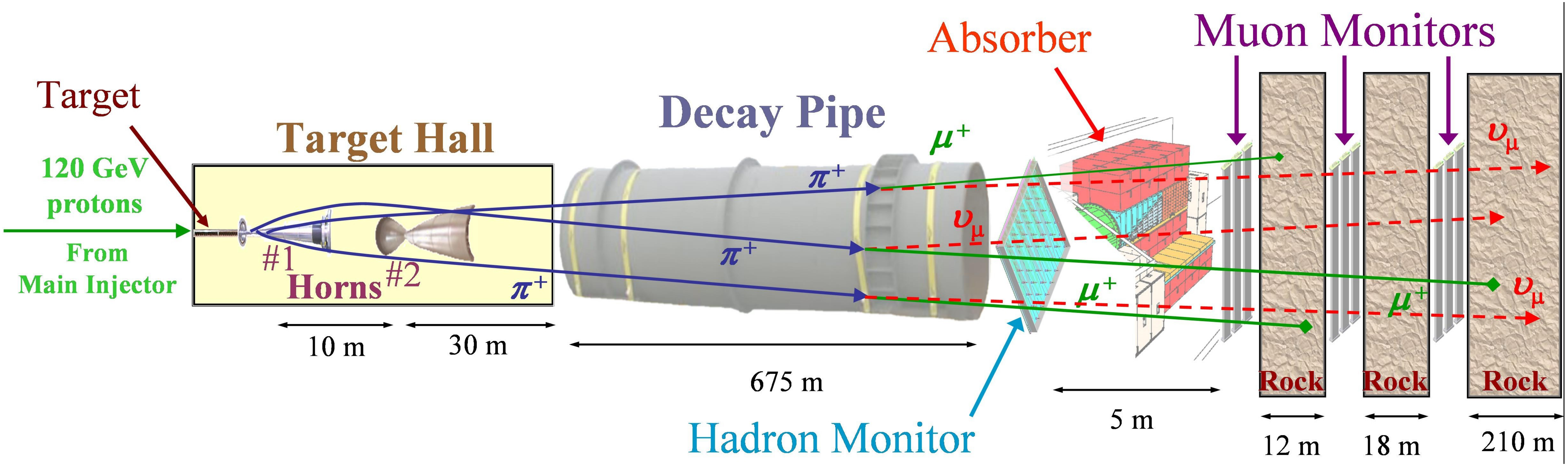
- **Long-Baseline NC disappearance search**
  - ✦ **Neutral-current interactions are not affected by three-flavor oscillations but mixing between active and sterile neutrinos will reduce the rate of NC events at the FD**

True Length



Distance travelled by neutrinos interacting in NOvA near detector

NuMI Beam


Absorber
Muon Monitors
Target
Decay Pipe
Target Hall
120 GeV protons
From Main Injector
#1
Horns
#2
π^+
π^+
π^+
μ^+
υ_μ
μ^+
μ^+
υ_μ
υ_μ
Rock
Rock
Rock
10 m
30 m
675 m
5 m
12 m
18 m
210 m
Hadron Monitor

Charged Current Cross Sections

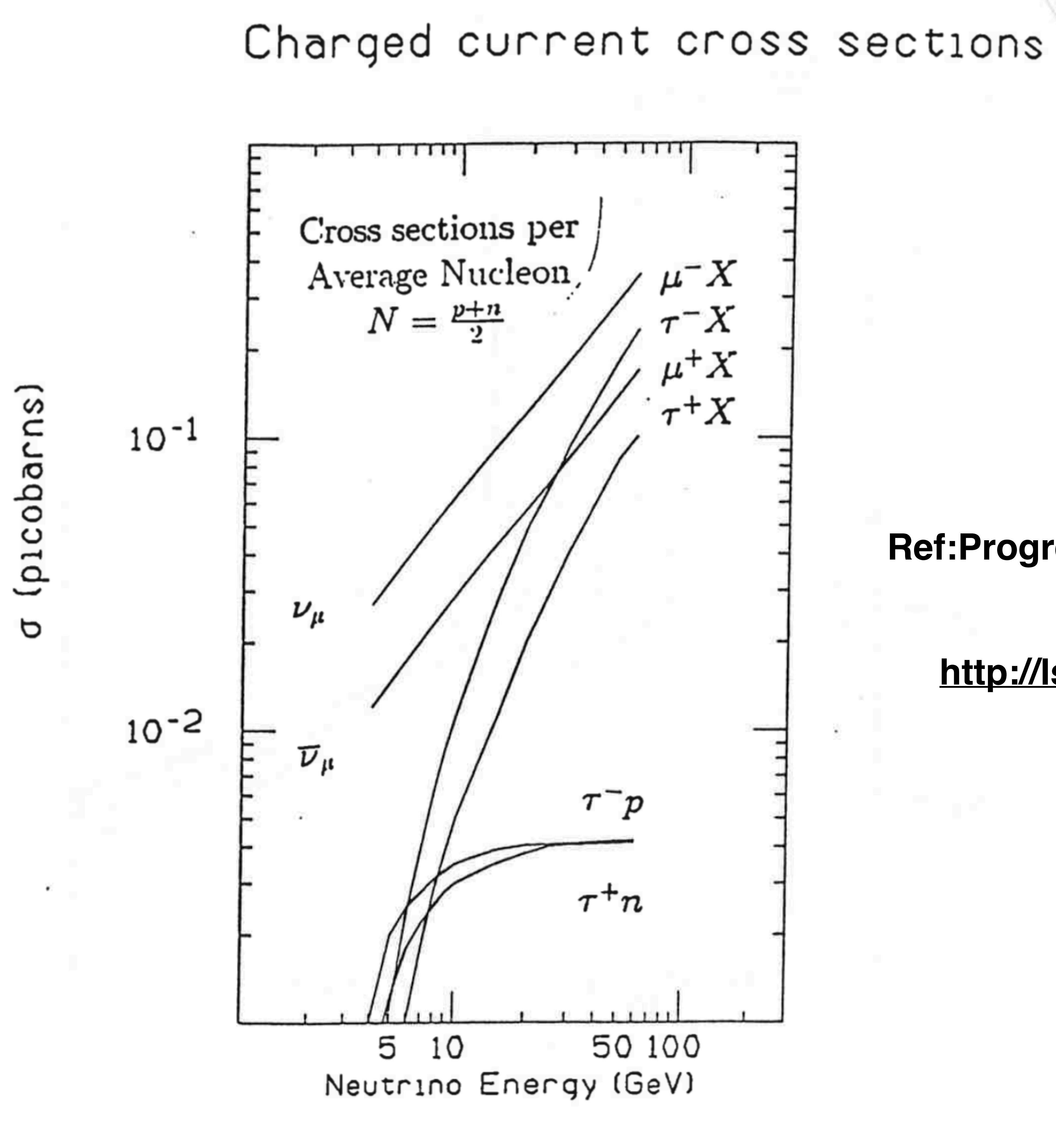


Figure 10: Calculated ν_τ cross sections

Ref:Progress Report and Revised P822 Proposal to Fermilab, 12 October 1993.
FERMILAB-PROPOSAL 0822
http://lss.fnal.gov/archive/test-proposal/0000/fermilab-proposal-0822.pdf