NOvA's Short-baseline Joint Muon-neutrino Disappearance and Tau-neutrino Appearance Search

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NOvA Experiment

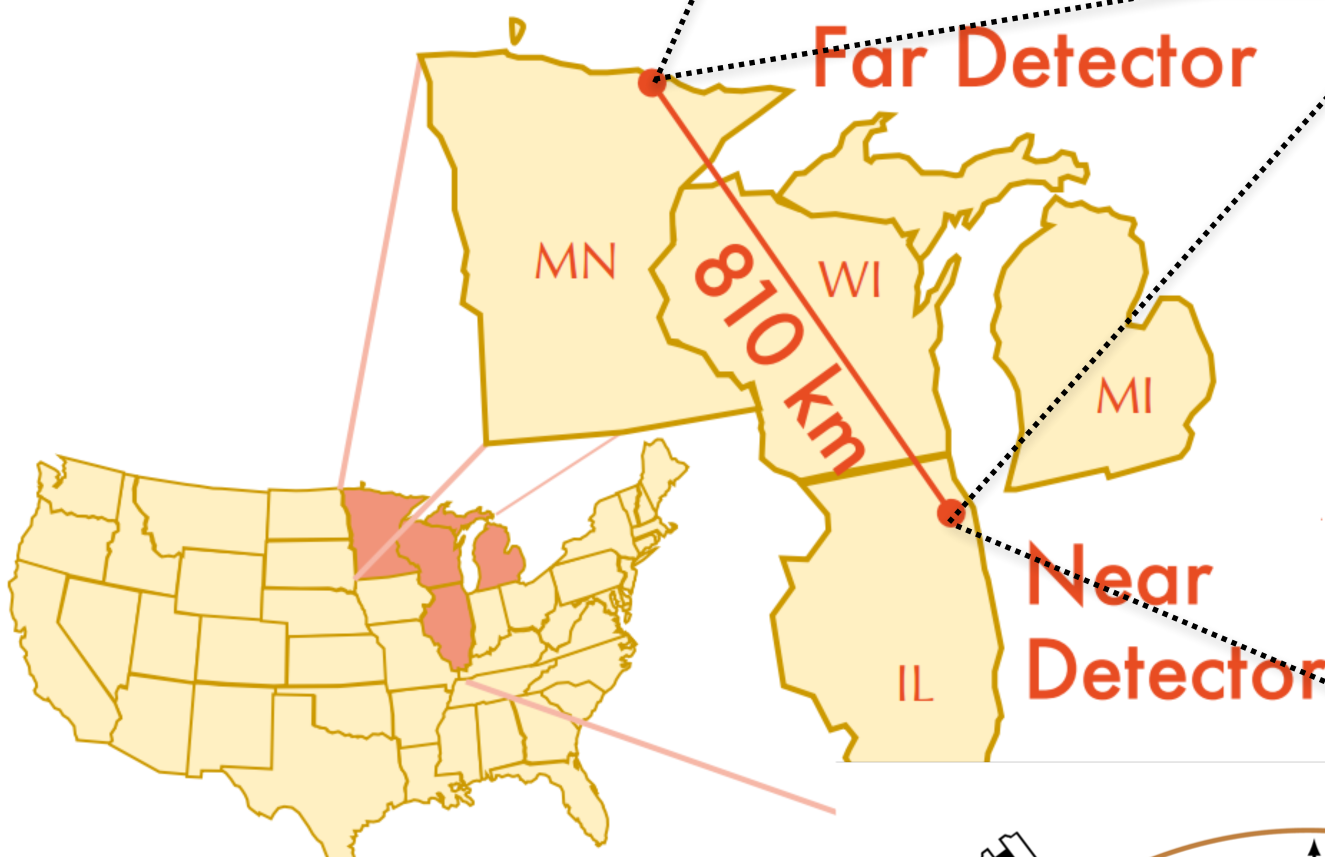
- Off-axis long-baseline neutrino oscillation experiment
- The detectors are located 0.8^{o} off NuMI beam axis
- As detectors are off-axis, a narrow energy flux peaks at 2 GeV

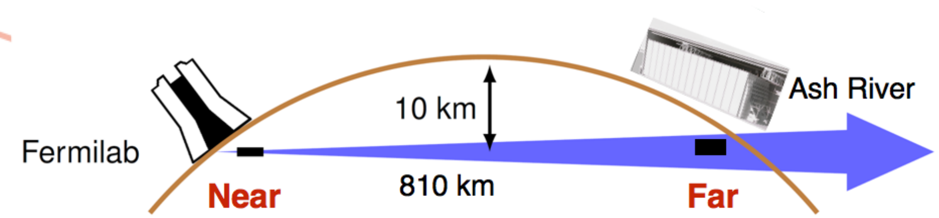
Near Detector:

- 105 m underground
- 1 km from target
- 0.3 kton

Far Detector:

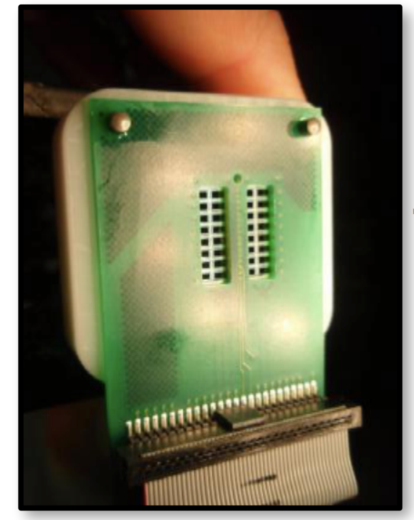
- Located on surface
- 810 km from target
- 14 kton

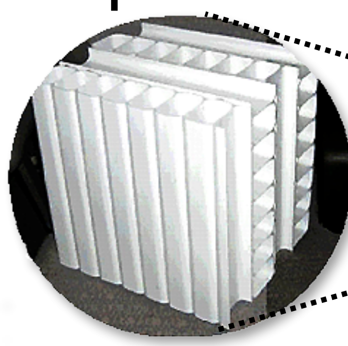


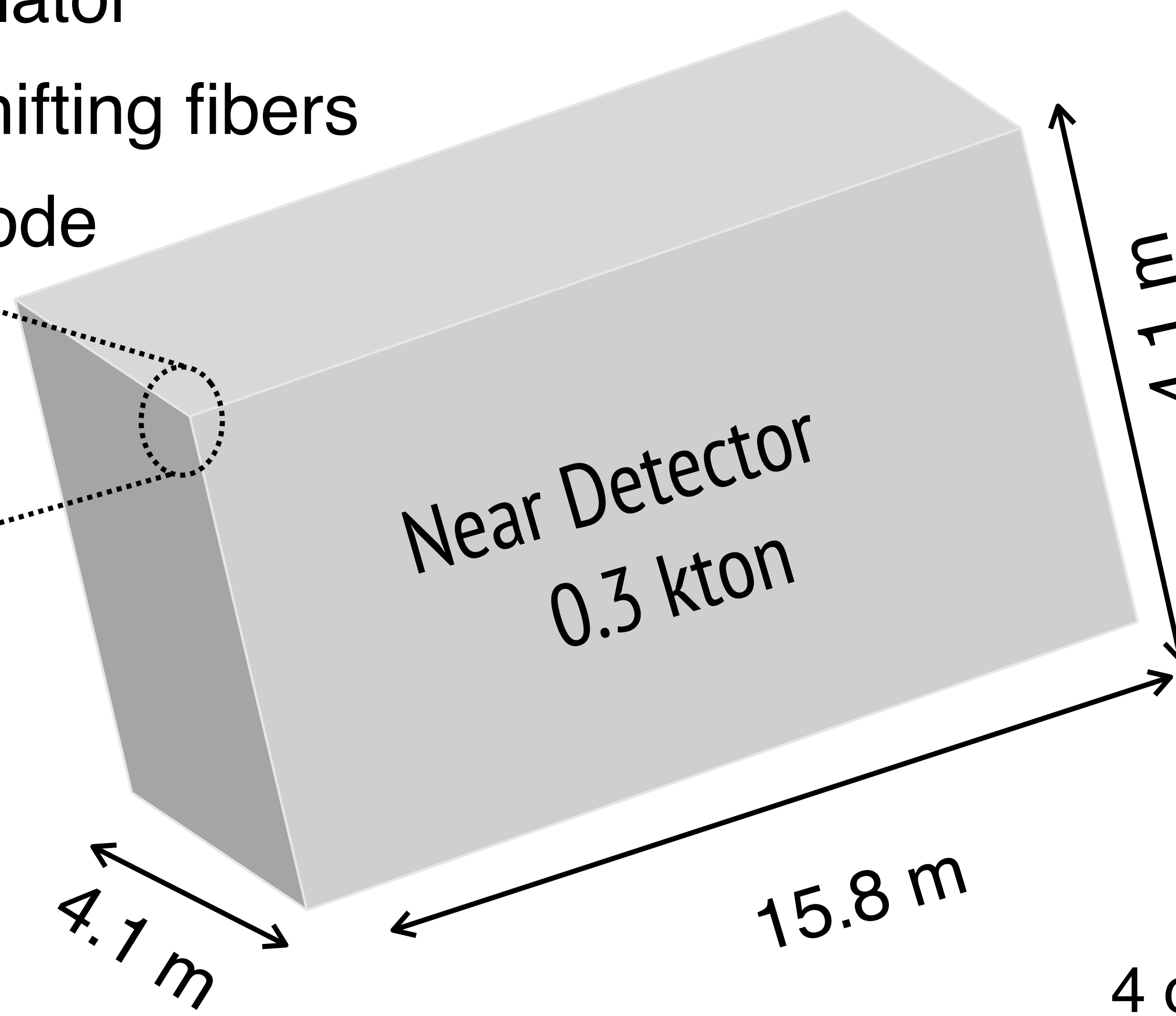


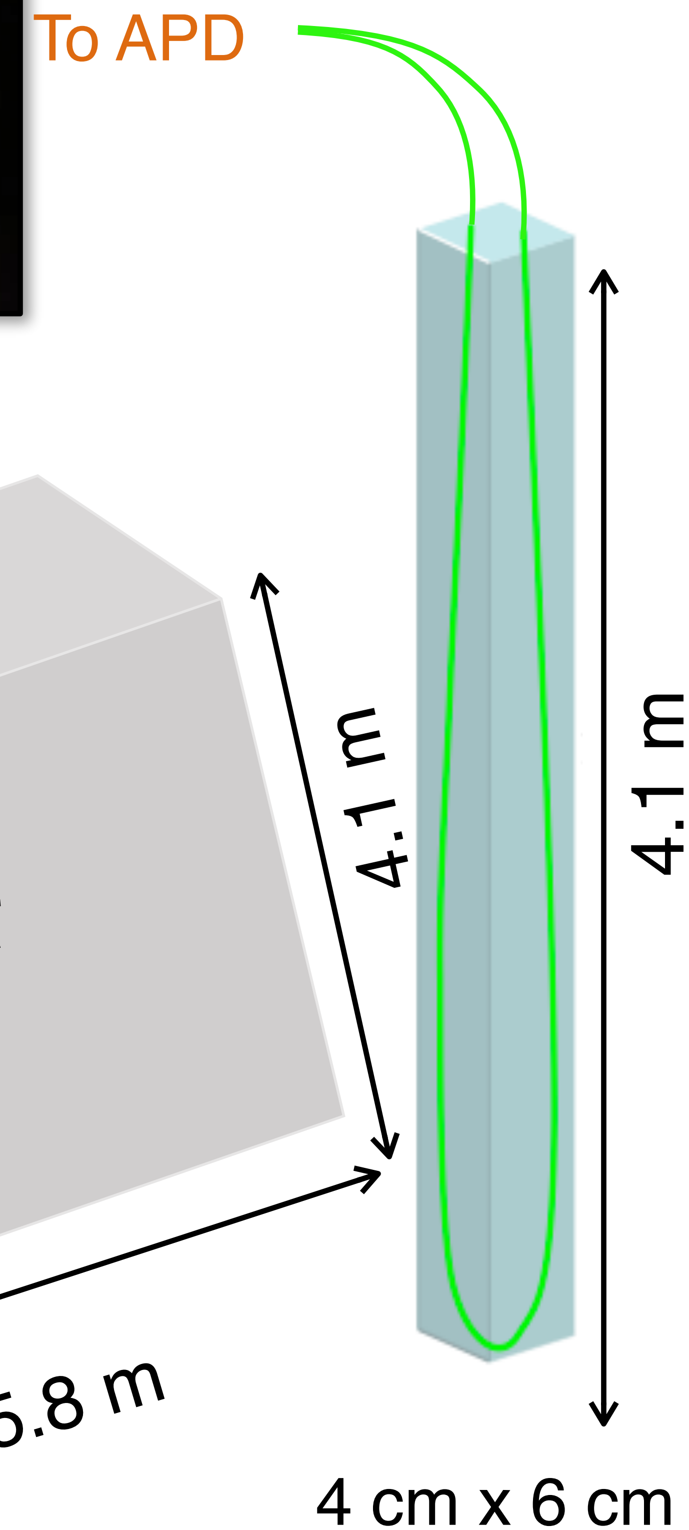
NOvA Detectors

- 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









Near detector:

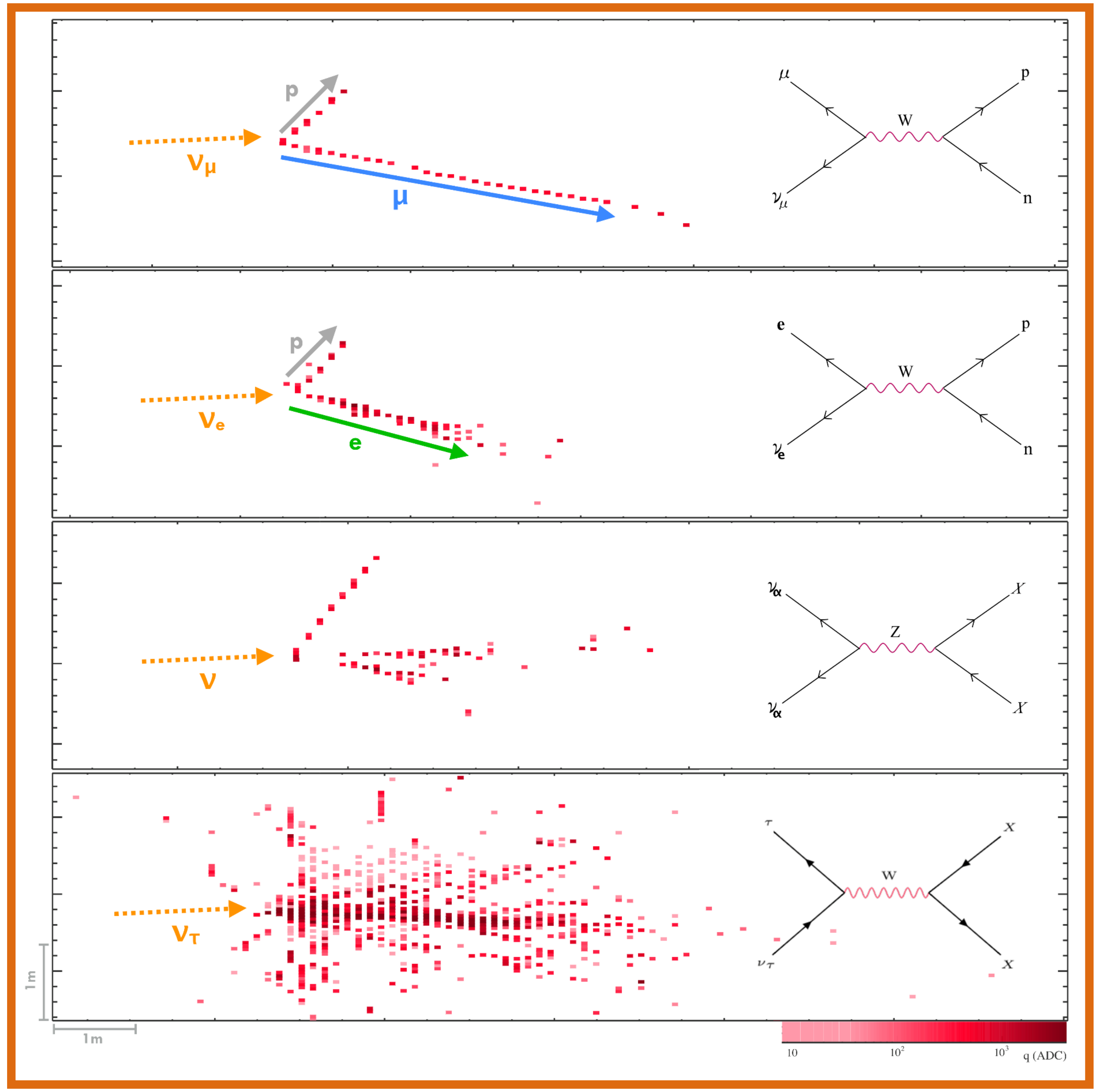
Fine-grained, low-Z, highly-active tracking calorimeter

→ 20k PVC cells

→ 65% active by mass

Neutrino Interactions In NOvA

- ν_μ CC → **Long muon track**
- ν_e CC → **Electronic Shower**
- NC → **Hadrons**
- ν_τ CC → **Tau Decay**



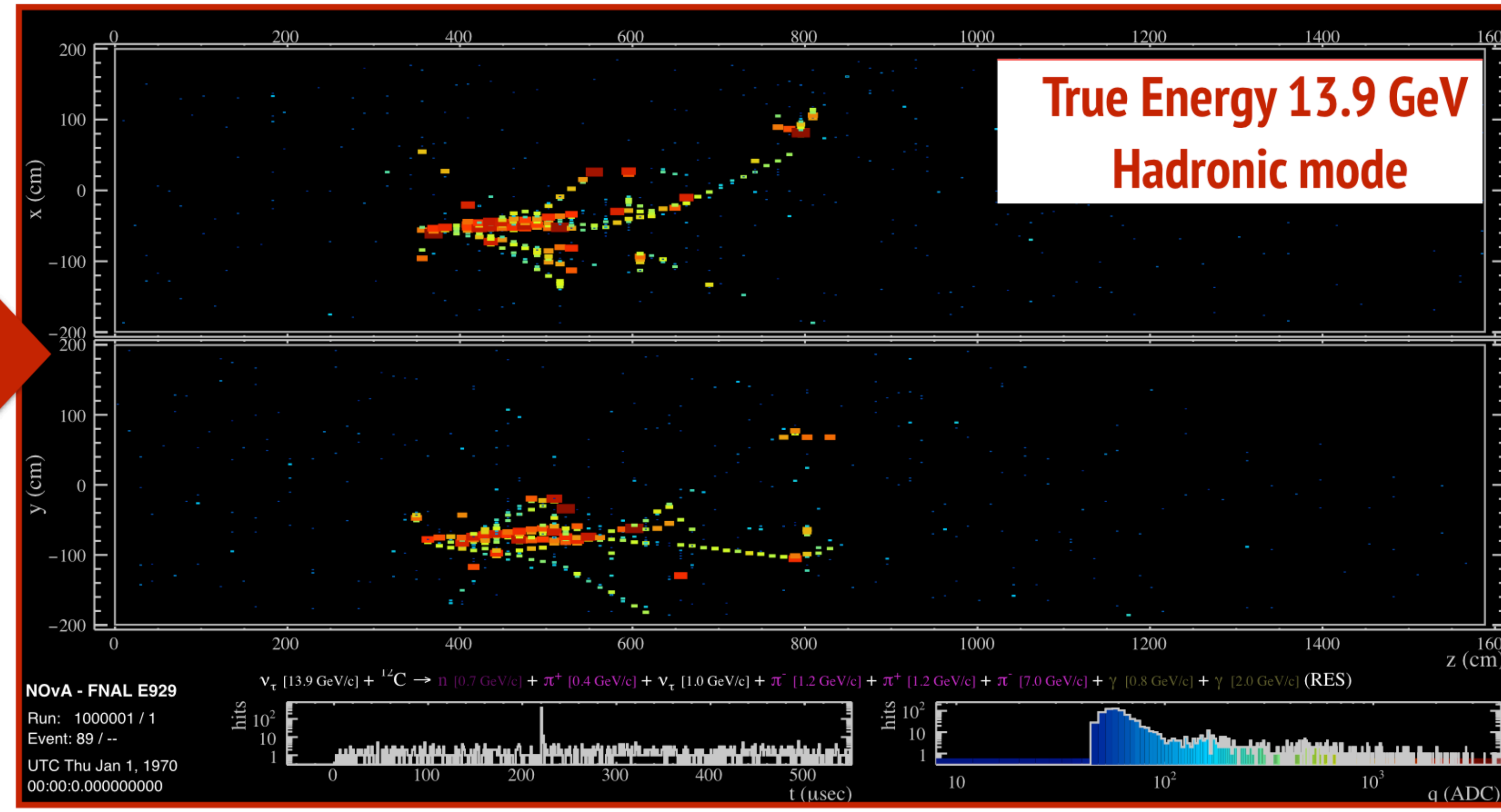
τ decay modes

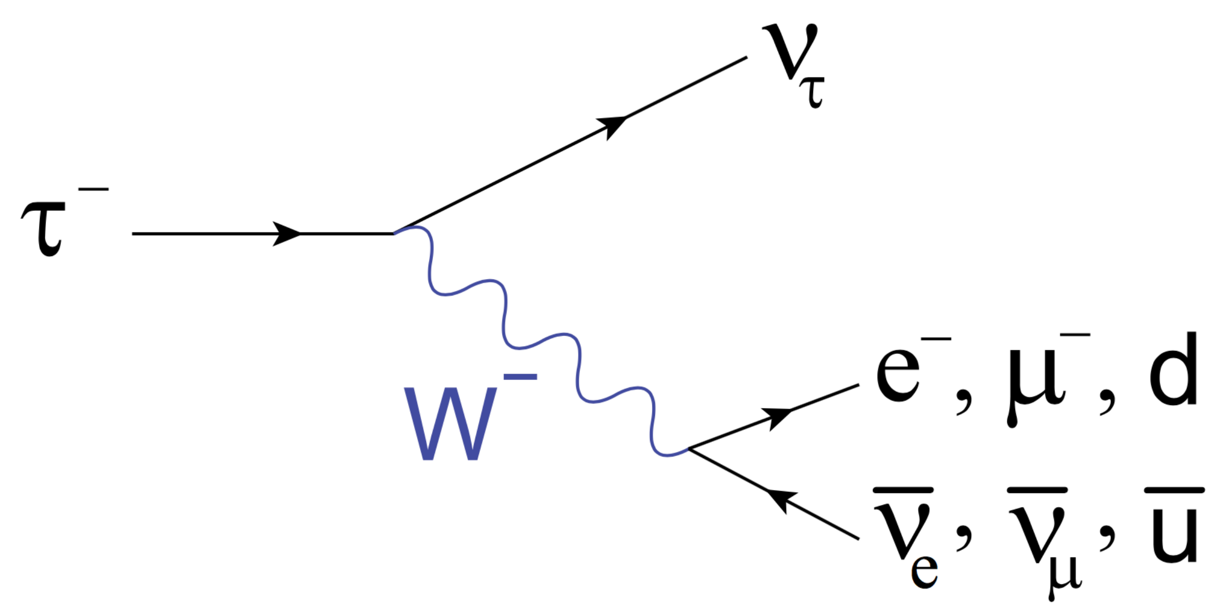
- Tau is the only lepton that can decay into hadrons
- ~ 65% hadronic
- Remaining leptonic
- Leptonic- either muonic or electronic
- This analysis looks only for hadronic τ decay

Top View

Side View

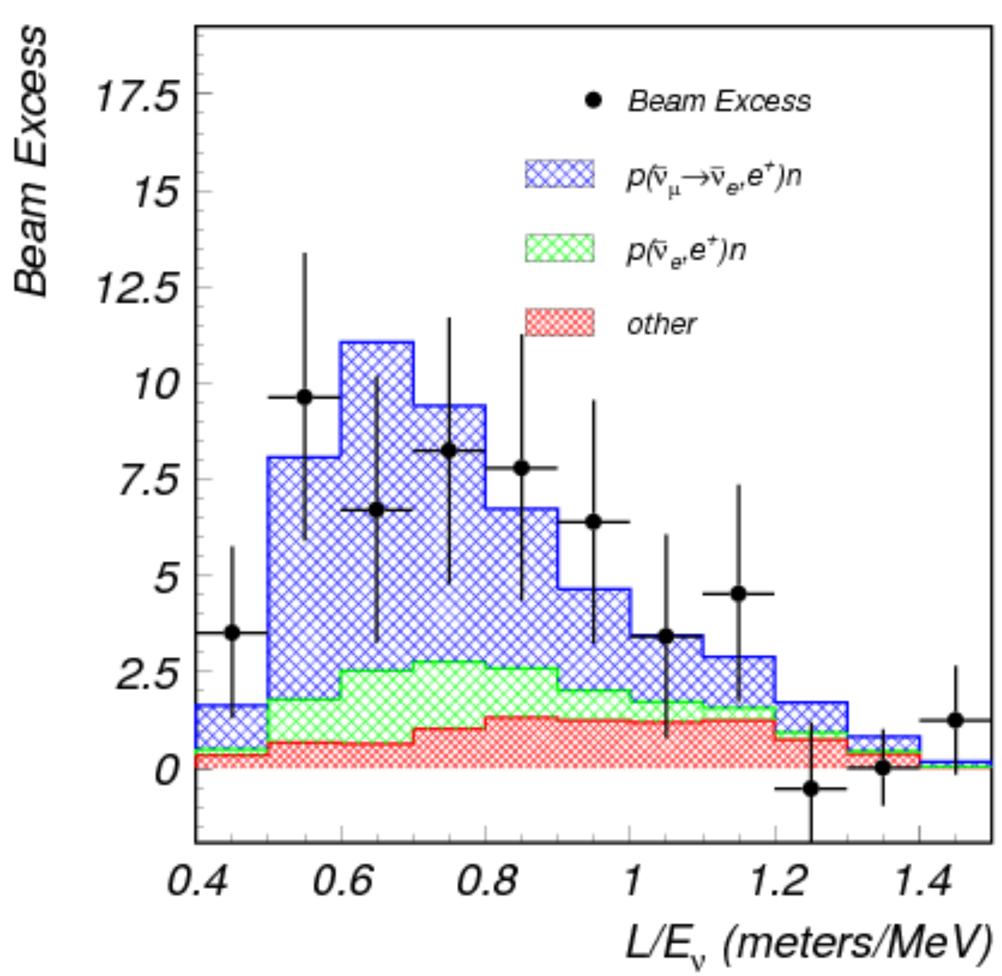
Beam

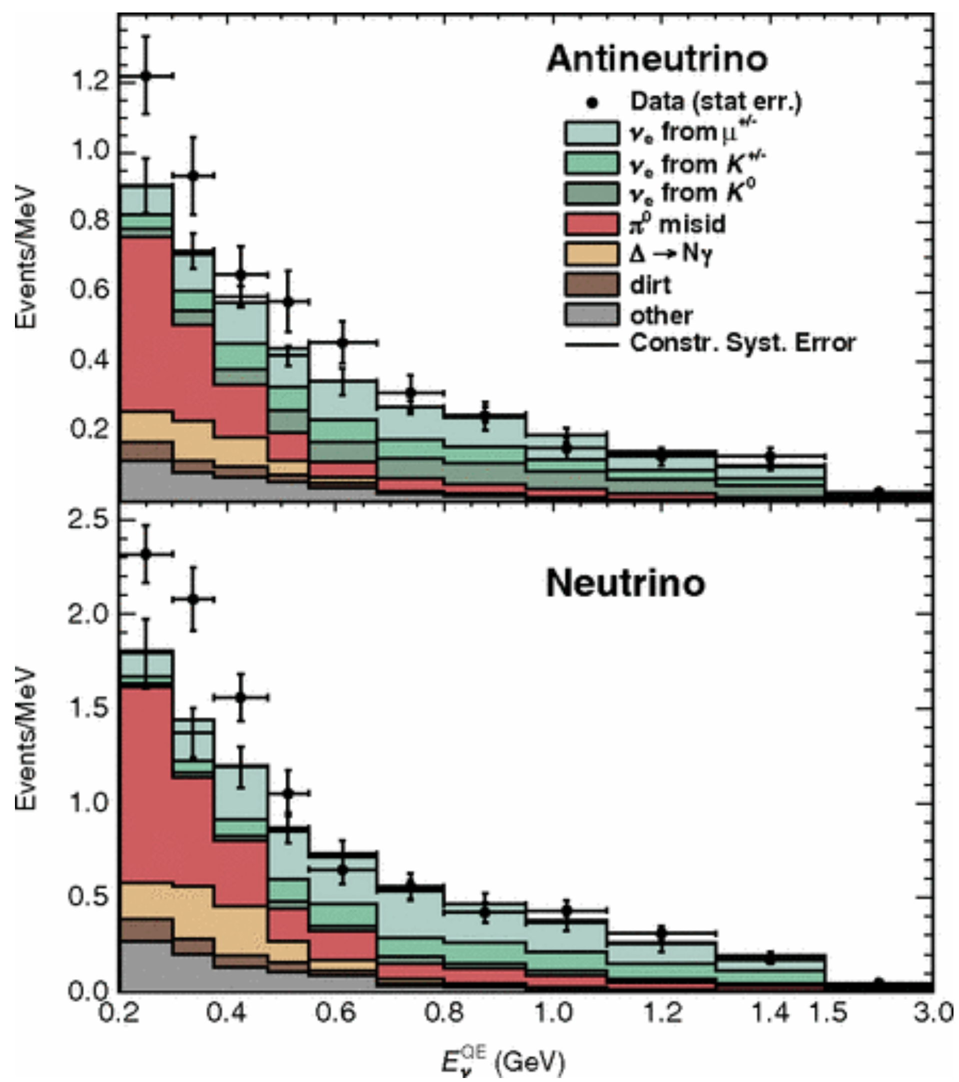




LSND and MiniBooNE Anomaly

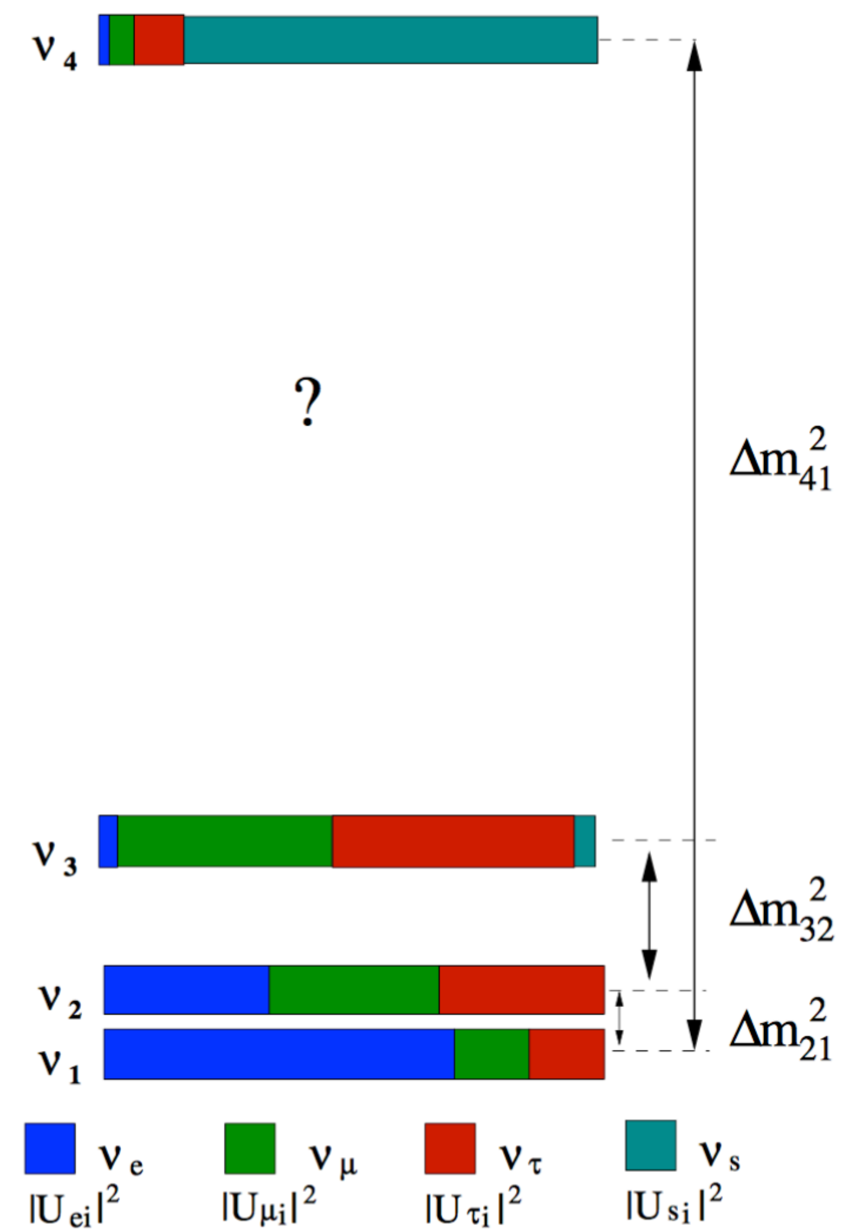
- LSND and miniBooNE reported a ν_e excess in anti-neutrino mode
- The evidence for the existence of sterile neutrinos?





Sterile Neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



- ν_α (α = e,μ,τ,s) and ν_i (i =1,2,3,4) are the flavor and mass eigen states respectively, and $U_{\alpha4}$ represents the mixing between active and sterile neutrino.

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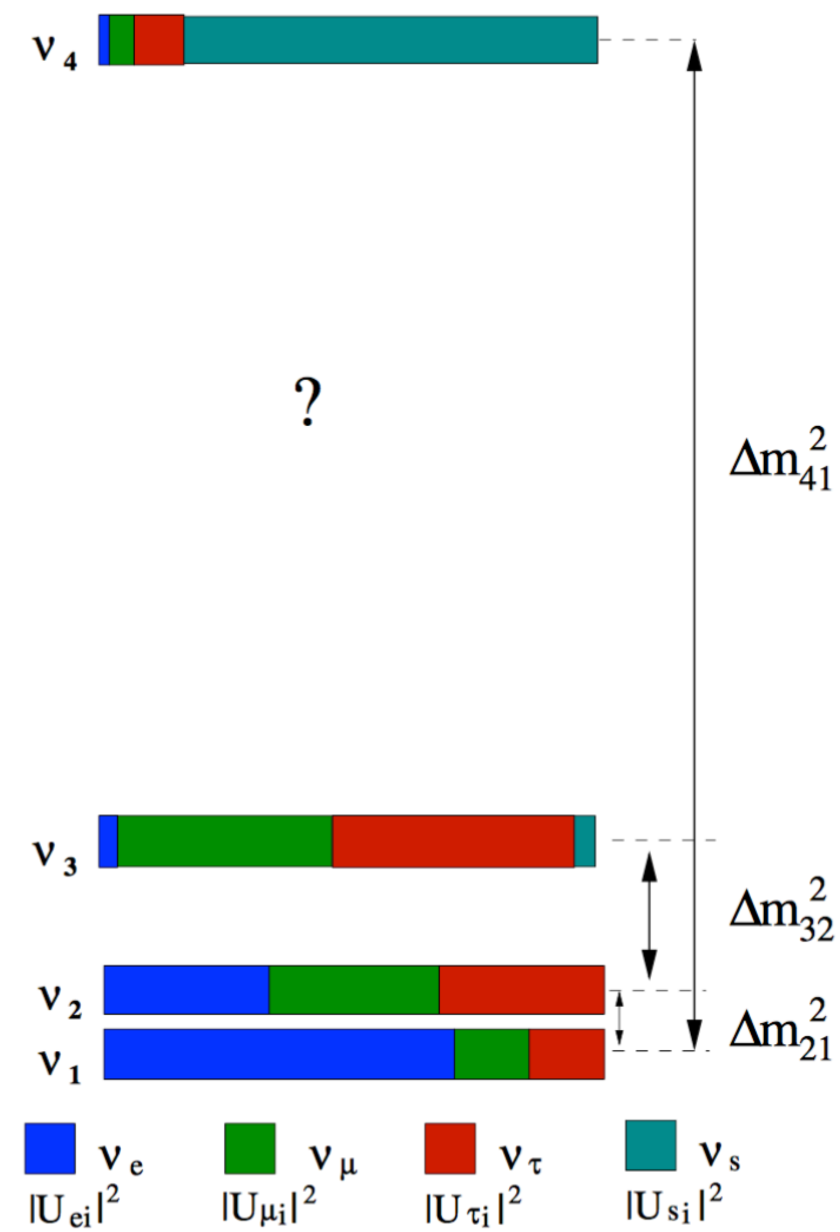


- ν_α (α = e,μ,τ,s) and ν_i (i =1,2,3,4) are the flavor and mass eigen states respectively, and $U_{\alpha 4}$ represents the mixing between active and sterile neutrino.

3+1 Oscillation Model

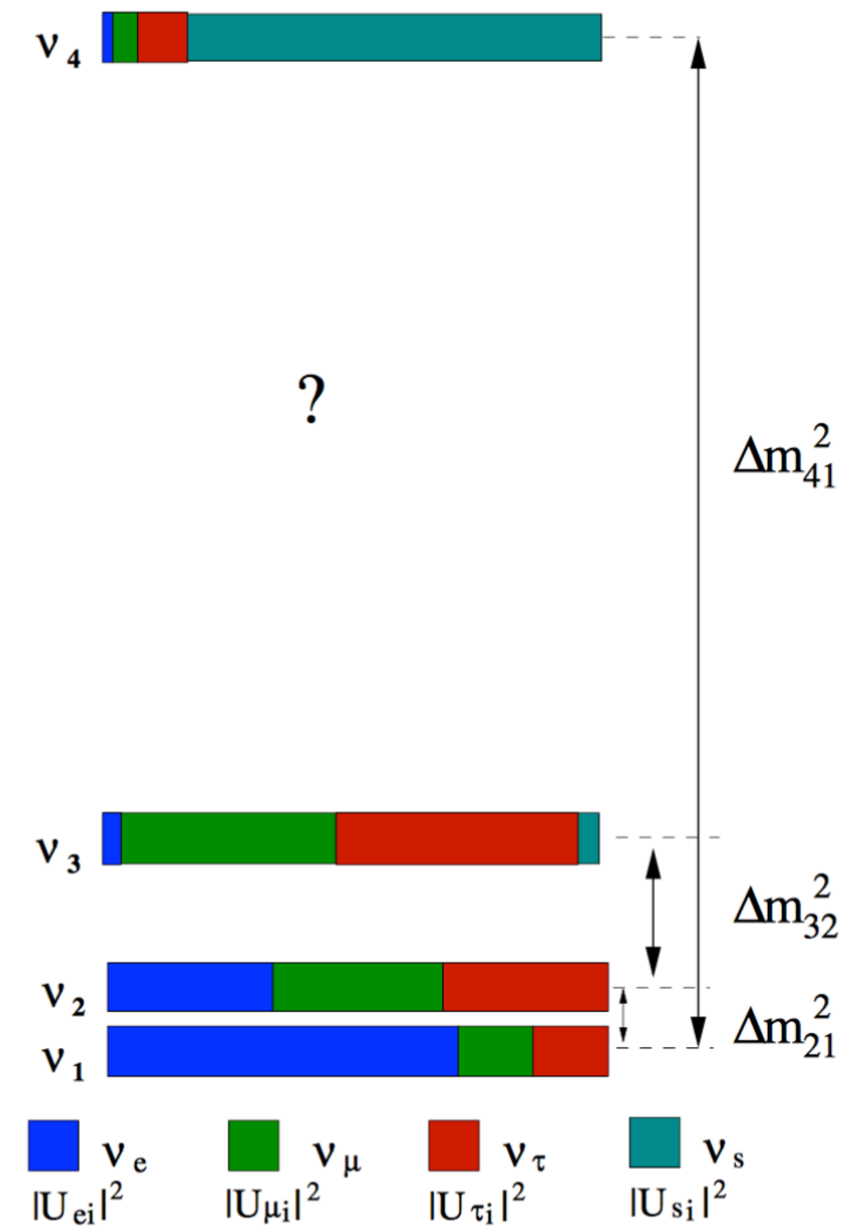
- The probability for ν_τ appearance and ν_μ disappearance using a 3+1 oscillation model in Short- Baseline(SBL) approximation:

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau} = \sin^2 2\theta_{\mu\tau} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

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

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

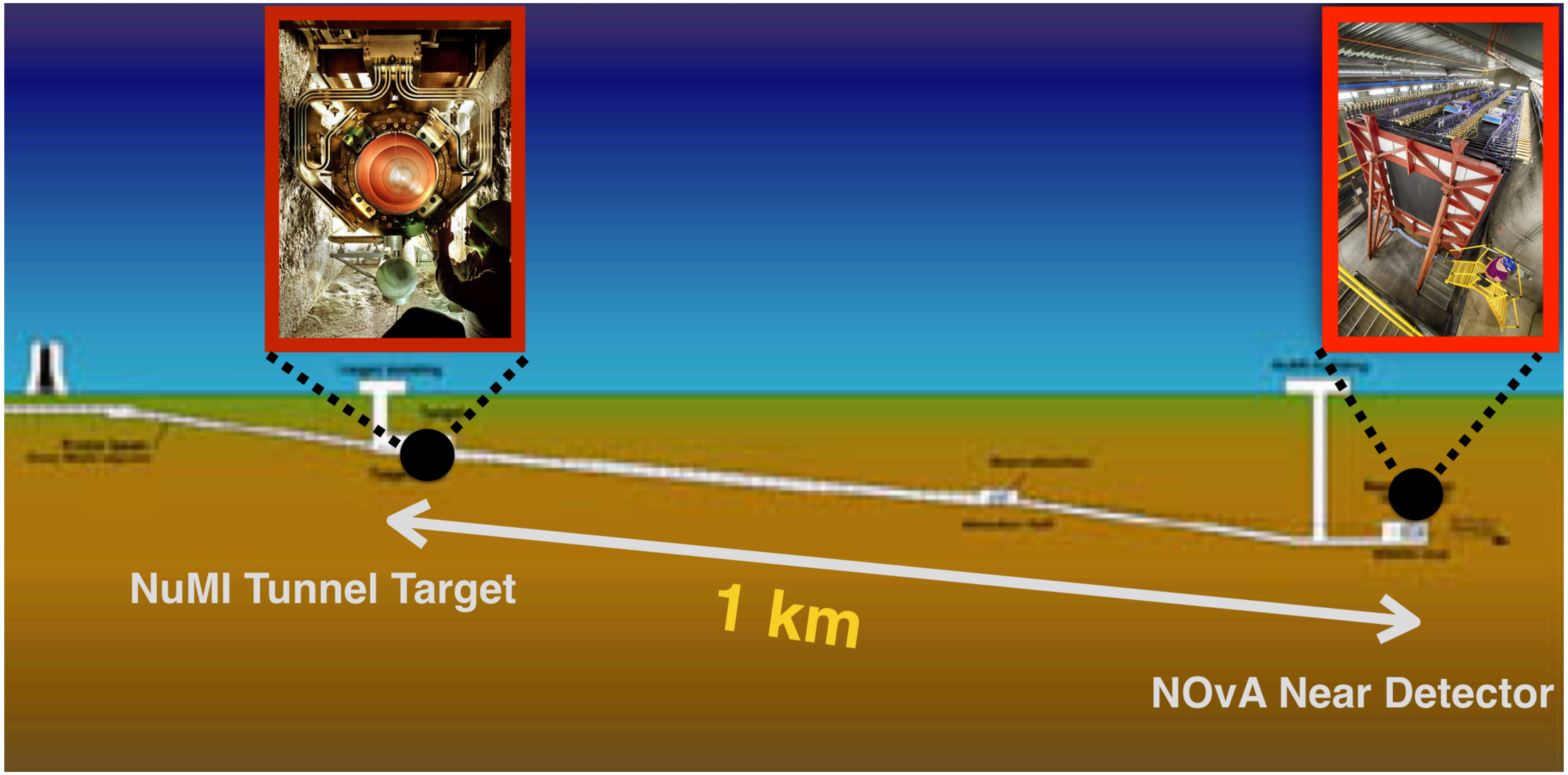
where $\sin^2 2\theta_{\mu\mu} = \cos^2 \theta_{14} \sin^2 \theta_{24}$



Analysis Overview

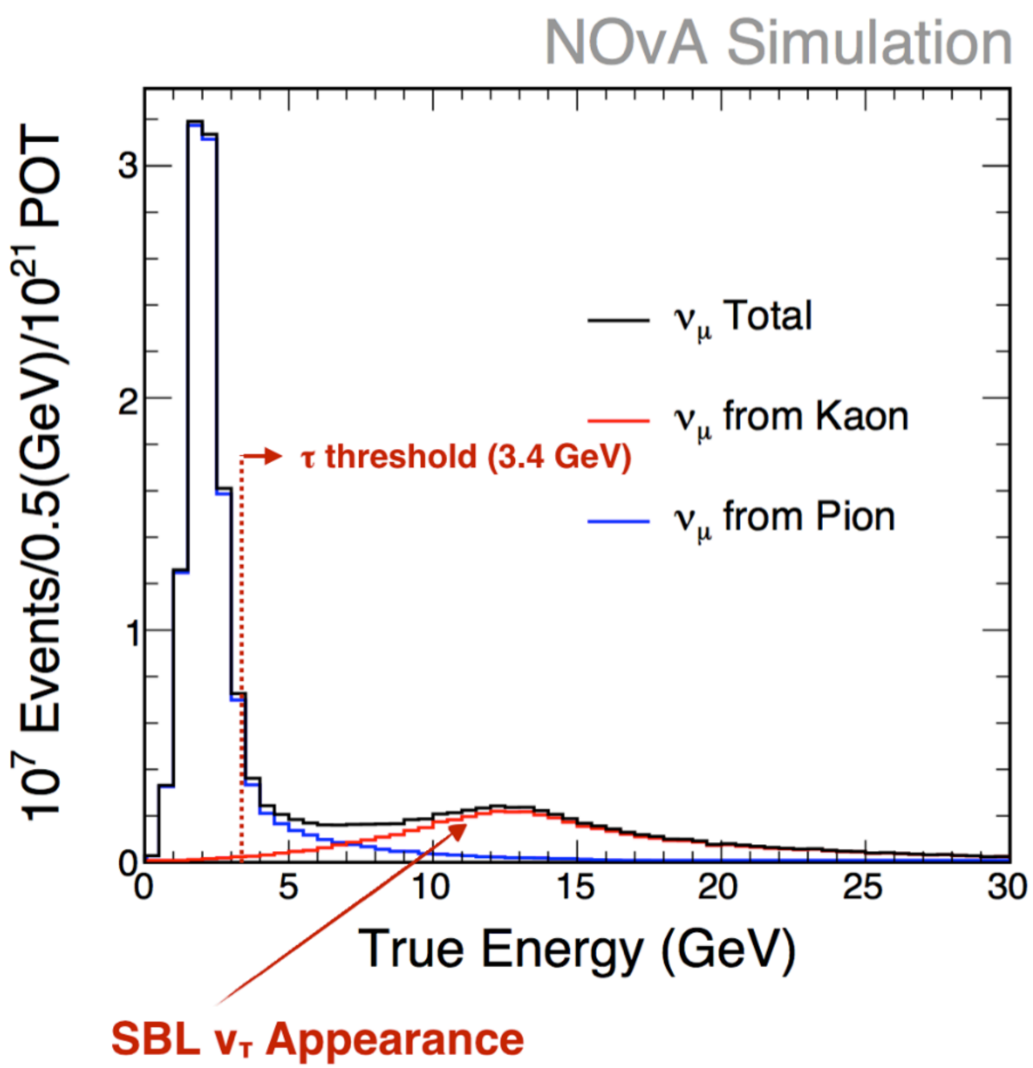
Analysis Goal:

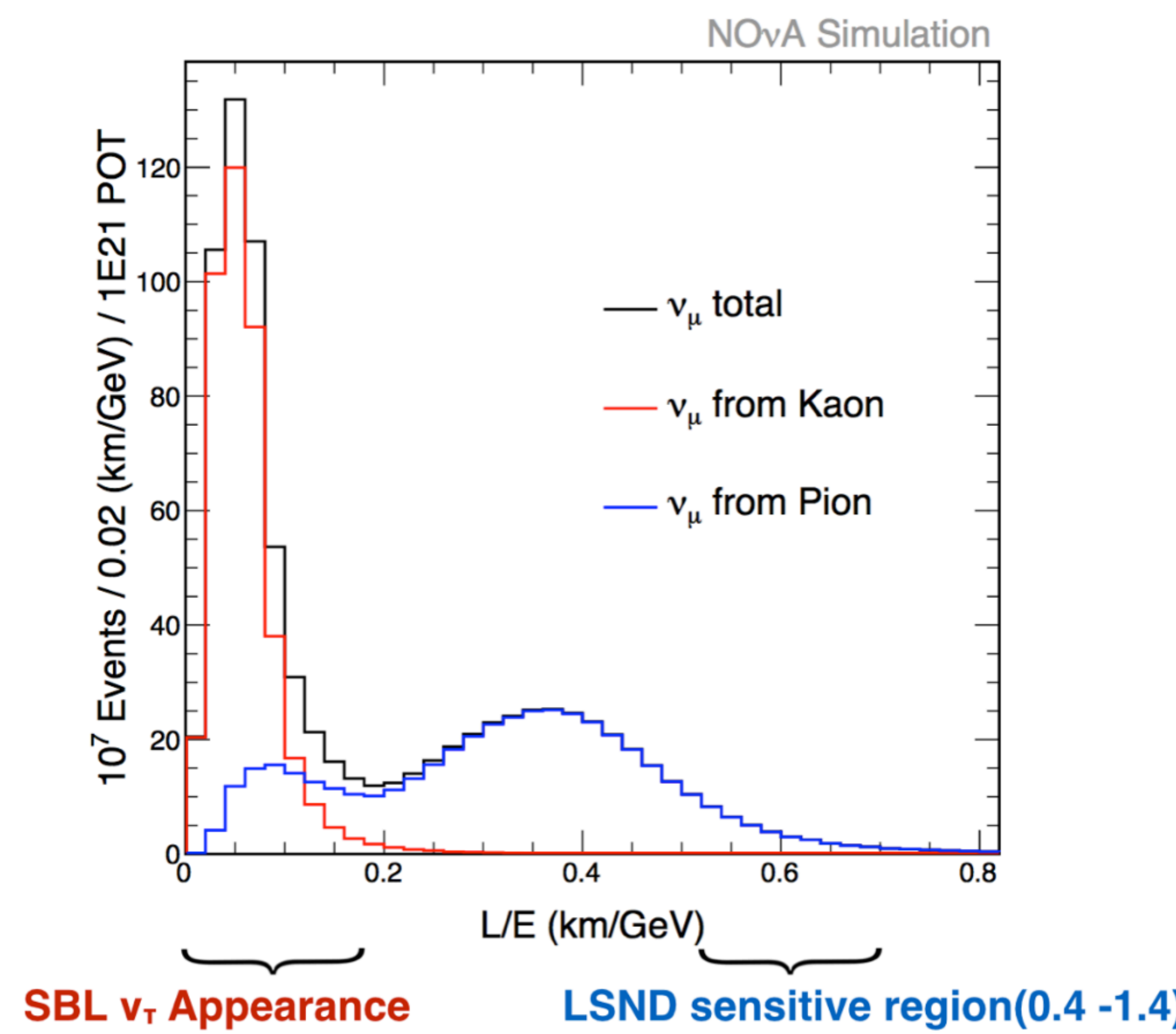
- Sterile neutrino search by looking at ν_μ disappearance and ν_τ appearance at NOvA Near Detector
- Constrain 3+1 oscillation parameters(Δm^2_{41}, $\sin^2\theta_{24}$ and $\sin^2 2\theta_{\mu\tau}$)



Analysis Overview

- Neutrinos in narrow-band beam peaked at 2 GeV predominantly created by pion decays
- But τ threshold is ~3.4 GeV
- Looking at the high energy neutrinos coming from kaons above τ threshold
- Search for $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations





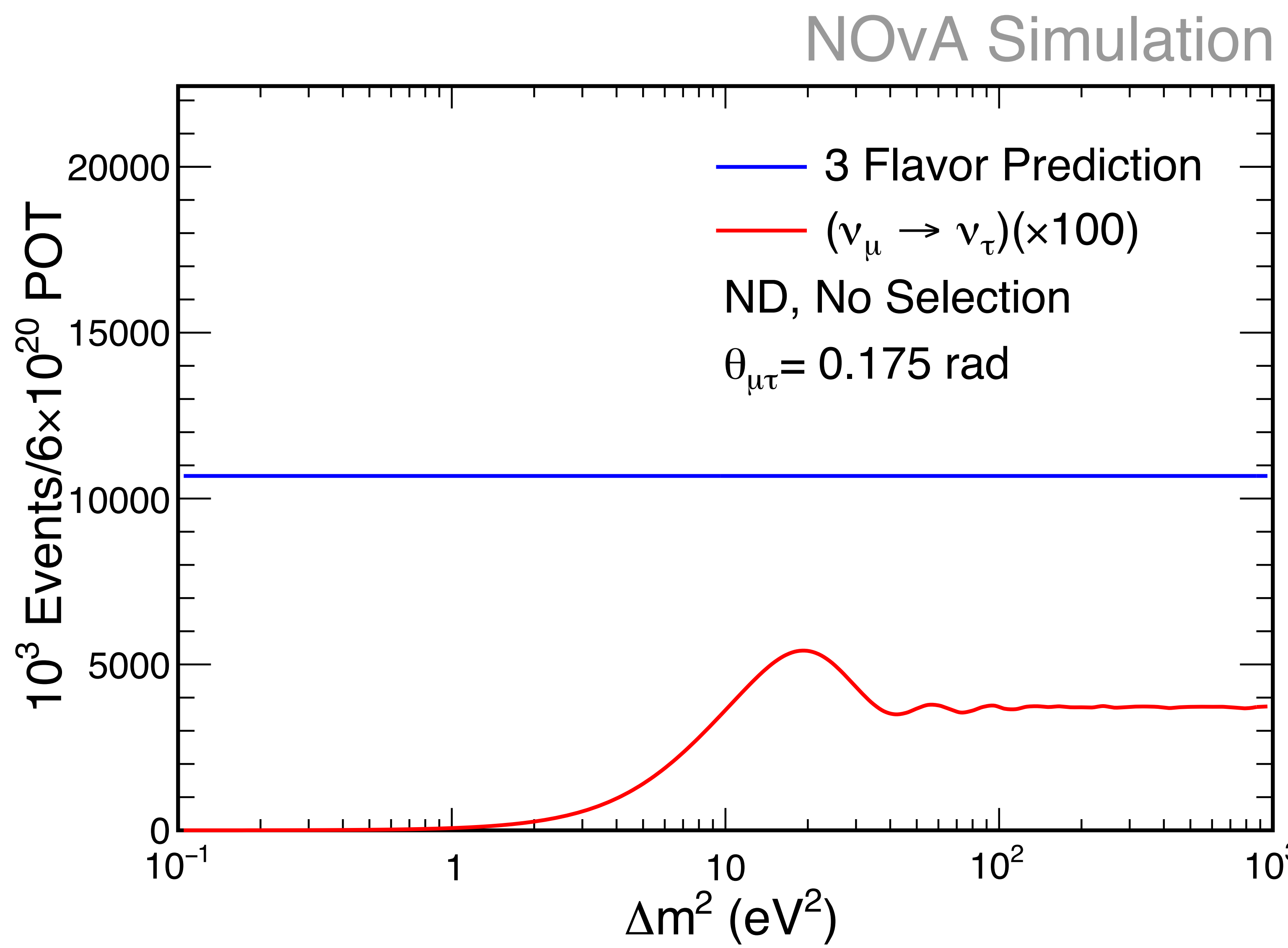
Analysis Strategy

- ν_τ event rates are maximized for $\Delta m^2_{41} = 22\ eV^2$ as looking at high energy region with low L/E.

- Use CVN and BDTs as primary selectors.

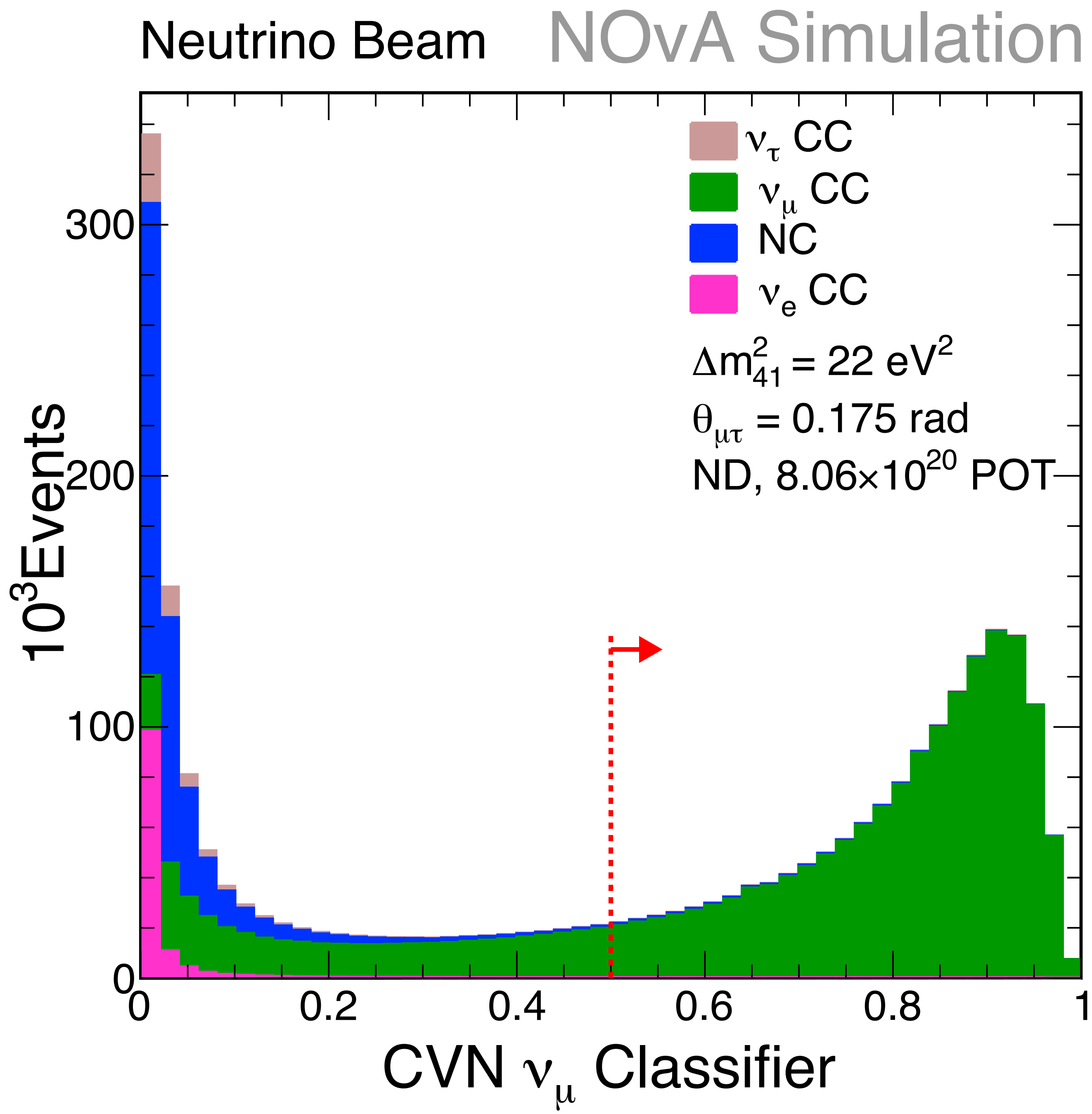
- A joint ν_μ-ν_τ fit to constrain huge systematic uncertainties.

- Rate only fit to the 3+1 oscillation parameters: Δm^2_{41} , $\sin^2\theta_{24}$ and $\sin^2 2\theta_{\mu\tau}$



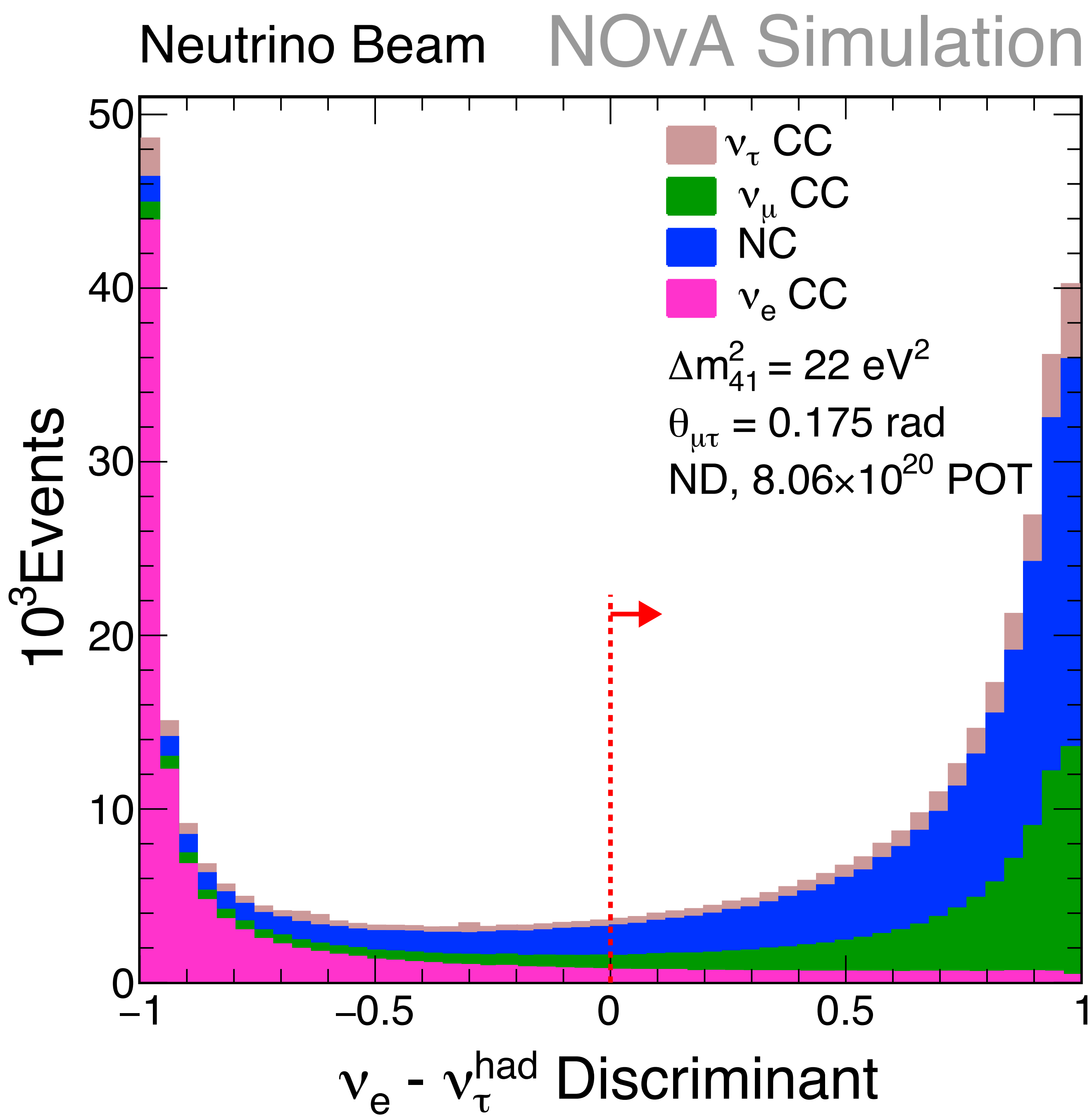
ν_μ Event Selection

- ν_μ CVN is used as a primary selector.
- Preselection cuts: To ensure the event quality and to remove the interactions in the surroundings of the detector.



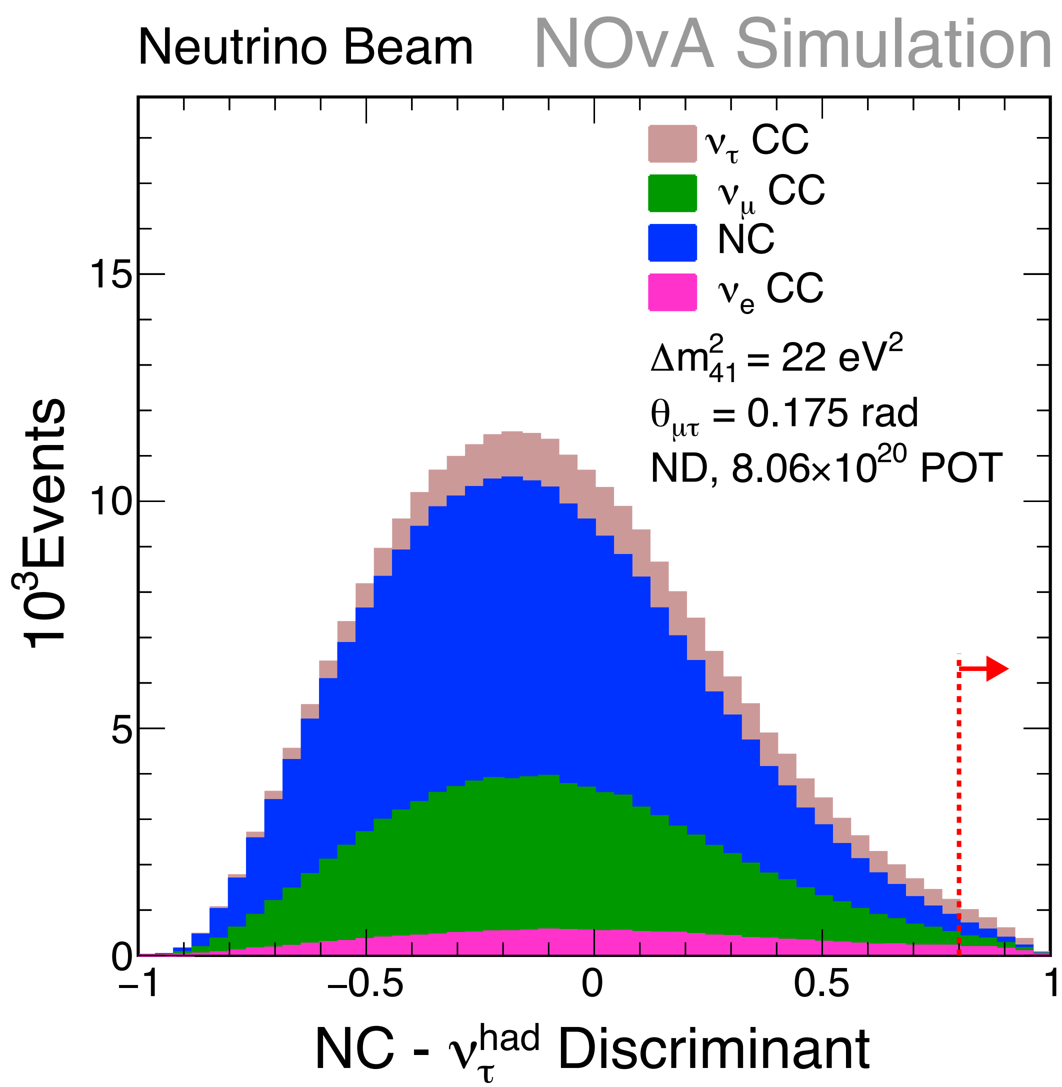
ν_τ Event Selection

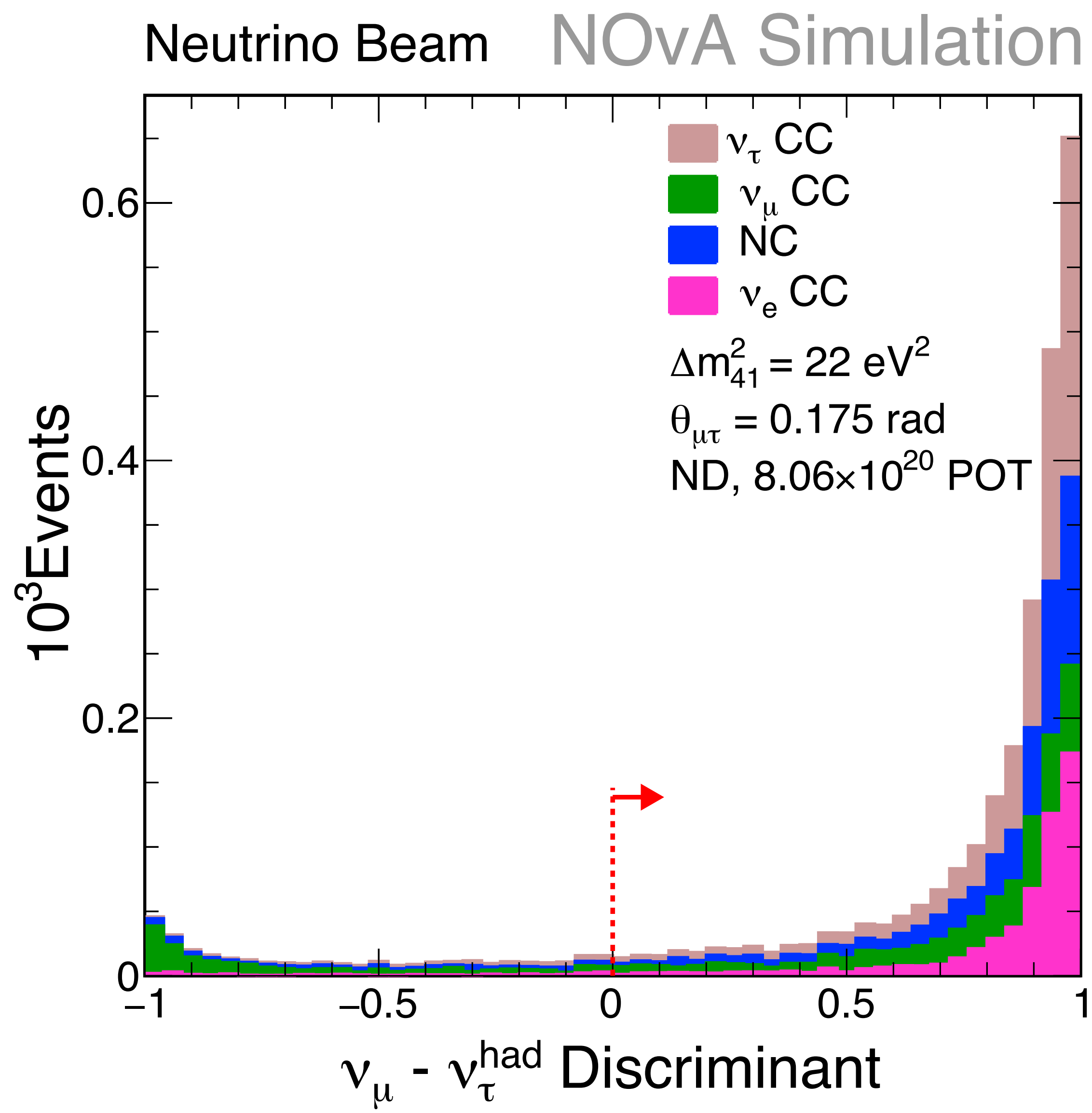
- 3 BDTs are used as the primary selectors (ν_μ, ν_e, *NC* $-\nu_\tau^{had}$ discriminants)
- Preselection cuts: To ensure the event quality and to remove the interactions in the surroundings of the detector.



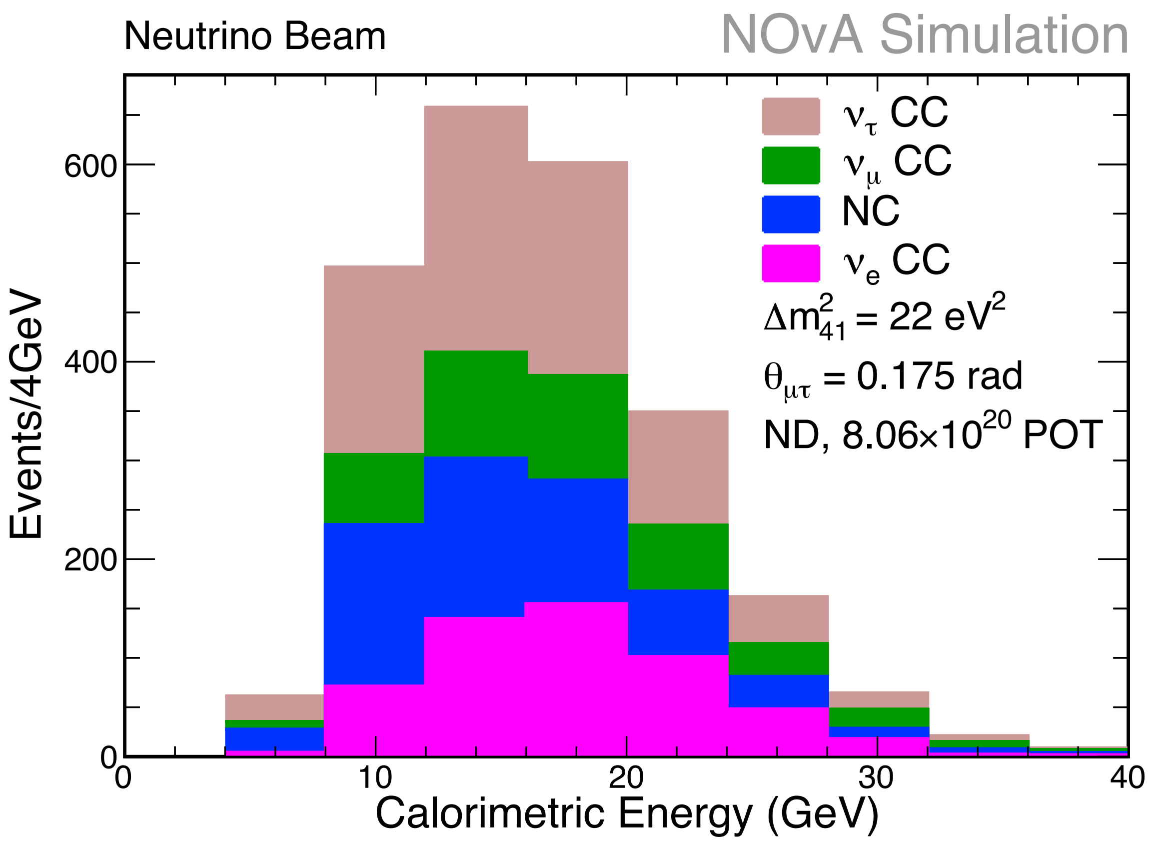
ν_τ Event Selection

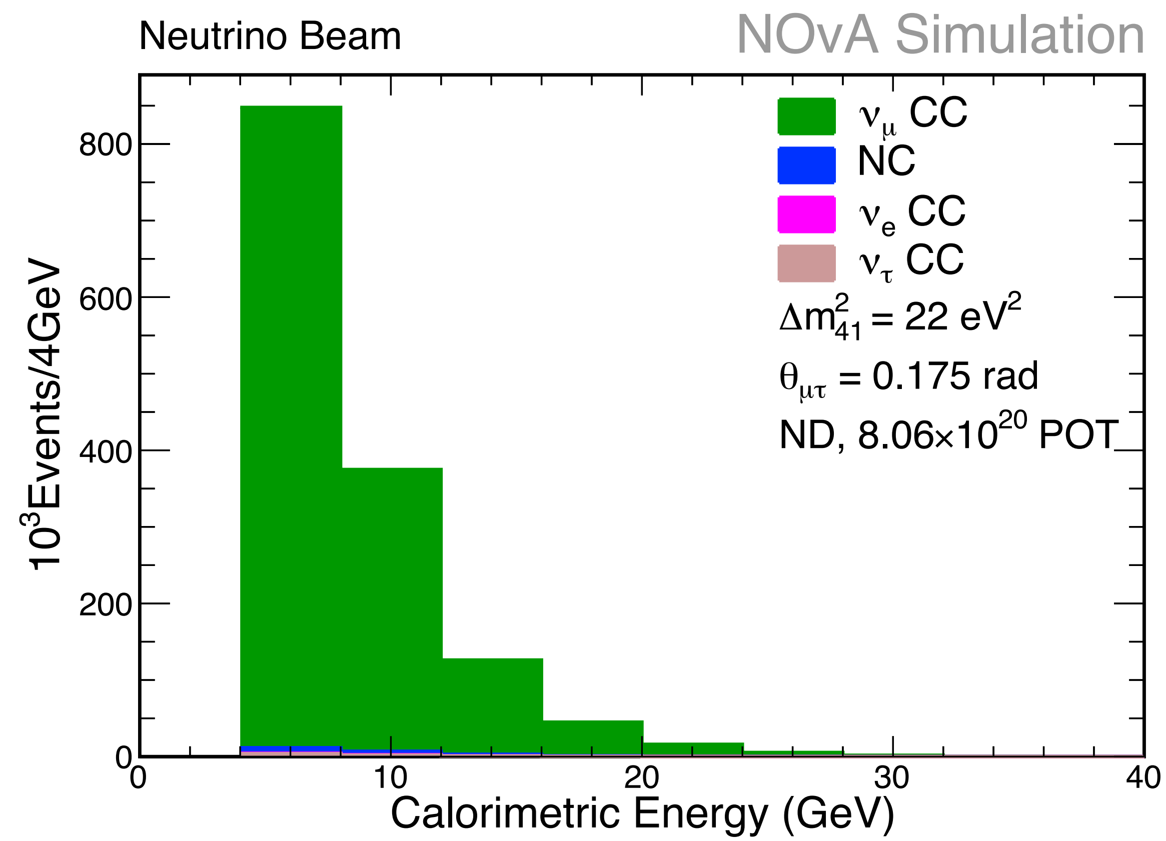
- These are the other two discriminants used for the ν_τ event selection





Signal Predictions





- ν_τ prediction after applying all the selection cuts, scaled to 8.06e20 POT
- ν_μ prediction after applying all the selection cuts, scaled to 8.06e20 POT

Signal Predictions

Selection	ν_μ CC	NC	ν_e CC	ν_τ CC	Purity(S/S+B) %
$\nu_\mu \to \nu_\mu$	1.52e+06	14252	2063	6694	98.5
$\nu_\mu \to \nu_\tau$	460	591	541	866	35.2

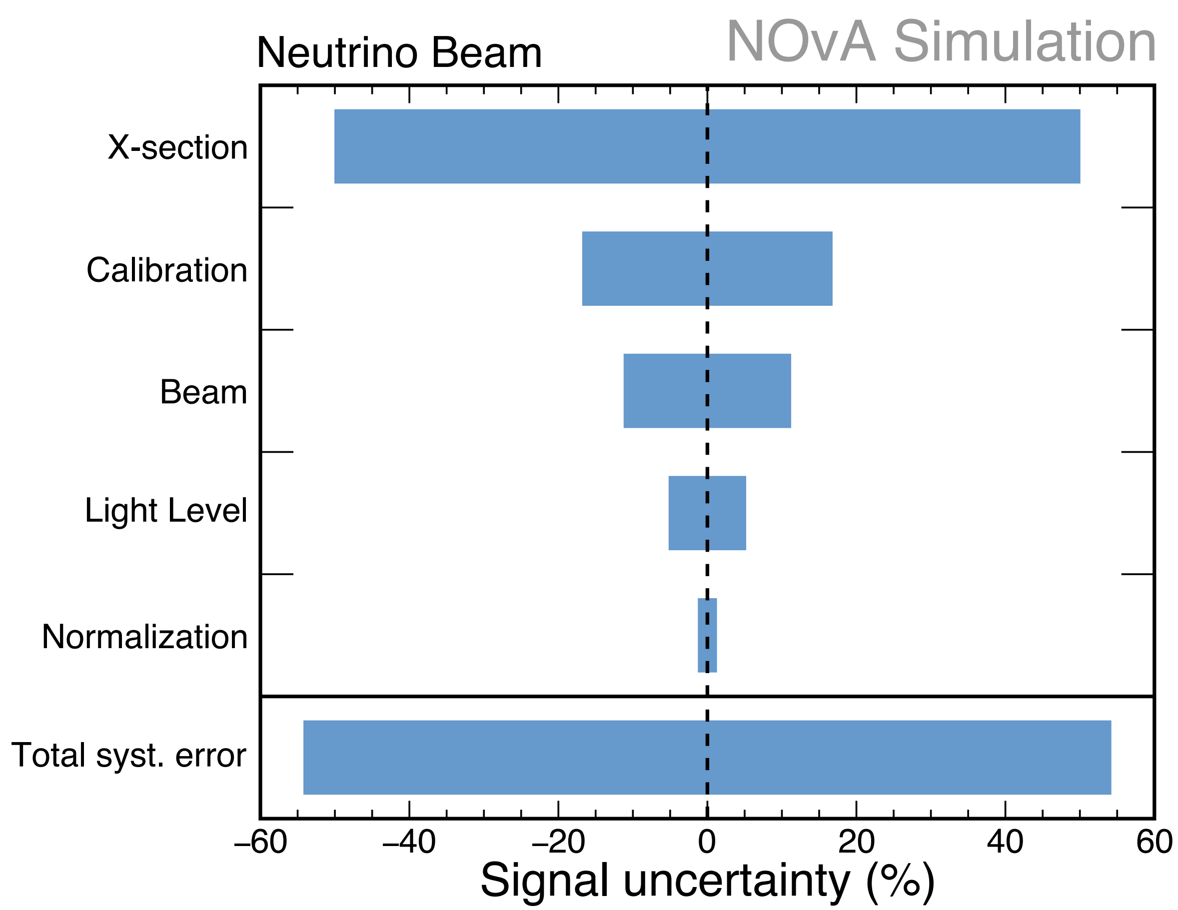
- $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ predictions at the point $\Delta m^2_{14} = 22$ eV^2 and $\theta_{\mu\tau} = 0.175$ rad. for 8.06×10^{20} POT. The disappearing ν_μ's are 1.2e+05 events (~ 8%) in $\nu_\mu \to \nu_\mu$ selection

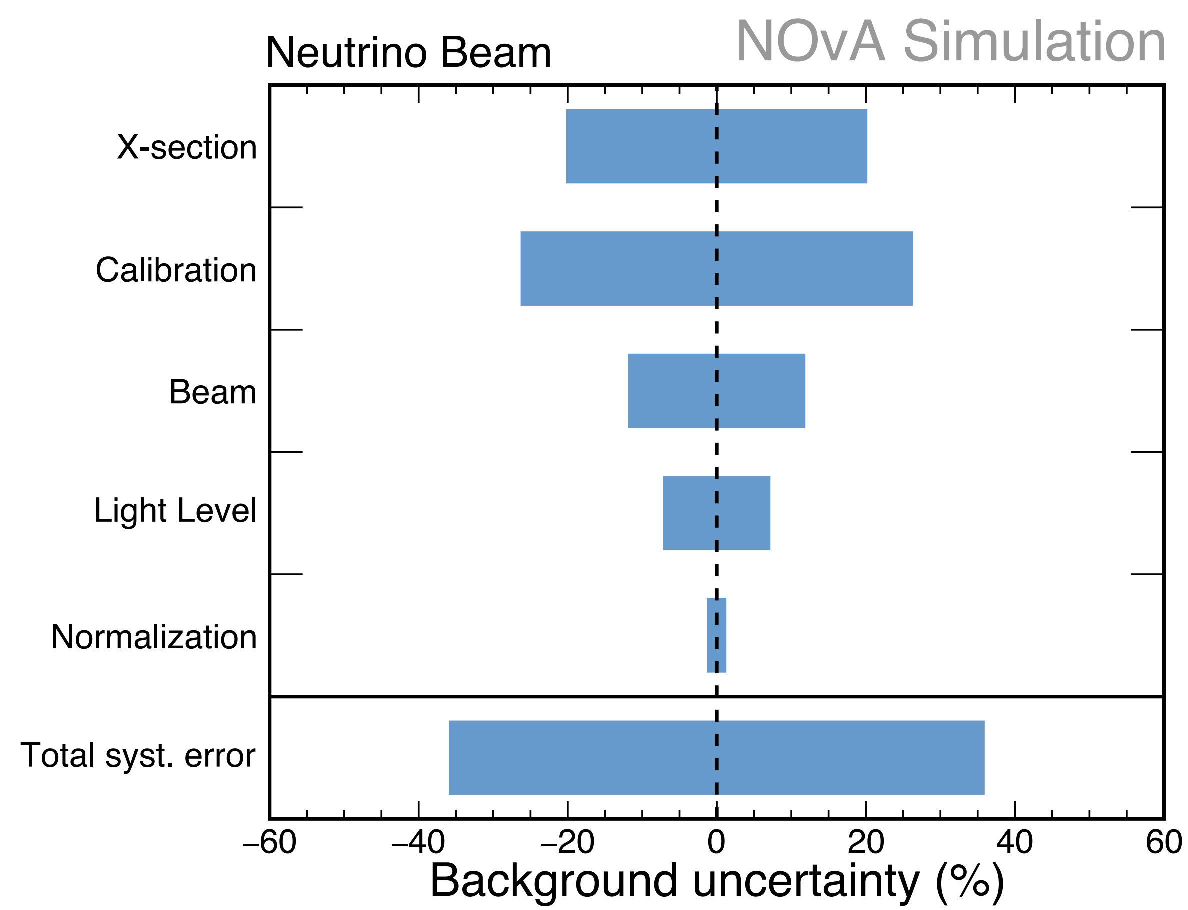
- We used $\Delta m^2_{14} = 22$ eV^2, the point where we see maximum signal events and $\theta_{\mu\tau} = 0.175$, the point where we start seeing the appearing τ signal even after including all the systematics.

Systematic Uncertainties

ν_τ Selection

- ν_τ cross-sections are not well constrained yet, so we added a 50% normalization uncertainty on just ν_τ cross-section.

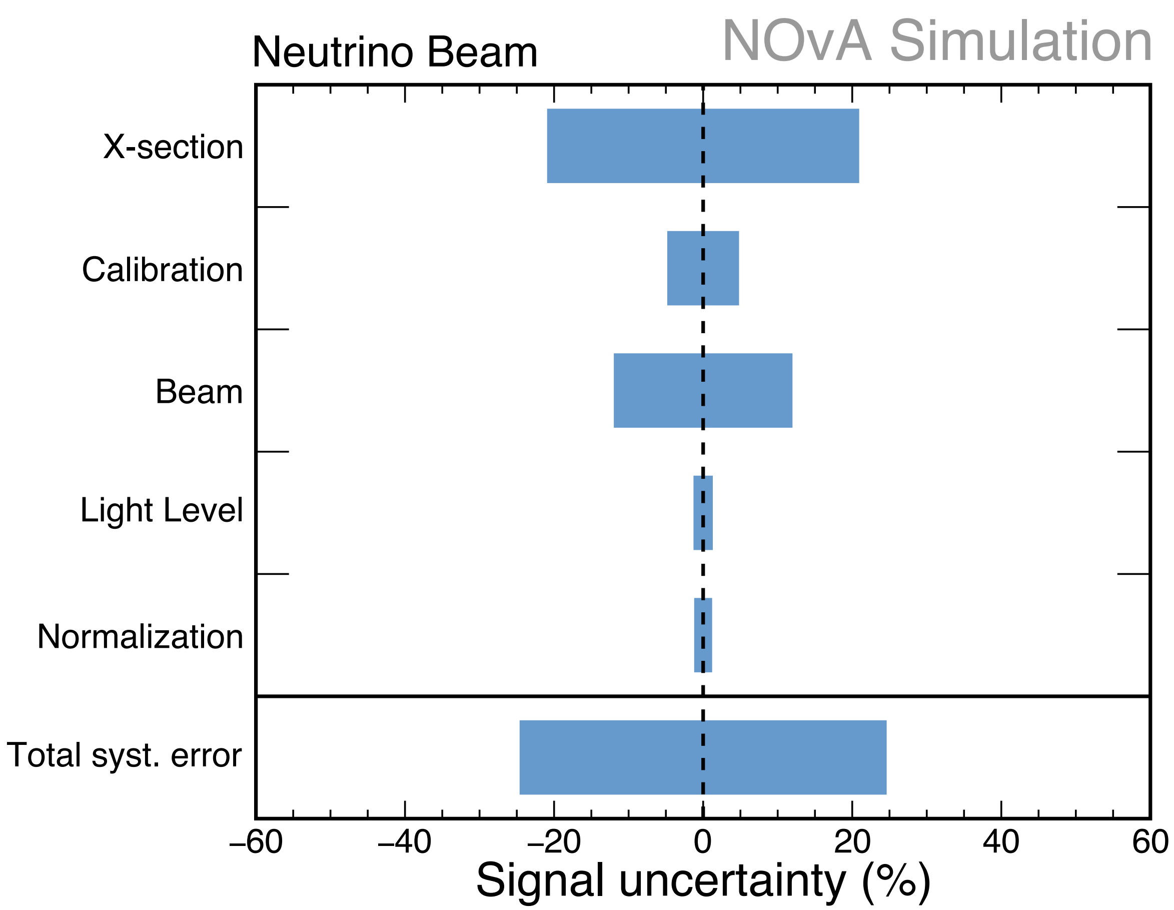


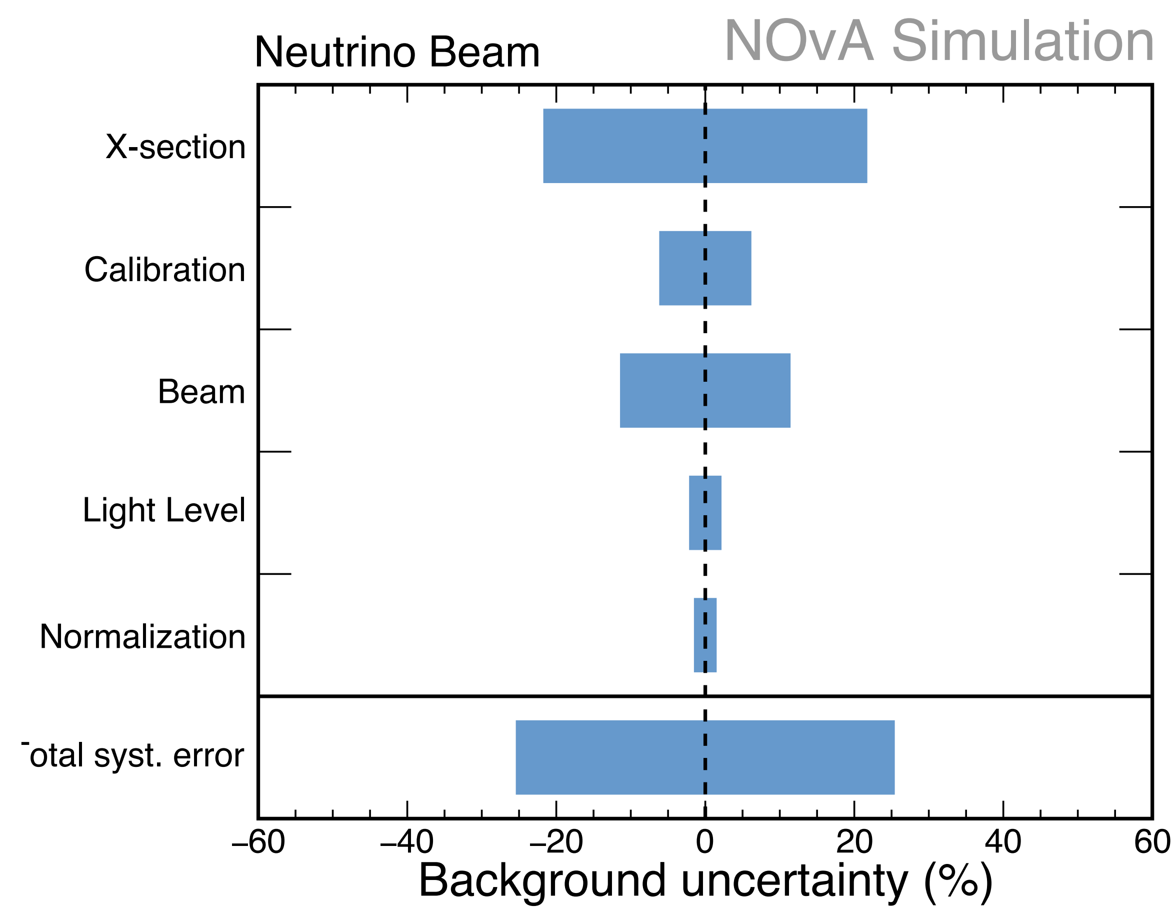


Systematic Uncertainties

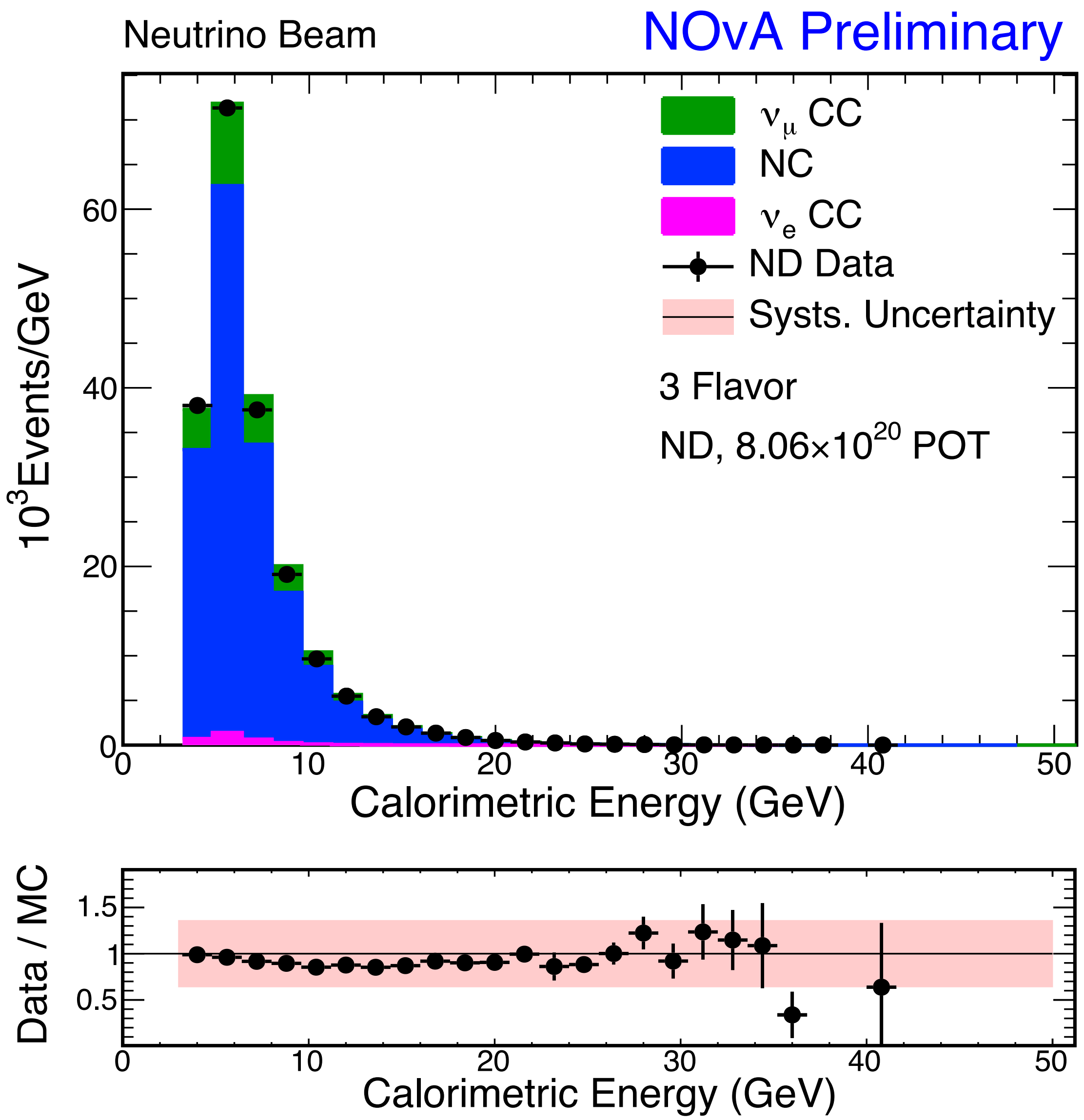
ν_μ Selection

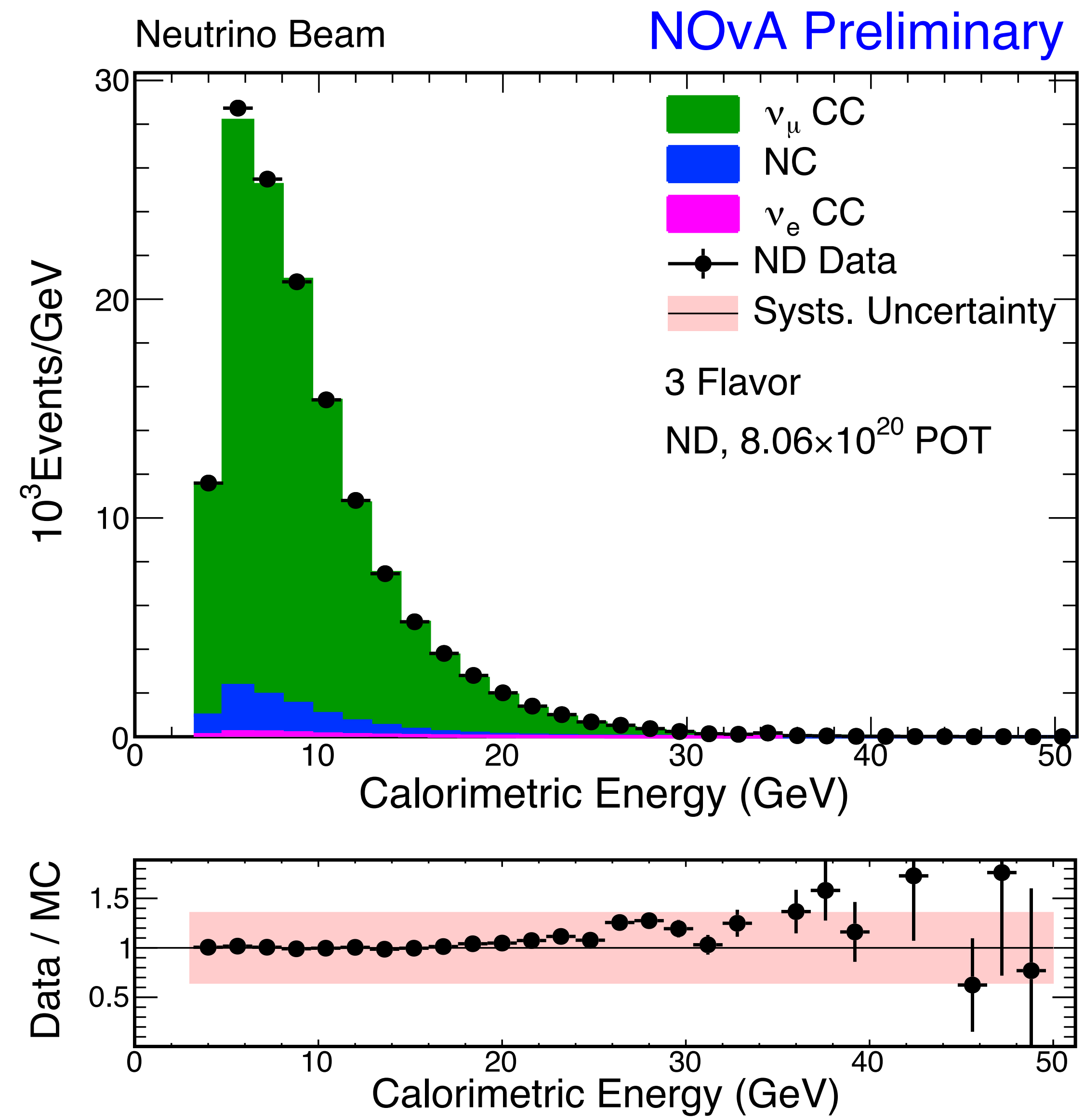
- Cross-section uncertainty and beam uncertainty are the dominant uncertainties for ν_μ selection.





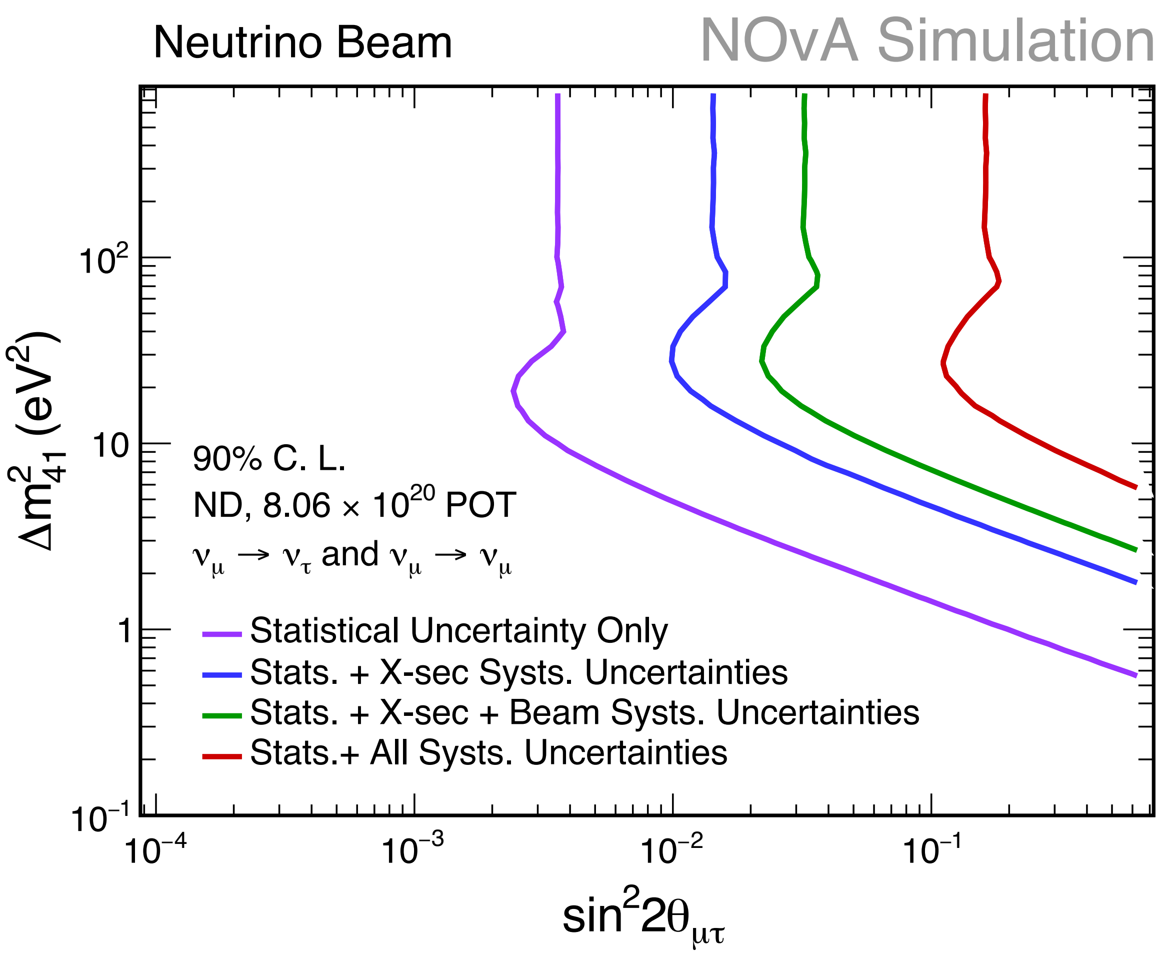
Sideband Studies

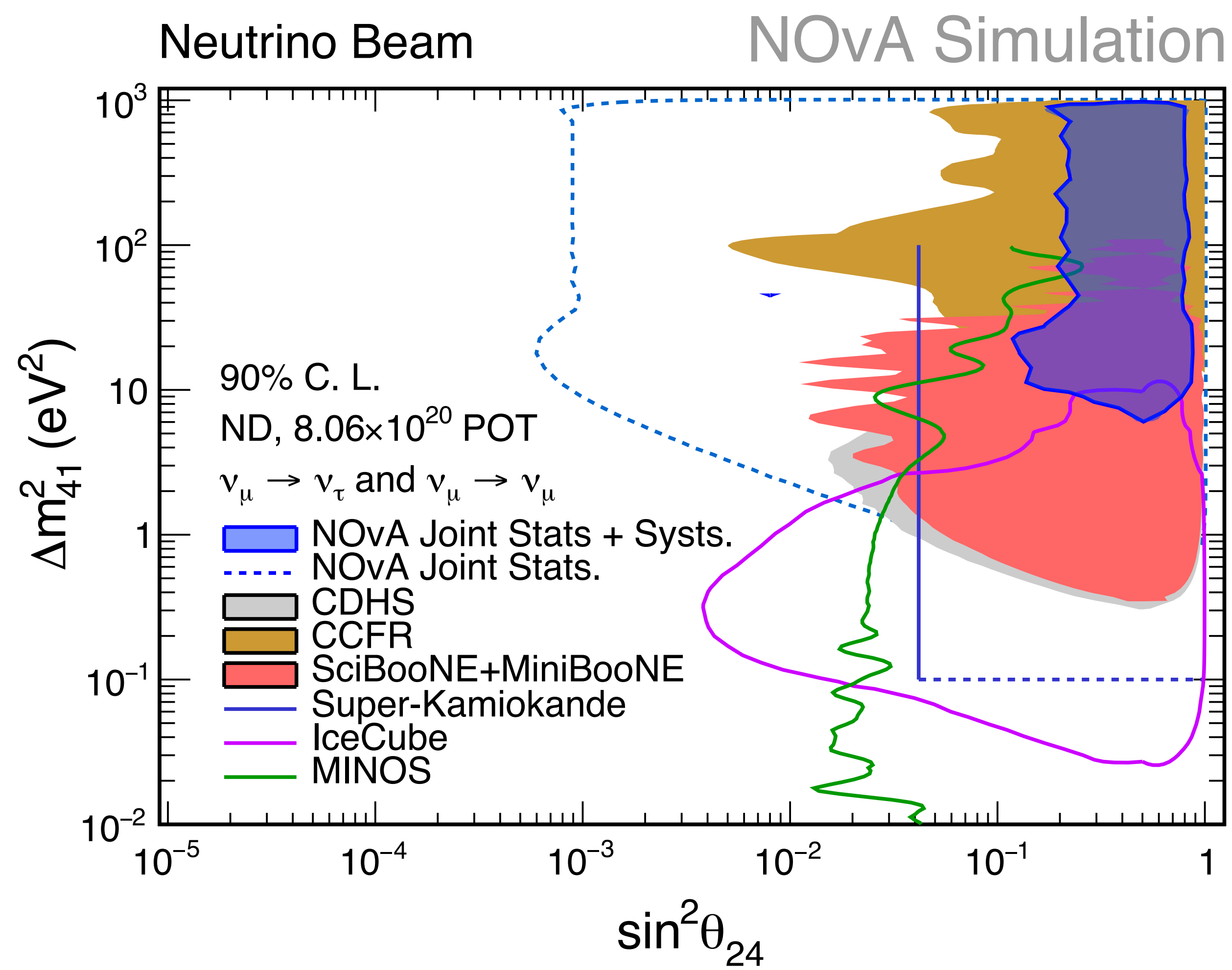




- ν_τ sideband: A high NC CVN sideband region for ν_τ selection. All the cuts are same except CVN NC cut (CVN NC > 0.62)
- ν_μ sideband: A mid ν_μ CVN sideband region for ν_μ Selection. All other selection cuts are same except CVN ν_μ cut ($0.35 < \text{CVN } \nu_\mu < 0.5$)

Sensitivity Studies





- Joint ν_μ - ν_τ fit to the 4-flavor oscillation parameters Δm^2_{41} and $\sin^2 2\theta_{\mu\tau}$.
- Marginalized over $\sin^2 2\theta_{24}$ and $\sin^2\theta_{34}$.

- Joint ν_μ - ν_τ fit to the 4-flavor oscillation parameters Δm^2_{41} and $\sin^2\theta_{24}$.
- Marginalized over $\sin^2\theta_{34}$.

Summary

- This analysis considers the advantage of joint fit between ν_τ appearance and ν_μ disappearance to probe the existence of sterile neutrinos
- Two sample selections were made - $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_\tau$
- Conducted systematics studies and sideband studies for these samples
- A joint sensitivity study is conducted using these samples to the sterile neutrino oscillation parameters Δm^2_{41} , $\sin^2\theta_{24}$ and $\sin^2 2\theta_{\mu\tau}$

Thanks for Your Attention!

http://novaexperiment.fnal.gov

Backup

τ decay - Branching

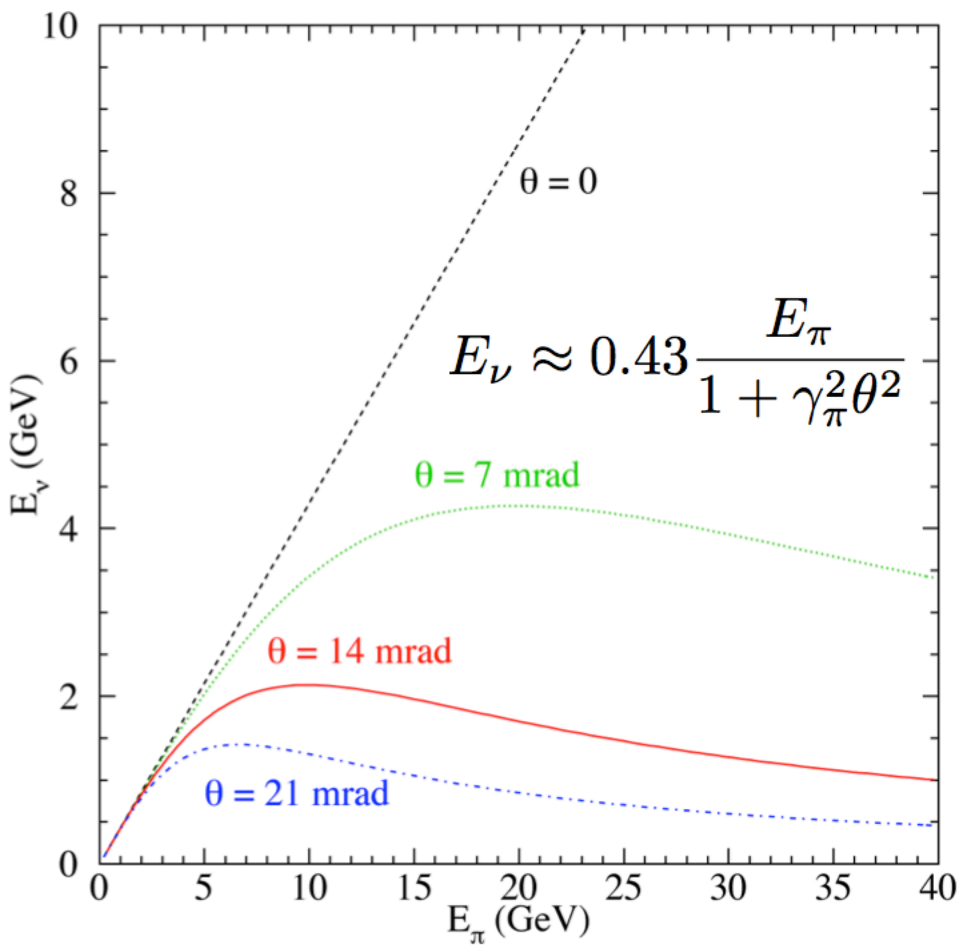
Decay Mode	Branching(%)
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	17.4
$\tau^- \to h^- \nu_\tau$	11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$	4.8
Other modes with hadrons	3.2
All modes containing hadrons	64.8

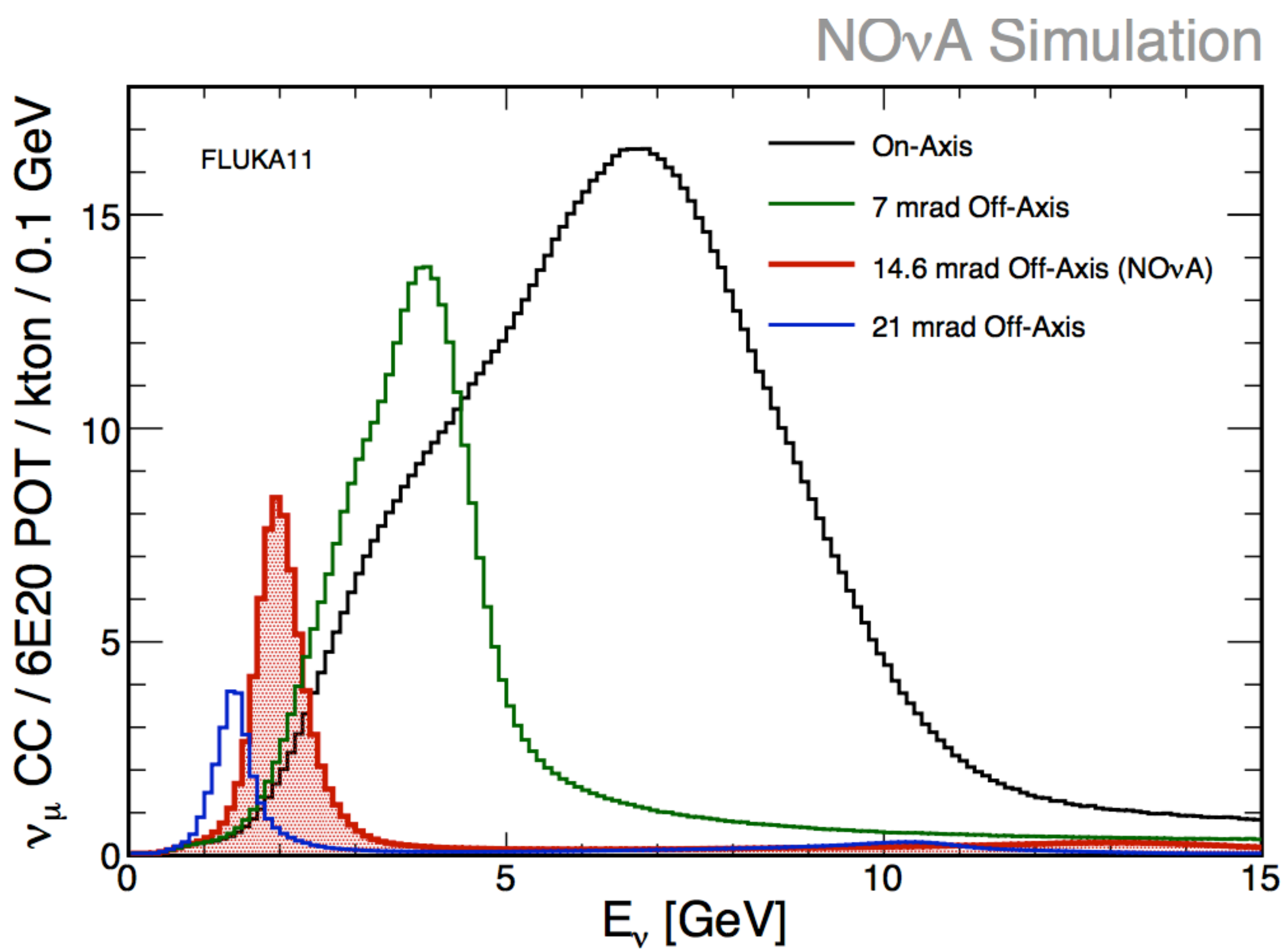
Systematics Summary

	ν_τ Sig.	Background	ν_μ Sig.	Background
Cross-section	50.0	20.14	20.87	21.68
Beam	7.41	8.22	4.39	4.70
PPFX	8.38	8.5	11.08	10.36
Calib +/-	14.77	24.99	4.28	6.12
Calib Shape	7.88	8.07	2.06	0.01
Light Level	4.78	7.07	0.92	2.00
Cherenkov	1.91	0.97	0.82	0.70
ND Rock	0.0	0.22	0.23	0.94
Overall Normalization	1.12	1.12	1.12	1.12
Sum in quadrature	**54.14**	**35.87**	**24.59**	**25.36**

Off-axis Beam

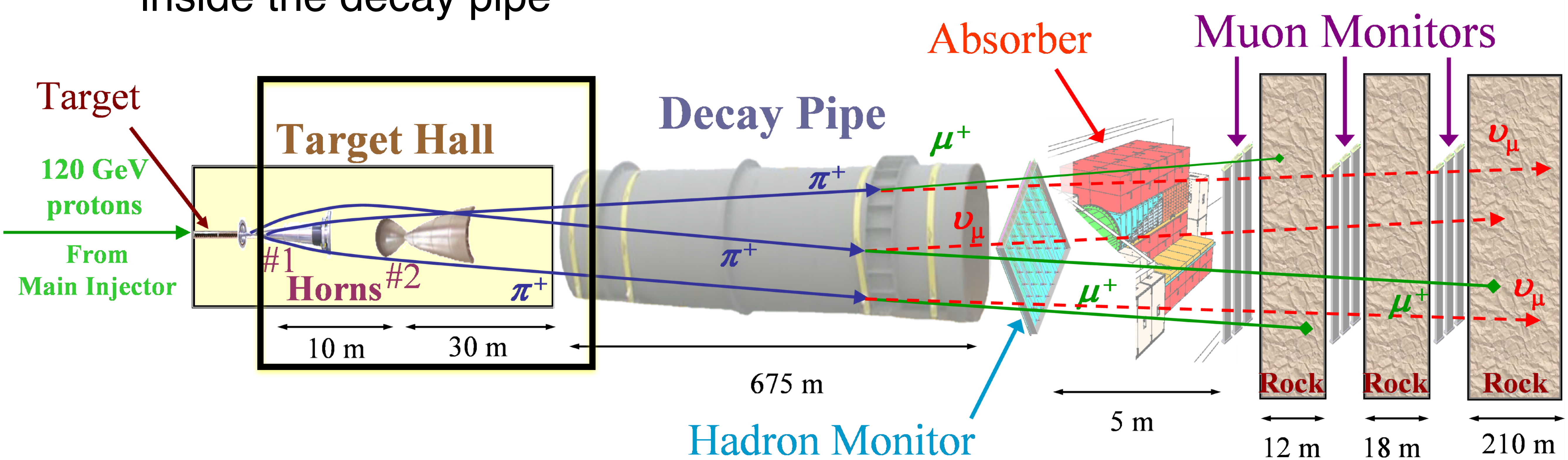
- Off-axis location reduces flux, but creates a narrowband beam
- The particular peak around 2 GeV was chosen to lie near the 'first' oscillation maximum for ν_μ disappearance to measure θ_{13} and δ



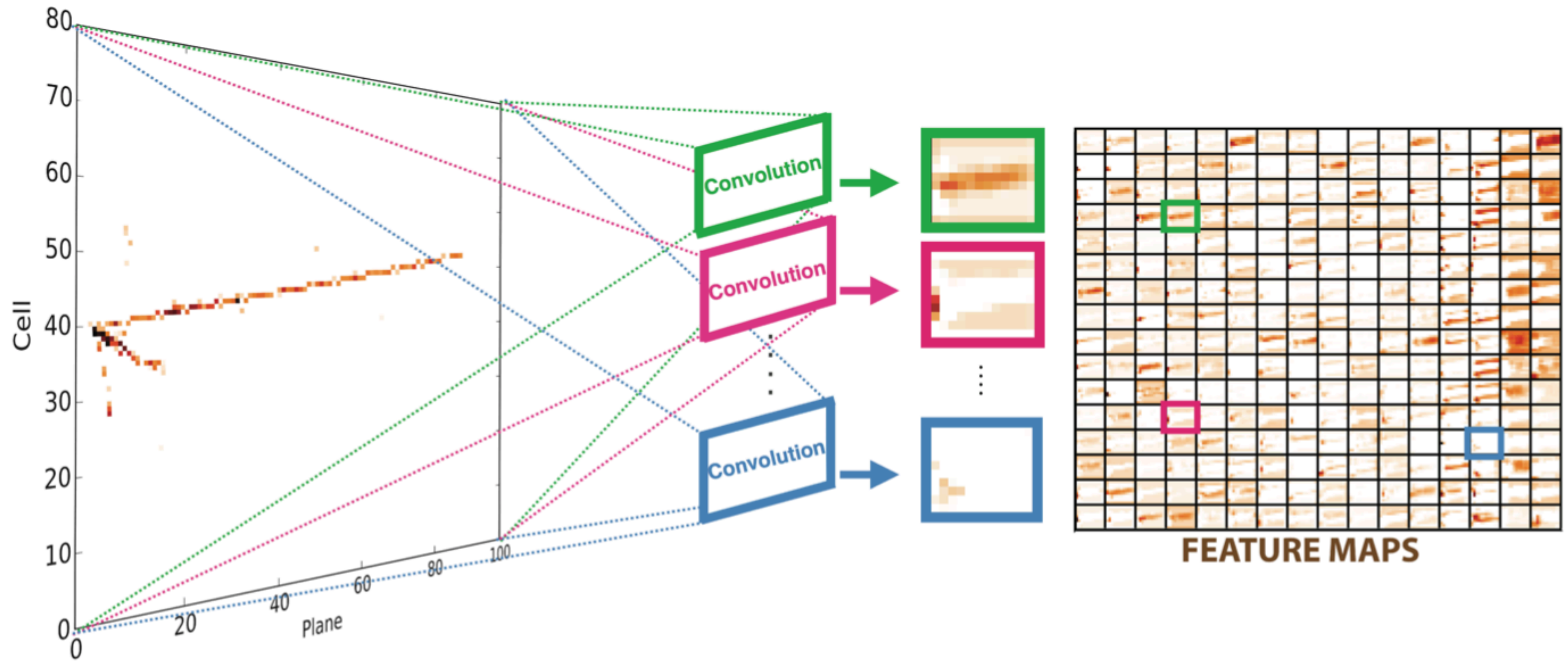


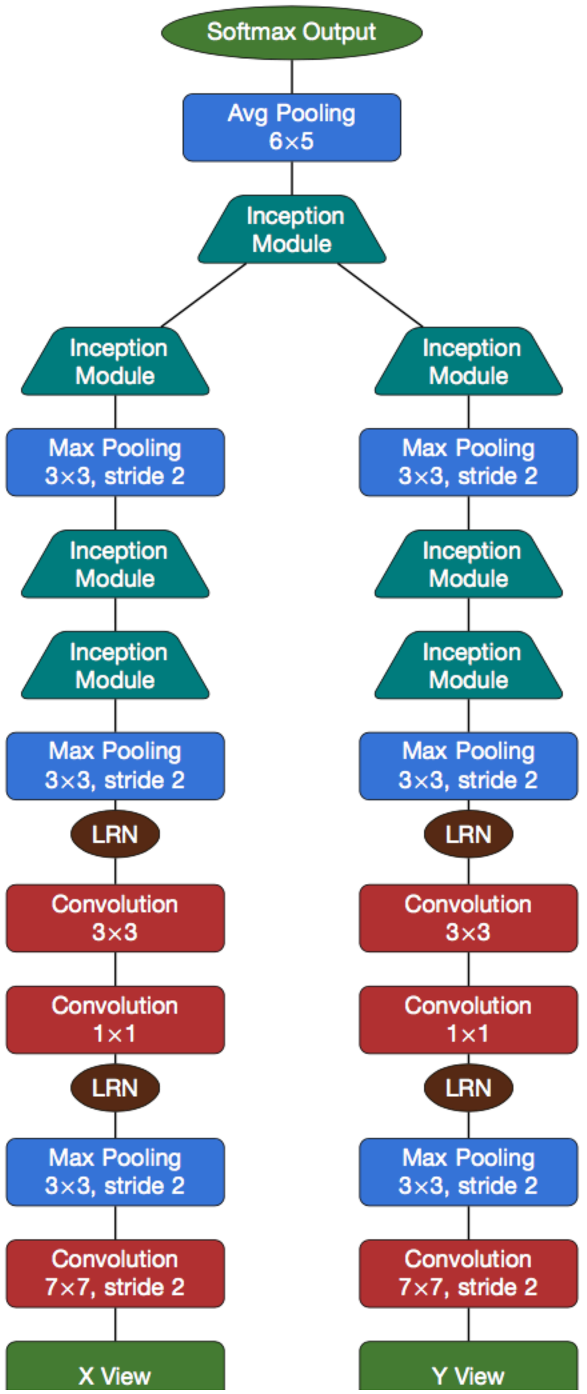
Neutrino Beam

- Protons collide with graphite target producing (mainly) pions and kaons
- Charged mesons are focused by two magnetic horns
  - Positively charged mesons focused for neutrino mode
  - Negatively charged mesons focused for anti-neutrino mode
- Focused particles decay to neutrinos and tertiary particles inside the decay pipe

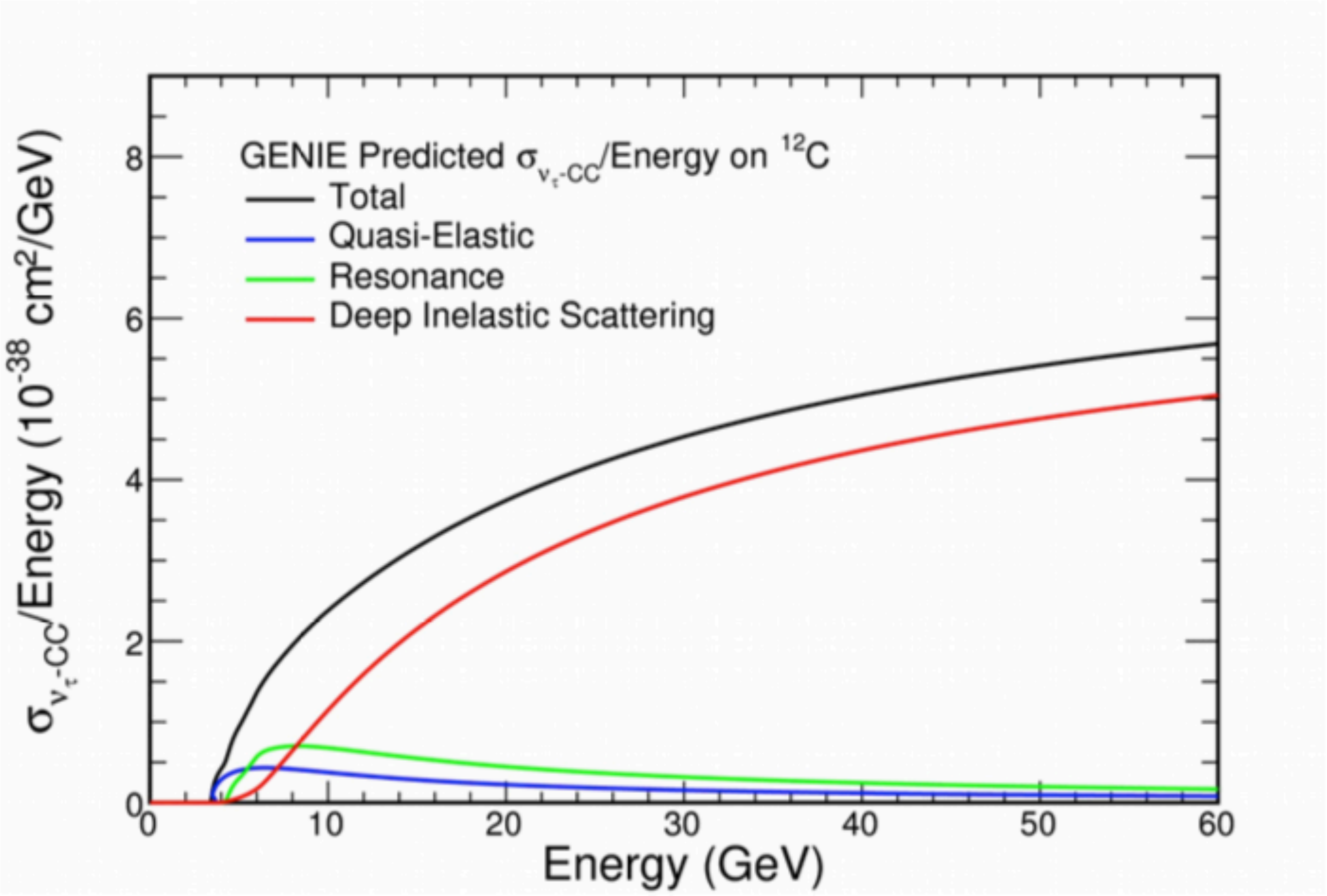


CVN Feature Maps





ν_τ Cross-section



The GENIE predicted cross-section for ν_τ CC events in C^{12} nucleus.