Accelerator Neutrino Experiments Status and Prospects

Stanley Wojcicki

IV International Pontecorvo Neutrino Physics School
October 1-2, 2010

Outline

Outline

- Introduction to ν beams

Outline

- Introduction to ν beams
- Determining energy spectra

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$
  - K2K

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$
  - K2K
  - MINOS

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$
  - K2K
  - MINOS
  - OPERA

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$
  - K2K
  - MINOS
  - OPERA
- The issue of $\sin^2(2\theta_{13})$

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$
  - K2K
  - MINOS
  - OPERA
- The issue of $\sin^2(2\theta_{13})$
- LSND and MiniBooNE

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$
  - K2K
  - MINOS
  - OPERA
- The issue of $\sin^2(2\theta_{13})$
- LSND and MiniBooNE
- Neutrino/antineutrino comparison

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$
  - K2K
  - MINOS
  - OPERA
- The issue of $\sin^2(2\theta_{13})$
- LSND and MiniBooNE
- Neutrino/antineutrino comparison
- Future efforts

Outline

- Introduction to ν beams
- Determining energy spectra
- Determining Δm^2_{31} and $\sin^2(2\theta_{23})$
  - K2K
  - MINOS
  - OPERA
- The issue of $\sin^2(2\theta_{13})$
- LSND and MiniBooNE
- Neutrino/antineutrino comparison
- Future efforts
- Cross sections

Neutrinos are Ubiquitous

Neutrinos are Ubiquitous

- They are made by nature:
  - In the Big Bang
  - By the elements in the earth, air, and water
  - By the sun and other stars
  - In the explosion of supernovae
  - By the cosmic rays

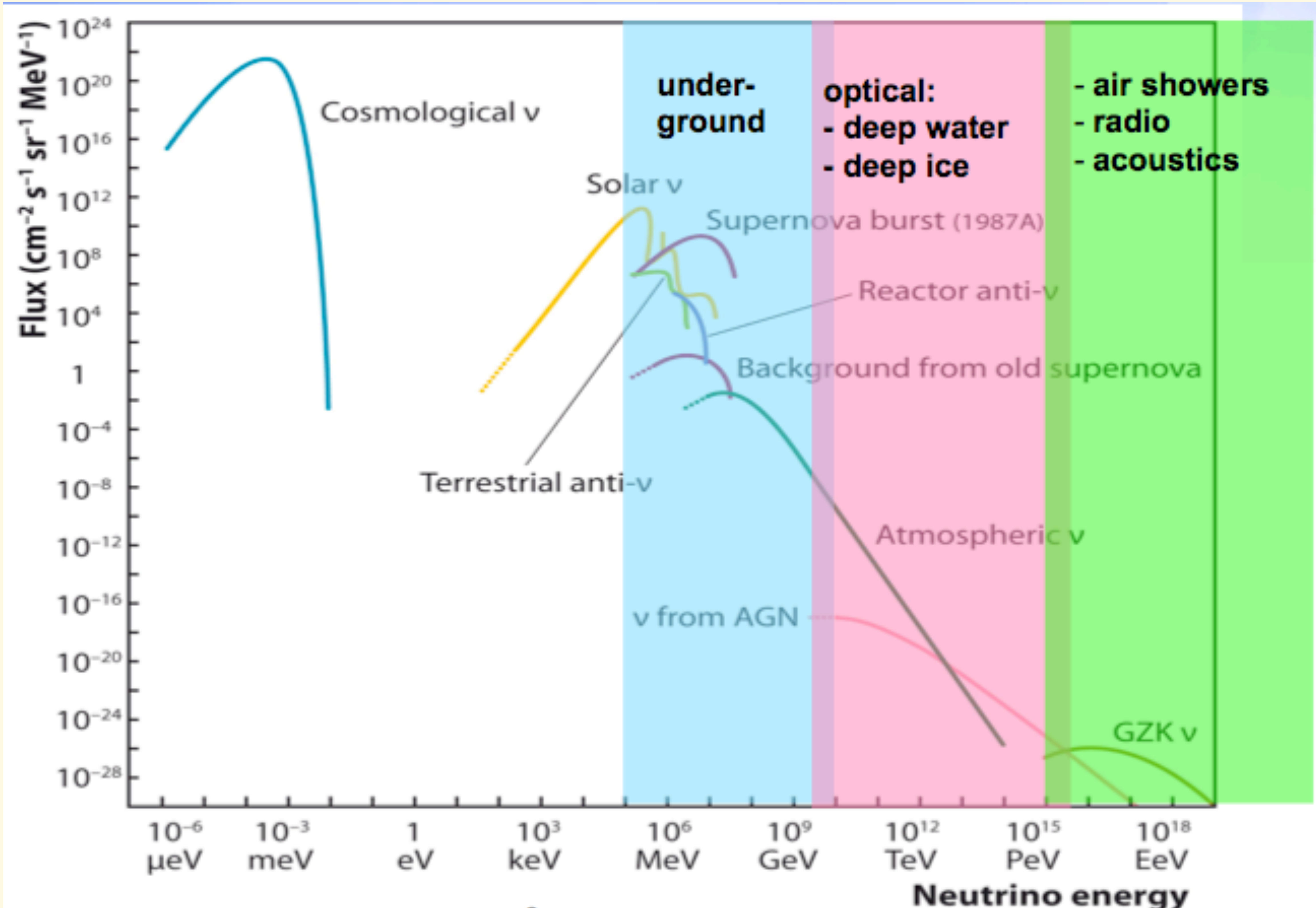
Neutrinos are Ubiquitous

- They are made by nature:
  - In the Big Bang
  - By the elements in the earth, air, and water
  - By the sun and other stars
  - In the explosion of supernovae
  - By the cosmic rays
- And they are made by humans:
  - In power plants (reactors)
  - In decays of artificially produced isotopes
  - In the accelerators
  - In nuclear explosions

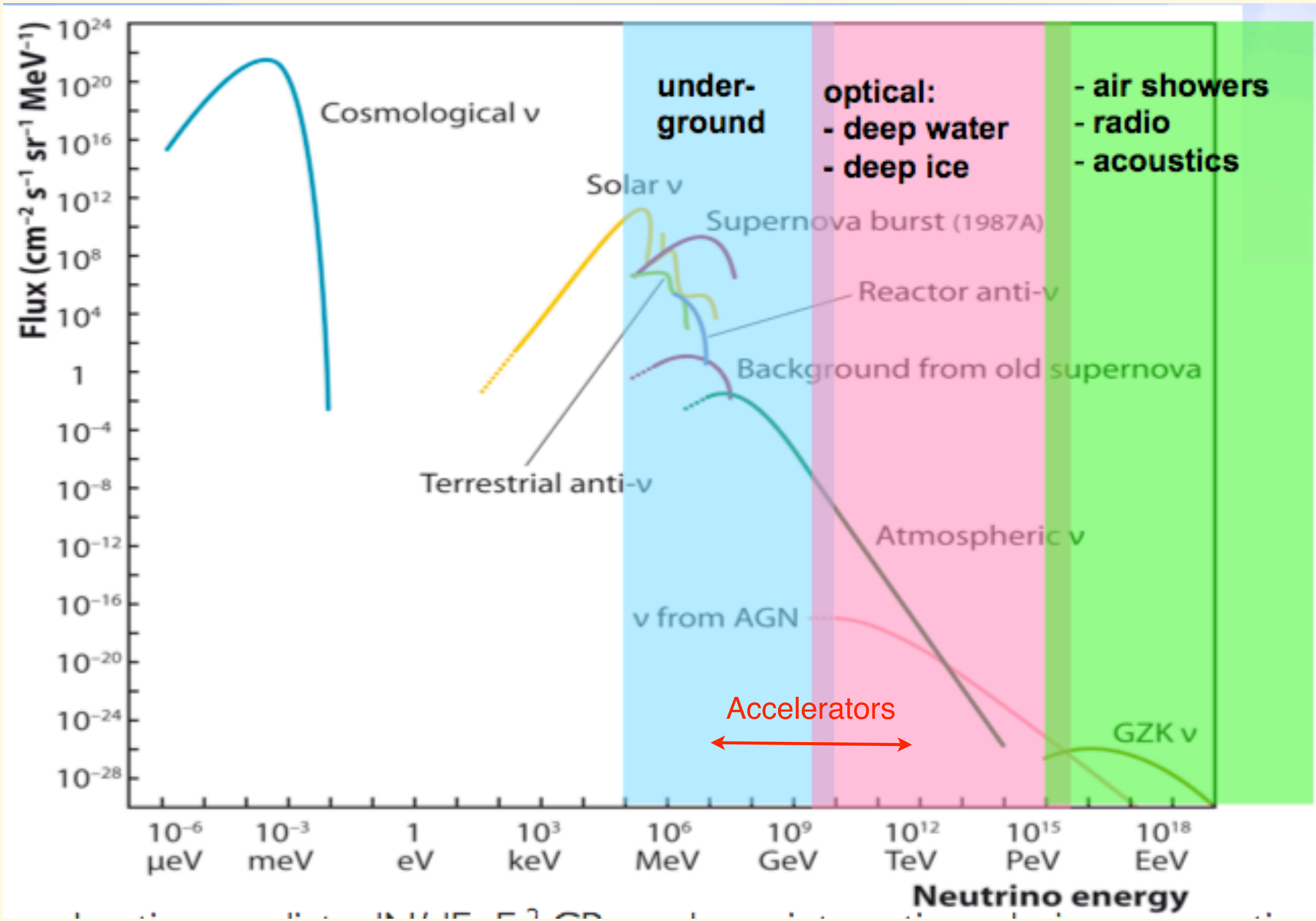
Neutrinos are Ubiquitous

- They are made by nature:
  - In the Big Bang
  - By the elements in the earth, air, and water
  - By the sun and other stars
  - In the explosion of supernovae
  - By the cosmic rays
- And they are made by humans:
  - In power plants (reactors)
  - In decays of artificially produced isotopes
  - In the accelerators
  - In nuclear explosions

Energy spectra



Energy spectra



Accelerator ν Sources

Accelerator ν Sources

The primary source of accelerator ν's are decays of π and K mesons produced by the accelerated protons

Accelerator ν Sources

The primary source of accelerator ν's are decays of π and K mesons produced by the accelerated protons

The main sources:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{BF} = 99.99\%$$

$$K^+ \rightarrow \pi^+ + \nu_\mu \quad \text{BF} = 63.44\%$$

Accelerator ν Sources

The primary source of accelerator ν's are decays of π and K mesons produced by the accelerated protons

The main sources:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{BF} = 99.99\%$$

$$K^+ \rightarrow \pi^+ + \nu_\mu \quad \text{BF} = 63.44\%$$

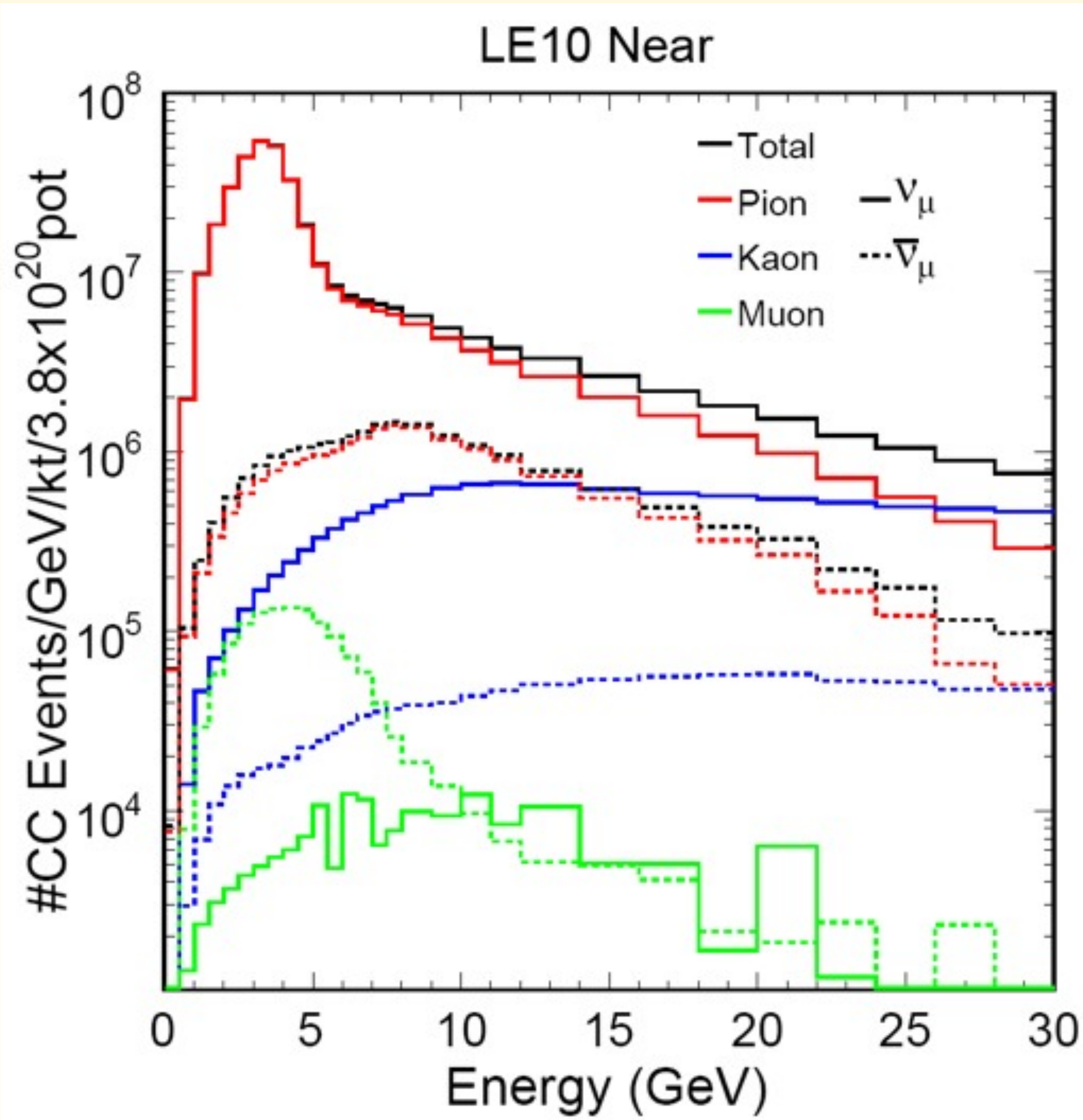
Secondary sources (last 2 important for ν_e's):

$$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu \quad \text{BF} = 3.32\%$$

$$K^+ \rightarrow \pi^0 + e^+ + \nu_e \quad \text{BF} = 4.98\%$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad \text{BF} =\sim 100\%$$

Example - NuMI Flux



The neutrinos from π decay have at most 42% of parent pion energy

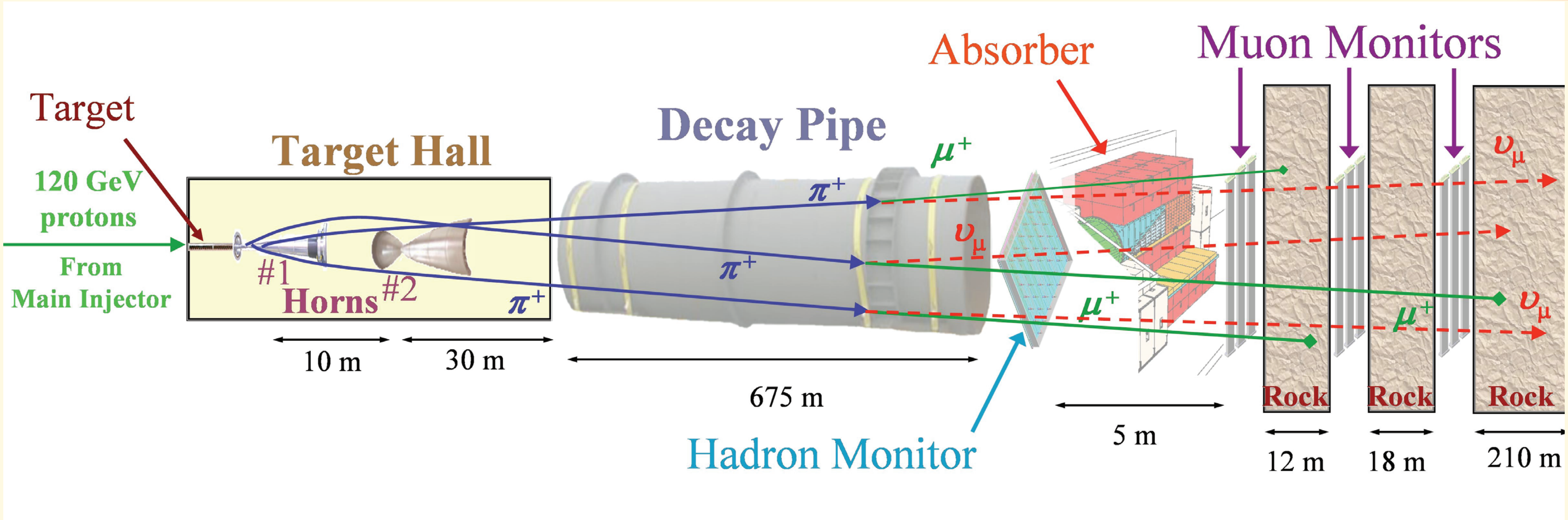
$E_\nu < 0.42 \times E_\pi$

But the neutrinos from K decay can have energies almost up to K energy

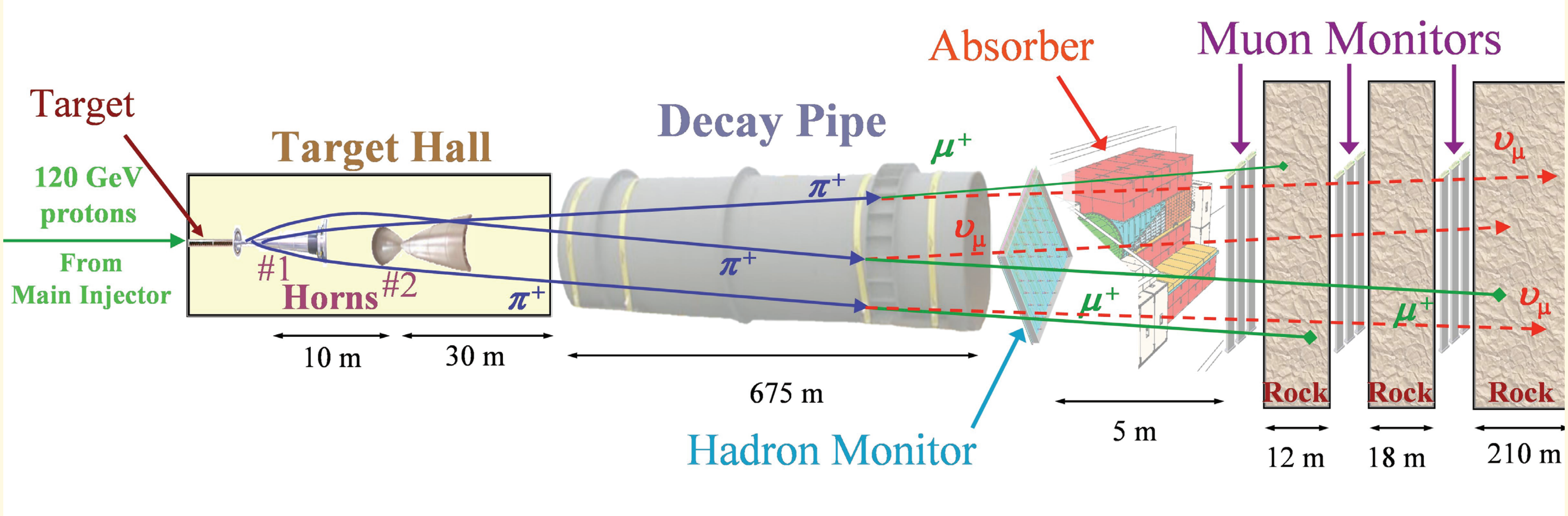
$E_\nu < E_K$

Example - NuMI Beam

Example - NuMI Beam

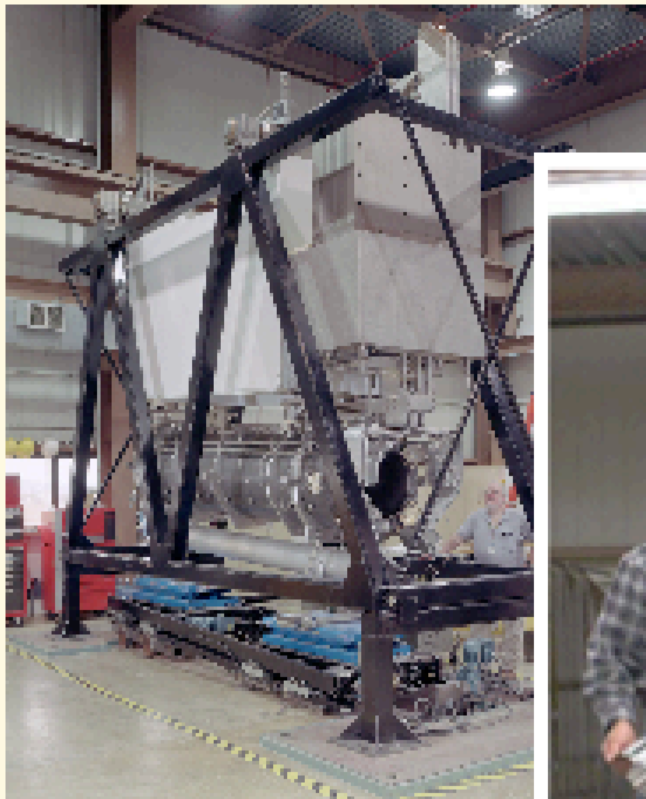


Example - NuMI Beam

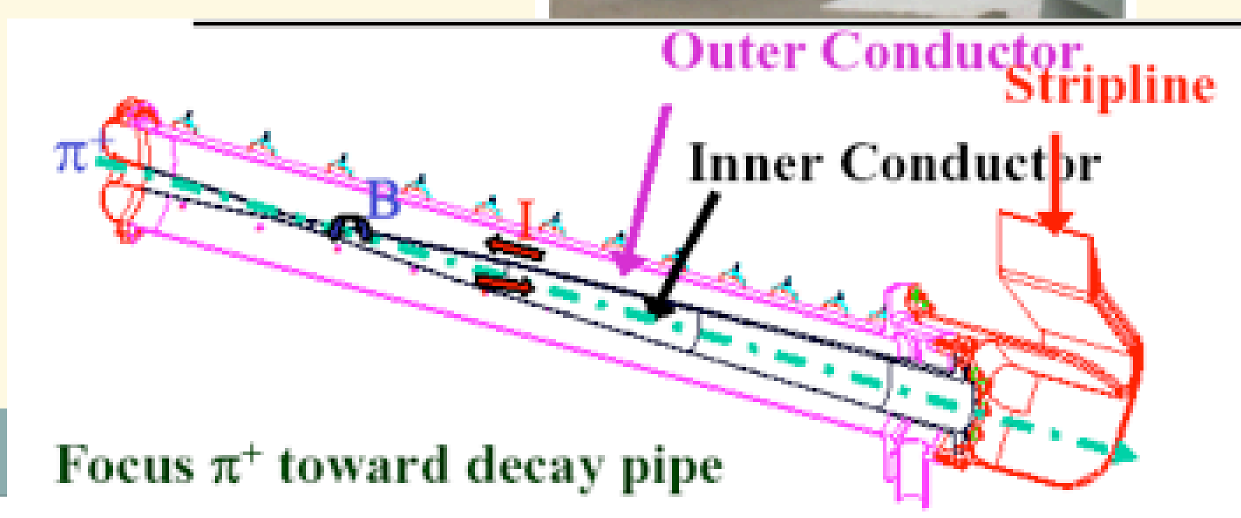


Target - interact protons, produce π and K mesons
Focusing horns - focus mesons with desired energies and charge
Decay pipe - allow mesons to decay into neutrinos; vacuum or He
Hadron monitor - used for tuning and monitoring total flux
Absorber - absorb residual protons and undecayed mesons
Muon monitors - monitor beam; secondary flux determination

Magnetic Horn

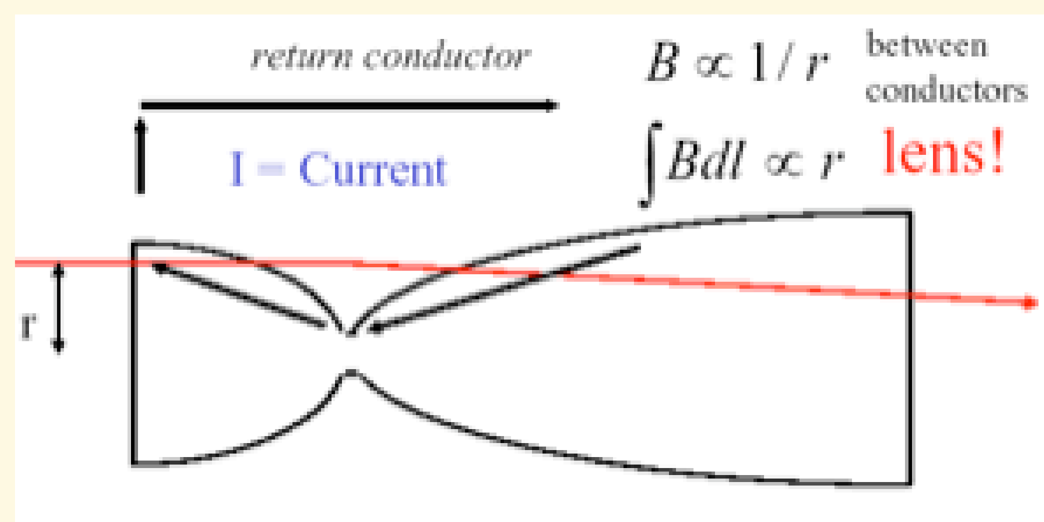


Magnetic focusing horn



More about horns

Example: NuMI horn



A Primer on Focusing

A Primer on Focusing

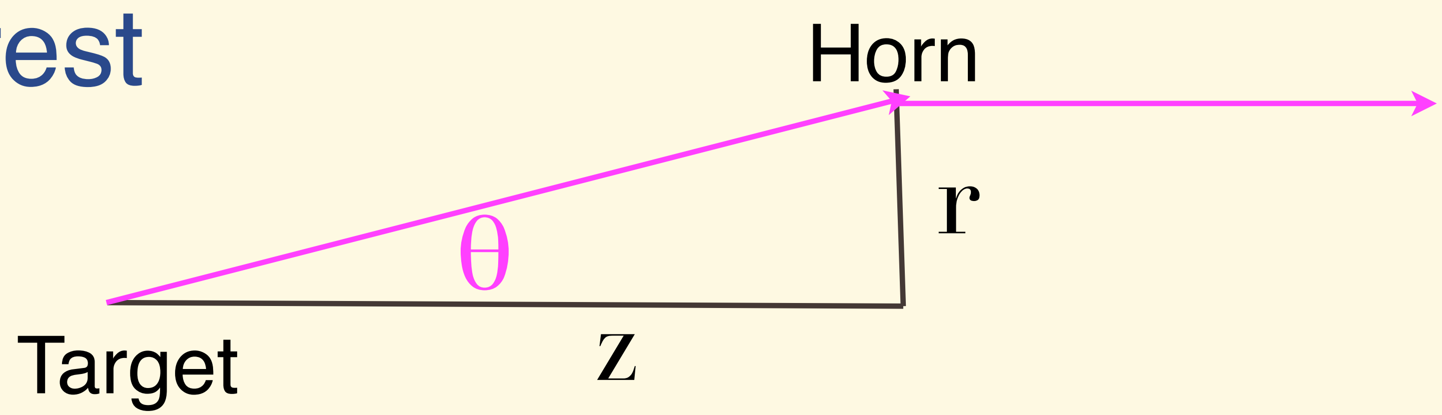
- Horn is a magnetic lens; how do we determine its optimum position and strength?

A Primer on Focusing

- Horn is a magnetic lens; how do we determine its optimum position and strength?
- Consider horn as a thin lens and target a point source; set to obtain parallel beam for energy of interest

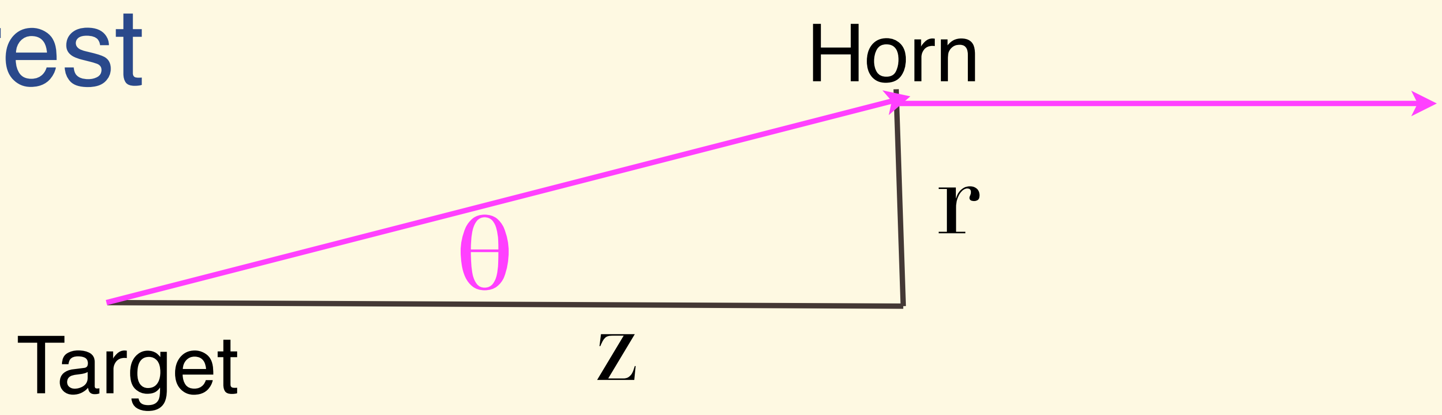
A Primer on Focusing

- Horn is a magnetic lens; how do we determine its optimum position and strength?
- Consider horn as a thin lens and target a point source; set to obtain parallel beam for energy of interest

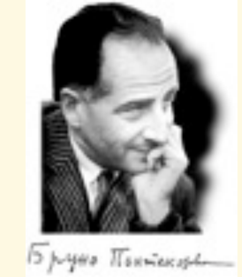


A Primer on Focusing

- Horn is a magnetic lens; how do we determine its optimum position and strength?
- Consider horn as a thin lens and target a point source; set to obtain parallel beam for energy of interest

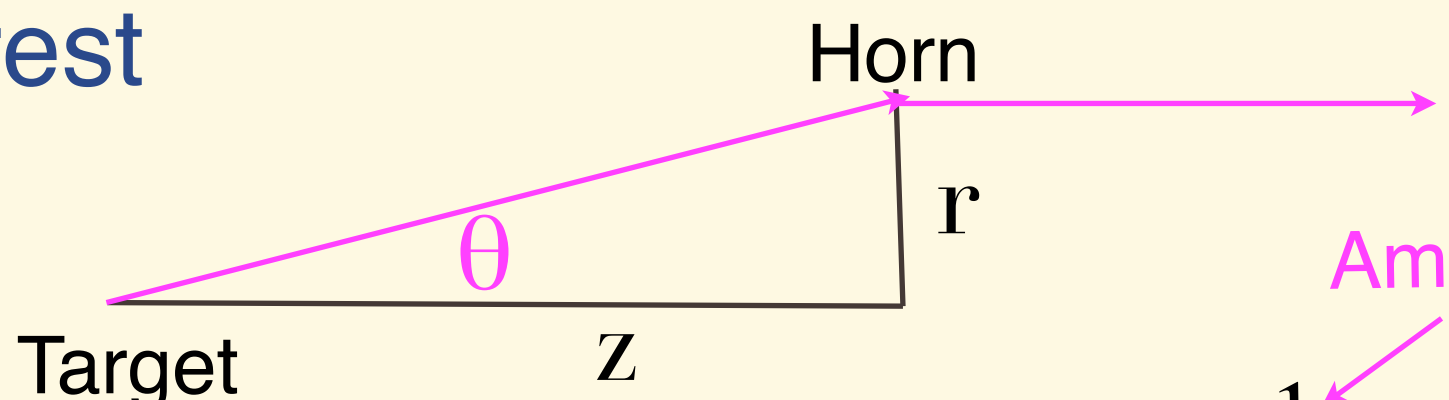


$$\theta = p_T^{beam} / p = r / z$$



A Primer on Focusing

- Horn is a magnetic lens; how do we determine its optimum position and strength?
- Consider horn as a thin lens and target a point source; set to obtain parallel beam for energy of interest



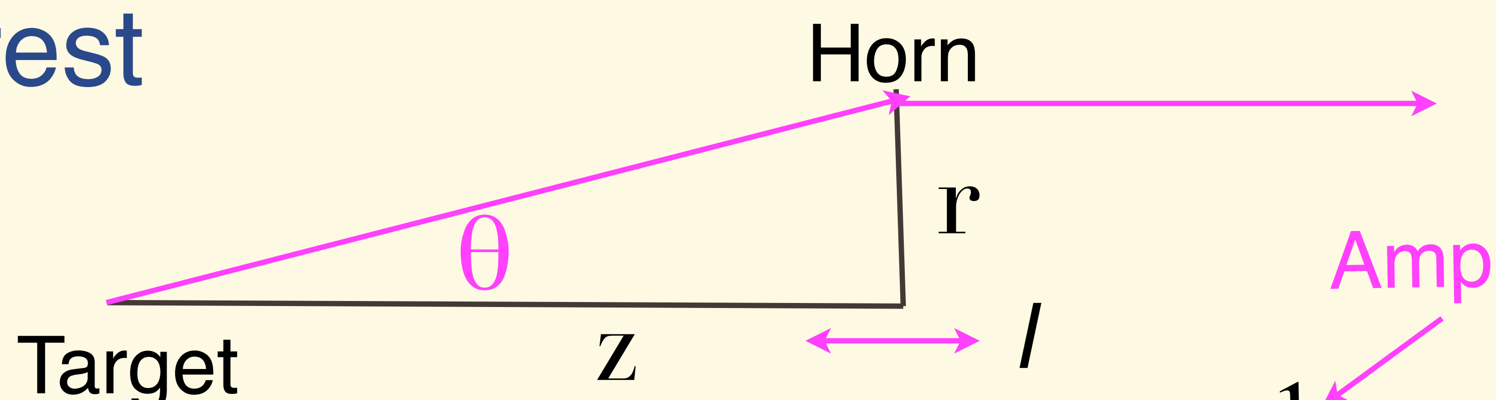
$$\theta = p_T^{beam} / p = r / z \qquad p_T^{horn} \alpha \int B\, dl = k \frac{1}{r} r^2 = kr$$

Ampere's Law

Parabolic Horn: $d=r^2$

A Primer on Focusing

- Horn is a magnetic lens; how do we determine its optimum position and strength?
- Consider horn as a thin lens and target a point source; set to obtain parallel beam for energy of interest



$$\theta = p_T^{beam} / p = r / z$$

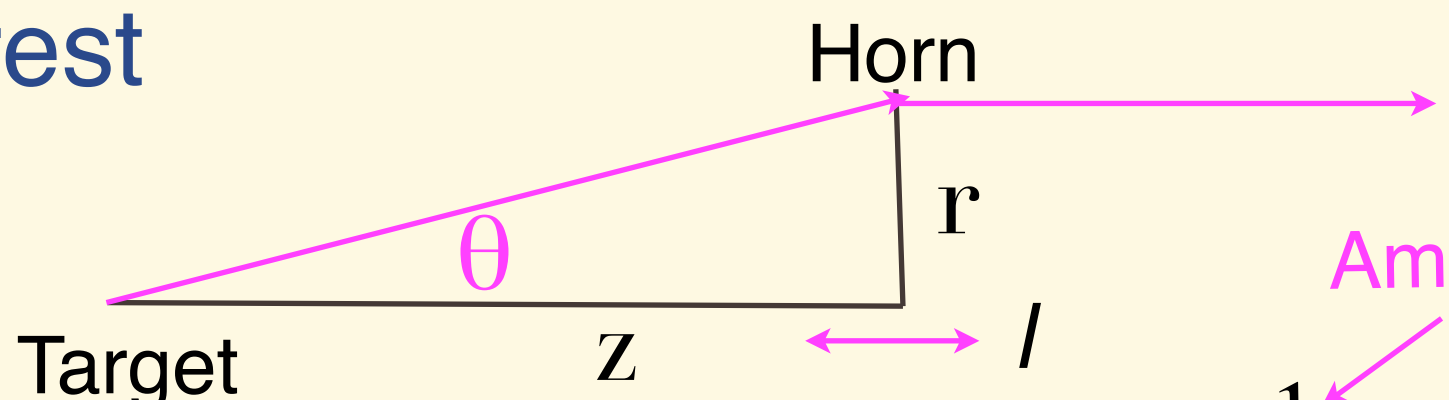
$$p_T^{horn} \alpha \int B\, dl = k \frac{1}{r} r^2 = kr$$

Ampere's Law ($\frac{1}{r}$)

Parabolic Horn: d=r^2 (r^2)

A Primer on Focusing

- Horn is a magnetic lens; how do we determine its optimum position and strength?
- Consider horn as a thin lens and target a point source; set to obtain parallel beam for energy of interest



$$\theta = p_T^{beam} / p = r / z$$

$$p_T^{horn} \alpha \int B\, dl = k \frac{1}{r} r^2 = kr$$

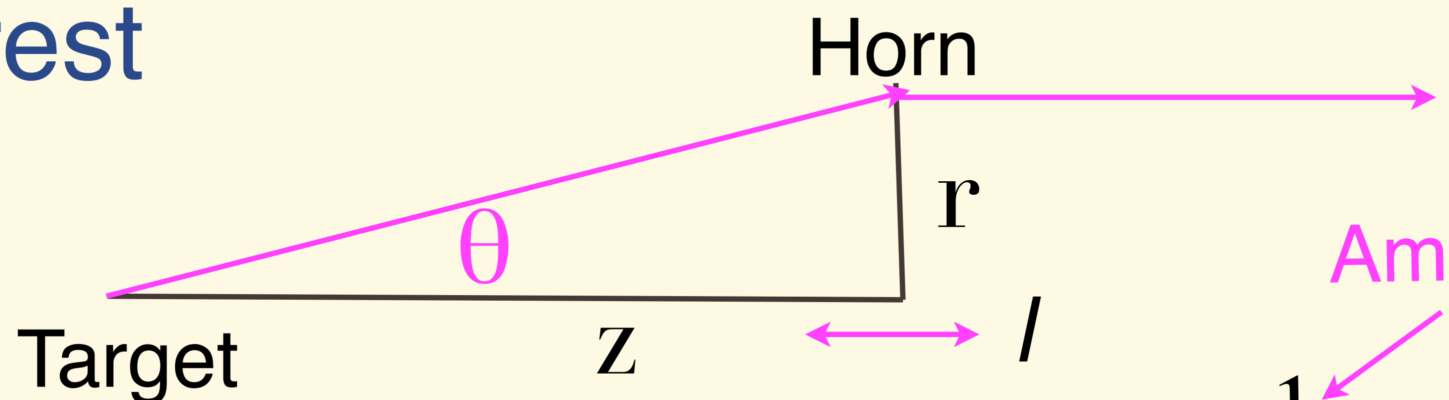
Ampere's Law

Parabolic Horn: $d=r^2$

- If possible, we set horn current so as to focus the most likely value of p_T^{beam}

A Primer on Focusing

- Horn is a magnetic lens; how do we determine its optimum position and strength?
- Consider horn as a thin lens and target a point source; set to obtain parallel beam for energy of interest



$$\theta = p_T^{beam} / p = r / z \qquad p_T^{horn} \alpha \int B\, dl = k \frac{1}{r} r^2 = kr$$

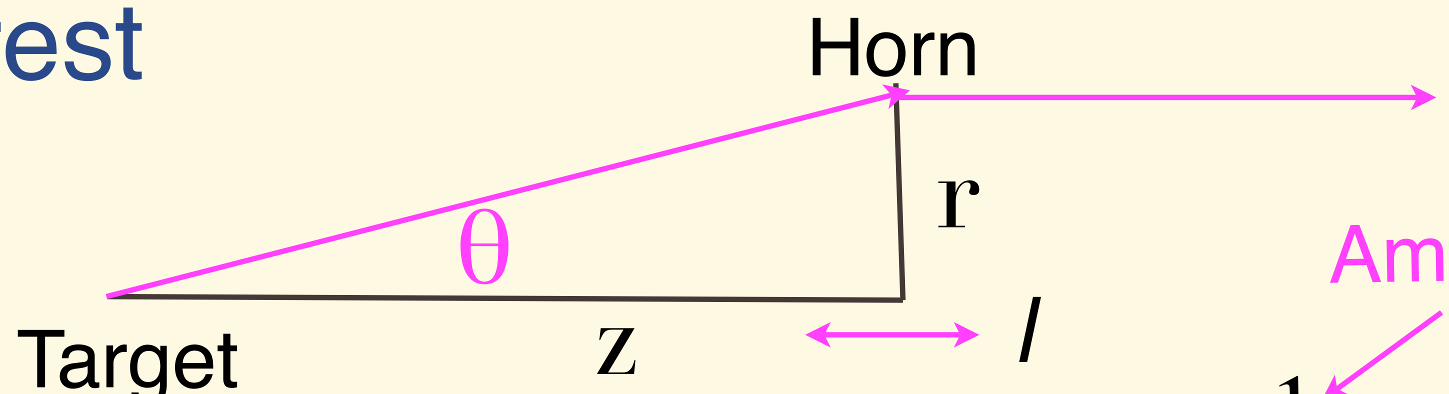
Ampere's Law

Parabolic Horn: $d=r^2$

- If possible, we set horn current so as to focus the most likely value of p_T^{beam}
- Hence $p_T^{beam} = p_T^{horn}$

A Primer on Focusing

- Horn is a magnetic lens; how do we determine its optimum position and strength?
- Consider horn as a thin lens and target a point source; set to obtain parallel beam for energy of interest



$$\theta = p_T^{beam} / p = r / z \qquad p_T^{horn} \alpha \int B\,dl = k \frac{1}{r} r^2 = kr$$

Ampere's Law

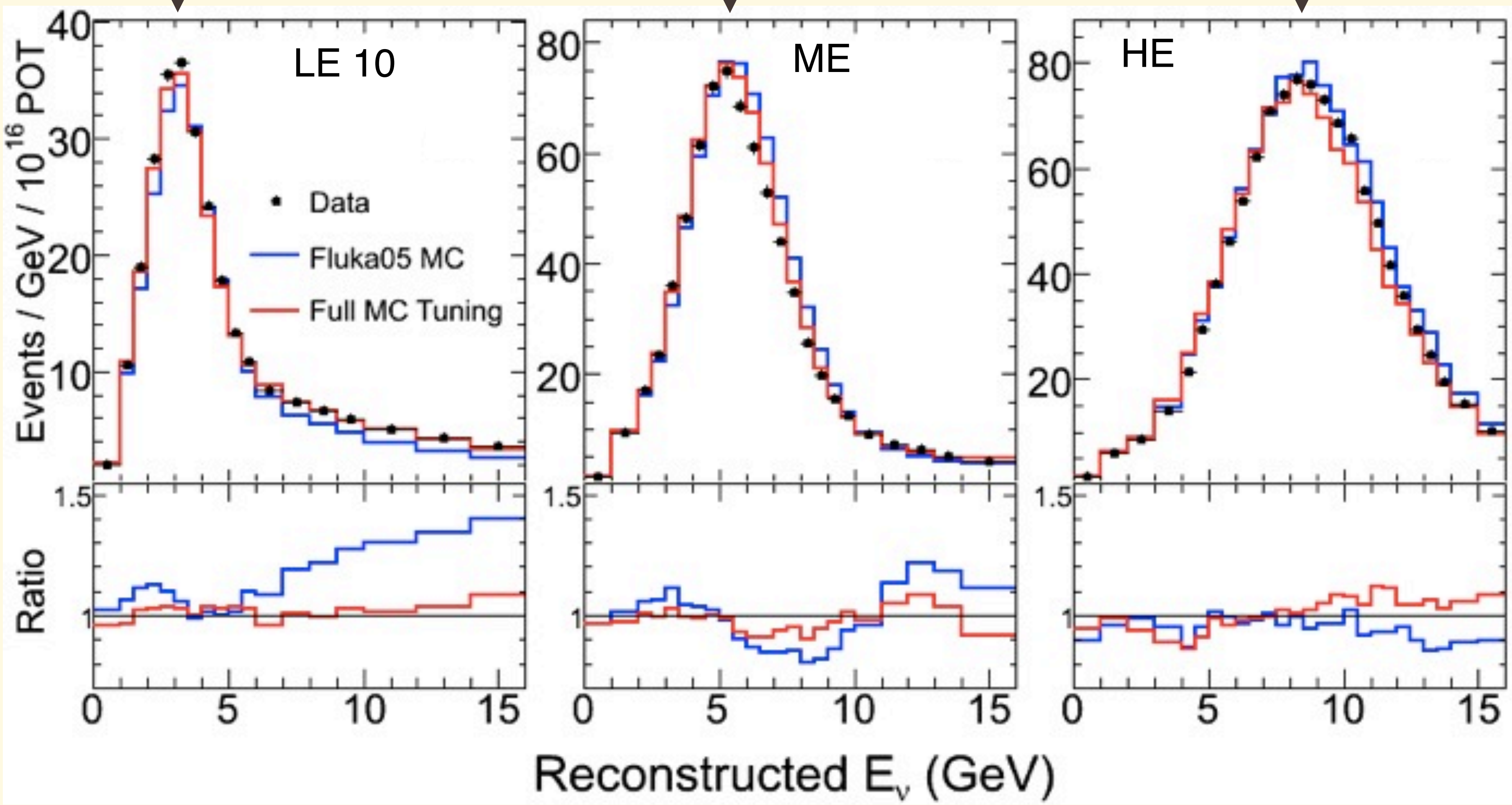
Parabolic Horn: $d=r^2$

- If possible, we set horn current so as to focus the most likely value of p_T^{beam}
- Hence $p_T^{beam} = p_T^{horn} \qquad pr / z = kr \rightarrow \boxed{p / z = k}$

Example: NuMI Beam

Thus as we move target back, we focus higher momenta; but due to other effects there are deviations from strict linearity.

3 GeV 5.5 GeV 8.5 GeV



z = 10cm 100 cm 250 cm

Other effects:

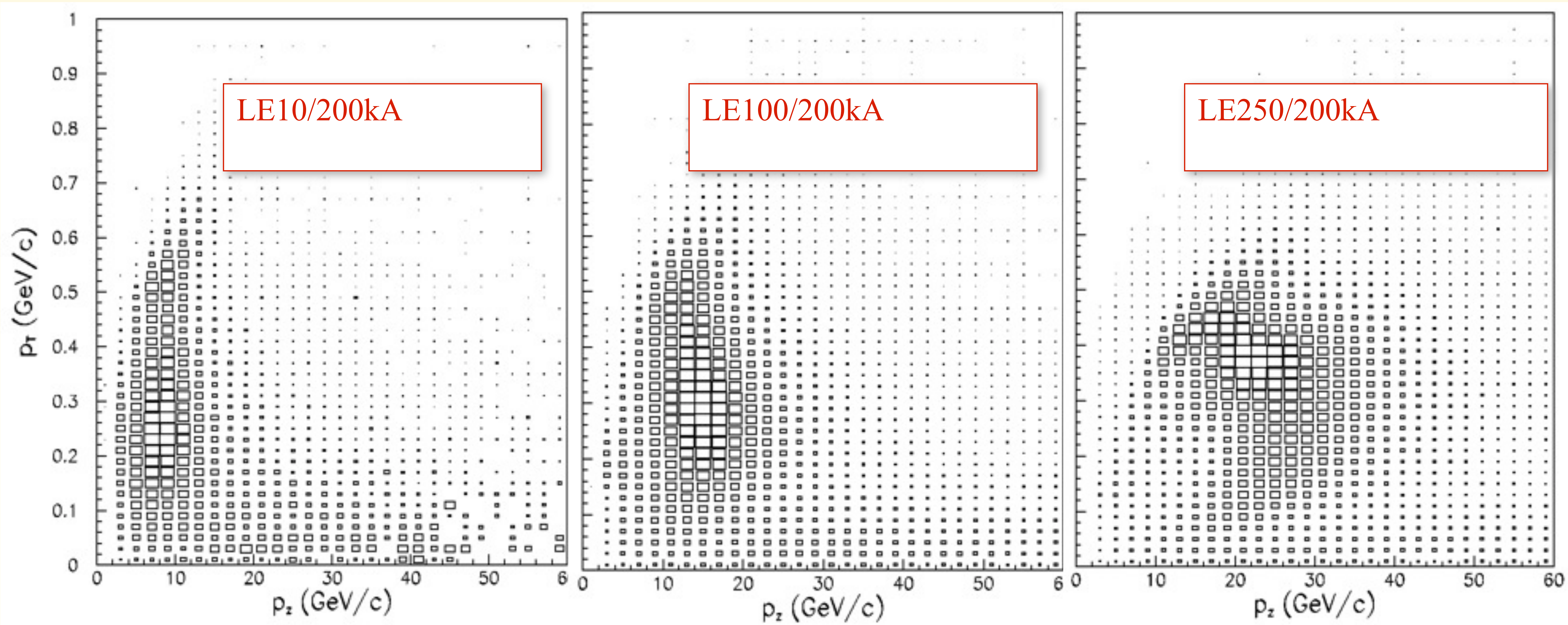
2nd horn

Finite length target

Finite horn length

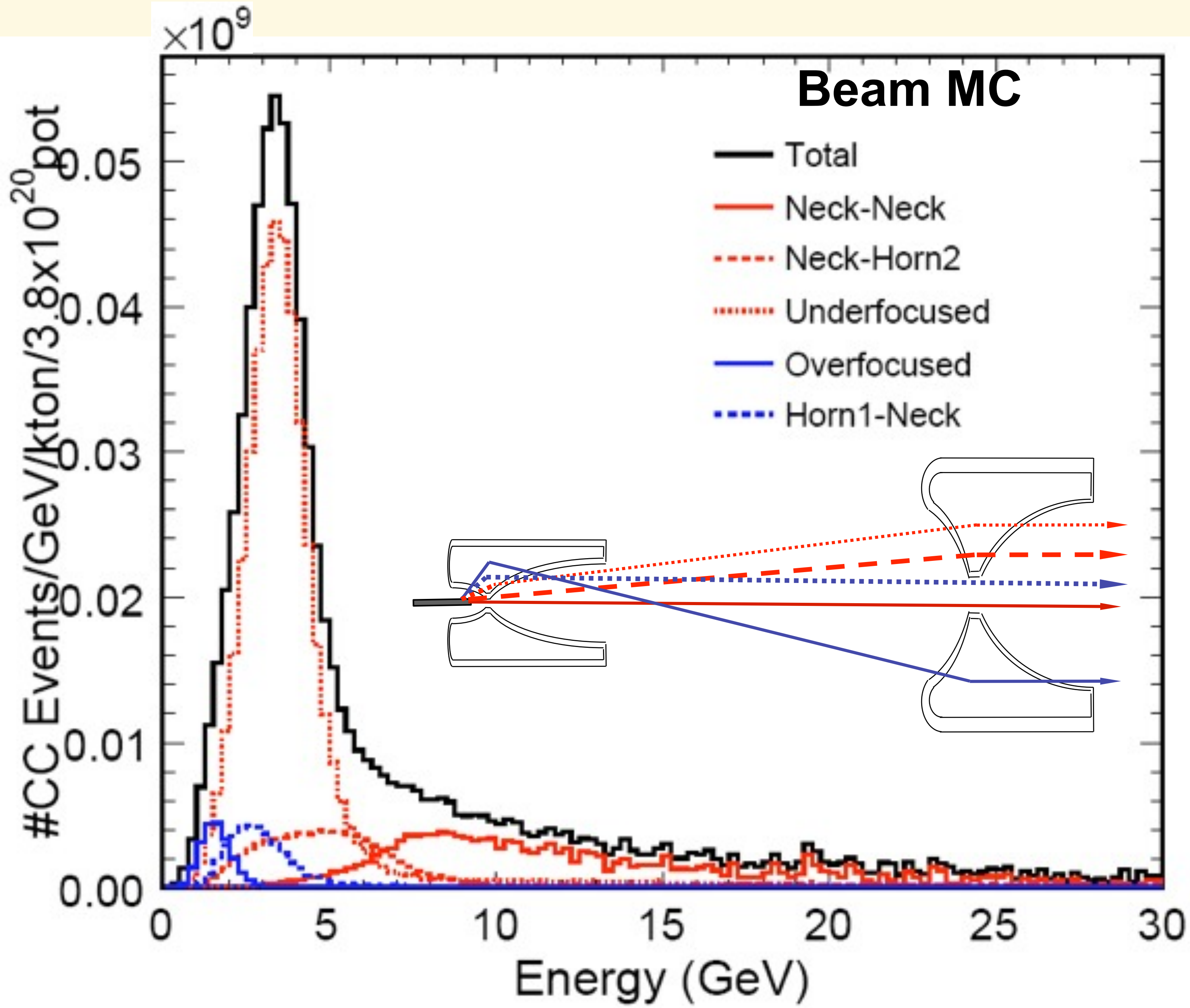
Secondary interactions

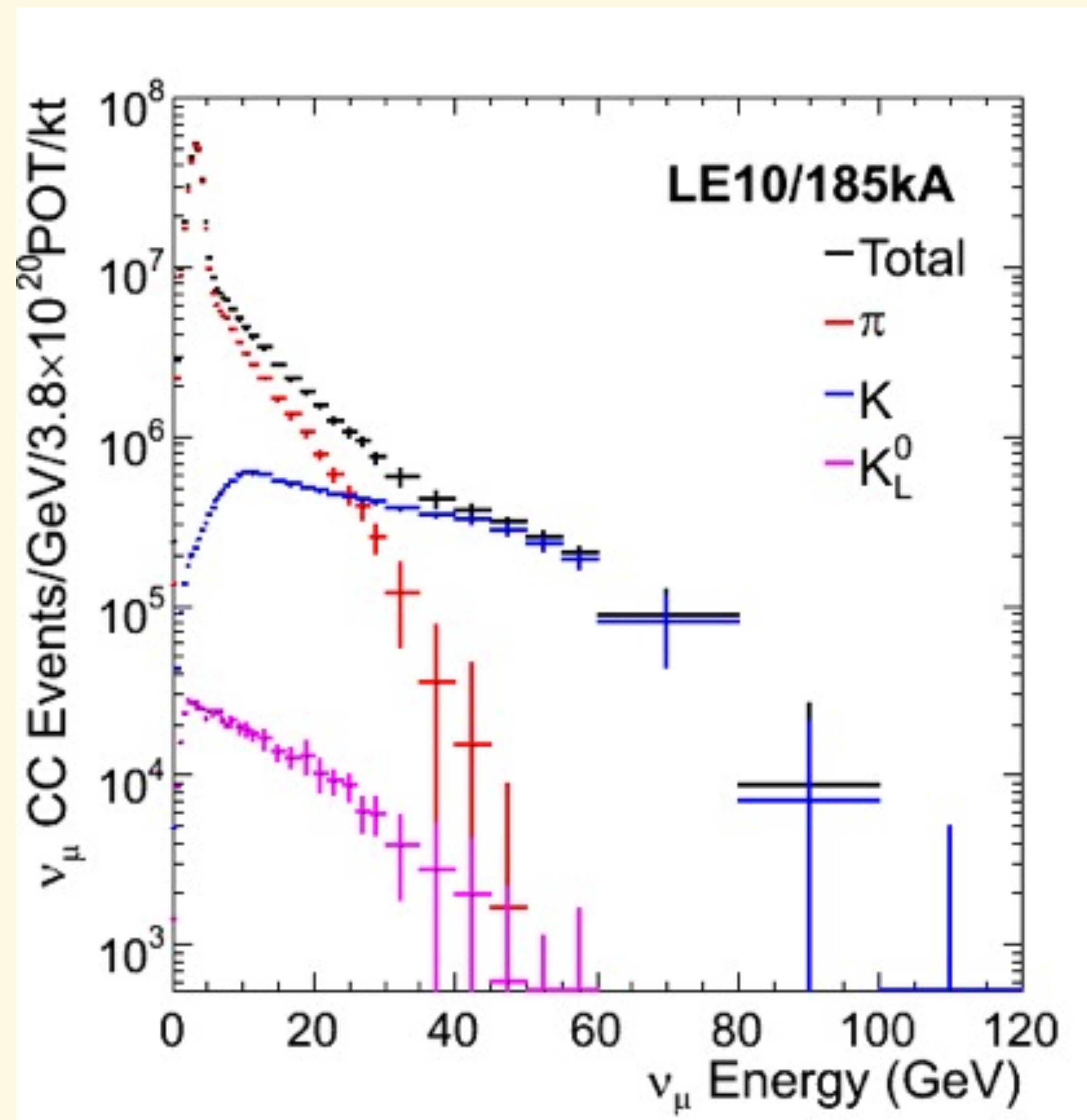
P_T - P_z Distributions



As target is moved back, the p_z distribution of accepted events shifts to higher values but p_T does not change very much

Trajectories





Variations

Variations

- There are a number of variations on the standard conventional (wide band) beam

Variations

- There are a number of variations on the standard conventional (wide band) beam
  - Sign selected beam; use a dipole to reject mesons of other sign

Variations

- There are a number of variations on the standard conventional (wide band) beam
  - Sign selected beam; use a dipole to reject mesons of other sign
  - Narrow band beam; selects specific Δp

Variations

- There are a number of variations on the standard conventional (wide band) beam
  - Sign selected beam; use a dipole to reject mesons of other sign
  - Narrow band beam; selects specific Δp
  - Beam dump “beam”:

Variations

- There are a number of variations on the standard conventional (wide band) beam
  - Sign selected beam; use a dipole to reject mesons of other sign
  - Narrow band beam; selects specific Δp
  - Beam dump “beam”:
    - one variant is a low energy version using ν’s from stopped π and μ decays; low energy; well defined spectrum

Variations

- There are a number of variations on the standard conventional (wide band) beam
  - Sign selected beam; use a dipole to reject mesons of other sign
  - Narrow band beam; selects specific Δp
  - Beam dump "beam":
    - one variant is a low energy version using ν's from stopped π and μ decays; low energy; well defined spectrum
    - other version is high energy; gives high fraction of ν's from short lived particles; useful as a source of ν_τ's

Variations

- There are a number of variations on the standard conventional (wide band) beam
  - Sign selected beam; use a dipole to reject mesons of other sign
  - Narrow band beam; selects specific Δp
  - Beam dump "beam":
    - one variant is a low energy version using ν's from stopped π and μ decays; low energy; well defined spectrum
    - other version is high energy; gives high fraction of ν's from short lived particles; useful as a source of ν_τ's
  - Off-axis beam; the detector is positioned at a small angle away from the beam axis. This enhances a narrow band of neutrino energies

More on Off-axis Beam

More on Off-axis Beam

At certain angles pions of different energies generate neutrinos in a relatively narrow band of energies

As a results a relatively narrow band beam is created with a flux in the desired energy range greater than in that portion of the on-axis beam

More on Off-axis Beam

At certain angles pions of different energies generate neutrinos in a relatively narrow band of energies

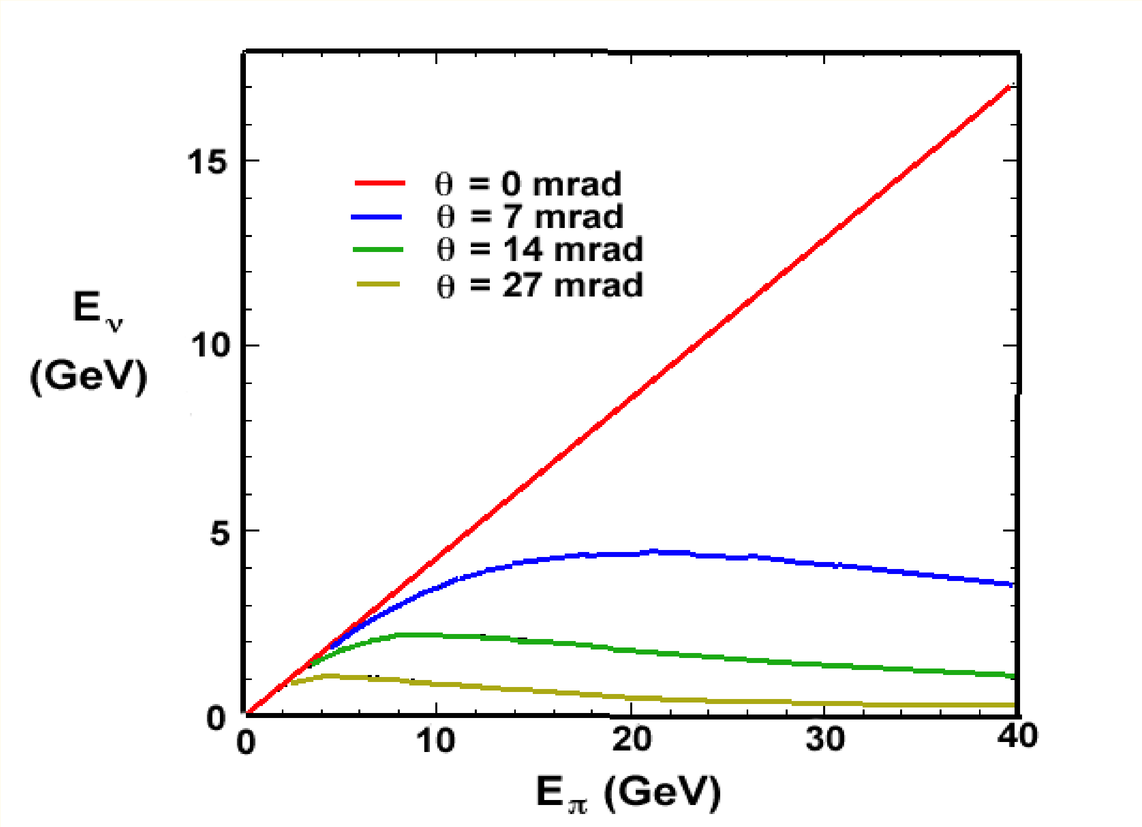
As a results a relatively narrow band beam is created with a flux in the desired energy range greater than in that portion of the on-axis beam

Example of this principle from NuMI beam

More on Off-axis Beam

At certain angles pions of different energies generate neutrinos in a relatively narrow band of energies

As a results a relatively narrow band beam is created with a flux in the desired energy range greater than in that portion of the on-axis beam

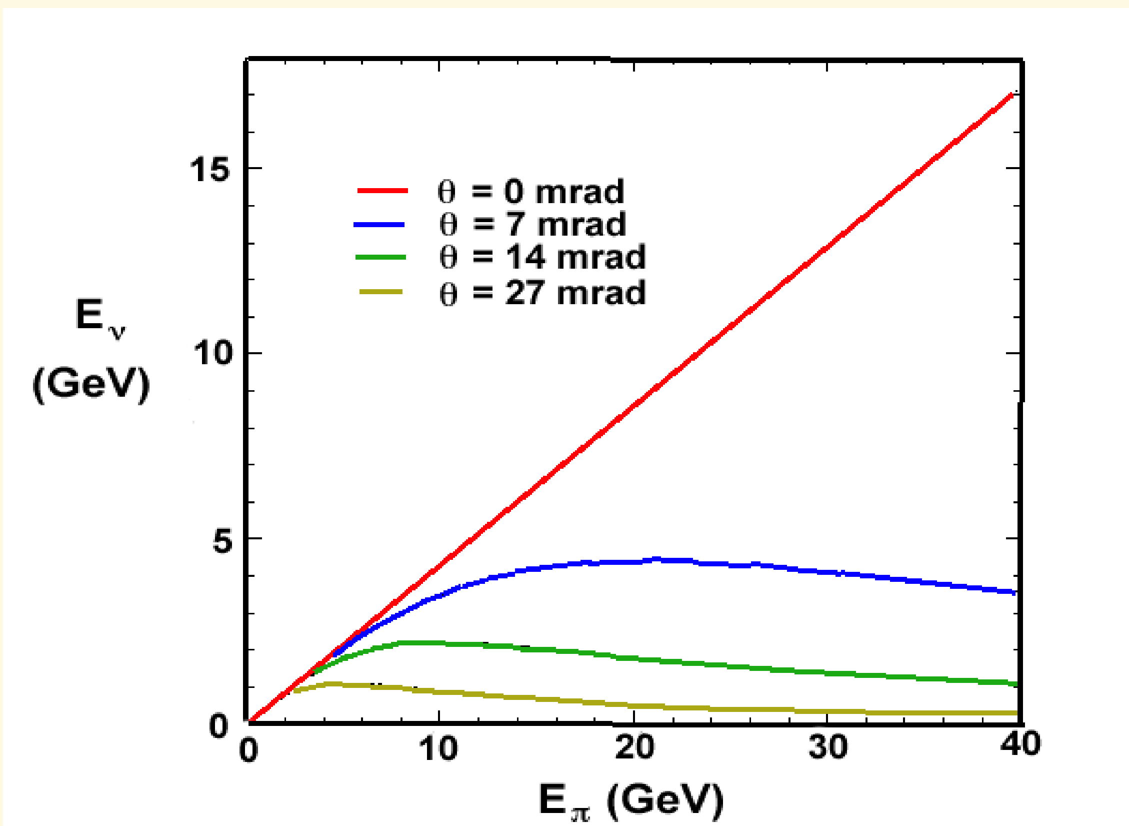


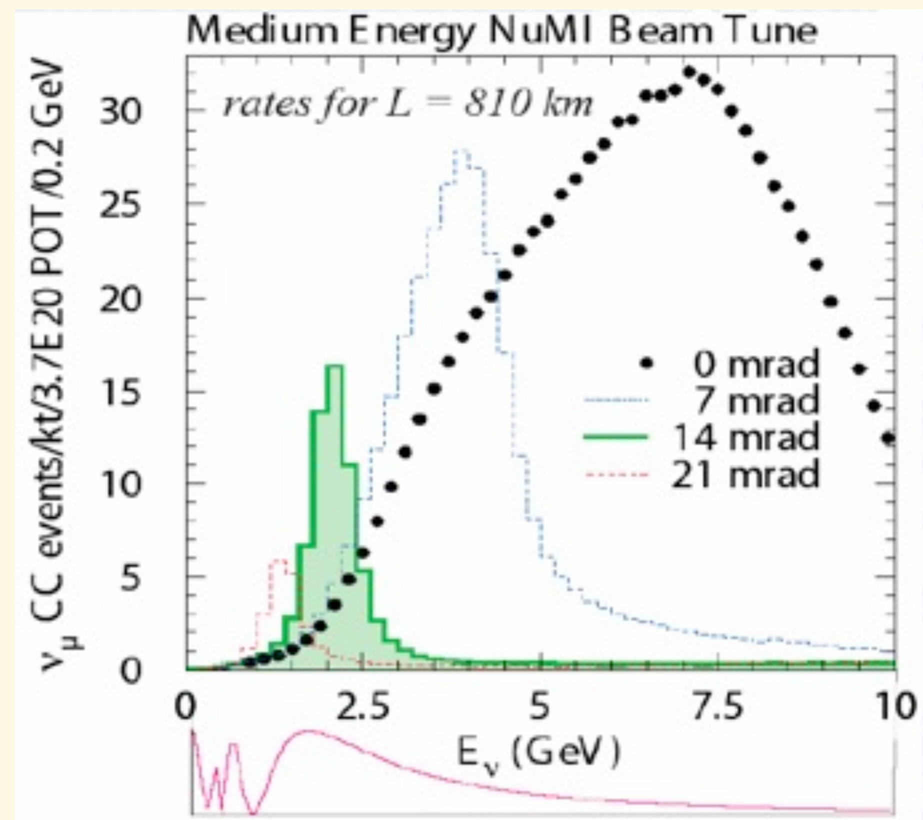
Example of this principle from NuMI beam

More on Off-axis Beam

At certain angles pions of different energies generate neutrinos in a relatively narrow band of energies

As a results a relatively narrow band beam is created with a flux in the desired energy range greater than in that portion of the on-axis beam





Example of this principle from NuMI beam

Obtaining Energy Spectrum

Obtaining Energy Spectrum

- Most experiments require knowledge of their neutrino energy spectrum to extract physics

Obtaining Energy Spectrum

- Most experiments require knowledge of their neutrino energy spectrum to extract physics
- In principle that information can be obtained from hadronic (parent) production data

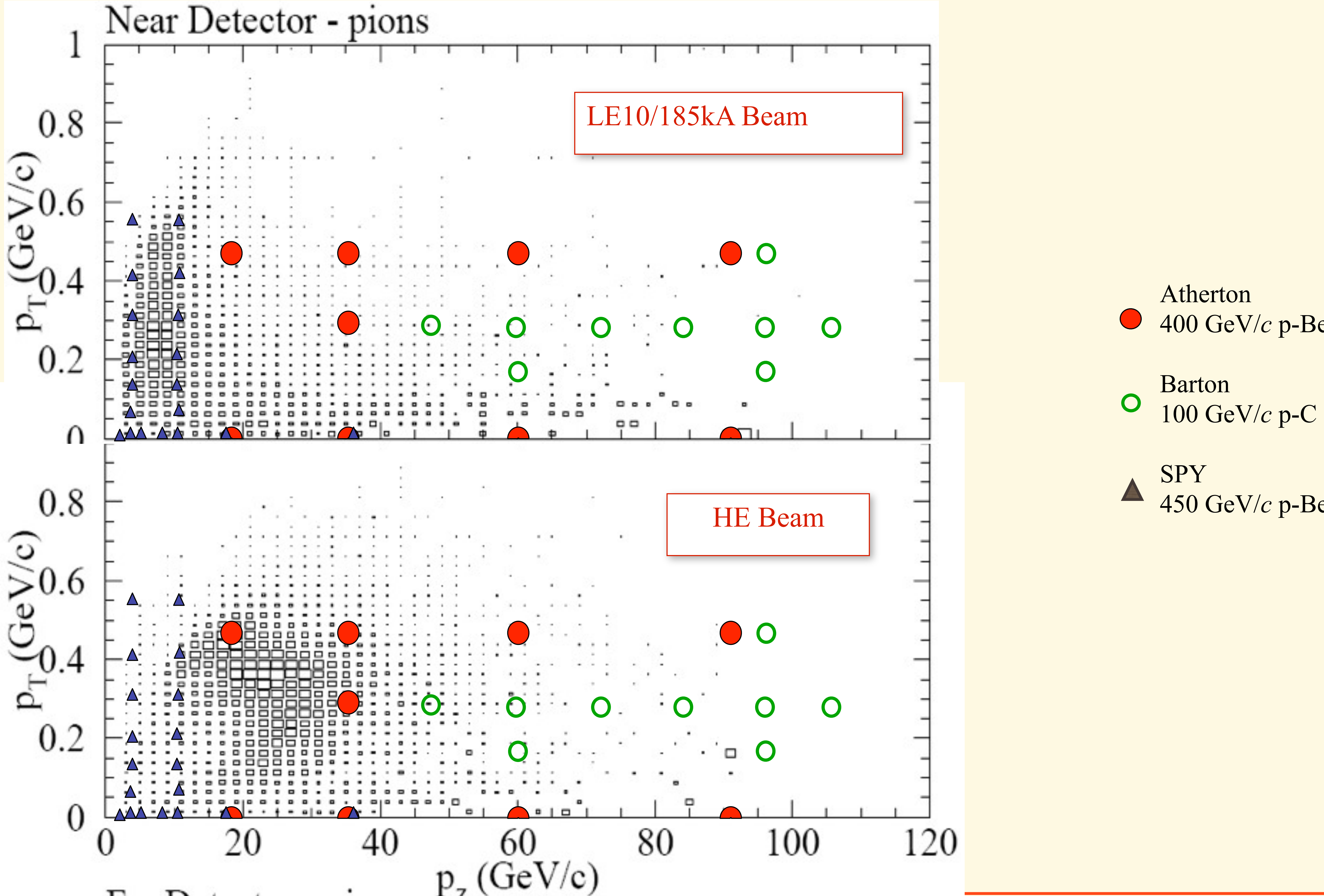
Obtaining Energy Spectrum

- Most experiments require knowledge of their neutrino energy spectrum to extract physics
- In principle that information can be obtained from hadronic (parent) production data
- But currently those data are not adequate and there are potential issues with the effect of surroundings

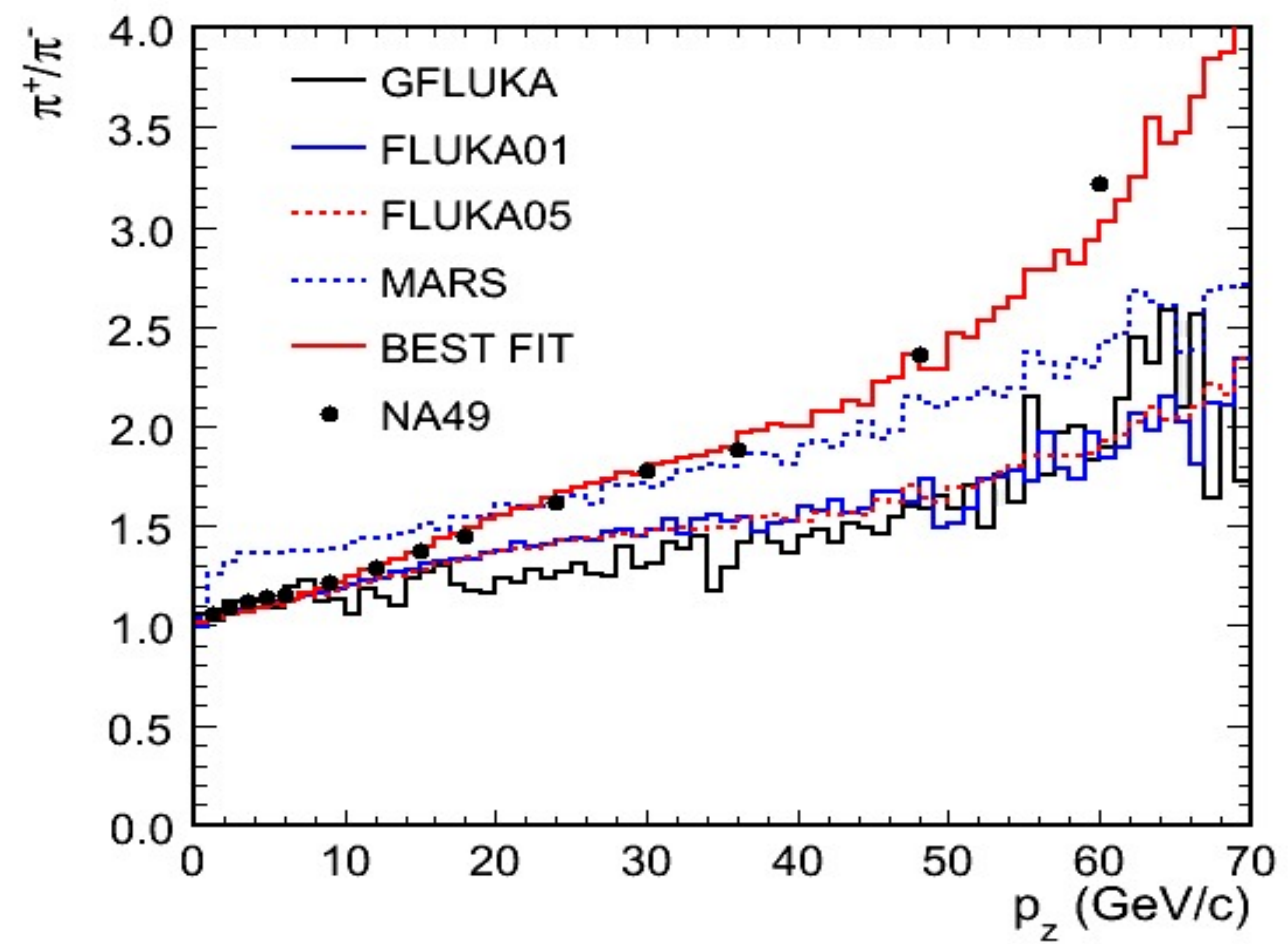
Obtaining Energy Spectrum

- Most experiments require knowledge of their neutrino energy spectrum to extract physics
- In principle that information can be obtained from hadronic (parent) production data
- But currently those data are not adequate and there are potential issues with the effect of surroundings
- 2 detector configuration, allowing extraction of Far Detector flux from Near Detector data appears to be the currently favored method to do this for long baseline oscillation experiments

Available Production Data



NuMI spectra



Near Detector Issues

Near Detector Issues

- There are two views regarding Near Detector

Near Detector Issues

- There are two views regarding Near Detector
  - It should be as identical as possible to the Far Detector in its composition

Near Detector Issues

- There are two views regarding Near Detector
  - It should be as identical as possible to the Far Detector in its composition
  - It should be designed for optimum determination of the neutrino flux composition and its energy

Near Detector Issues

- There are two views regarding Near Detector
  - It should be as identical as possible to the Far Detector in its composition
  - It should be designed for optimum determination of the neutrino flux composition and its energy
- Ideally you would like to have both since each has some advantages and disadvantages

Near Detector Issues

- There are two views regarding Near Detector
  - It should be as identical as possible to the Far Detector in its composition
  - It should be designed for optimum determination of the neutrino flux composition and its energy
- Ideally you would like to have both since each has some advantages and disadvantages
  - In the first, you may have pileup problems; do not learn the composition well

Near Detector Issues

- There are two views regarding Near Detector
  - It should be as identical as possible to the Far Detector in its composition
  - It should be designed for optimum determination of the neutrino flux composition and its energy
- Ideally you would like to have both since each has some advantages and disadvantages
  - In the first, you may have pileup problems; do not learn the composition well
  - In the second you do not learn about nuclear effects, detection efficiency, background which may be limiting factors in the experiment

Example: MINOS Strategy

Example: MINOS Strategy

MINOS strategy is to have the two detectors as similar as possible to each other

Example: MINOS Strategy

MINOS strategy is to have the two detectors as similar as possible to each other

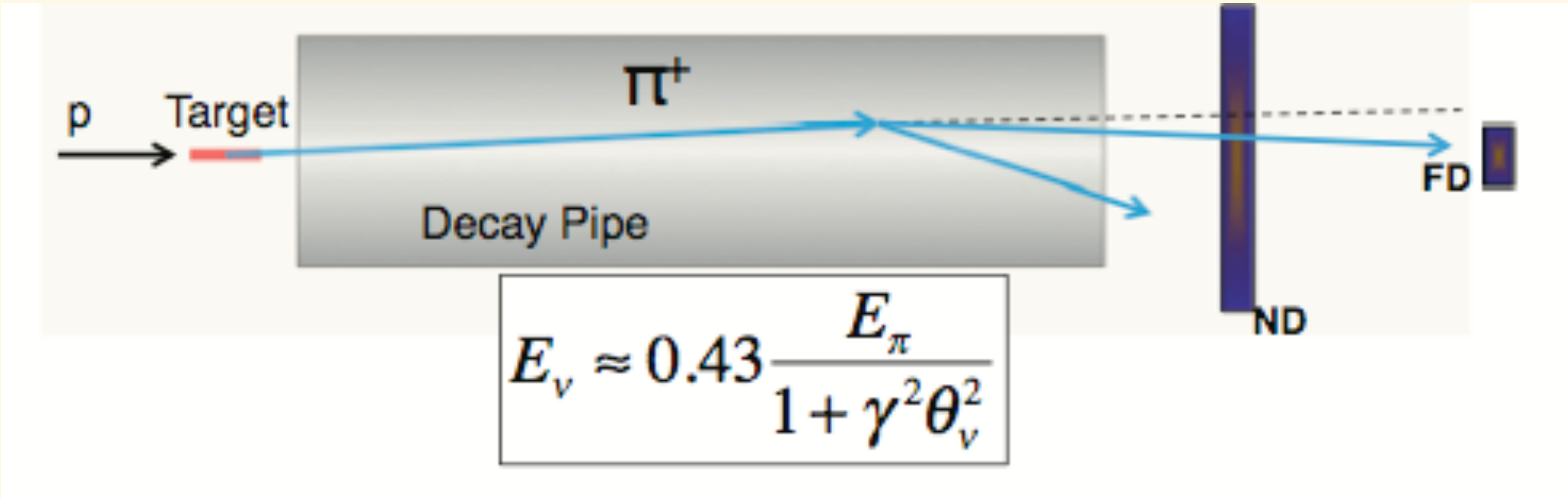
The spectra in the two detectors are similar but not identical in the two detectors

Example: MINOS Strategy

MINOS strategy is to have the two detectors as similar as possible to each other

The spectra in the two detectors are similar but not identical in the two detectors

The main reasons for the difference is that lower energy mesons decay closer to the target (smaller dΩ for ND) and give wider angle ν's in the ND



$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

Near Far Extrapolation

Near Far Extrapolation

The Far Detector flux can be obtained from:

$$N_{FD}^{pred} = \left(N_{FD}^{MC} / N_{ND}^{MC} \right) N_{ND}^{obs}$$

Near Far Extrapolation

The Far Detector flux can be obtained from:

$$N_{FD}^{pred} = \left(N_{FD}^{MC} / N_{ND}^{MC} \right) N_{ND}^{obs}$$

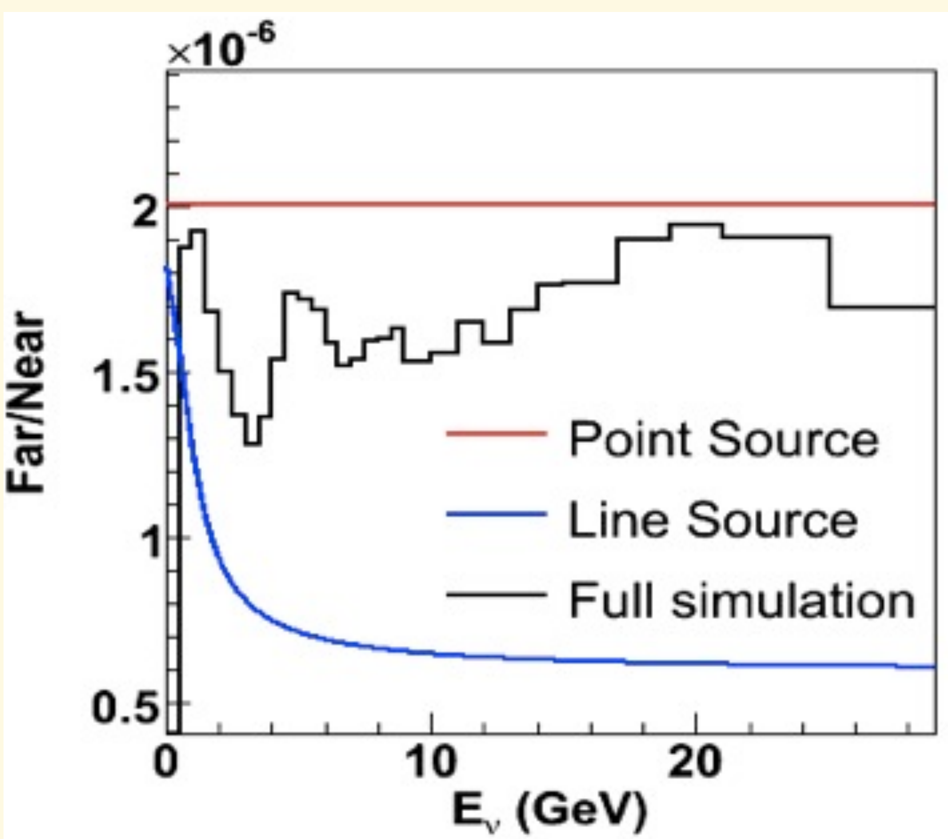
The Monte Carlo ratio can be either simple Far/Near ratio or a ratio obtained from matrix extrapolation

Near Far Extrapolation

The Far Detector flux can be obtained from:

$$N_{FD}^{pred} = \left(N_{FD}^{MC} / N_{ND}^{MC}\right) N_{ND}^{obs}$$

The Monte Carlo ratio can be either simple Far/Near ratio or a ratio obtained from matrix extrapolation

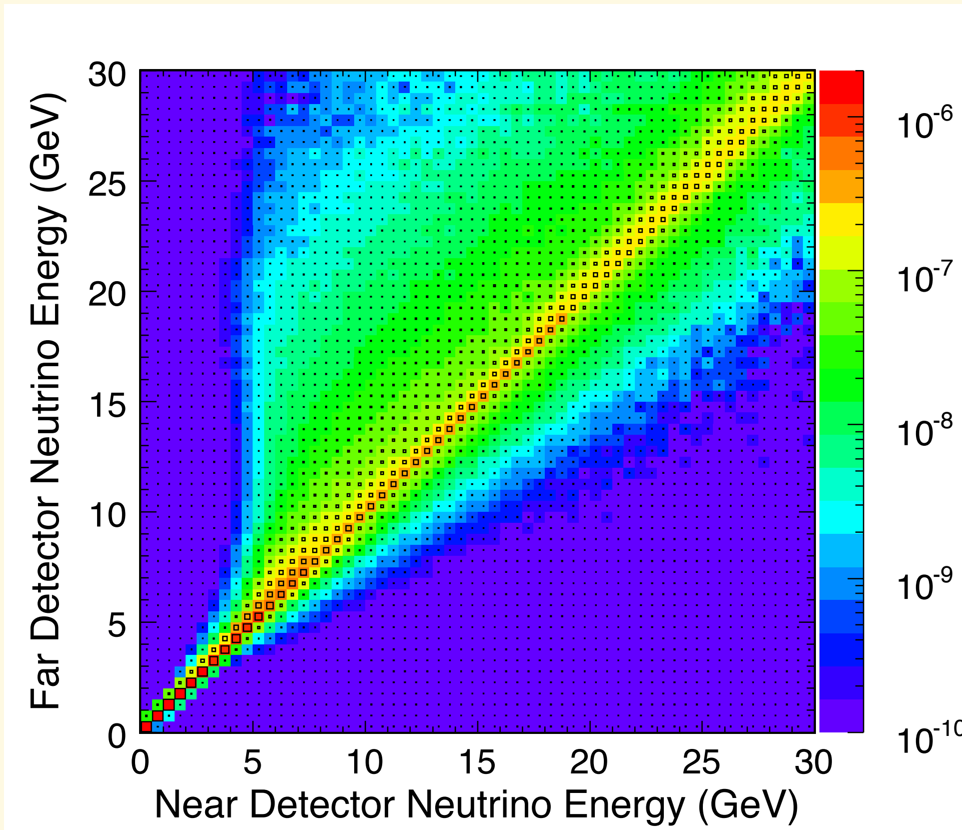


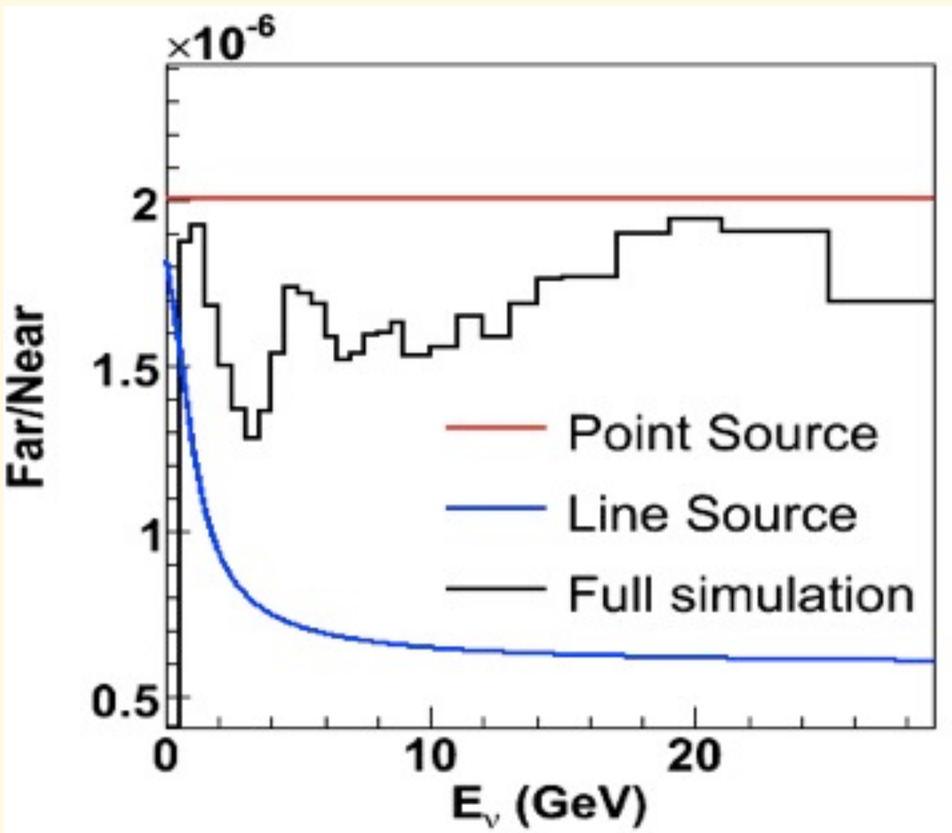
Near Far Extrapolation

The Far Detector flux can be obtained from:

$$N_{FD}^{pred} = \left(N_{FD}^{MC} / N_{ND}^{MC} \right) N_{ND}^{obs}$$

The Monte Carlo ratio can be either simple Far/Near ratio or a ratio obtained from matrix extrapolation



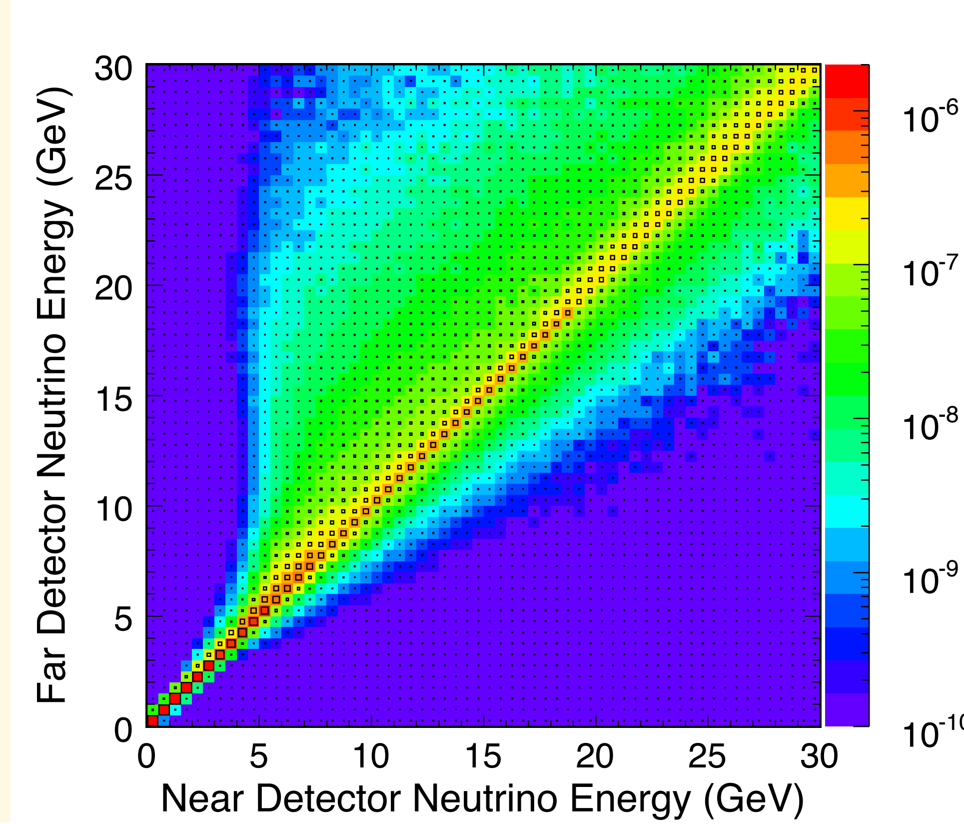


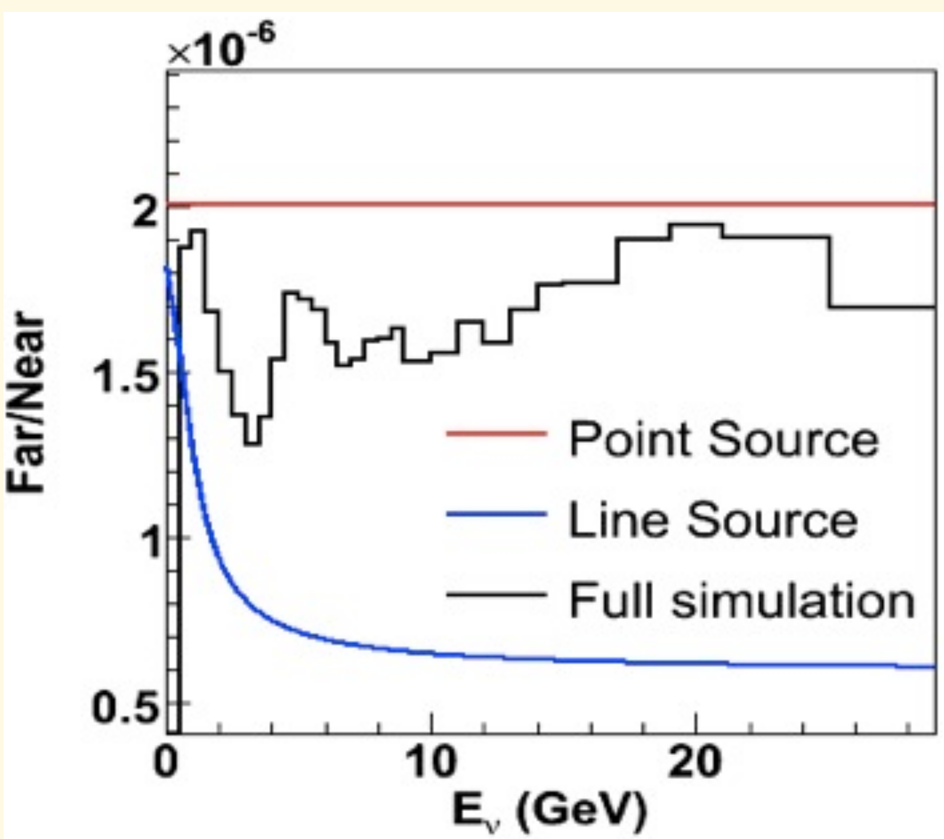
Near Far Extrapolation

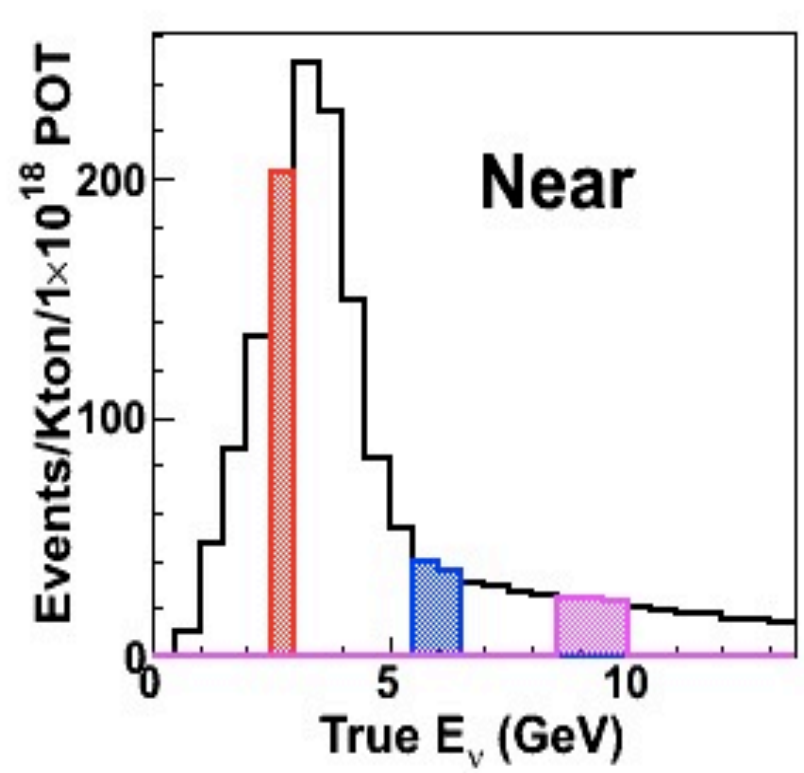
The Far Detector flux can be obtained from:

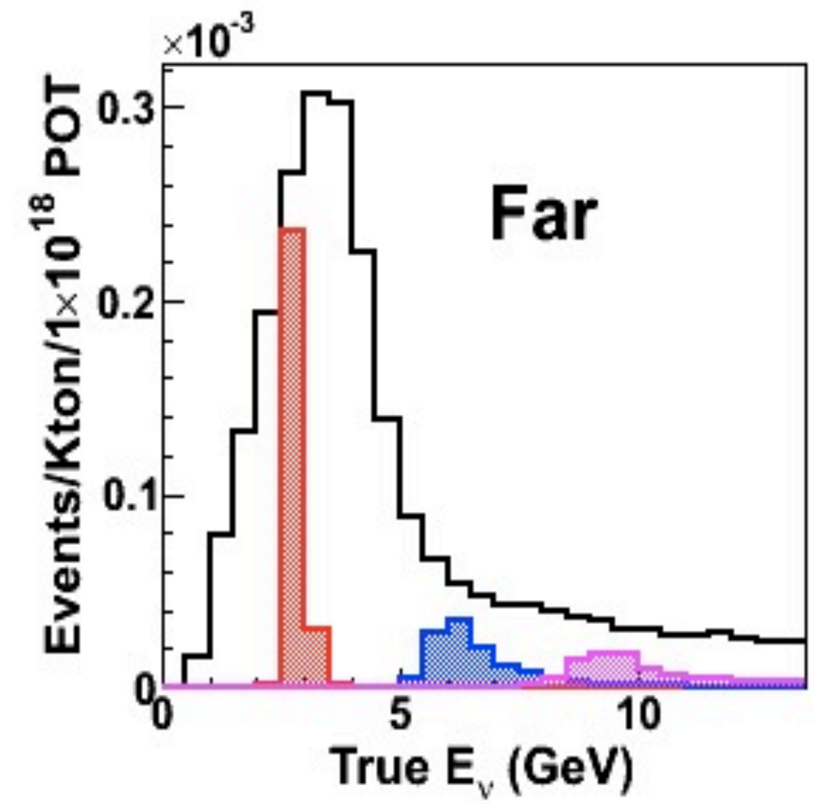
$$N_{FD}^{pred} = \left(N_{FD}^{MC} / N_{ND}^{MC} \right) N_{ND}^{obs}$$

The Monte Carlo ratio can be either simple Far/Near ratio or a ratio obtained from matrix extrapolation









Studies of $\sin^2(2\theta_{23})$ and Δm^2_{31}

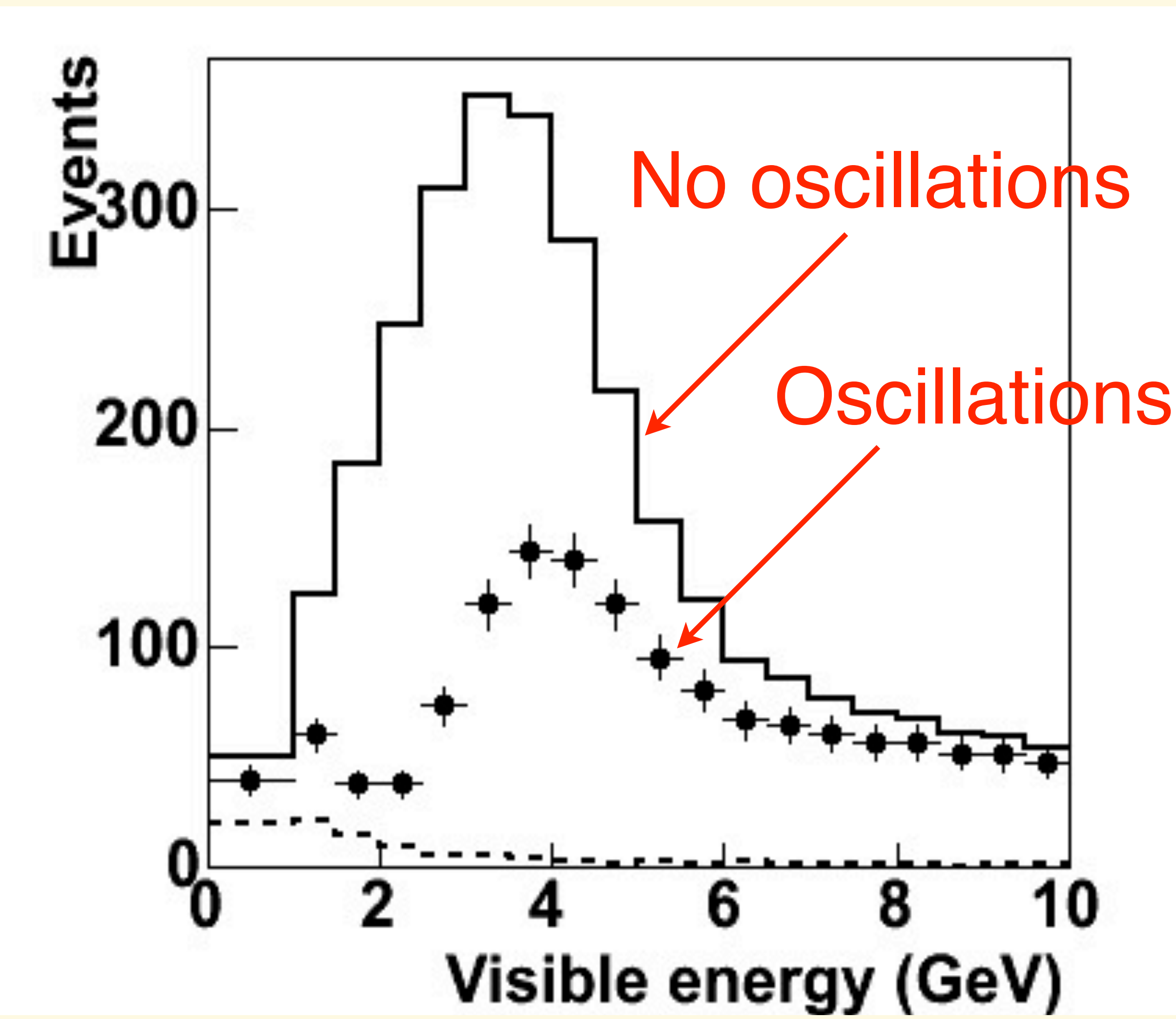
General Method

General Method

Two flavor approximation: $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$

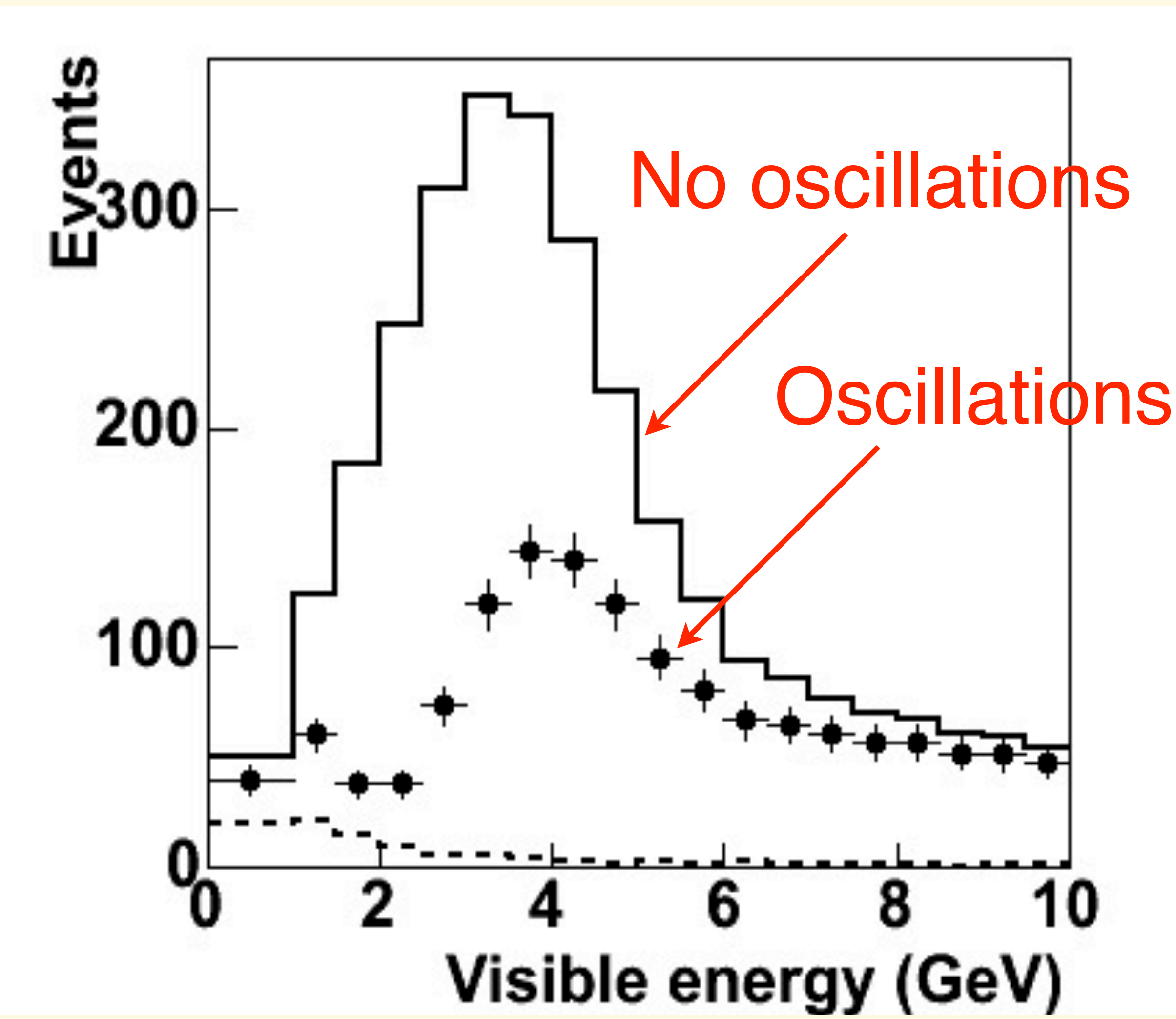
General Method

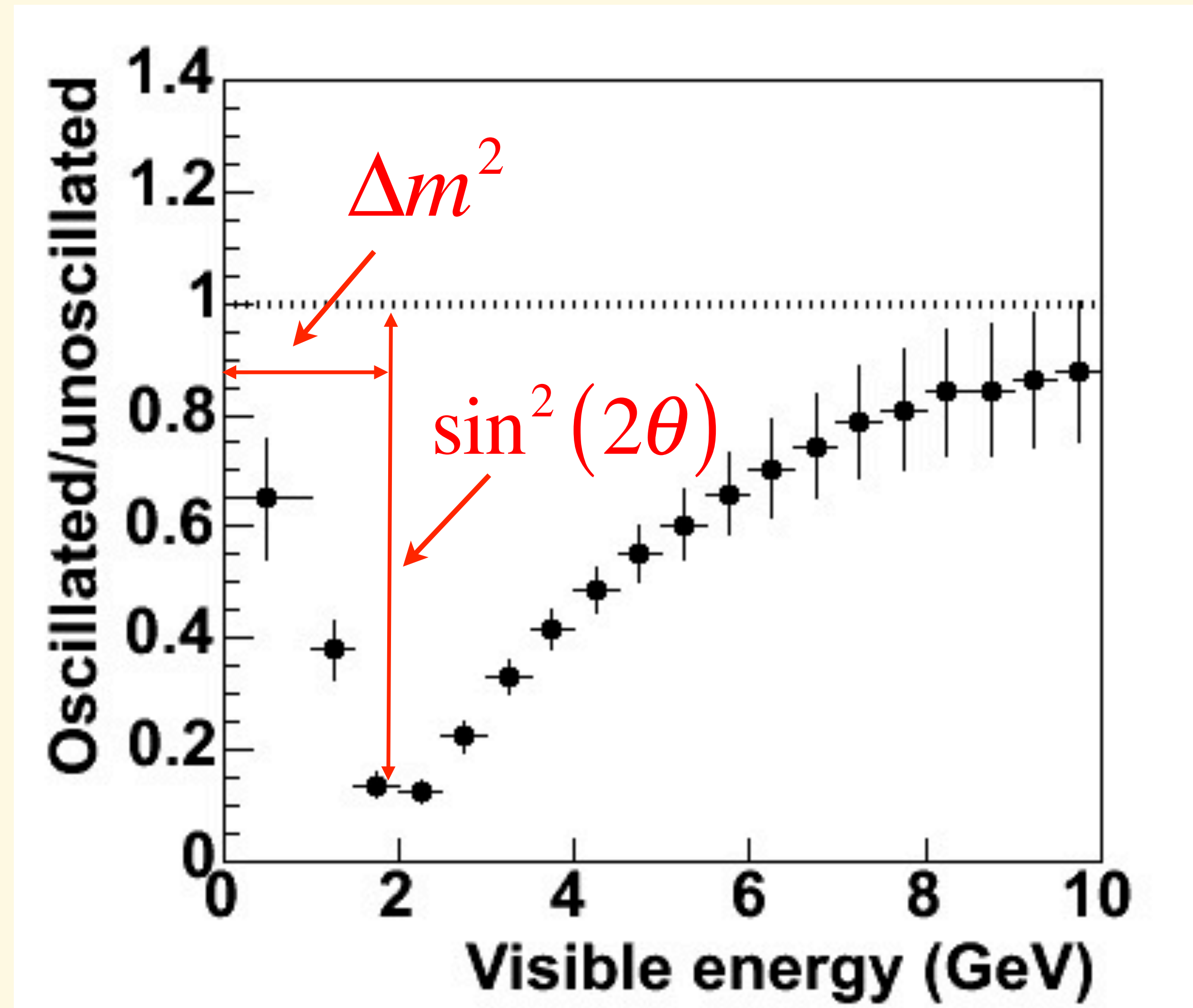
Two flavor approximation: $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$



General Method

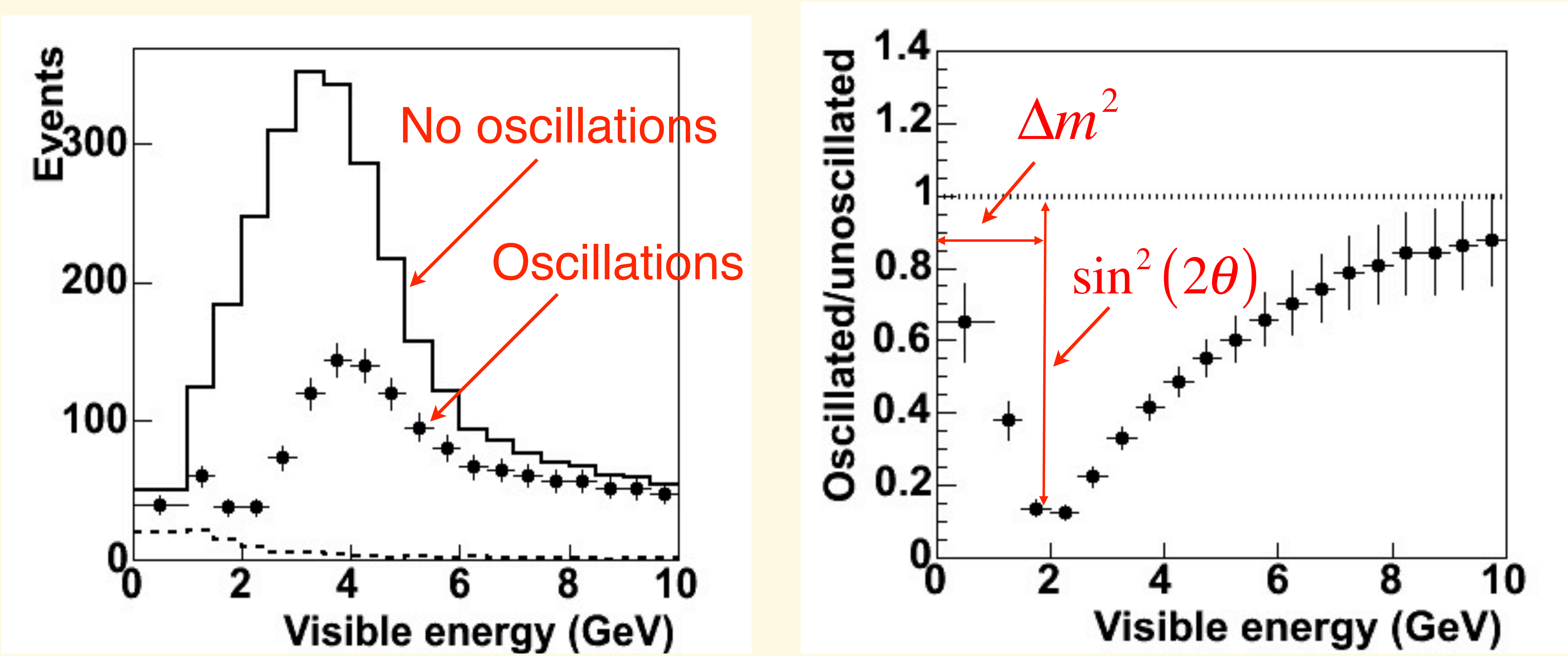
Two flavor approximation: $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$





General Method

Two flavor approximation: $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$



Size of dip gives the mixing angle; location of dip Δm^2

Parameters used in this example: $\sin^2(2\theta) = 1$, $\Delta m^2 = 3.35 \times 10^{-3}\ eV^2$

K2K Experiment

K2K Experiment

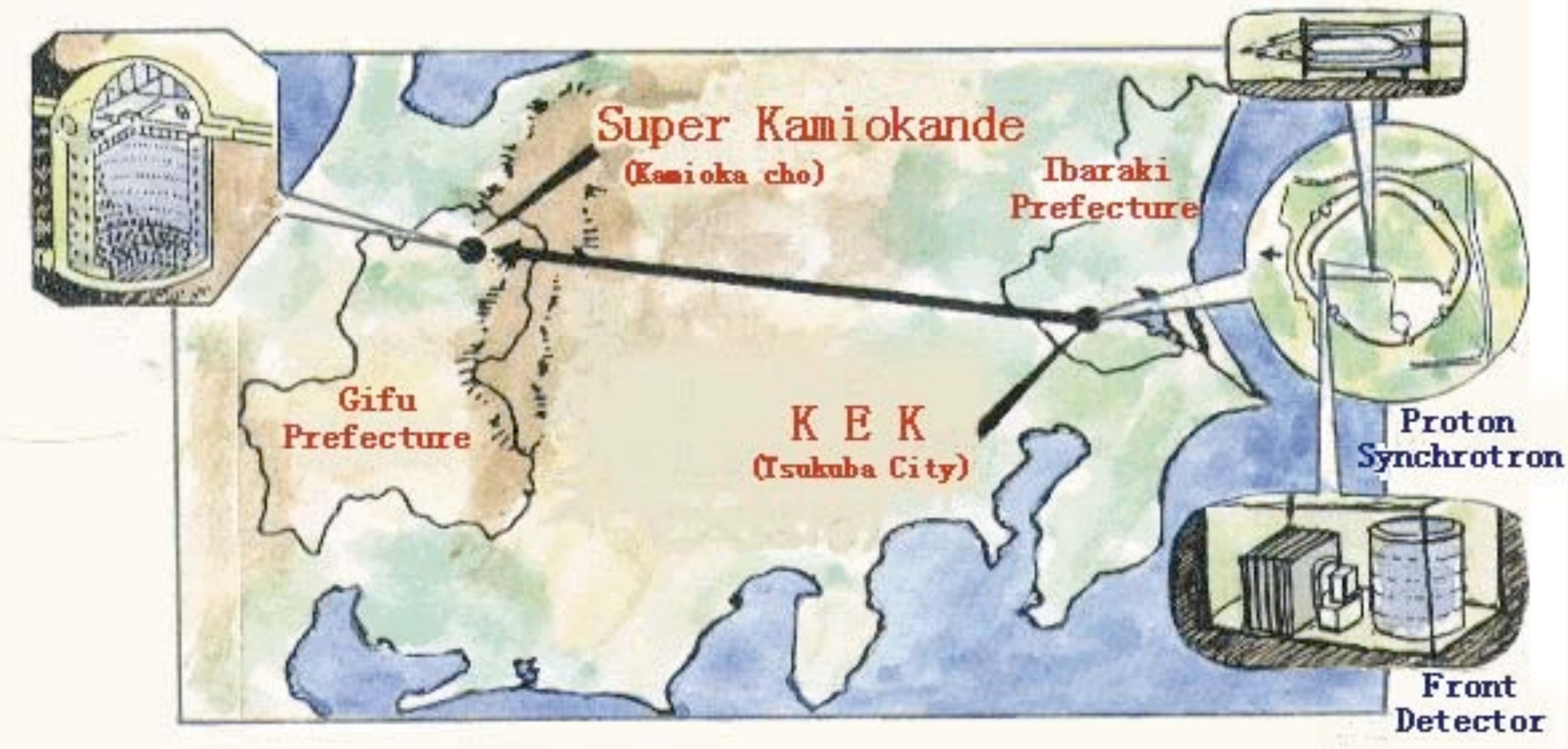
First accelerator long baseline experiment

Baseline = 225 km

K2K Experiment

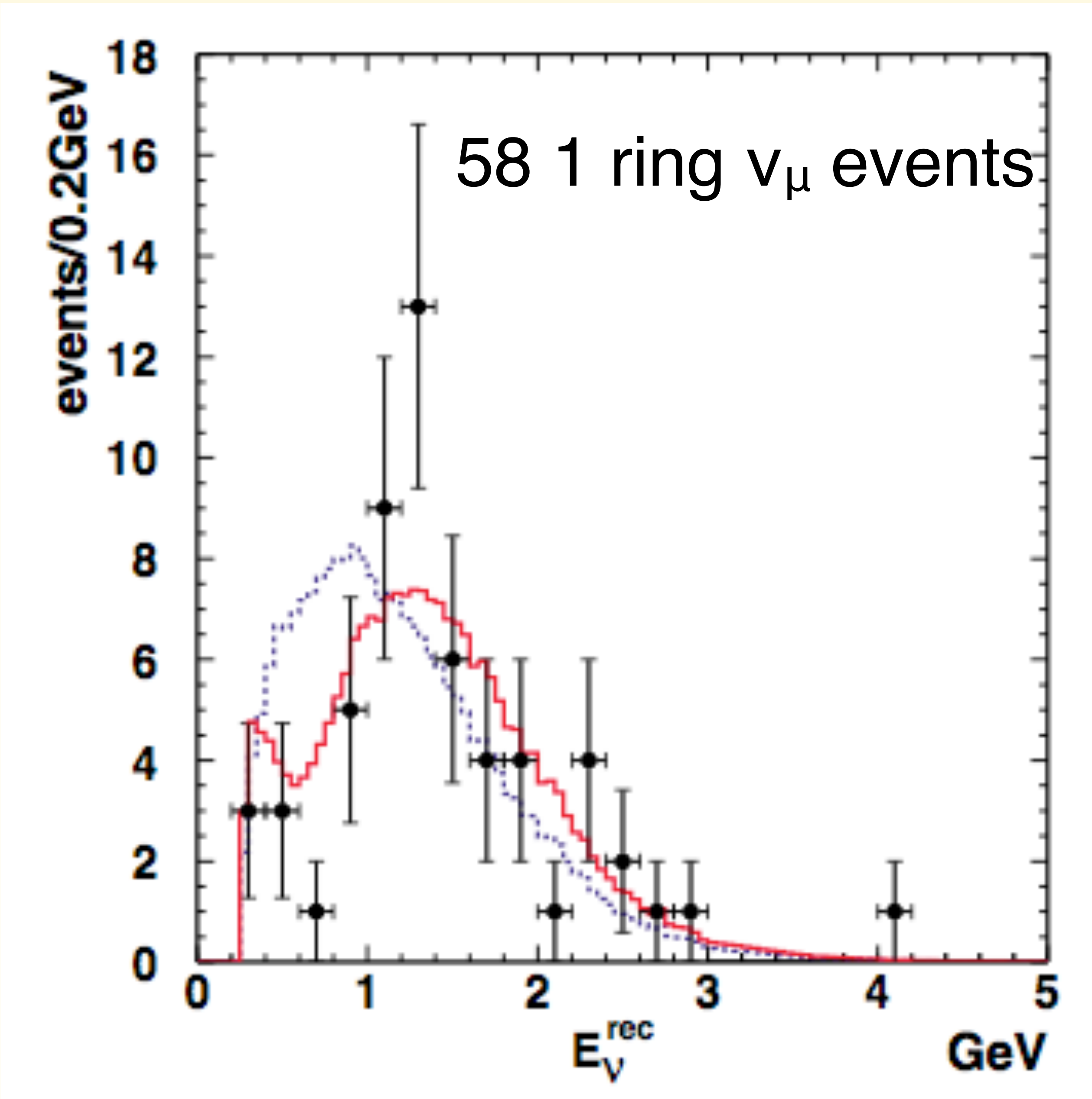
First accelerator long baseline experiment

Baseline = 225 km



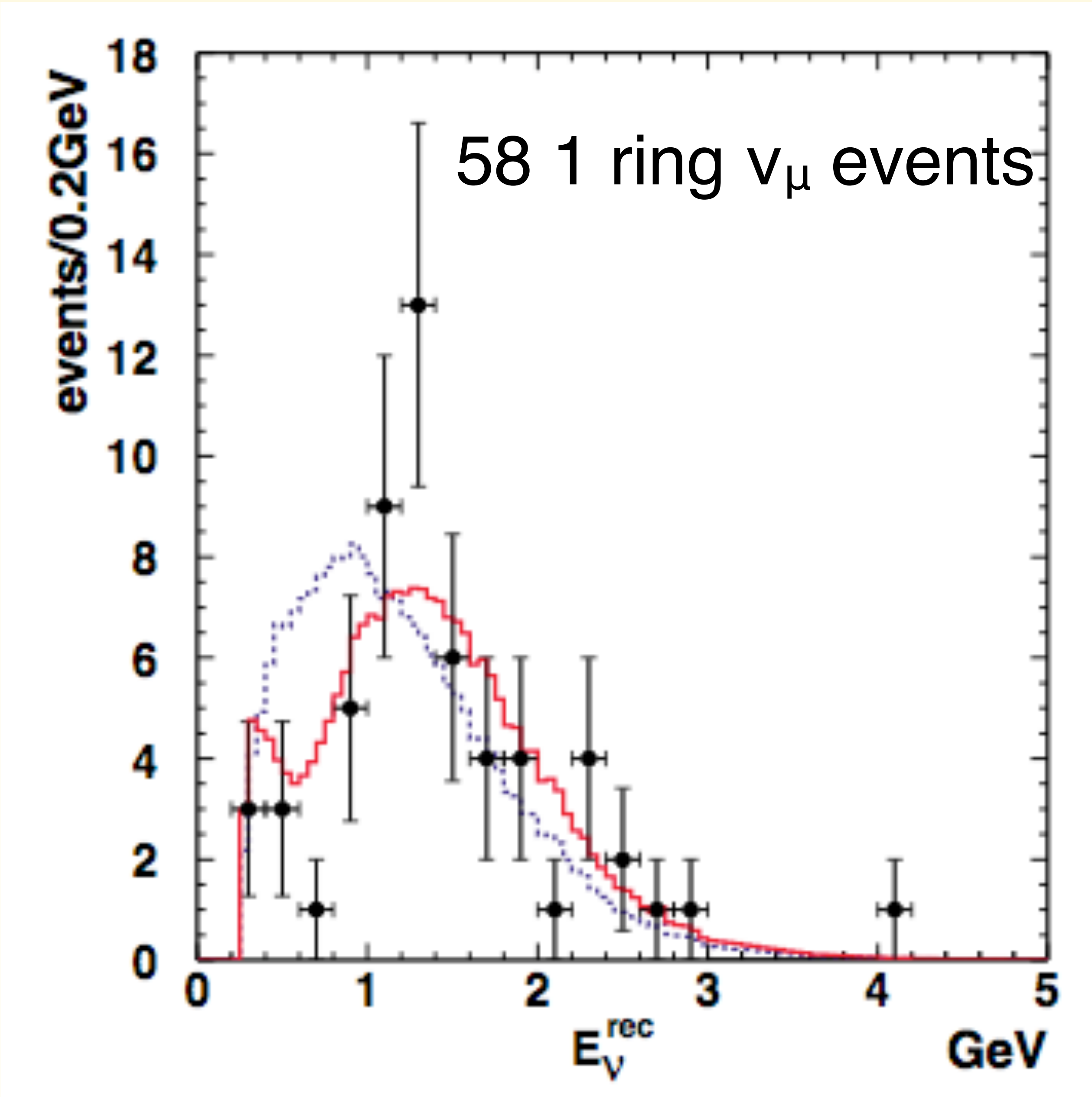
K2K Results

K2K Results

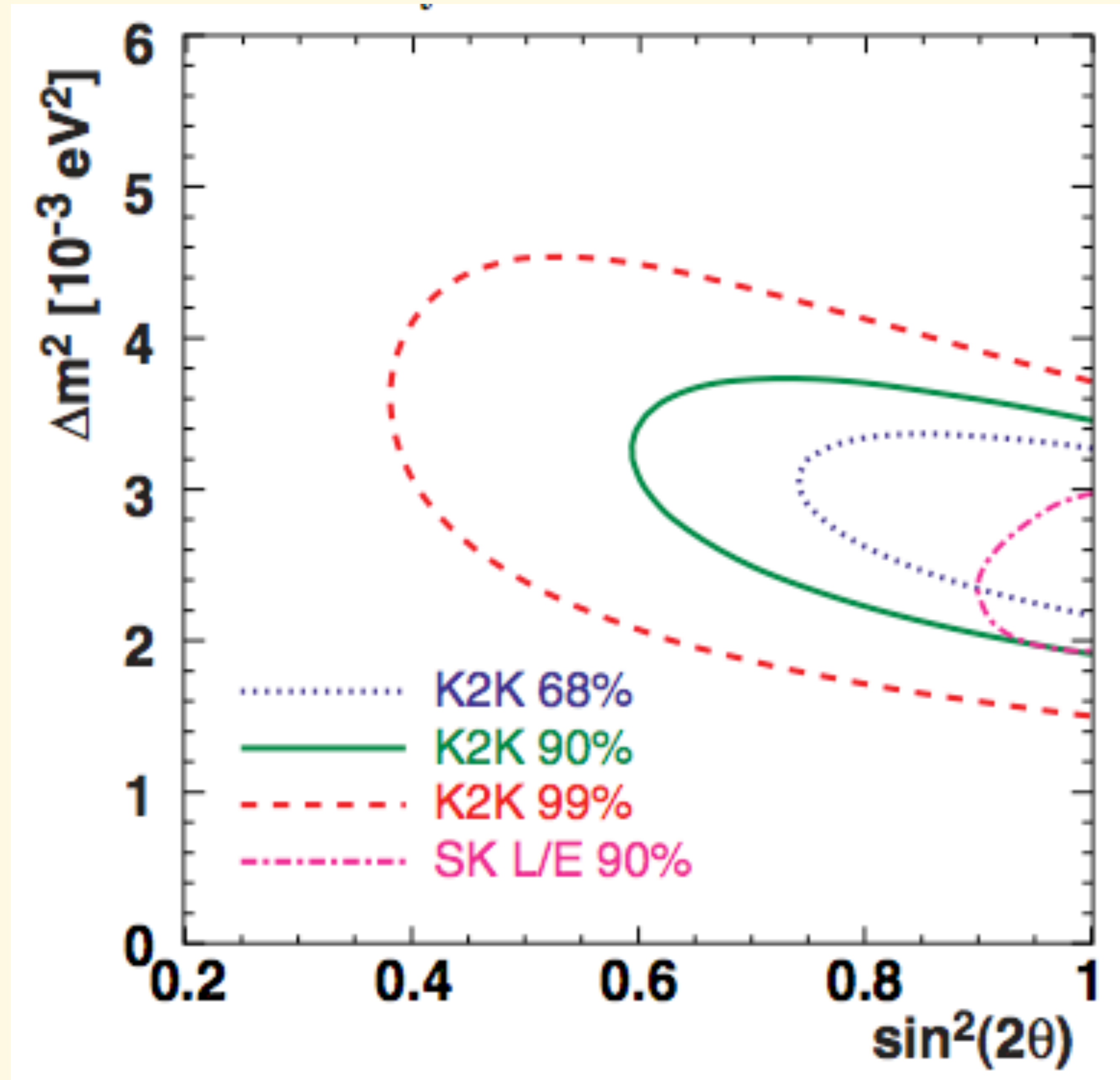


58 1 ring ν_μ events
events/0.2GeV
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
E_ν^{rec}
GeV

K2K Results



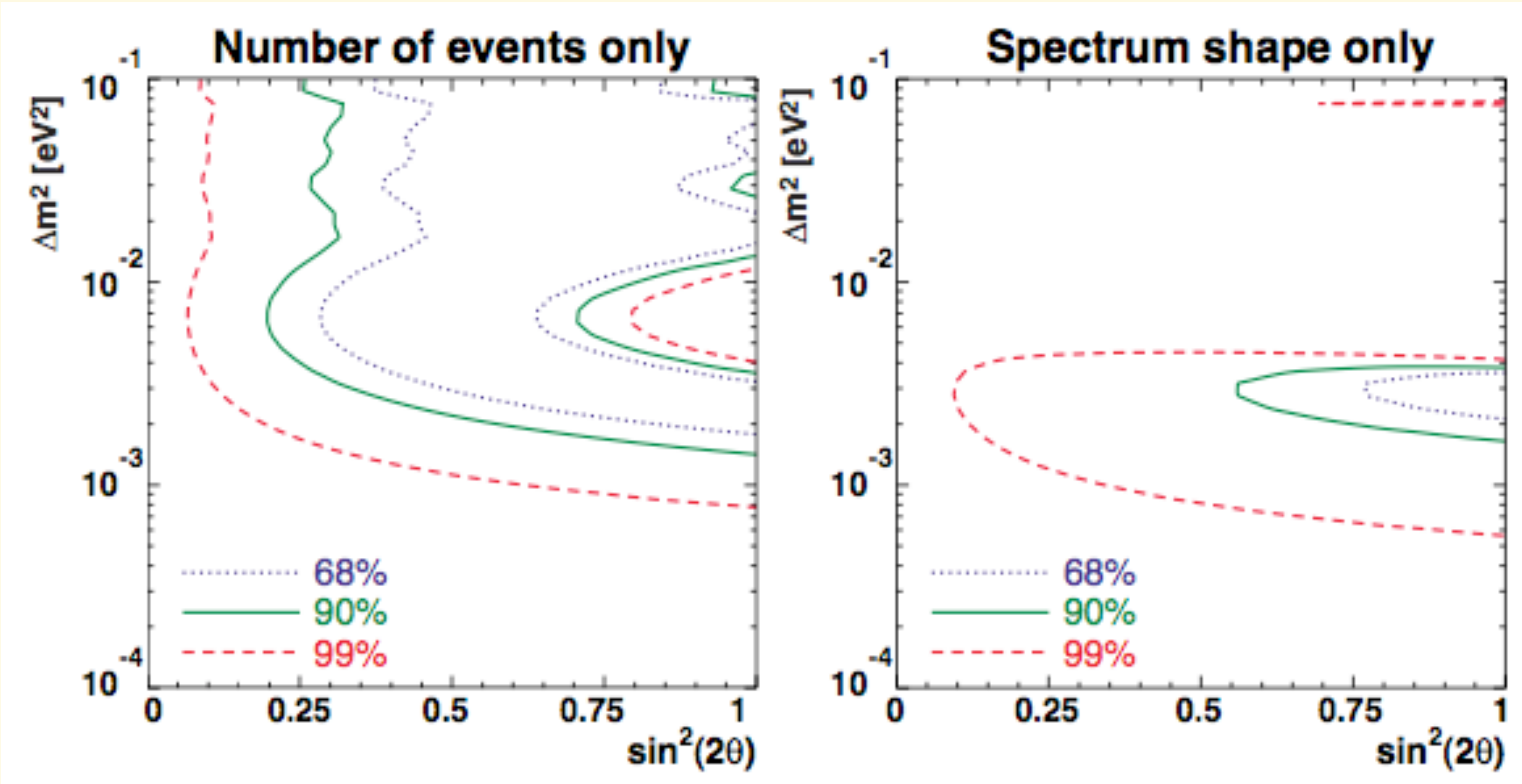
58 1 ring νμ events
events/0.2GeV
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
E_ν^rec
GeV



Δm² [10⁻³ eV²]
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1
sin²(2θ)
K2K 68%
K2K 90%
K2K 99%
SK L/E 90%

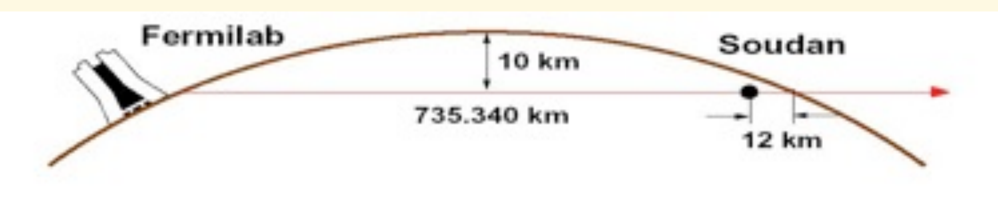
Rate or Shape

Rate or Shape



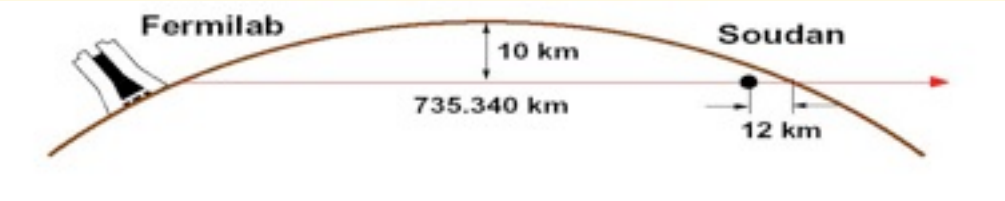
MINOS Experiment

MINOS Experiment



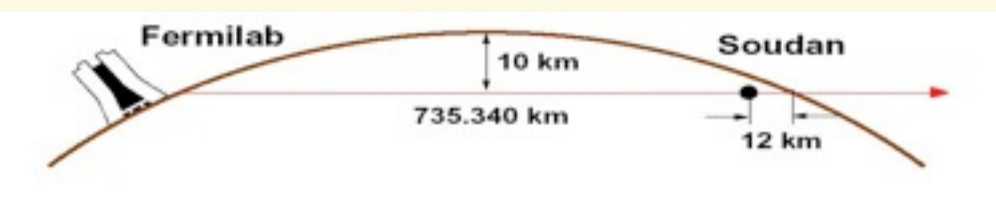
Neutrino beam produced at Fermilab
Near Detector - 1 km from the target
Far Detector - 735 km away and
710 m underground

MINOS Experiment

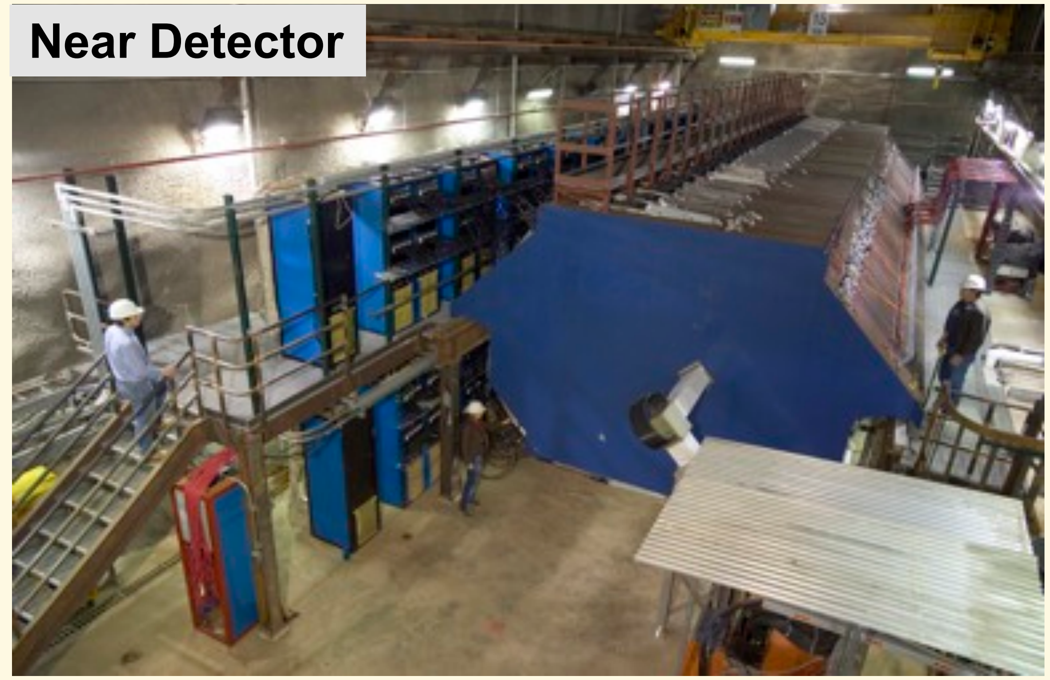


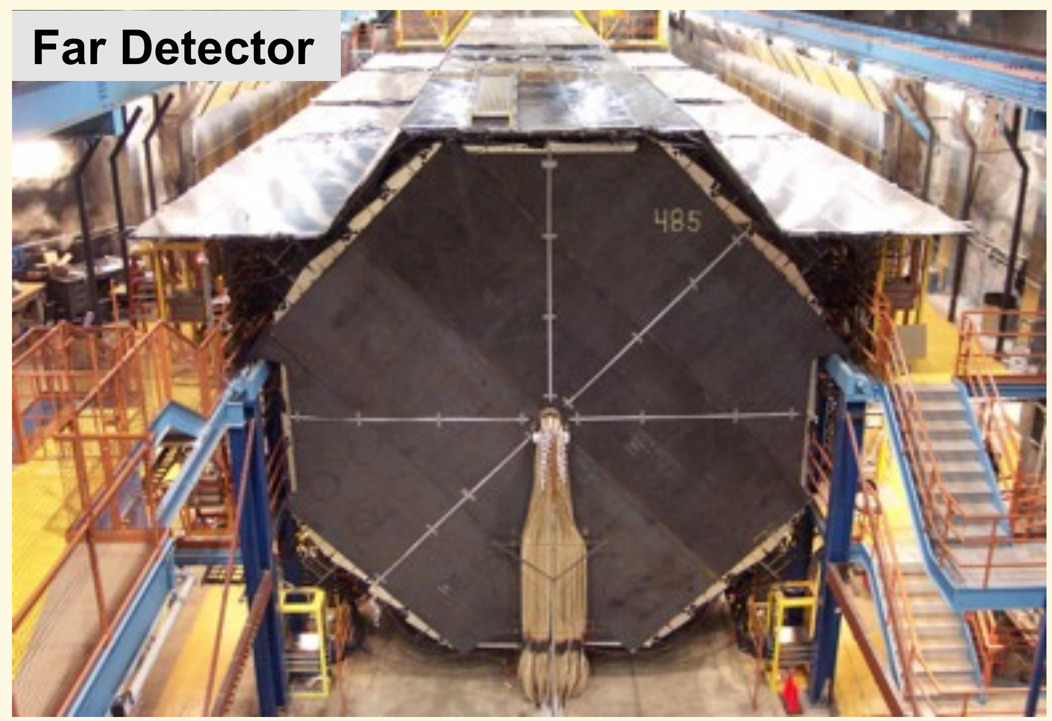
Neutrino beam produced at Fermilab
Near Detector - 1 km from the target
Far Detector - 735 km away and
710 m underground

MINOS Experiment

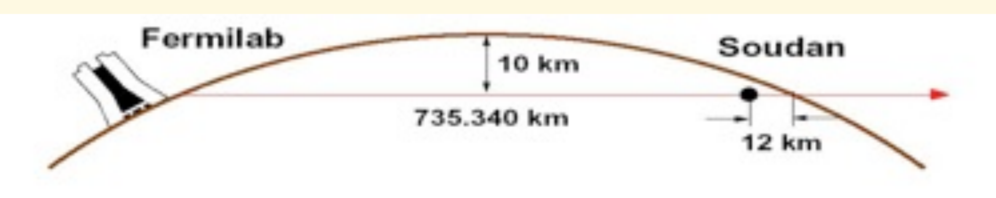


Neutrino beam produced at Fermilab
Near Detector - 1 km from the target
Far Detector - 735 km away and
710 m underground

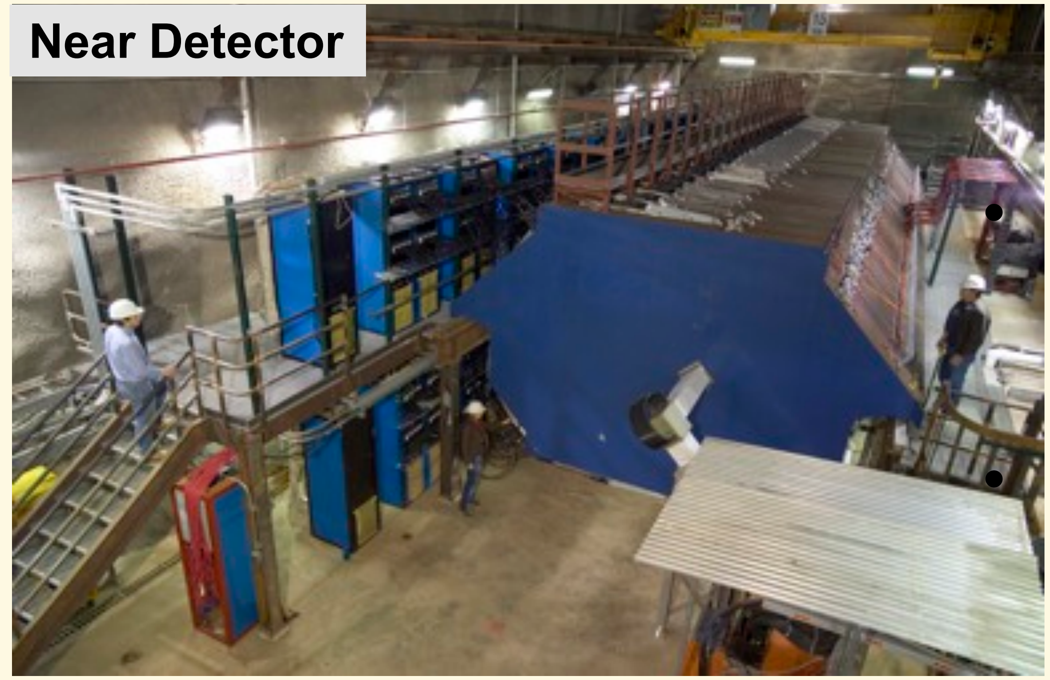


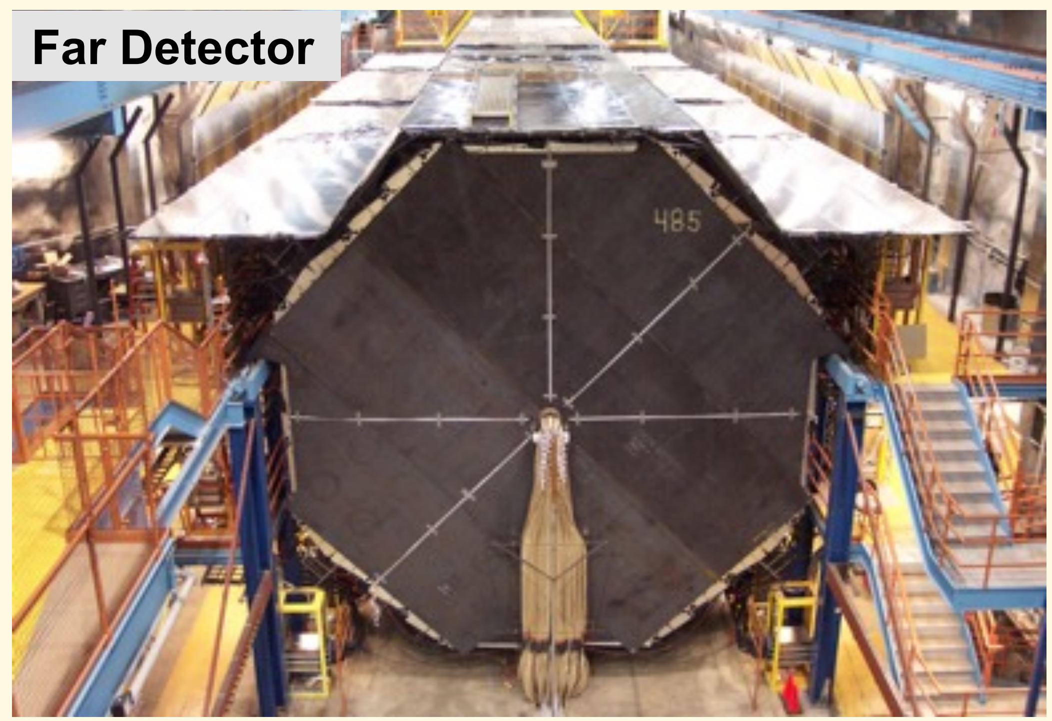


MINOS Experiment



Neutrino beam produced at Fermilab
Near Detector - 1 km from the target
Far Detector - 735 km away and
710 m underground

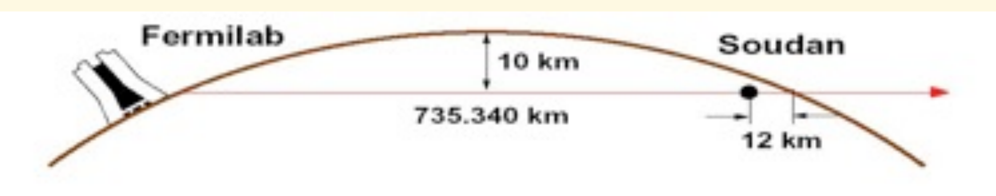




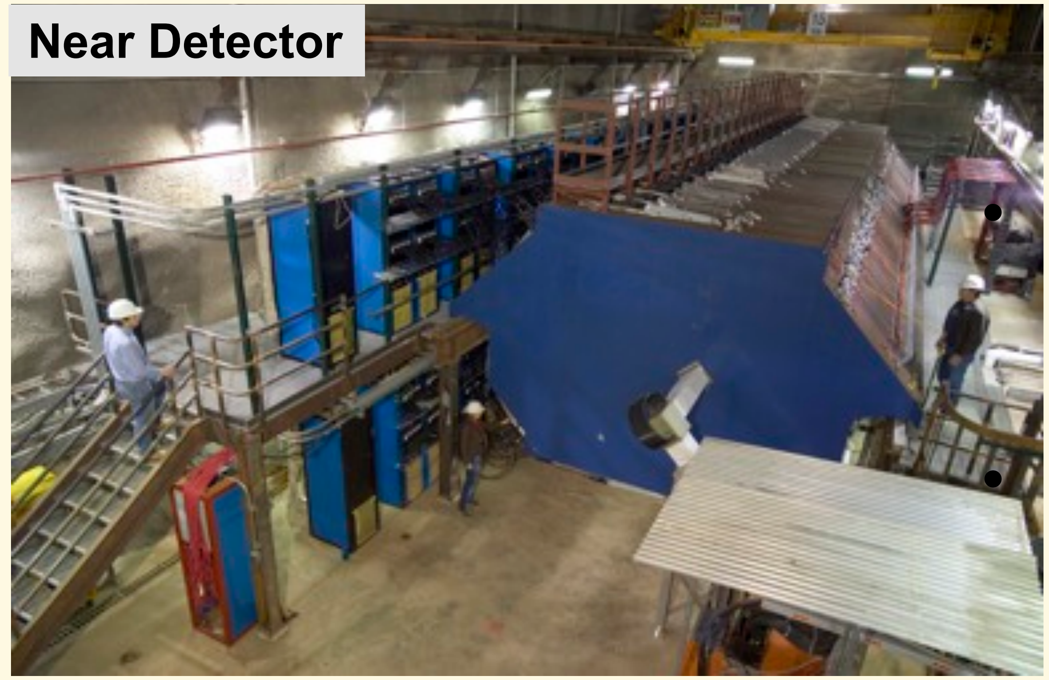
MINOS Detectors

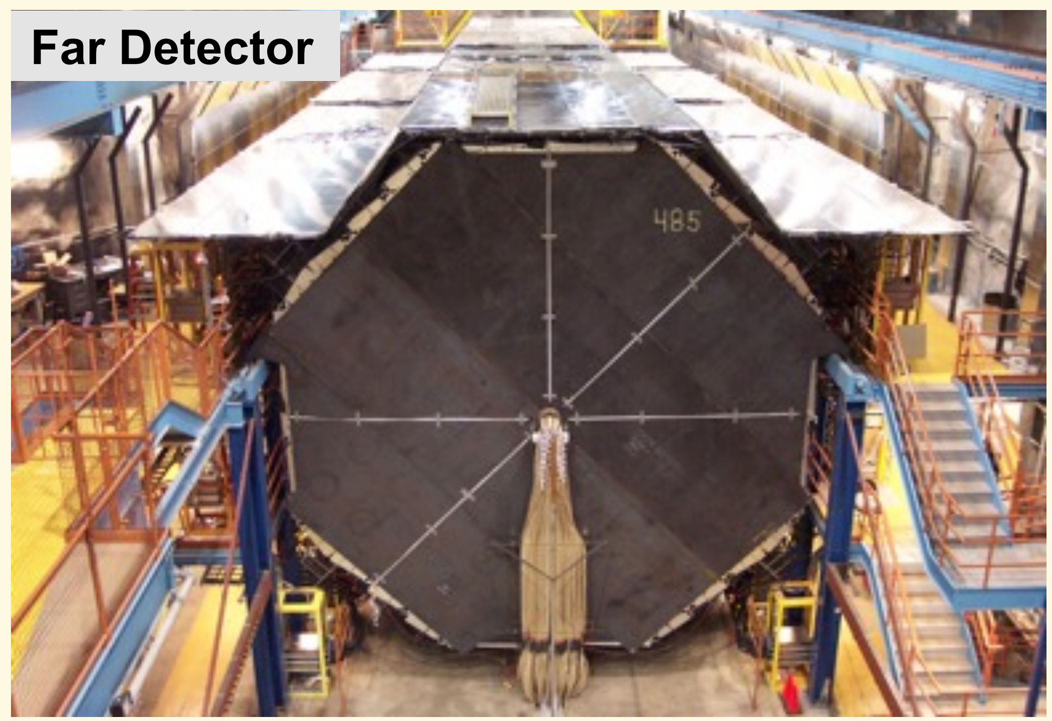
- Large Mass
  - Near: 0.98 kt
  - Far: 5.4 kt
- As similar as possible
  - steel planes
    - 2.5 cm thick
  - scintillator strips
    - successive planes oriented at 90º
    - 1 cm thick
    - 4.1 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

MINOS Experiment



Neutrino beam produced at Fermilab
Near Detector - 1 km from the target
Far Detector - 735 km away and
710 m underground





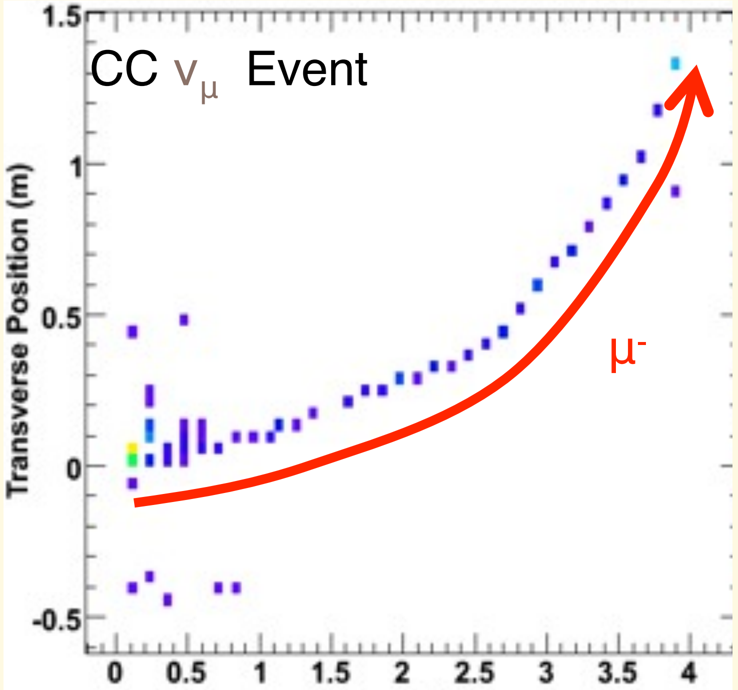
MINOS Detectors

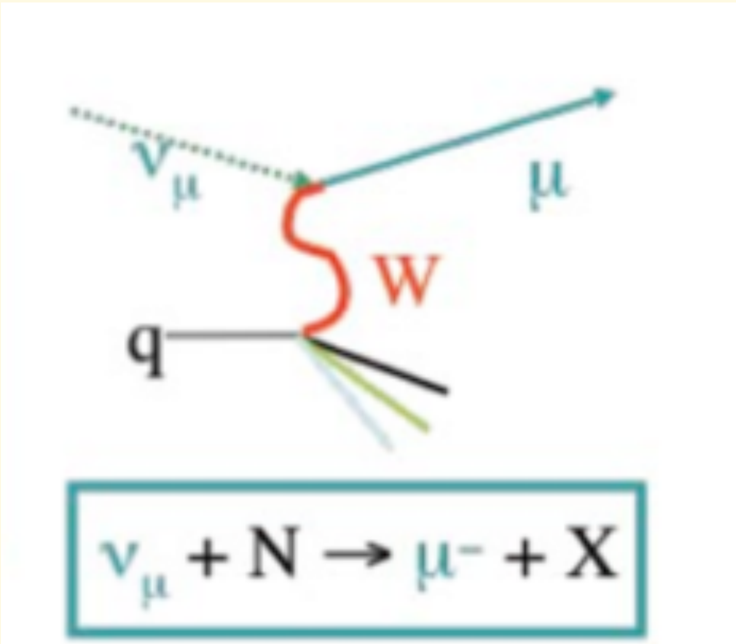
- Large Mass
  - Near: 0.98 kt
  - Far: 5.4 kt
- As similar as possible
  - steel planes
    - 2.5 cm thick
  - scintillator strips
    - successive planes oriented at 90^o
    - 1 cm thick
    - 4.1 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

The flux is measured in the Near Detector and then extrapolated to obtain prediction in the Far Detector

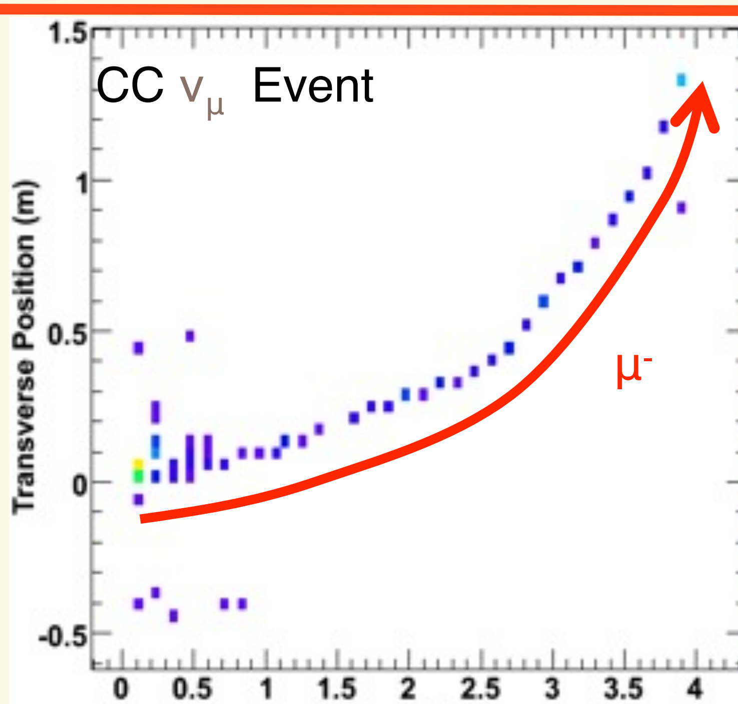
MINOS Events (MC)

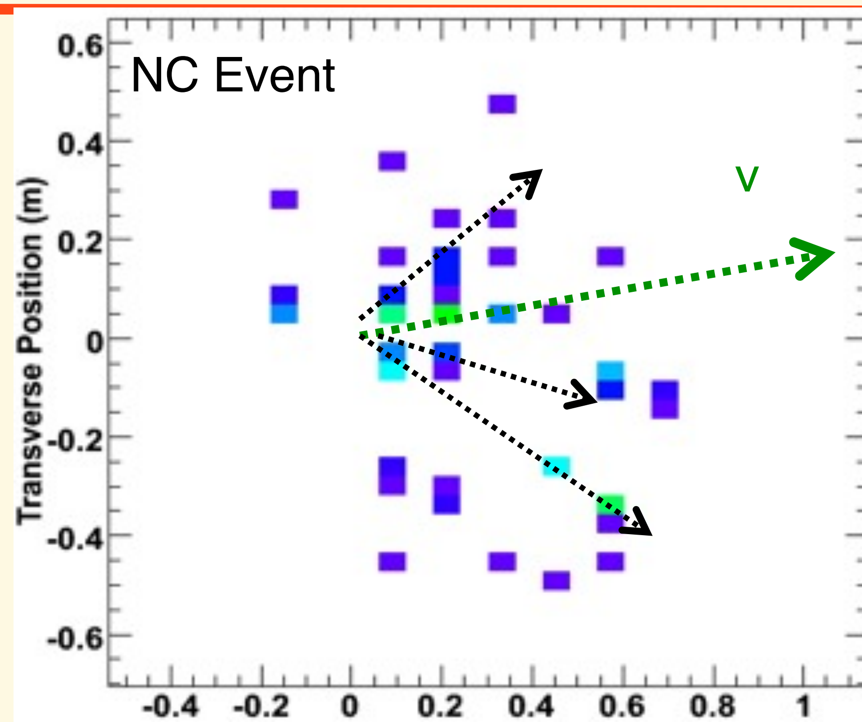
MINOS Events (MC)

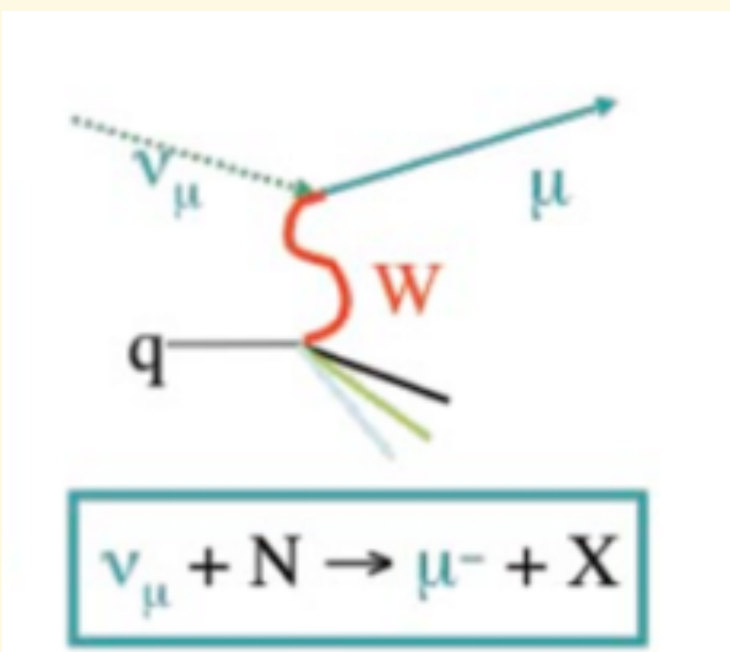


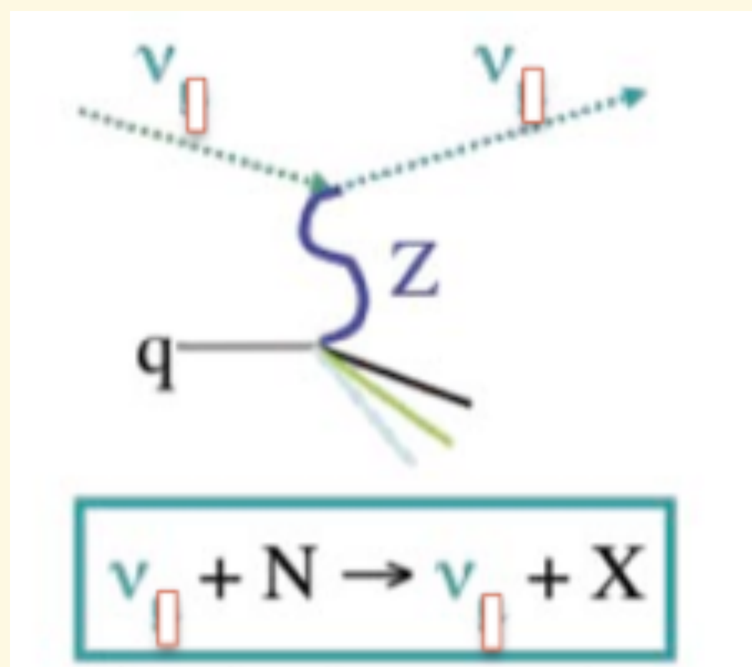


MINOS Events (MC)

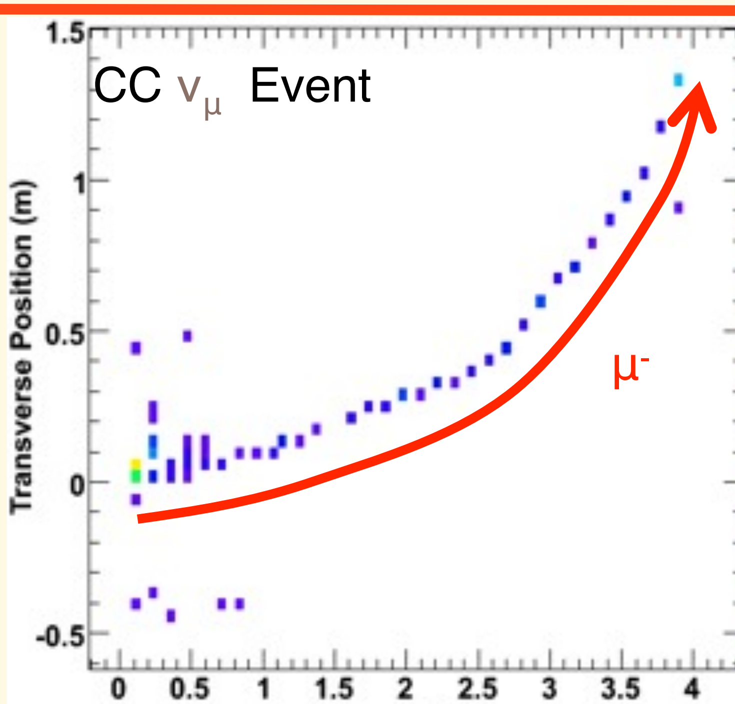


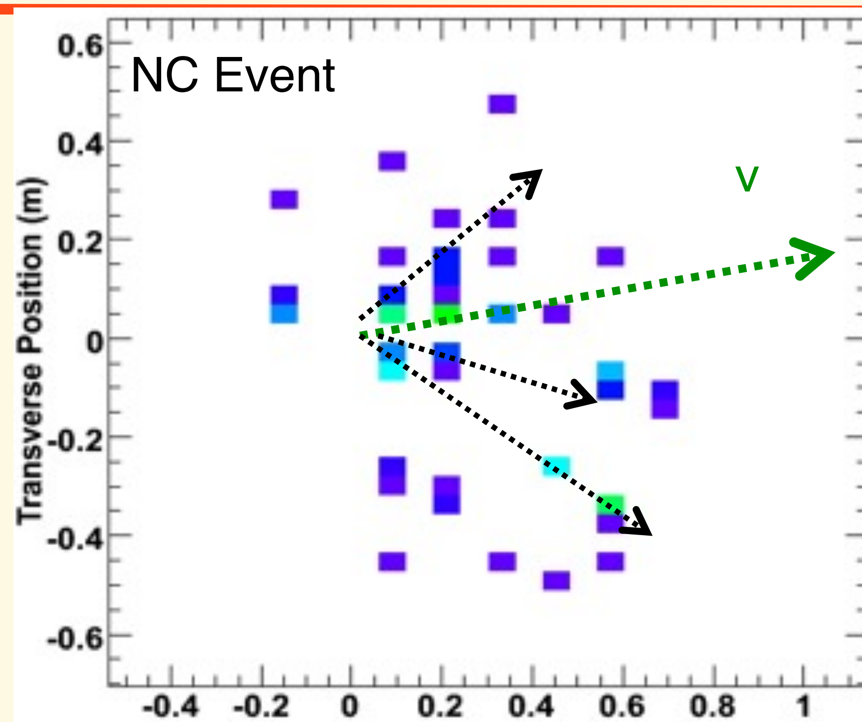


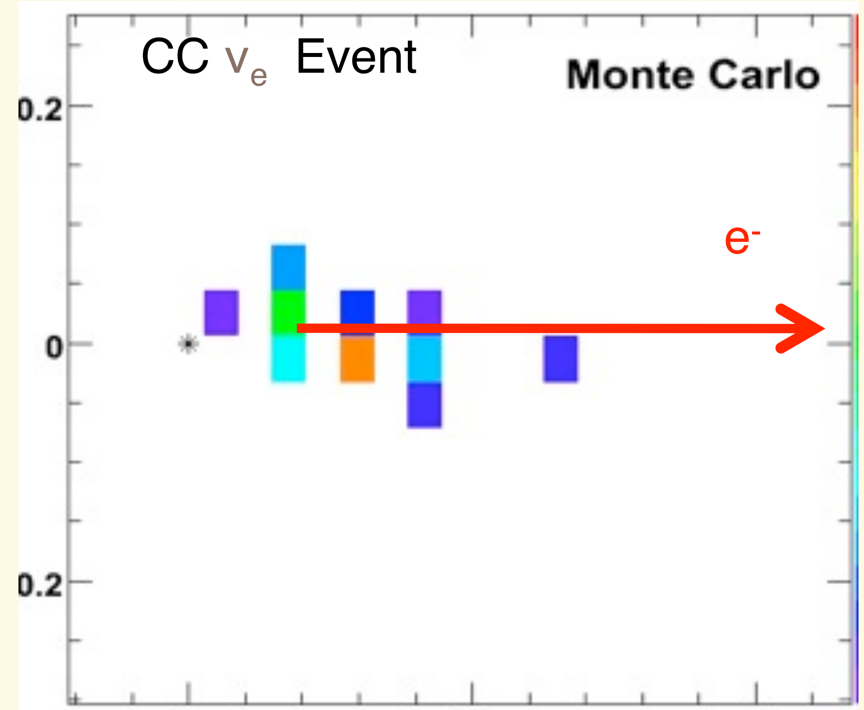


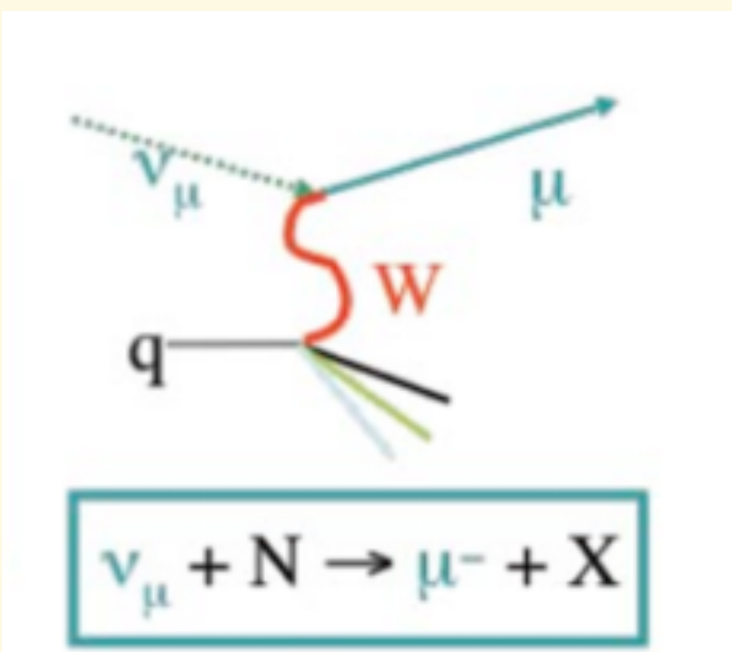


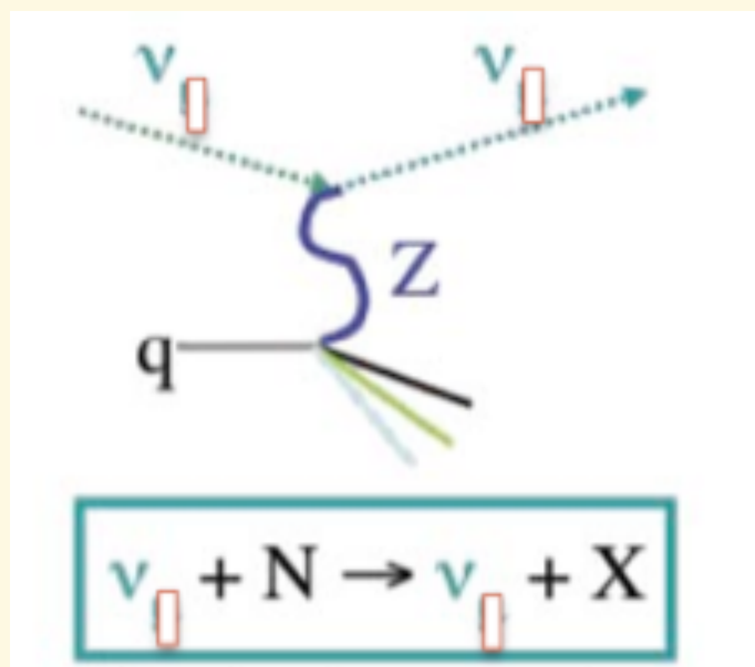
MINOS Events (MC)

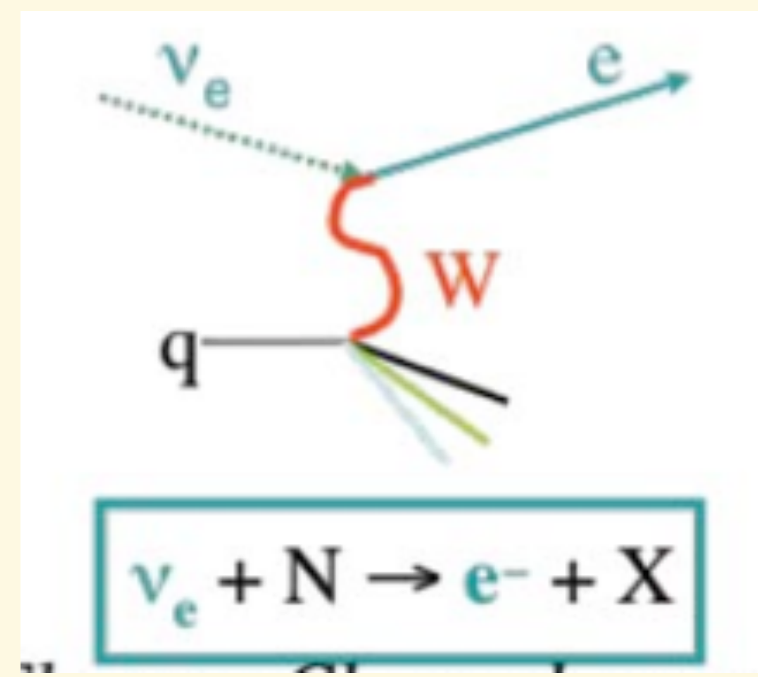




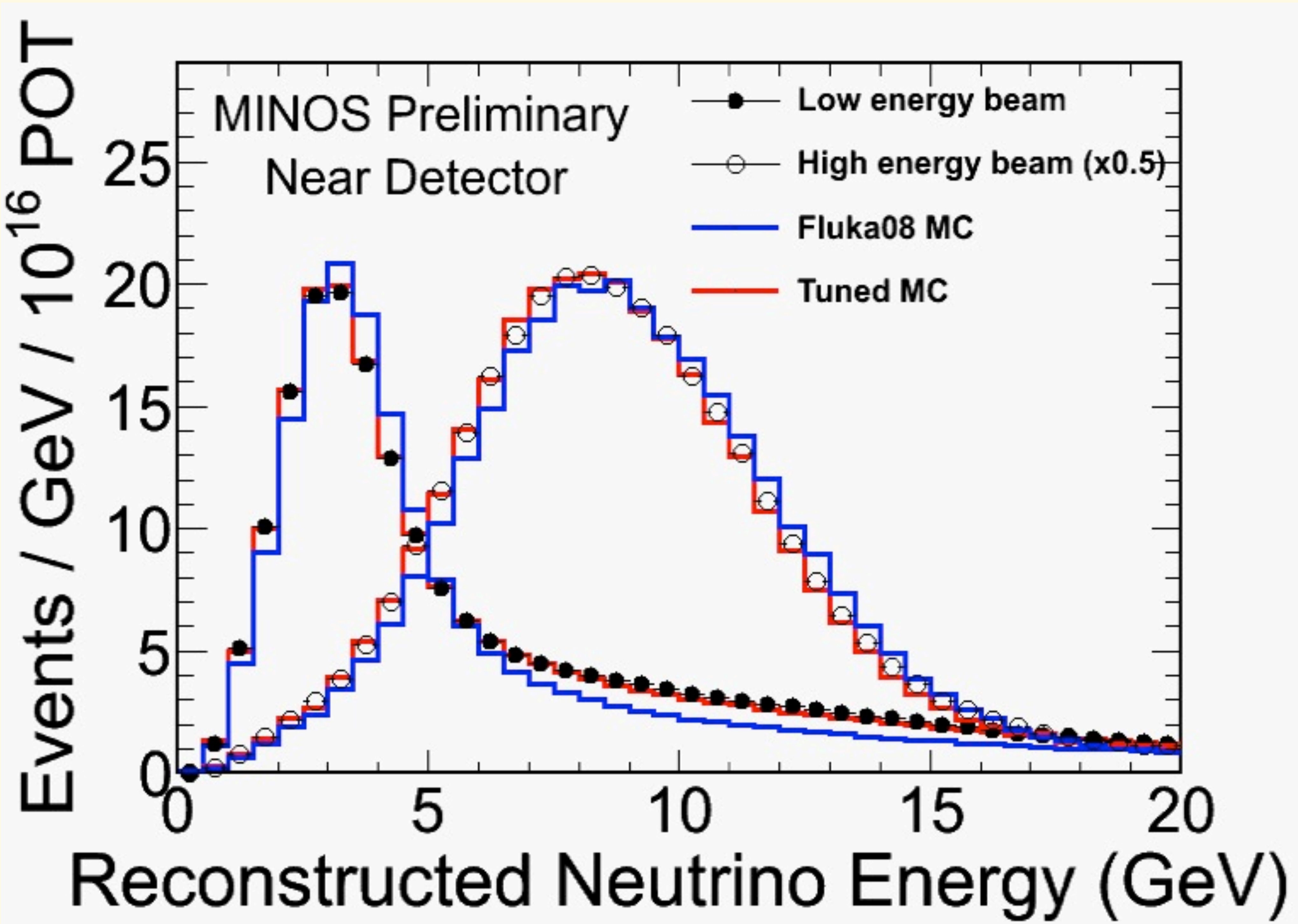




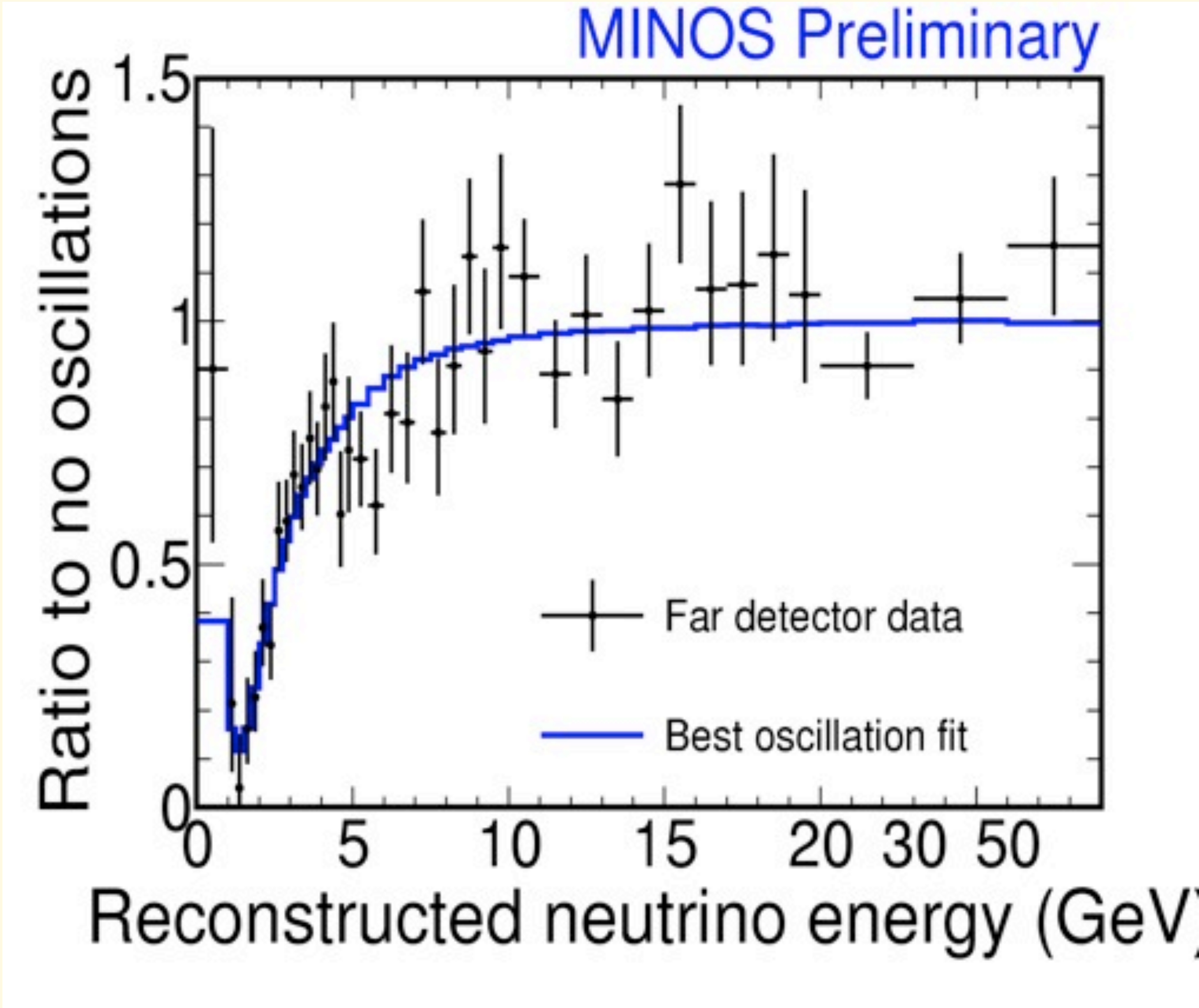




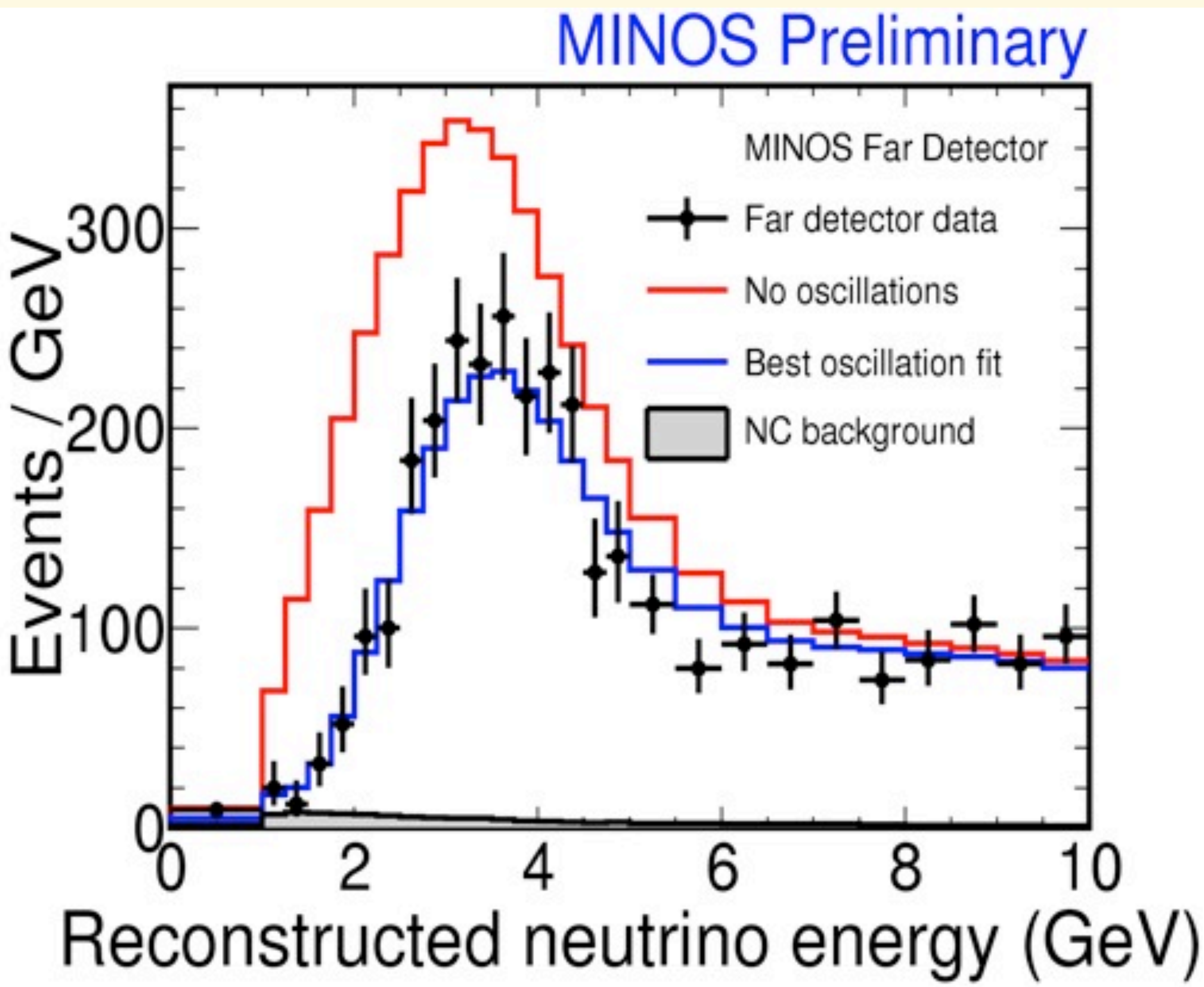
Near Detector Data

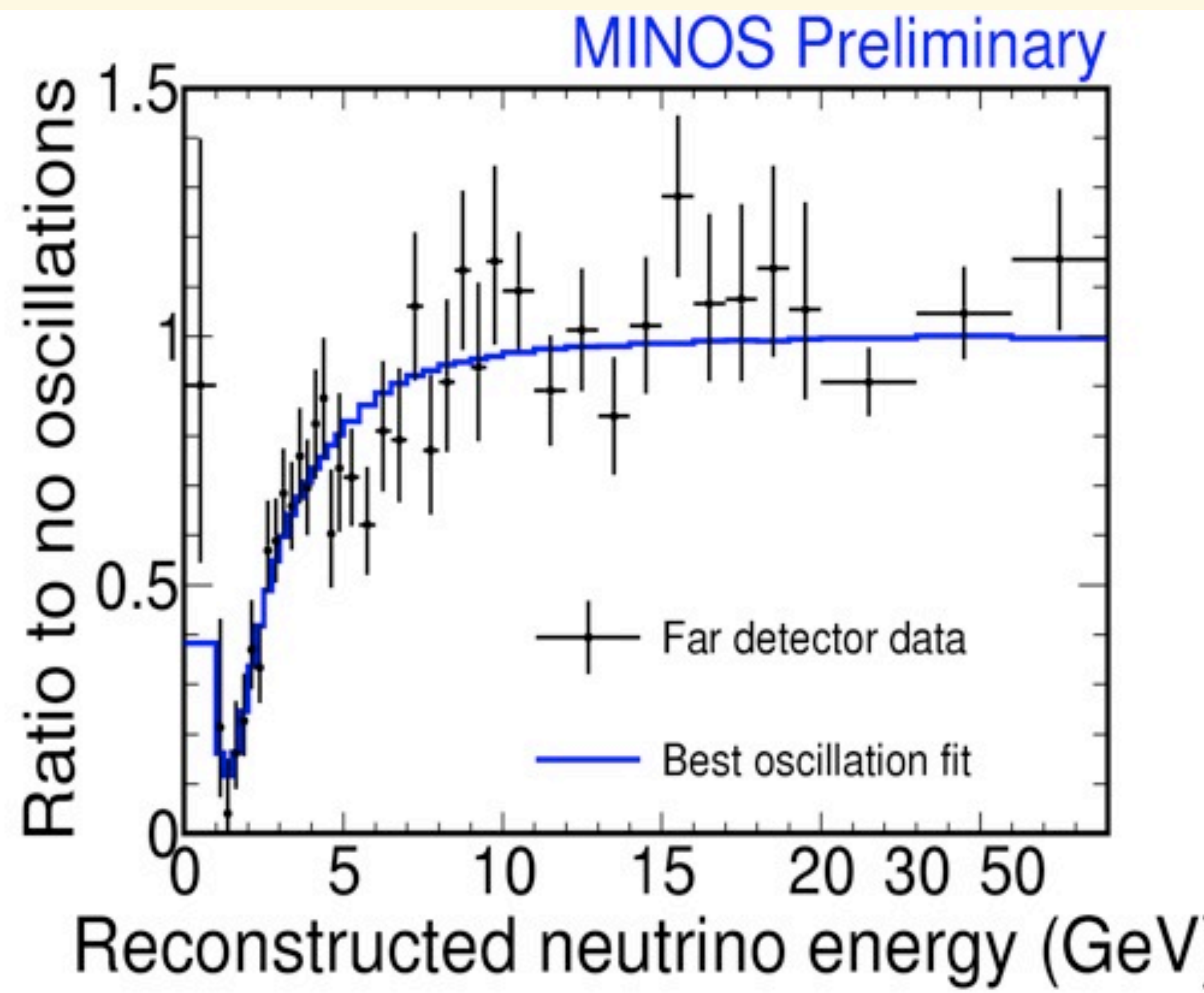


MINOS E_ν Spectrum

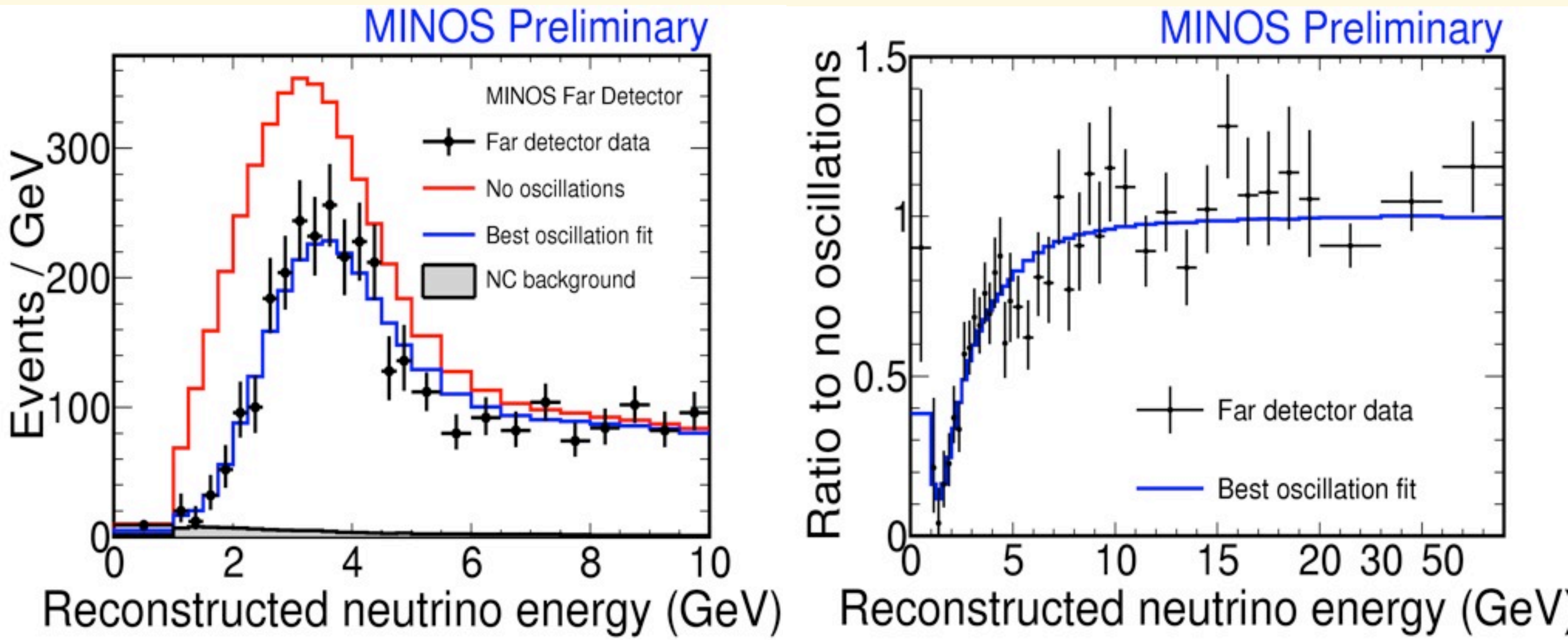


MINOS E_ν Spectrum





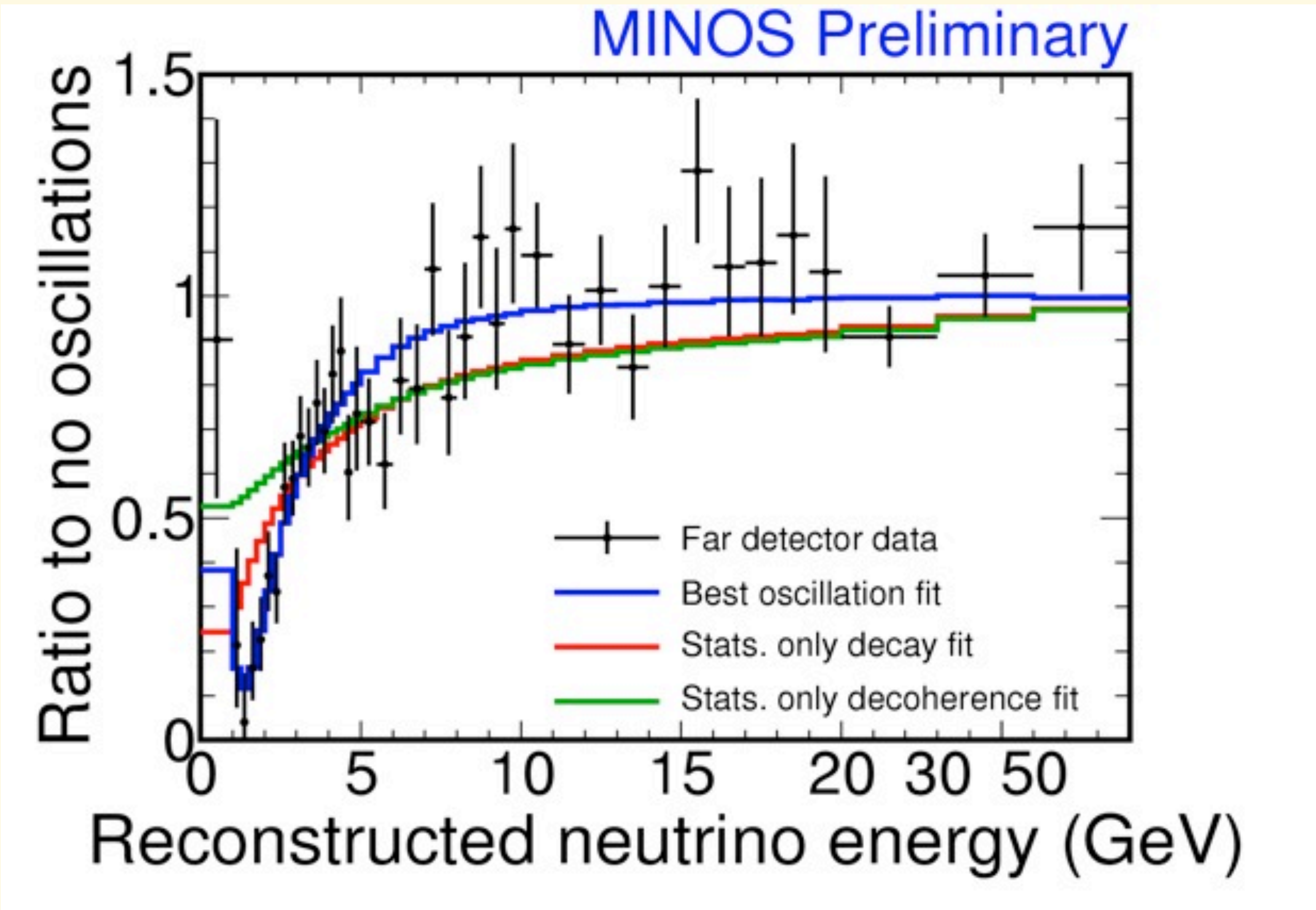
MINOS E_ν Spectrum



Good agreement with oscillation hypothesis
Alternative hypotheses (decay, decoherence) excluded at a significant level >6σ

Alternative Models

Alternative Models



Alternative Models

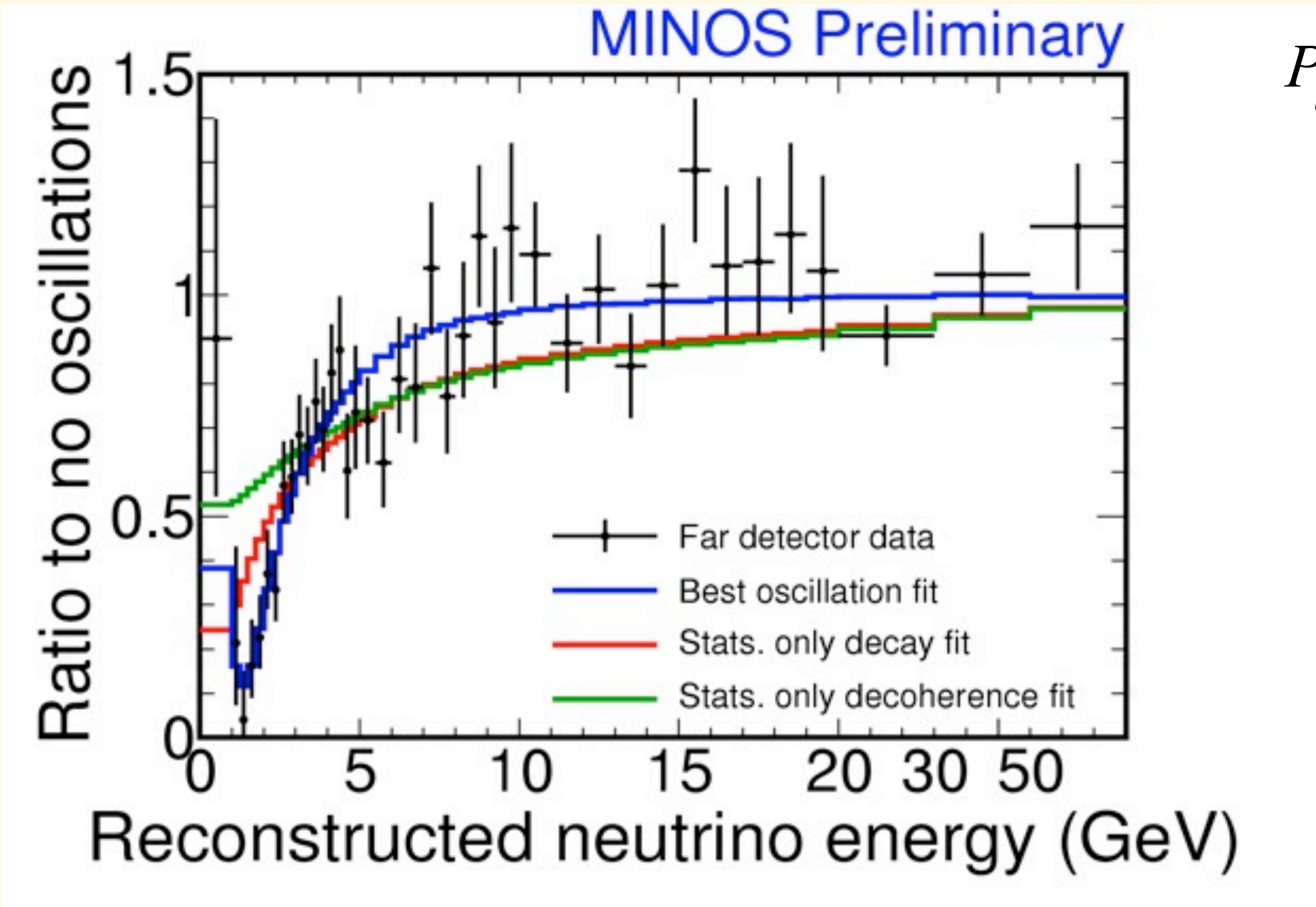
Decay:

$$P_{\mu\mu} = \left(\sin^2\theta + \cos^2\theta\,\exp(-\alpha L / E)\right)^2$$

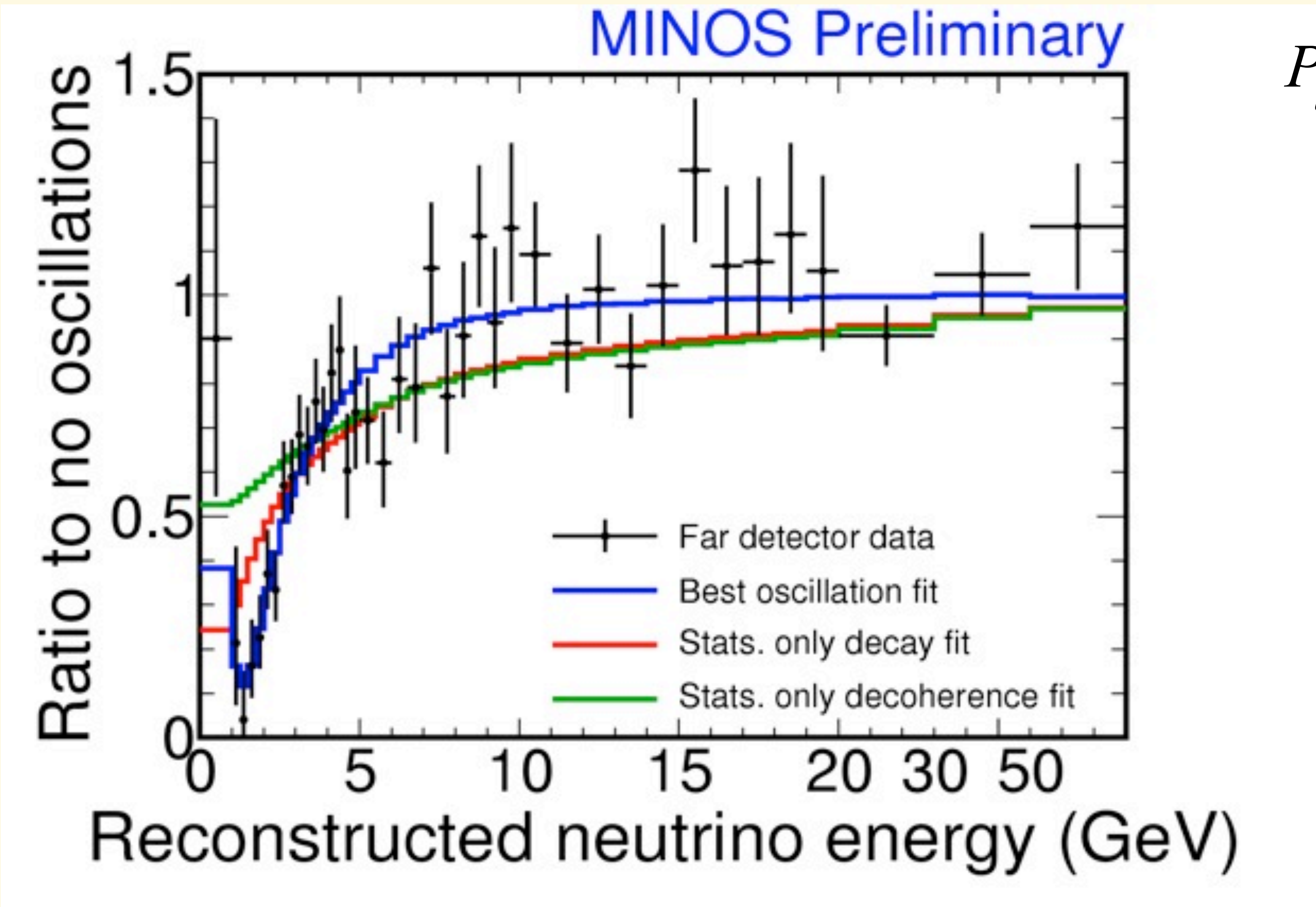
V. Barger *et al.*, PRL82:2640(1999)

$\Delta\chi^2 = 46.3$

disfavored at 6.8σ



Alternative Models



Decay:

$$P_{\mu\mu} = \left(\sin^2\theta + \cos^2\theta \exp(-\alpha L / E)\right)^2$$

V. Barger *et al.*, PRL82:2640(1999)

$\Delta\chi^2 = 46.3$

disfavored at 6.8σ

Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

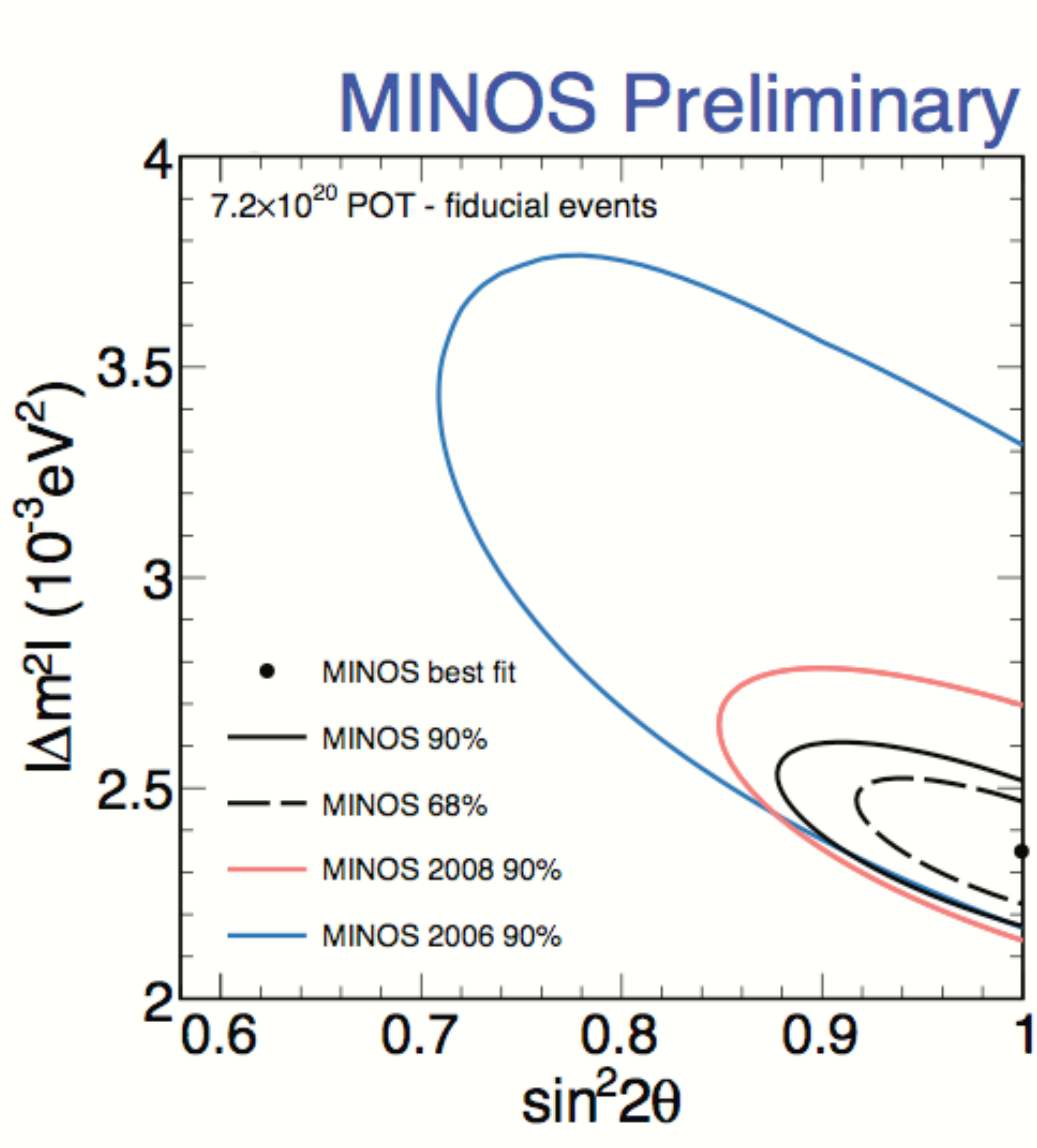
G.L. Fogli *et al.*, PRD67:093006 (2003)

$\Delta\chi^2 = 78.1$

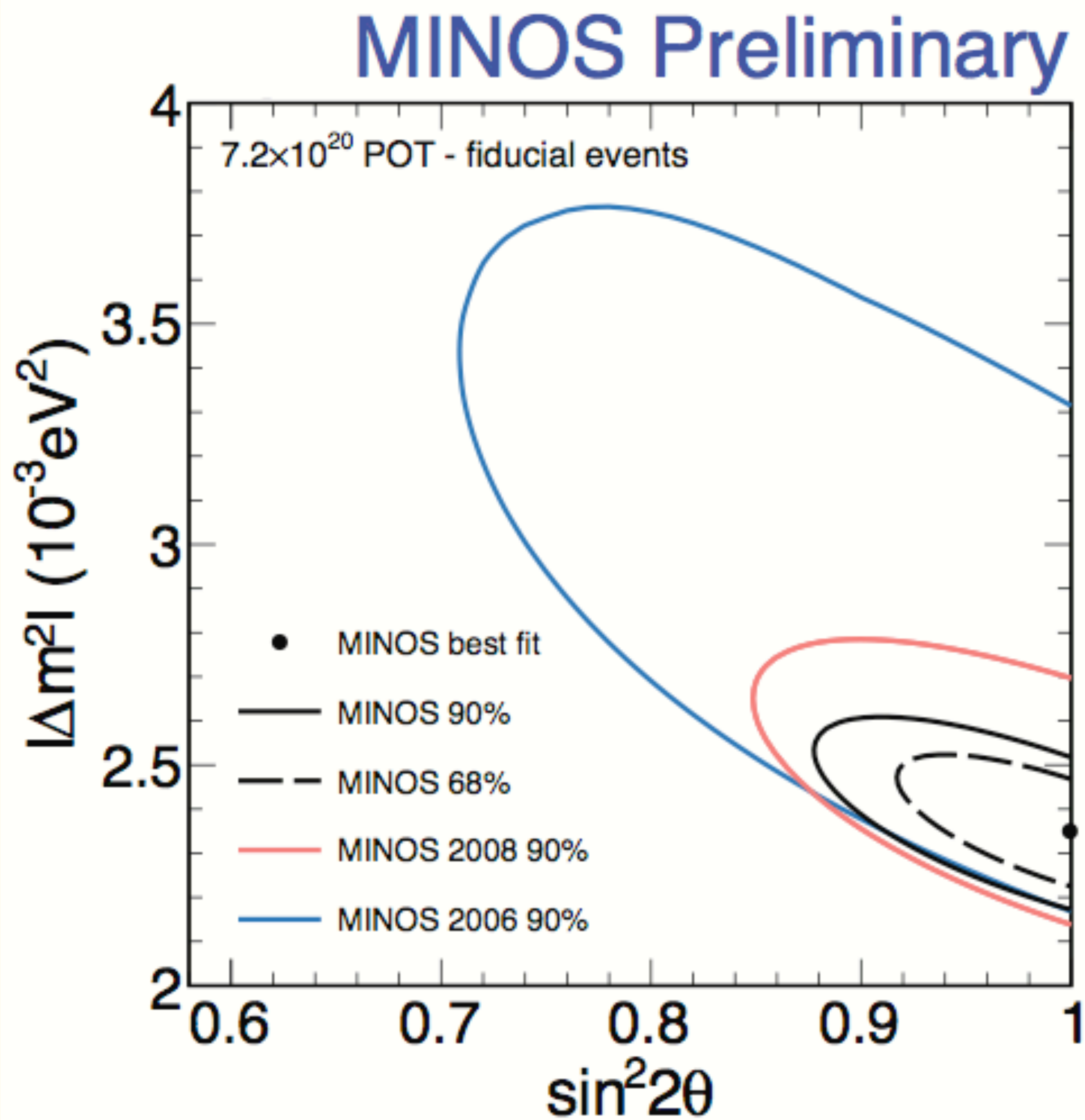
disfavored at 8.8σ

MINOS Contour

MINOS Contour



MINOS Contour



Fit results

$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\text{eV}^2$$

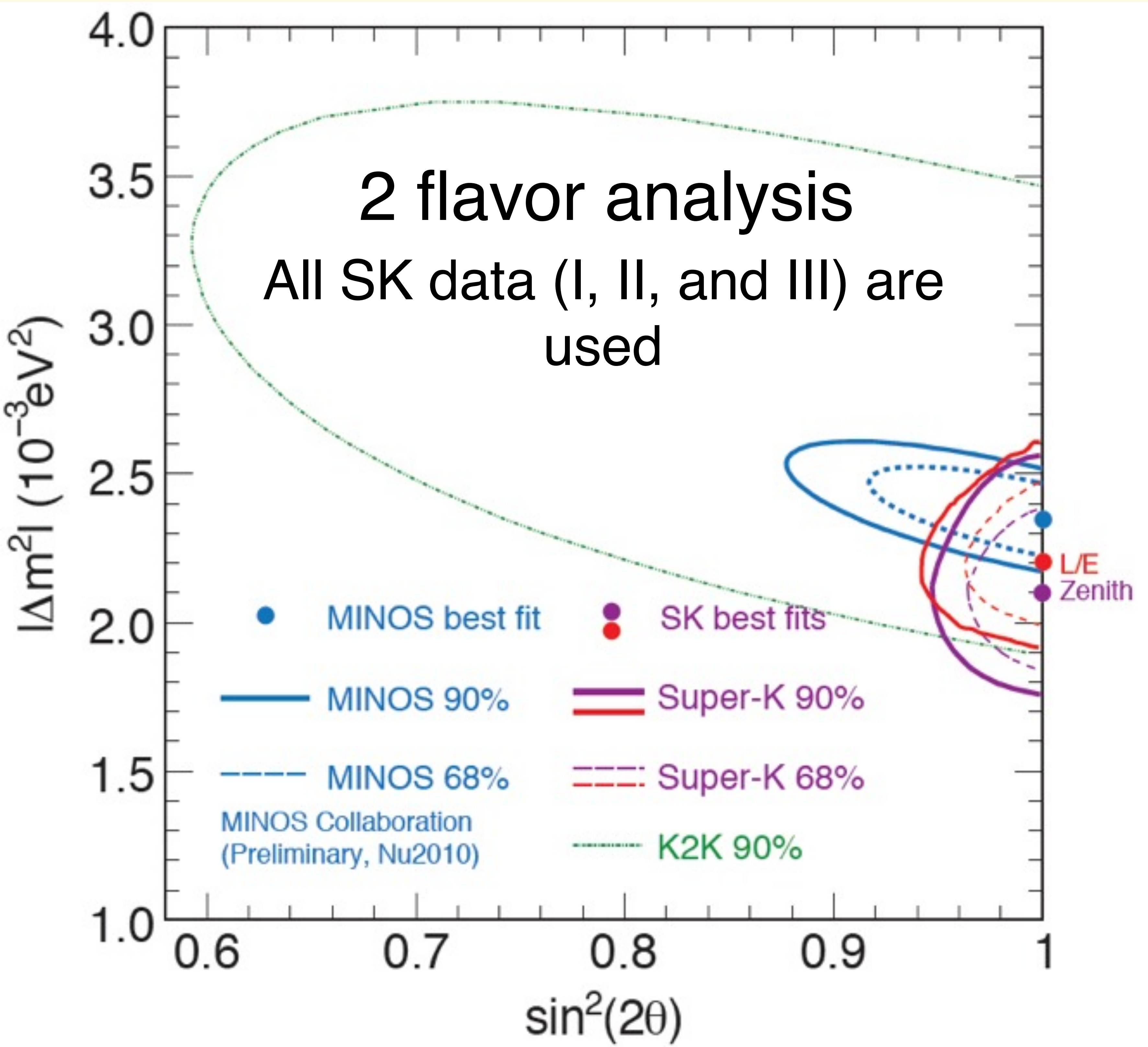
$$\sin^2(2\theta) > 0.91\ (90\%\ \text{C.L.})$$

The fit accounts for the principal systematic effects

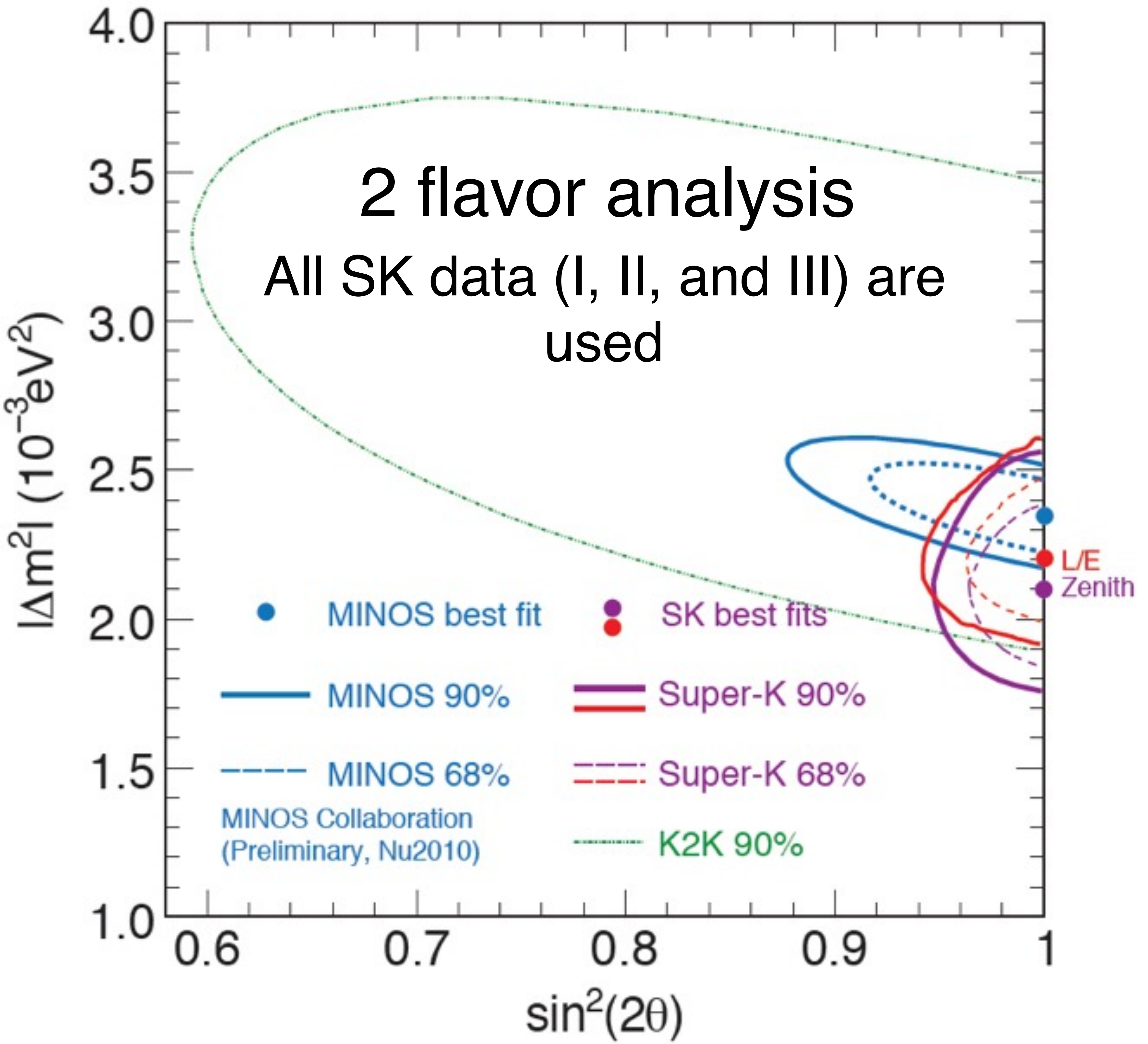
SuperK/MINOS

Y.Takeuchi Neutrino2010

SuperK/MINOS



SuperK/MINOS

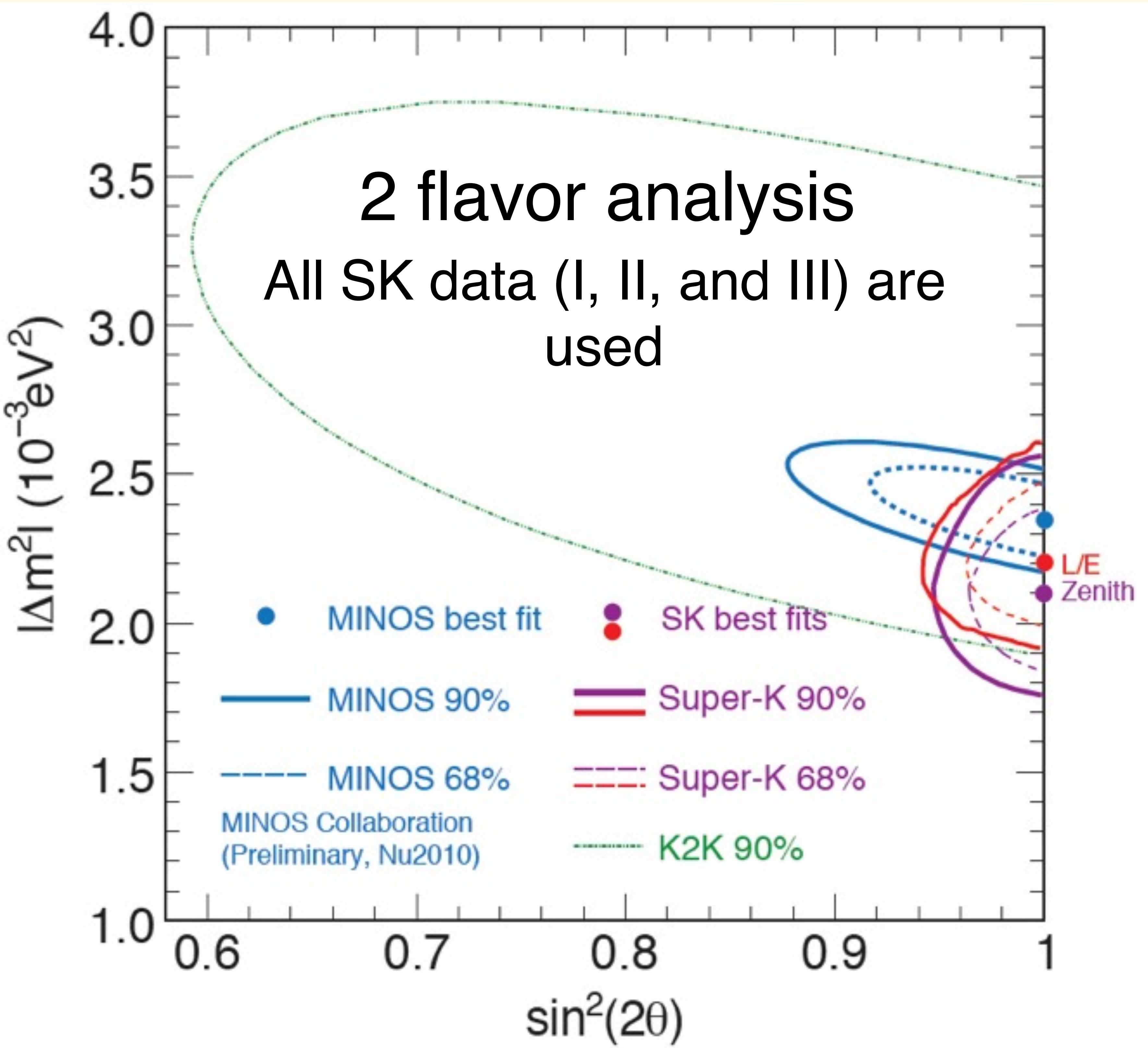


MINOS does better on Δm^2 determination

SuperK/MINOS

2 flavor analysis

All SK data (I, II, and III) are used



MINOS does better on Δm^2 determination

SuperK does better on the mixing angle

Summary - Atmospheric sector

Summary - Atmospheric sector

Oscillation analysis	$\sin^2 2\theta_{23}$ (90% C.L.)	Δm^2_{31} (eV^2)
SuperK (2ν, zenith angle)	>0.96	$2.11^{+0.11}_{-0.19} \times 10^{-3}$
SuperK (2ν, L/E)	>0.96	$2.19^{+0.14}_{-0.13} \times 10^{-3}$
SuperK (3ν, normal mass hierarchy)	>0.93	$2.11^{+0.43}_{-0.12} \times 10^{-3}$
SuperK (3ν, inverted mass hierarchy)		$2.51^{+0.13}_{-0.42} \times 10^{-3}$
MINOS	>0.91	$2.31^{+0.11}_{-0.08} \times 10^{-3}$

Summary - Atmospheric sector

Oscillation analysis	$\sin^2 2\theta_{23}$ (90% C.L.)	Δm^2_{31} (eV^2)
SuperK (2ν, zenith angle)	>0.96	$2.11^{+0.11}_{-0.19} \times 10^{-3}$
SuperK (2ν, L/E)	>0.96	$2.19^{+0.14}_{-0.13} \times 10^{-3}$
SuperK (3ν, normal mass hierarchy)	>0.93	$2.11^{+0.43}_{-0.12} \times 10^{-3}$
SuperK (3ν, inverted mass hierarchy)		$2.51^{+0.13}_{-0.42} \times 10^{-3}$
MINOS	>0.91	$2.31^{+0.11}_{-0.08} \times 10^{-3}$

No significant preference on mass hierarchy or CP phase seen in SuperK 3 flavor fit

Oscillation to what?

Oscillation to what?

- Both SuperK and MINOS show that ν_μ's disappear via oscillations

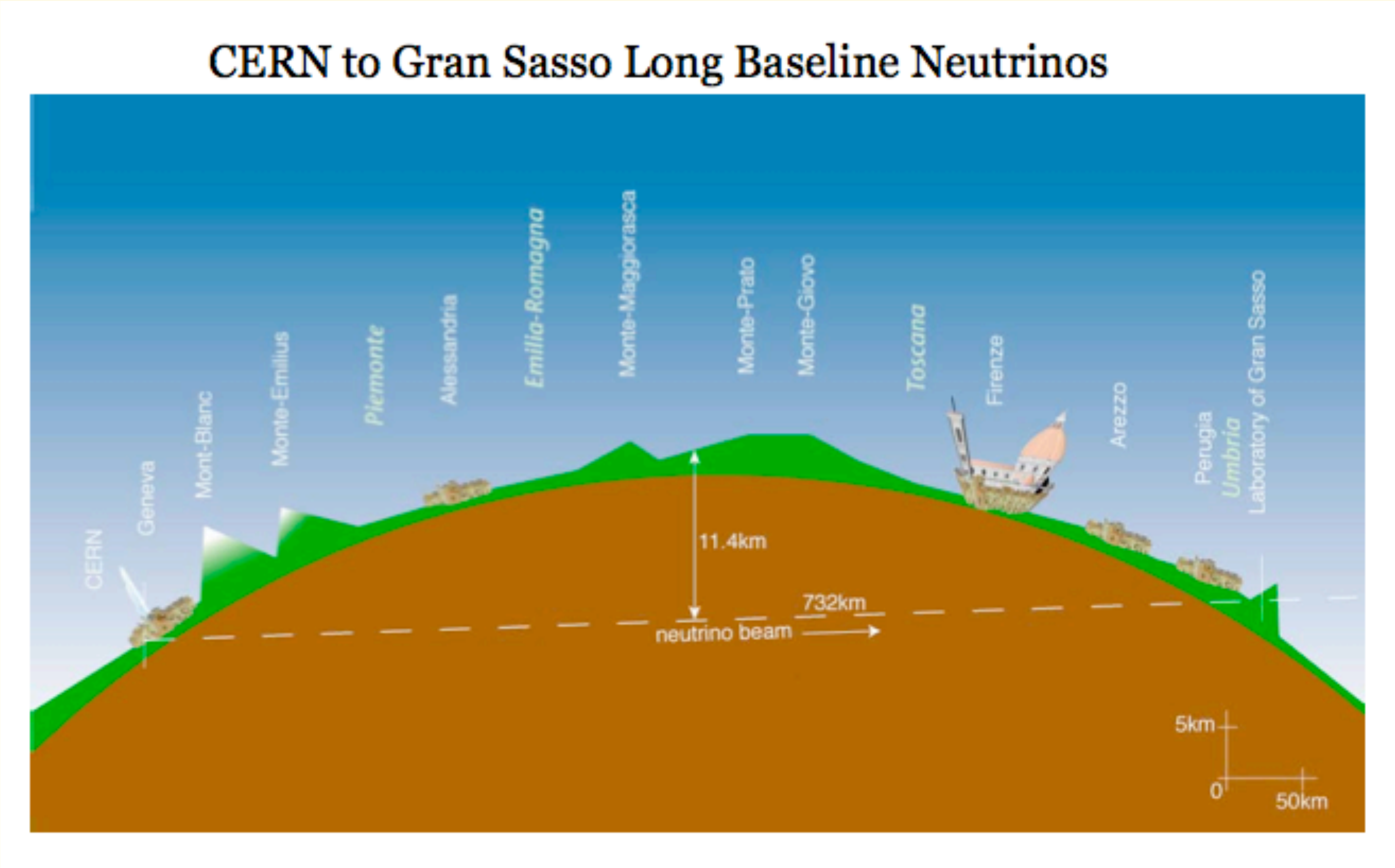
Oscillation to what?

- Both SuperK and MINOS show that ν_μ's disappear via oscillations
- But being disappearance experiments, they do not tell us what is the final state neutrino

Oscillation to what?

- Both SuperK and MINOS show that ν_μ's disappear via oscillations
- But being disappearance experiments, they do not tell us what is the final state neutrino
- Most likely possibility is ν_τ's
  - Any significant contribution from ν_e's excluded by SuperK (atmospheric), CHOOZ (reactor), and MINOS (accelerator)
  - Some small contribution from $\nu_{sterile}$ allowed

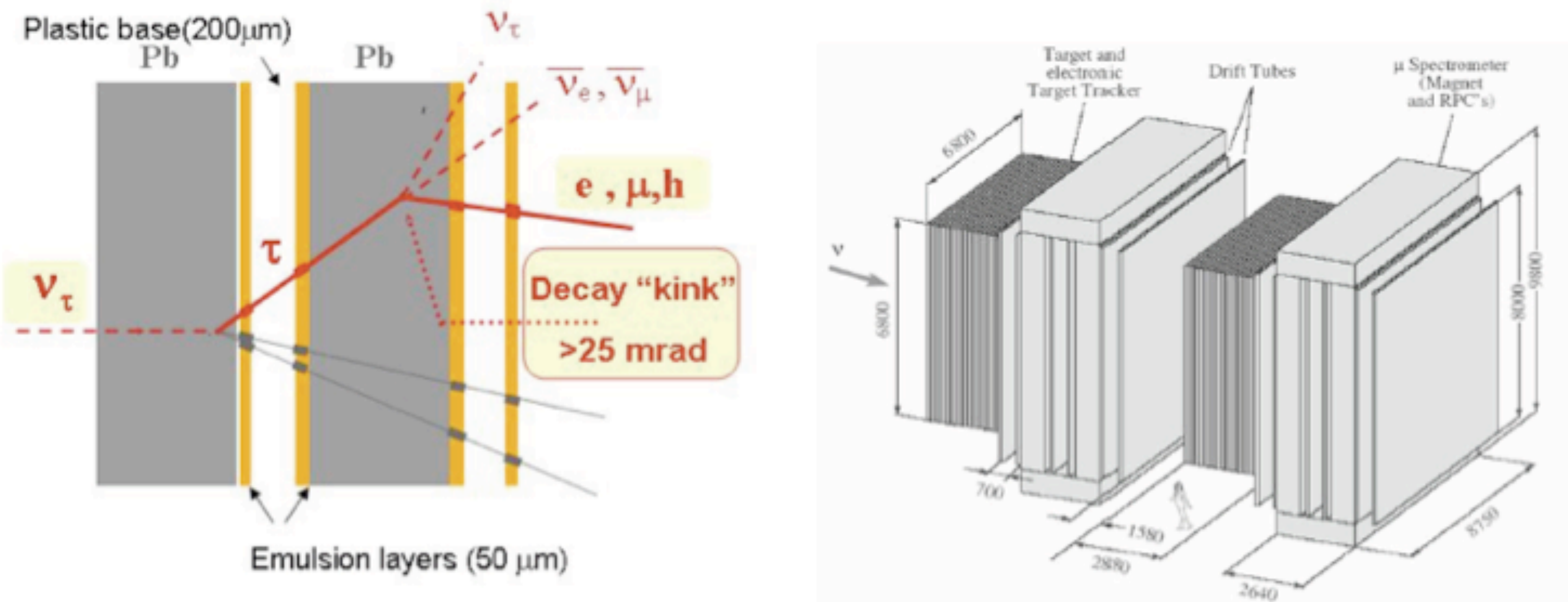
OPERA Experiment



Method and Schematic

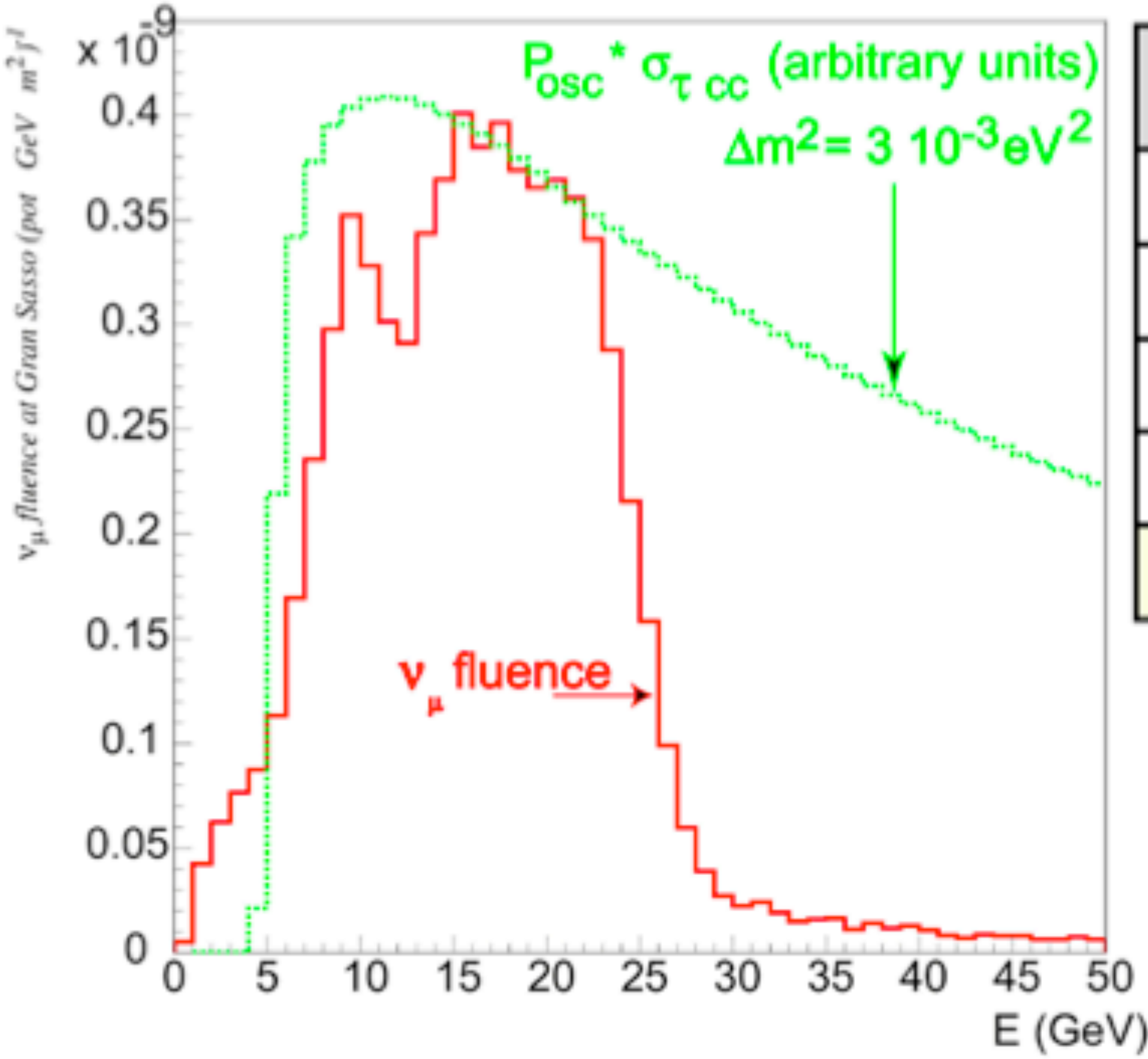
Method and Schematic

10th Int. Conf. on Topics in Astroparticle and Underground Physics (TAUP2007) IOP Publishing
Journal of Physics: Conference Series 120 (2008) 052042 doi:10.1088/1742-6596/120/5/052042



How to Choose the Energy

How to Choose the Energy



Decay channel	Detection efficiency(%)	Branching ratio(%)	Signal ($\Delta m^2 = 2.5 \times 10^{-3}$)	Background
$\tau \to \mu$	17.5	17.7	2.9	0.17
$\tau \to e$	20.8	17.8	3.5	0.17
$\tau \to h$	5.8	49.5	3.1	0.24
$\tau \to 3h$	6.3	15	0.9	0.17
ALL	effxBR=10.6%		**10.4**	**0.75**

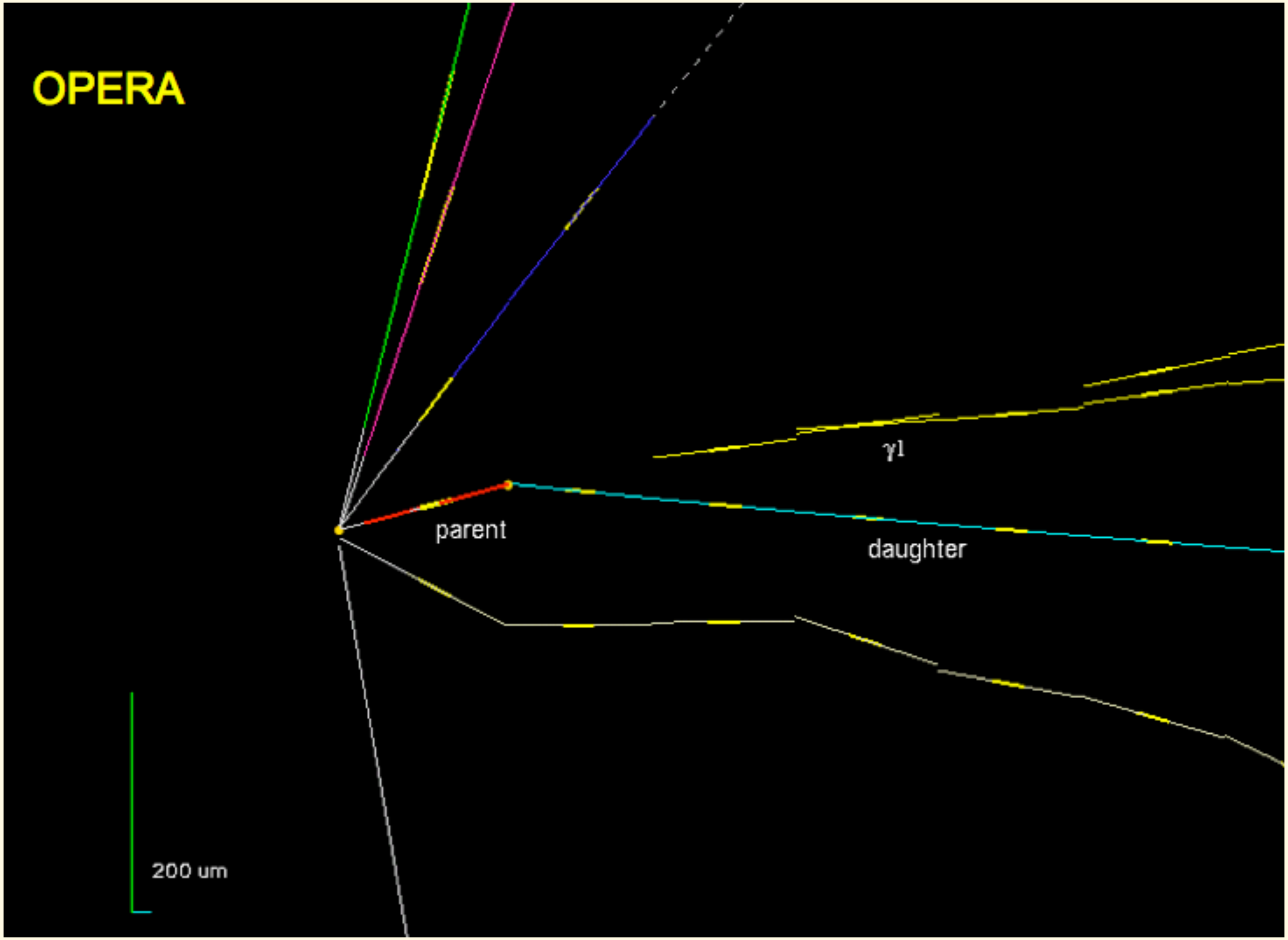
5 year exposure @4.5x10^{19} POT/year

Difficult experiment, and can only expect a handful of events...

OPERA - 1st Candidate

→

OPERA - 1st Candidate



First candidate $\nu_\mu \rightarrow \nu_\tau \quad \tau^- \rightarrow \pi^- + \pi^0$

Issue of $\sin^2(2\theta_{13})$

Mixed (Subdominant) Sector

Mixed (Subdominant) Sector

- 3 distinct approaches can be used

Mixed (Subdominant) Sector

- 3 distinct approaches can be used
- Reactor experiments (disappearance):
  - Simple analysis - only θ_{13} dependence
  - But subtract two large numbers; systematics

Mixed (Subdominant) Sector

- 3 distinct approaches can be used
- Reactor experiments (disappearance):
  - Simple analysis - only θ_{13} dependence
  - But subtract two large numbers; systematics
- Accelerator experiments (appearance):
  - Dependance also on $\theta_{23,}$ mass hierarchy, δ_{CP}

Mixed (Subdominant) Sector

- 3 distinct approaches can be used
- Reactor experiments (disappearance):
  - Simple analysis - only θ_{13} dependence
  - But subtract two large numbers; systematics
- Accelerator experiments (appearance):
  - Dependance also on θ_{23}, mass hierarchy, δ_{CP}
- Atmospheric and solar experiments:
  - Look for small effects in 3-flavor analyses

Mixed (Subdominant) Sector

- 3 distinct approaches can be used
- Reactor experiments (disappearance):
  - Simple analysis - only θ_{13} dependence
  - But subtract two large numbers; systematics
- Accelerator experiments (appearance):
  - Dependance also on $\theta_{23,}$ mass hierarchy, δ_{CP}
- Atmospheric and solar experiments:
  - Look for small effects in 3-flavor analyses

Caution: Values (limits) are quoted both for $\sin^2(2\theta_{13})$ -accelerators and reactors, and $\sin^2(\theta_{13})$ - 3 flavor

Reactors - CHOOZ limit

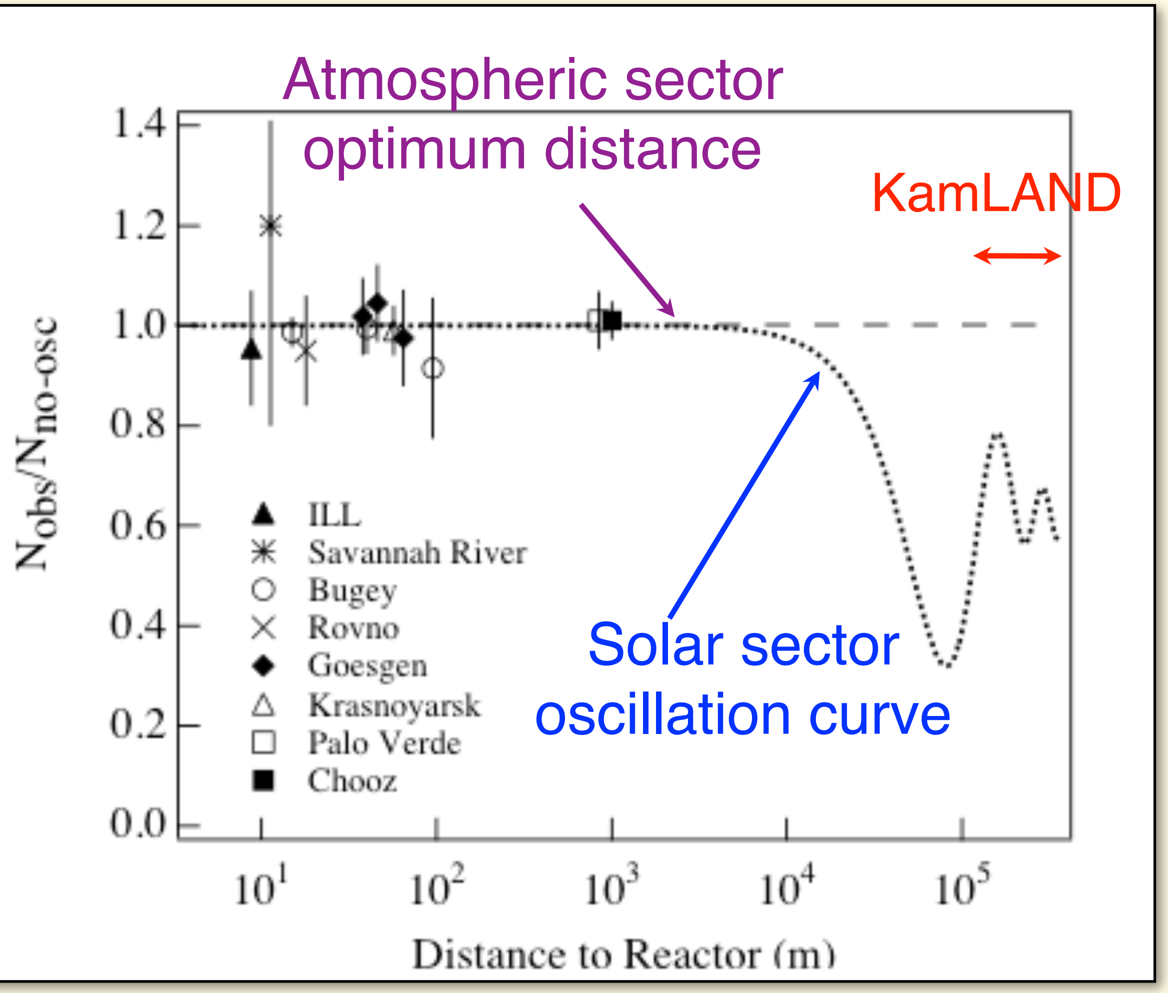
Reactors - CHOOZ limit

Previous reactor experiments showed no depletion of neutrino flux, signature of oscillations

Reactors - CHOOZ limit

Previous reactor experiments showed no depletion of neutrino flux, signature of oscillations

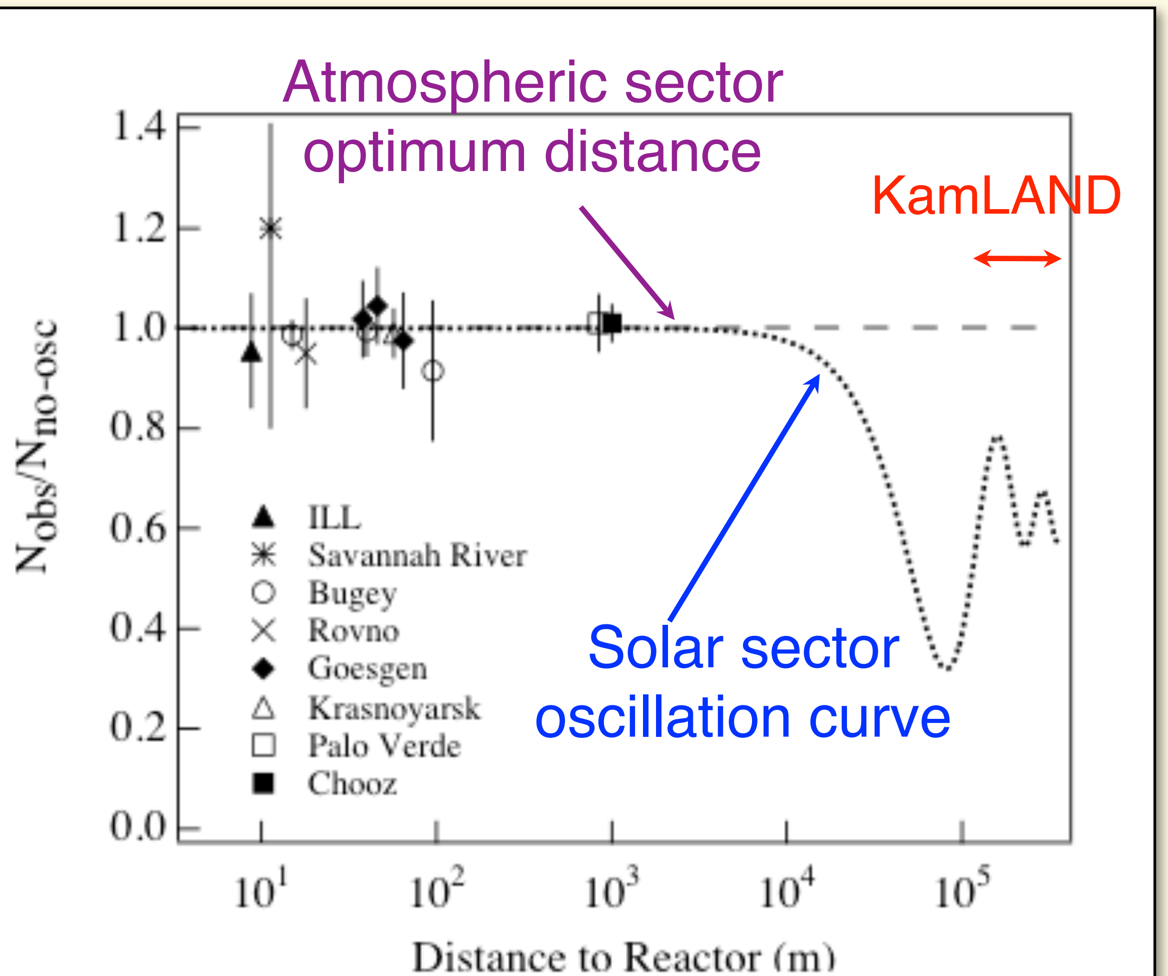
Previous experiments



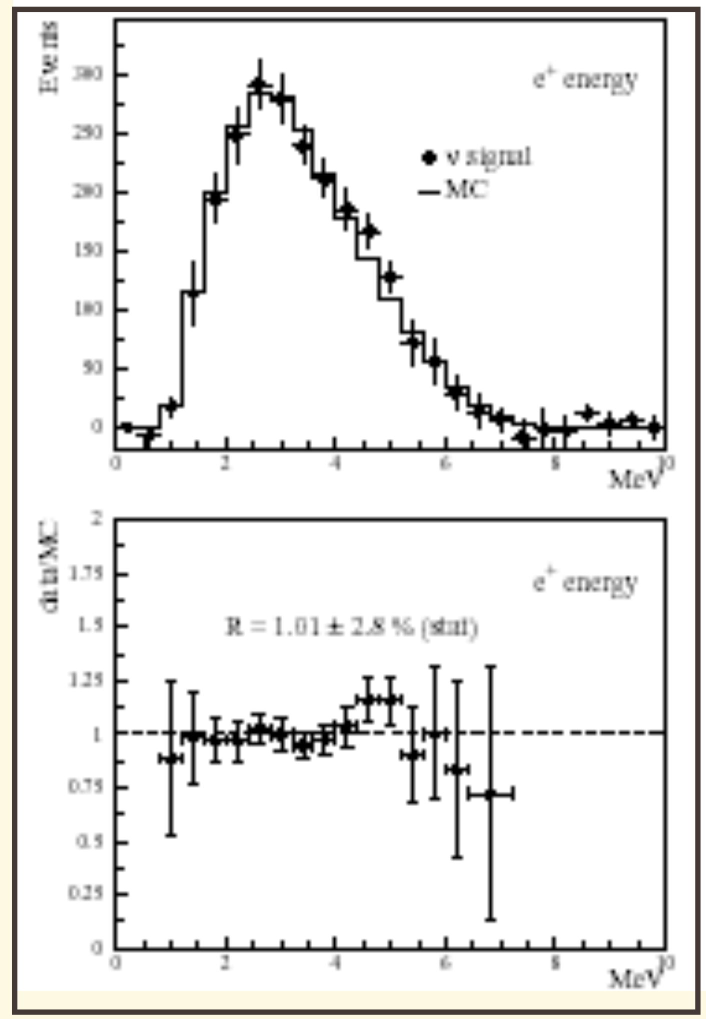
Reactors - CHOOZ limit

Previous reactor experiments showed no depletion of neutrino flux, signature of oscillations

Previous experiments



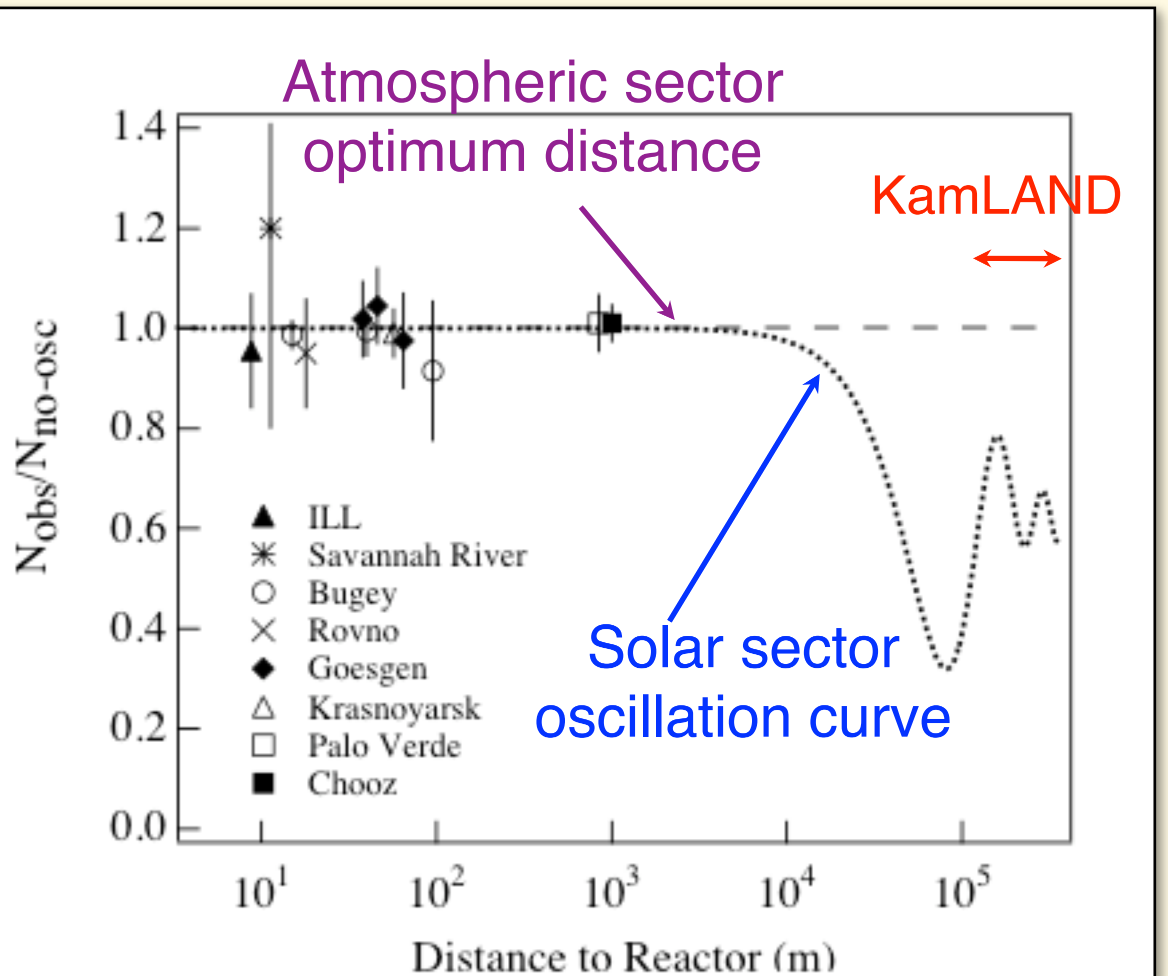
CHOOZ Spectra



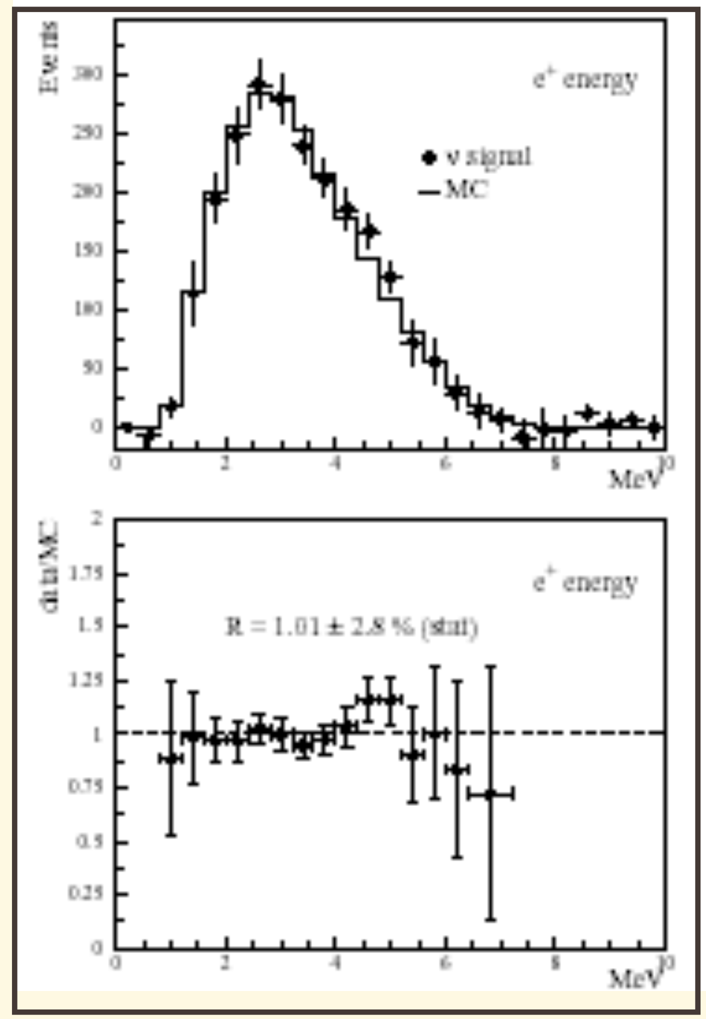
Reactors - CHOOZ limit

Previous reactor experiments showed no depletion of neutrino flux, signature of oscillations

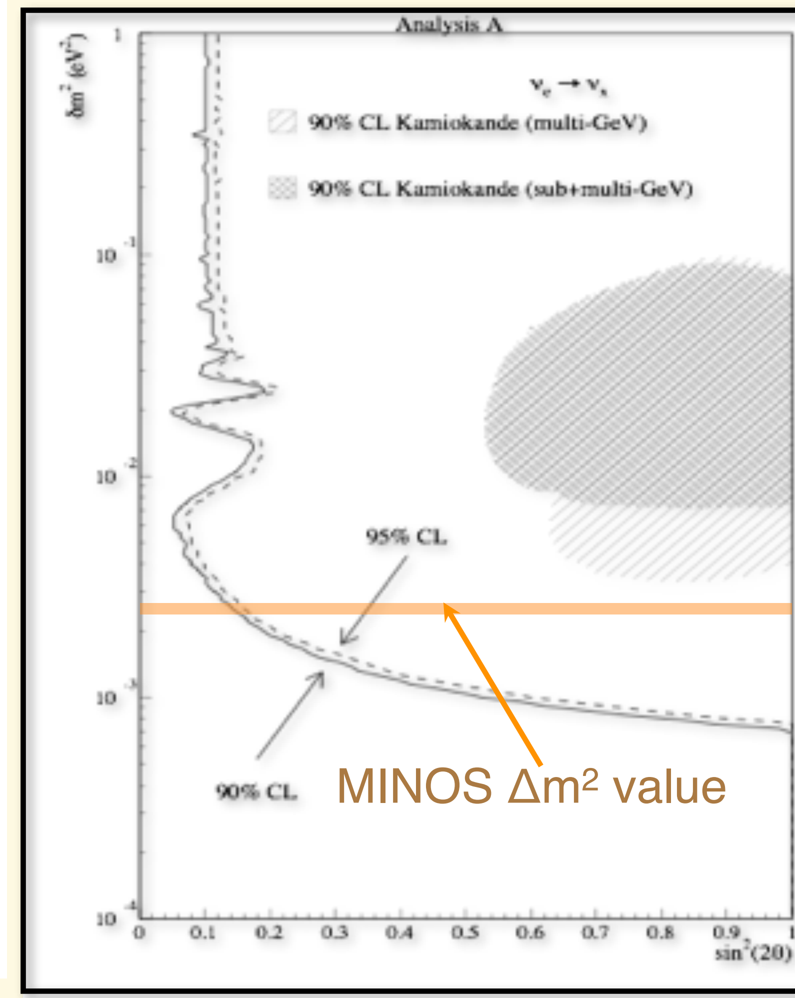
Previous experiments



CHOOZ Spectra



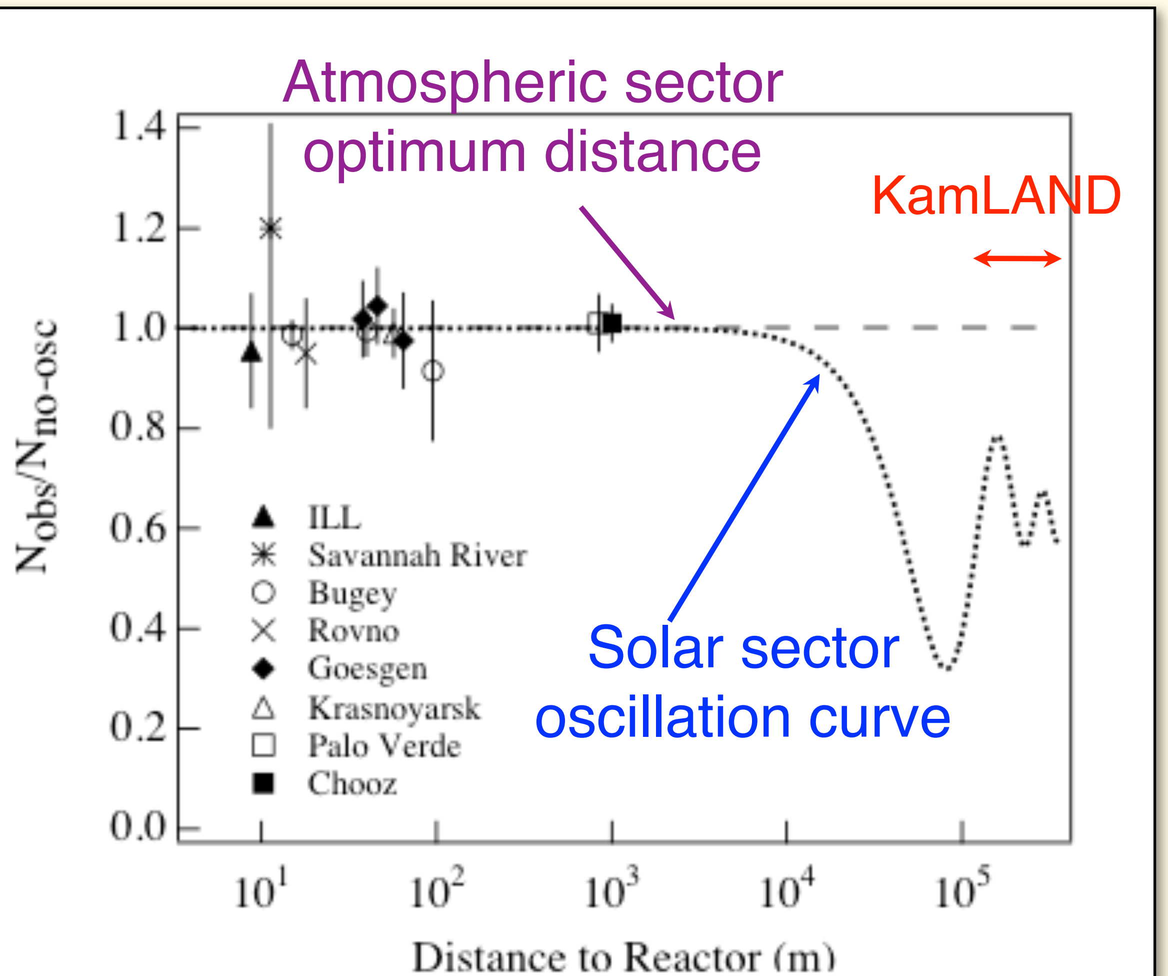
CHOOZ Limits



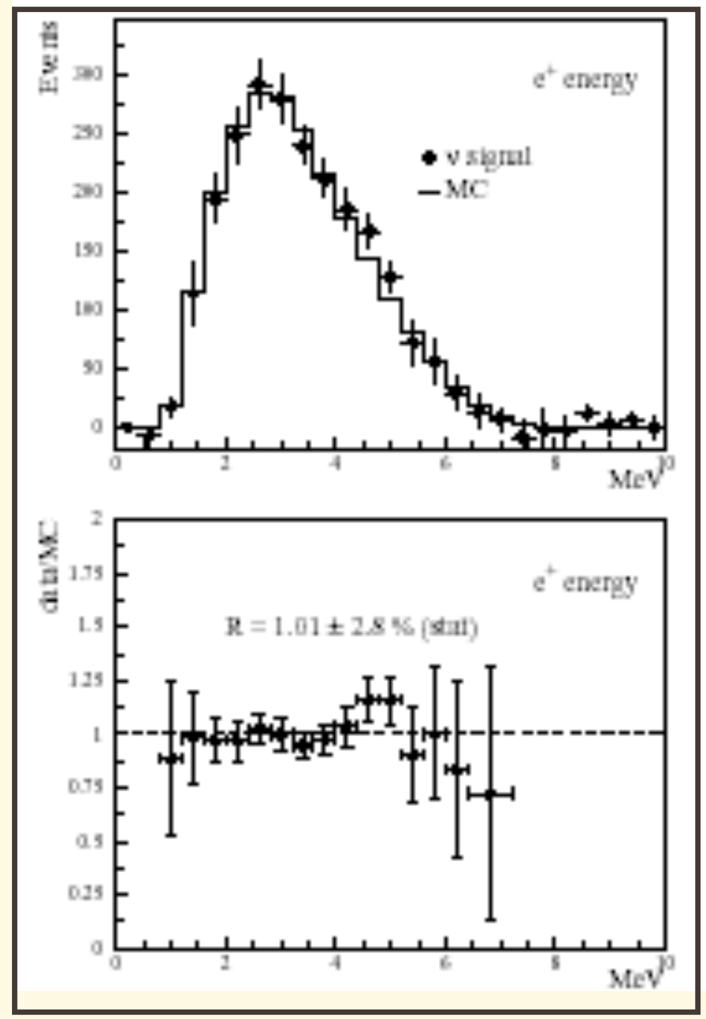
Reactors - CHOOZ limit

Previous reactor experiments showed no depletion of neutrino flux, signature of oscillations

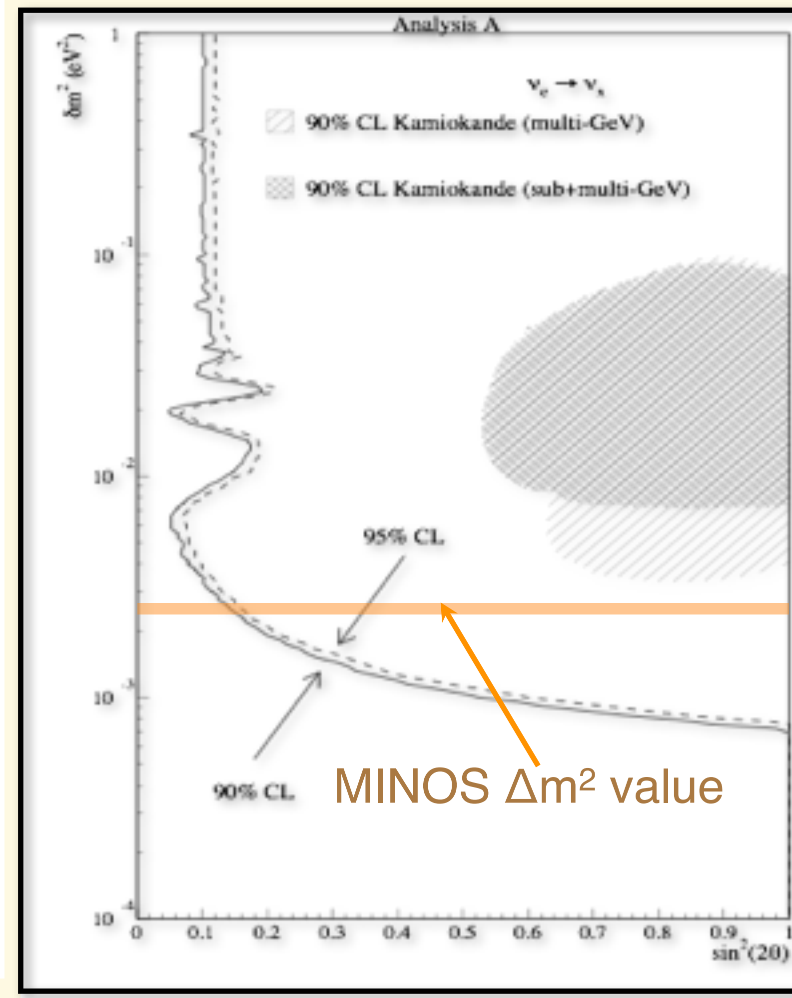
Previous experiments



CHOOZ Spectra



CHOOZ Limits



CHOOZ limit: $\sin^2(2\theta_{13})<0.15$ (90% C.L.)

(at $\Delta m^2_{31} = 2.3 \times 10^{-3}\ eV^2$)

ν_e Appearance

ν_e Appearance

The probability of $\nu_\mu \to \nu_e$ transitions depends not only on θ_{13} but also on θ_{23}, θ_{12}, δ_{CP} and mass hierarchy

ν_e Appearance

The probability of $\nu_\mu \to \nu_e$ transitions depends not only on θ_{13} but also on θ_{23}, θ_{12}, δ_{CP} and mass hierarchy

$$P(\nu_\mu \to \nu_e) \approx \mathbf{\sin^2(2\theta_{13})}\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$

Main "atmospheric" term

$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$

Solar term

$$\mathbf{\sin(2\theta_{13})}\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E} \pm \delta_{\mathrm{CP}}\right)$$

ν_e Appearance

The probability of $\nu_\mu \to \nu_e$ transitions depends not only on θ_{13} but also on θ_{23}, θ_{12}, δ_{CP} and mass hierarchy

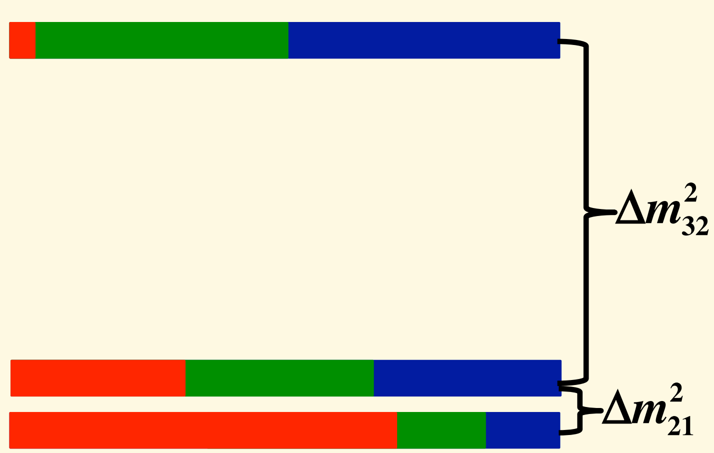
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$

Main "atmospheric" term

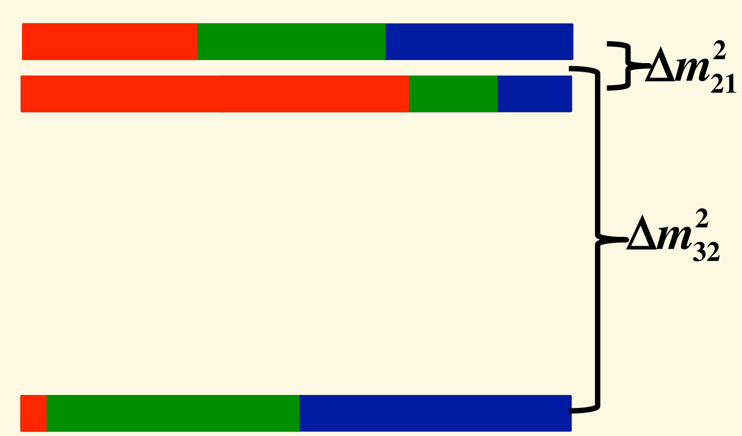
$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$

Solar term

$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E} \pm \delta_{CP}\right)$$



Normal hierarchy

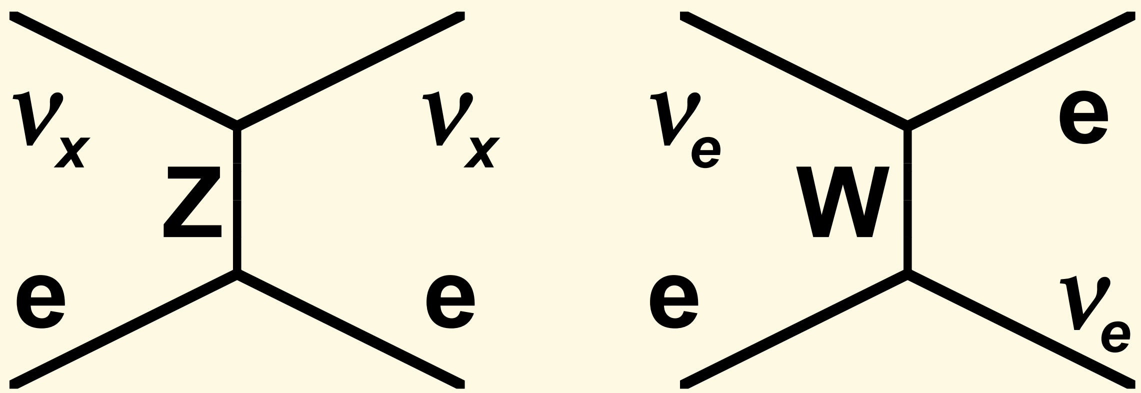


Inverted hierarchy

Matter Effects

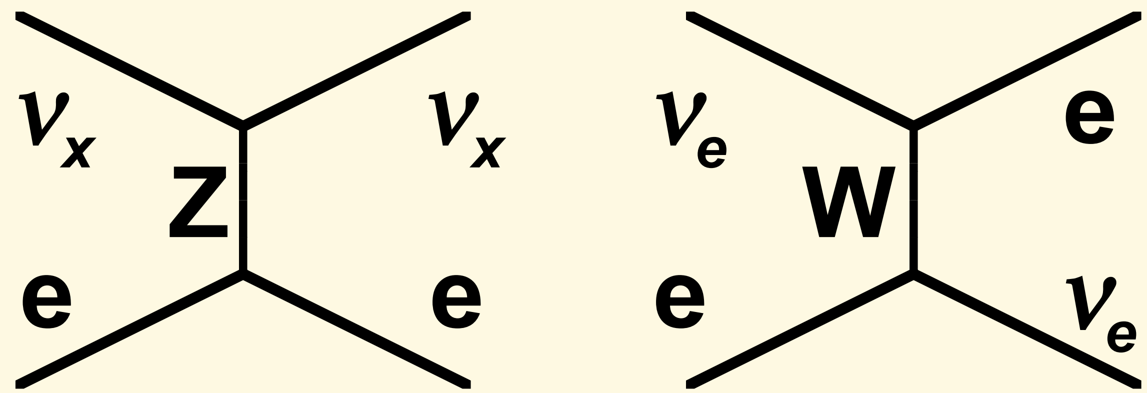
Matter Effects

In matter, ν_e's interact differently than other flavor neutrinos because of additional interaction with electrons



Matter Effects

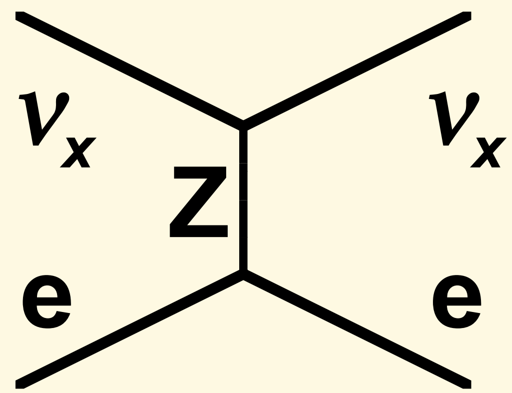
In matter, ν_e's interact differently than other flavor neutrinos because of additional interaction with electrons

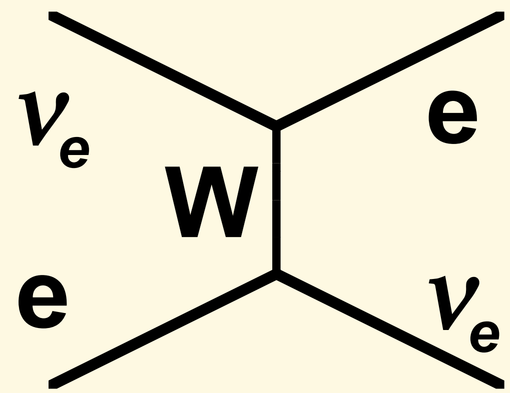


As a result, the transition $\nu_\mu \to \nu_e$ will be enhanced for normal hierarchy and suppressed for inverse hierarchy. Opposite will be true for antineutrinos.

Matter Effects

In matter, ν_e's interact differently than other flavor neutrinos because of additional interaction with electrons





As a result, the transition ν_μ->ν_e will be enhanced for normal hierarchy and suppressed for inverse hierarchy. Opposite will be true for antineutrinos.

Thus this is a means of distinguishing between the two hierarchies. The effect increases with energy. For MINOS (735 km) it is about 30% difference

ν_e appearance - MINOS

ν_e appearance - MINOS

- The principal challenge is reduction and prediction of background (mainly NC)

ν_e appearance - MINOS

- The principal challenge is reduction and prediction of background (mainly NC)
- A neural network (ANN) consisting of several variables characterizing topology of the event is used to distinguish NC and CC backgrounds from ν_e signal

ν_e appearance - MINOS

- The principal challenge is reduction and prediction of background (mainly NC)
- A neural network (ANN) consisting of several variables characterizing topology of the event is used to distinguish NC and CC backgrounds from ν_e signal
- The ANN distribution in the Near Detector is then used to optimize the cuts and predict the background in the Far Detector

Analysis strategy

Analysis strategy

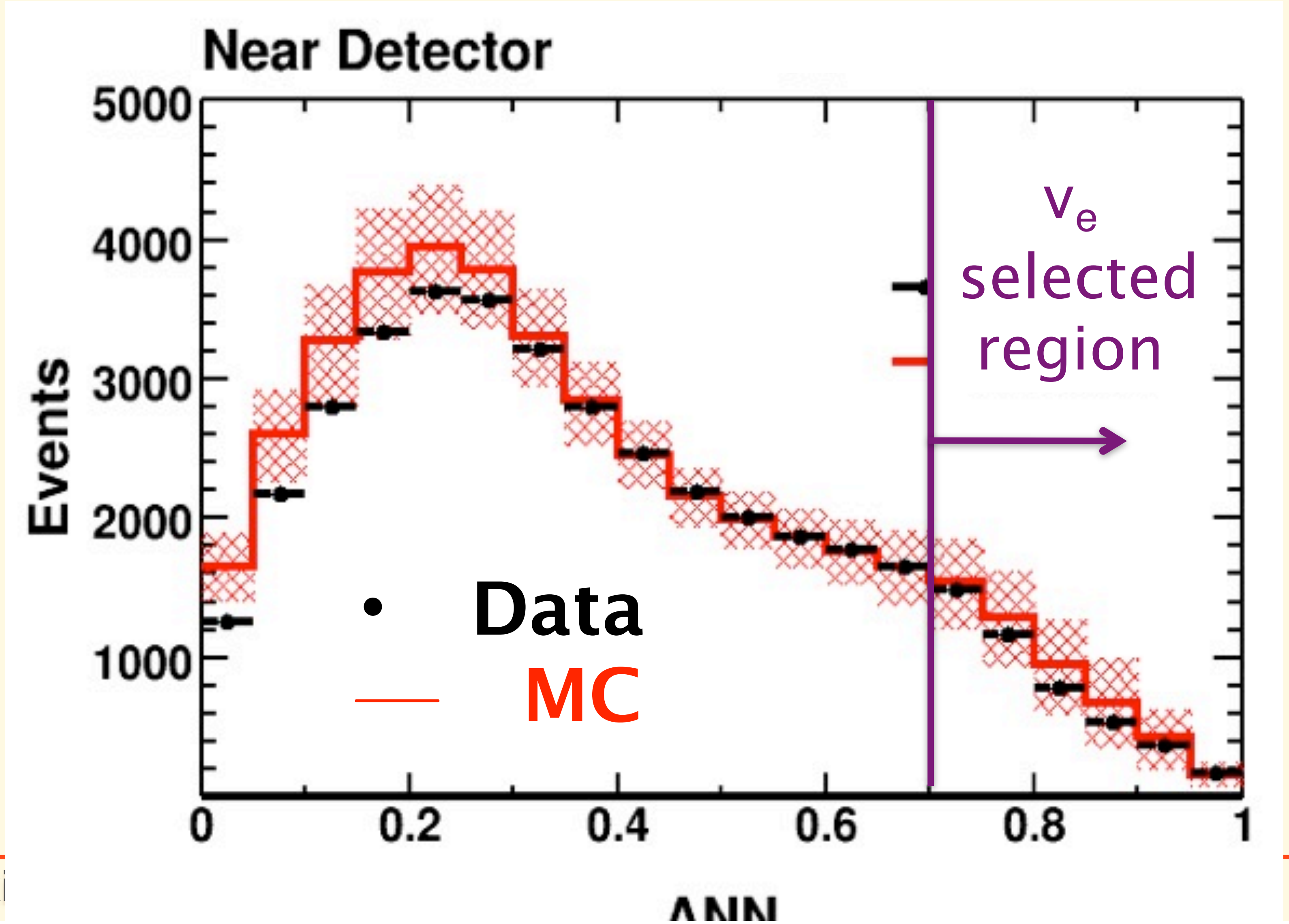
- Use 11 shape variables in a Neural Net (ANN) which characterize event topology

Analysis strategy

- Use 11 shape variables in a Neural Net (ANN) which characterize event topology
- Apply selection to ND data to predict background level in FD

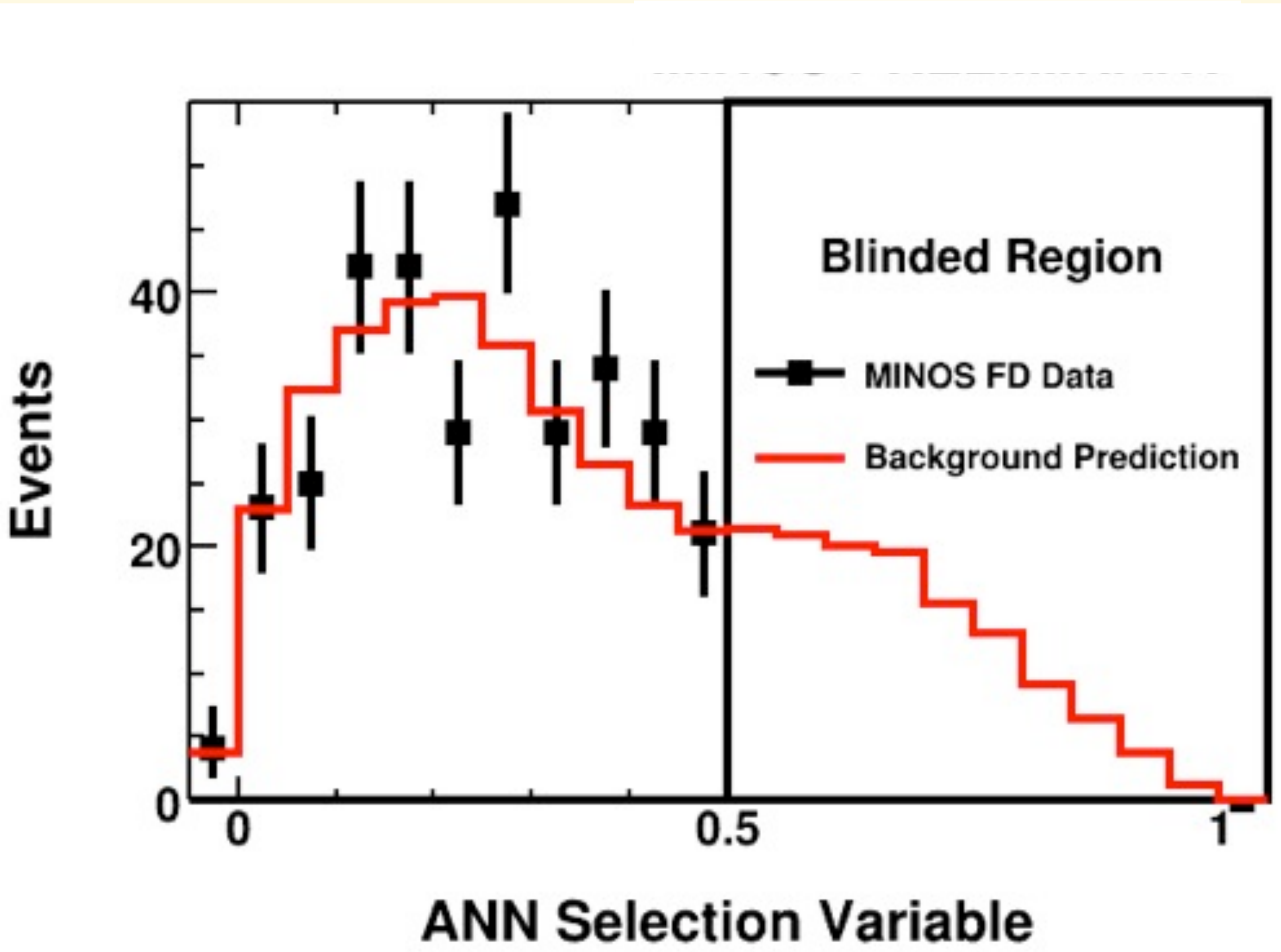
Analysis strategy

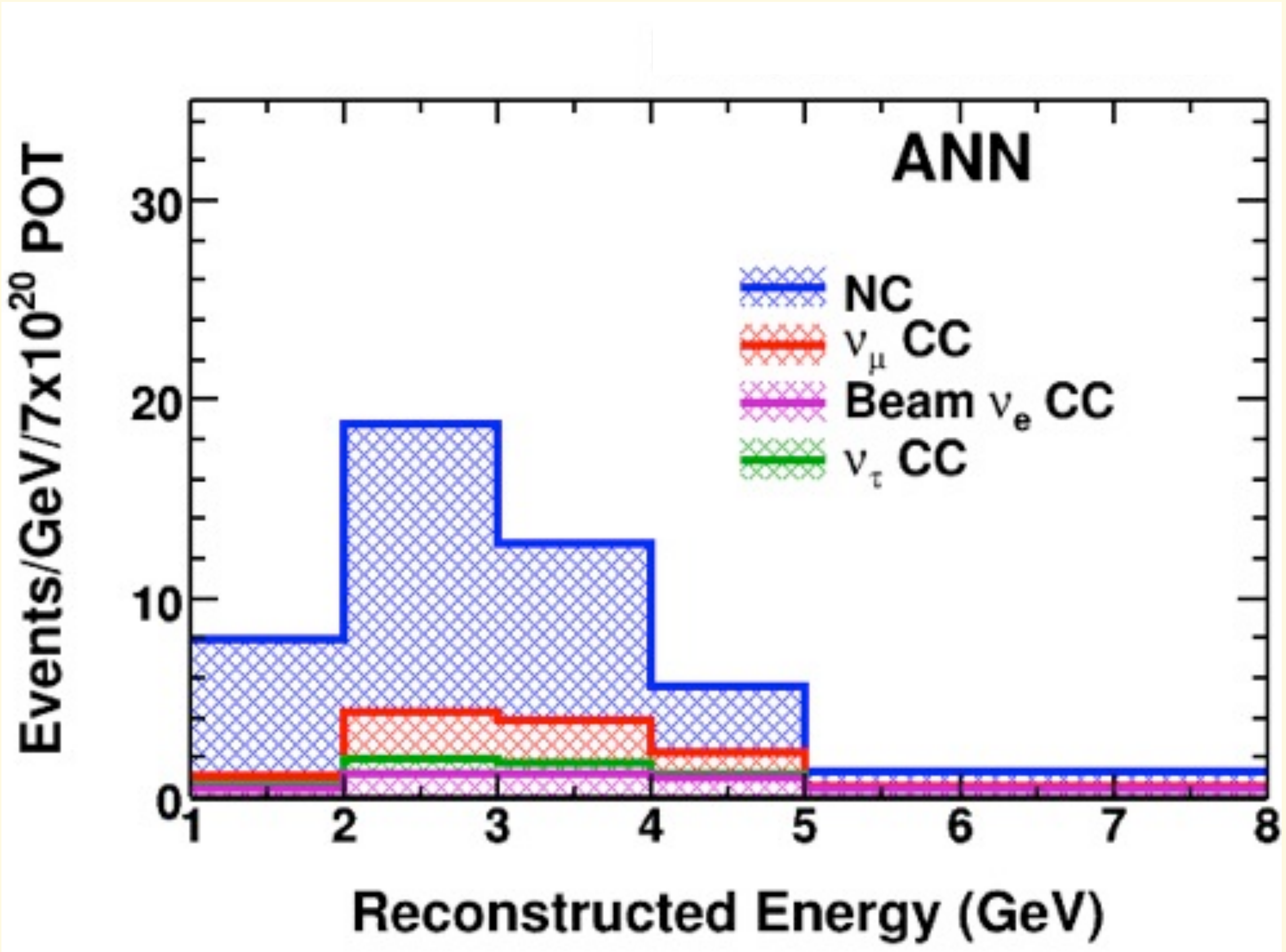
- Use 11 shape variables in a Neural Net (ANN) which characterize event topology
- Apply selection to ND data to predict background level in FD



ν_e Appearance Results

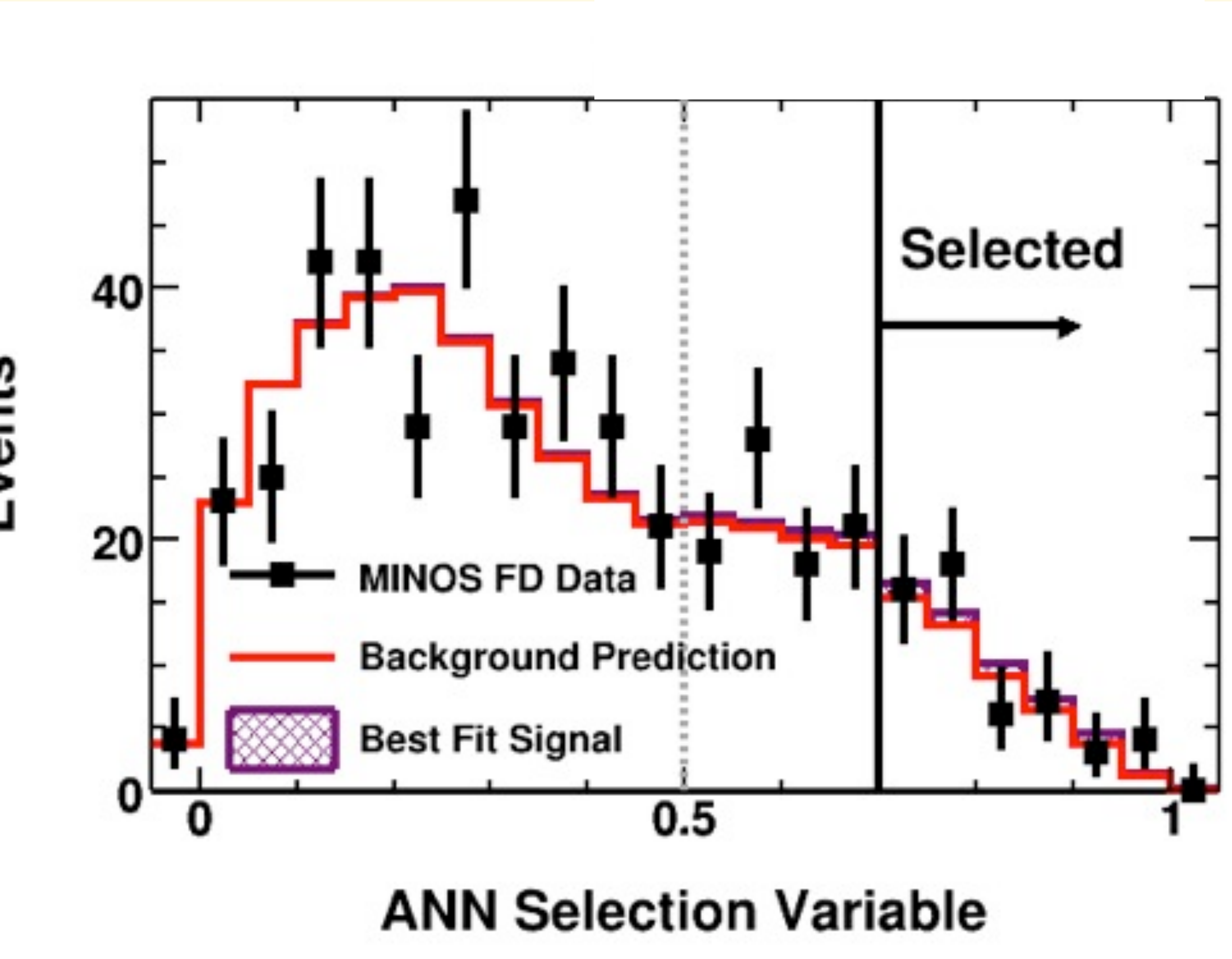
- Based on ND data, expect: **49.1±7.0 (stat.)±2.7(syst.)**



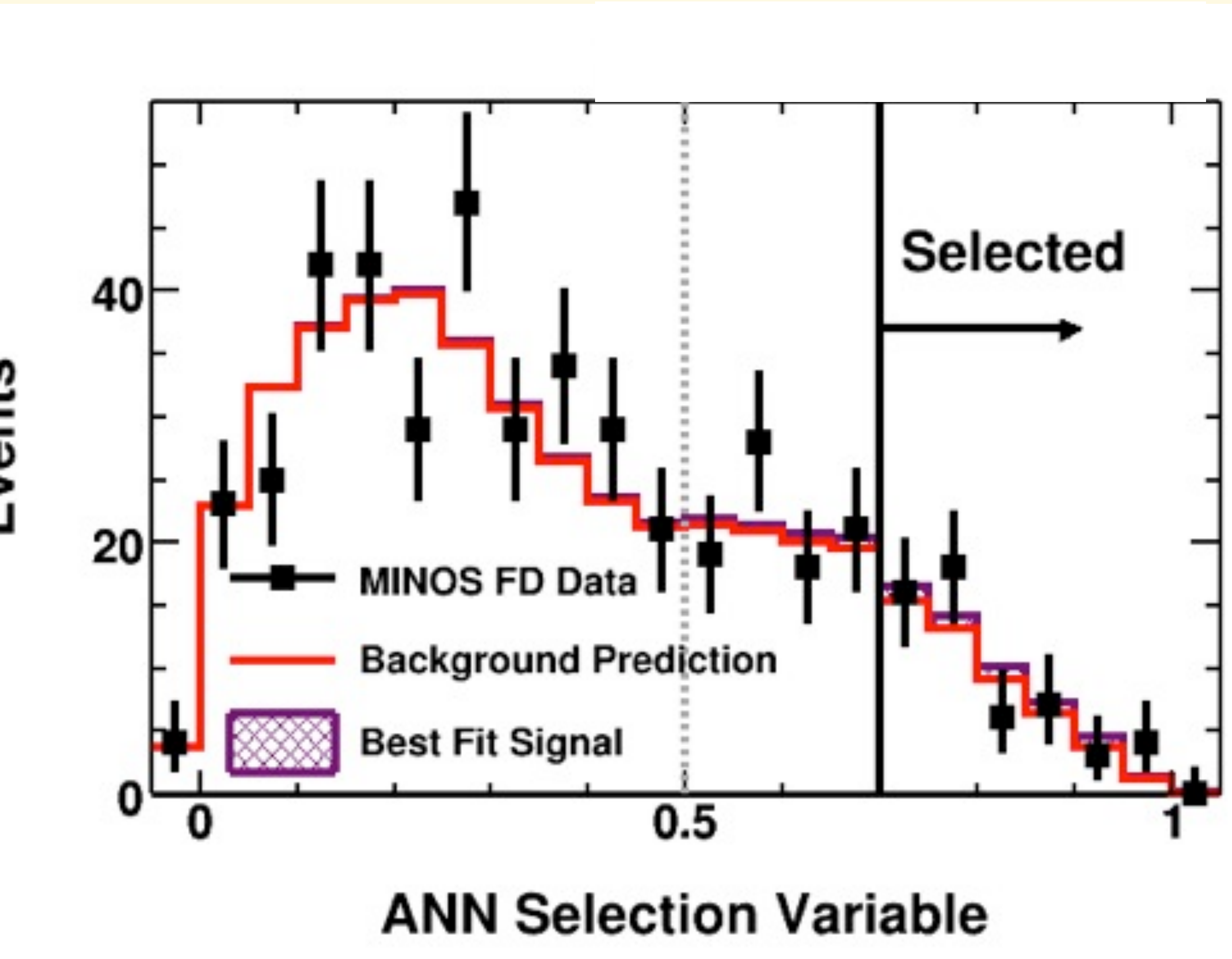


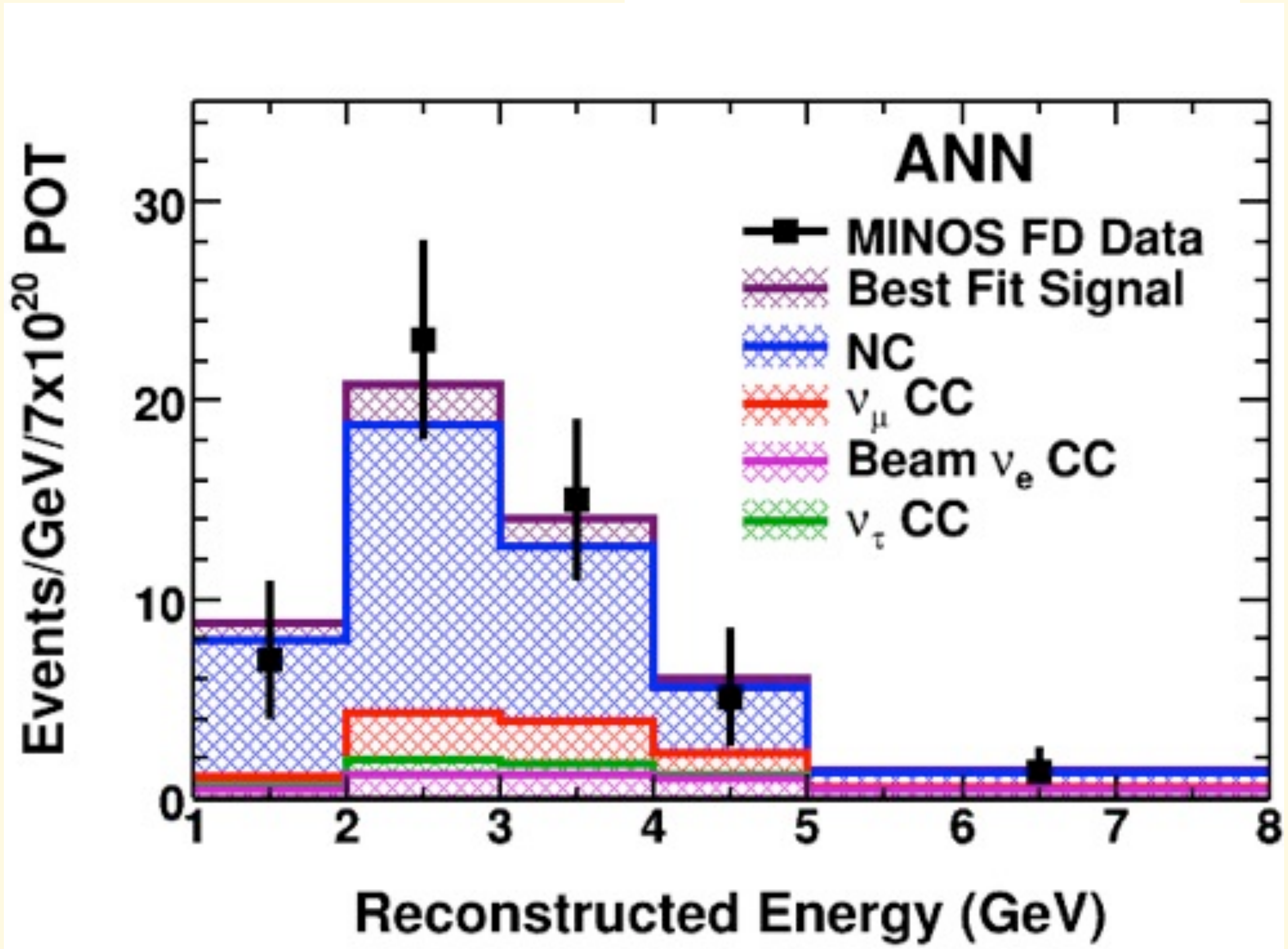
ν_e Appearance Results

ν_e Appearance Results

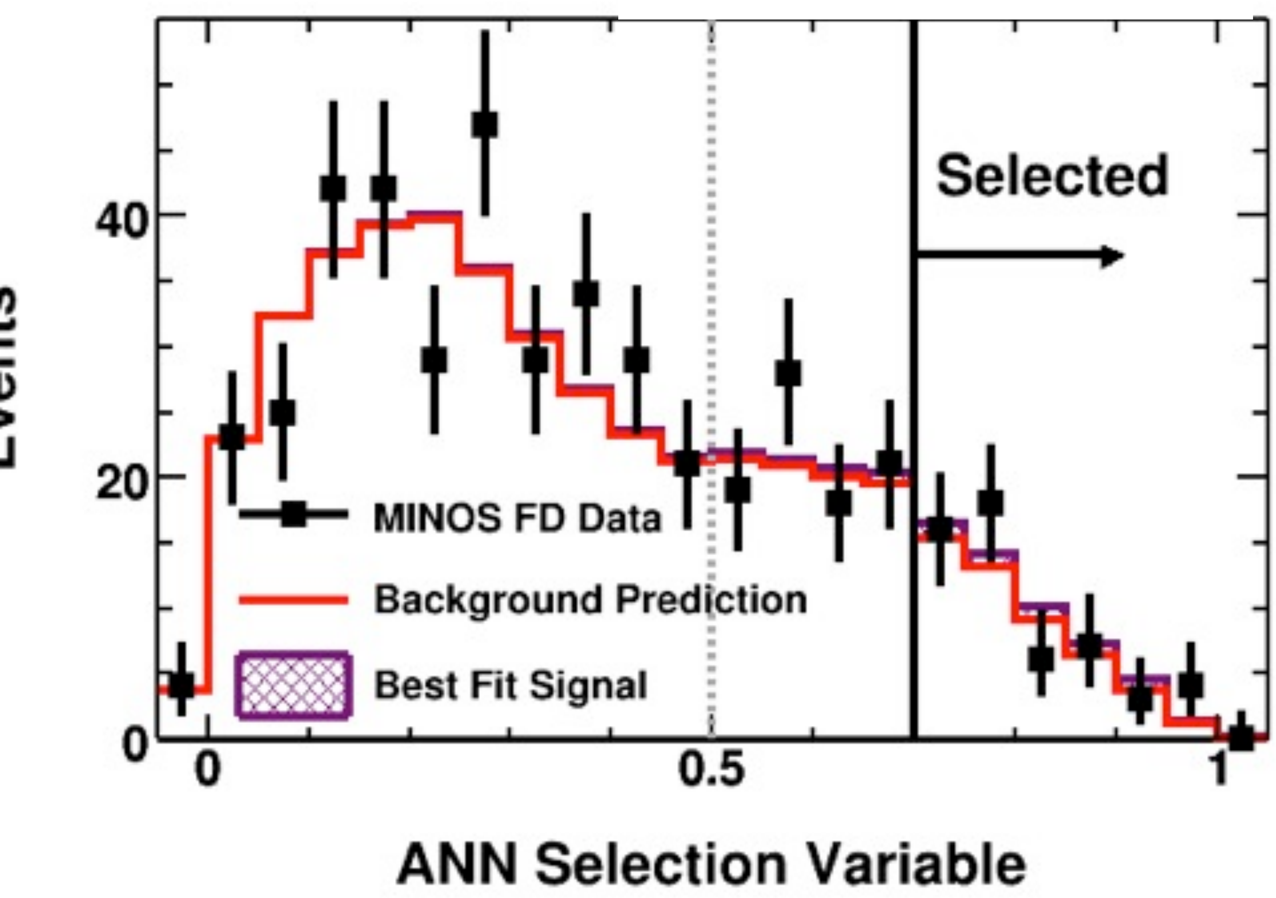


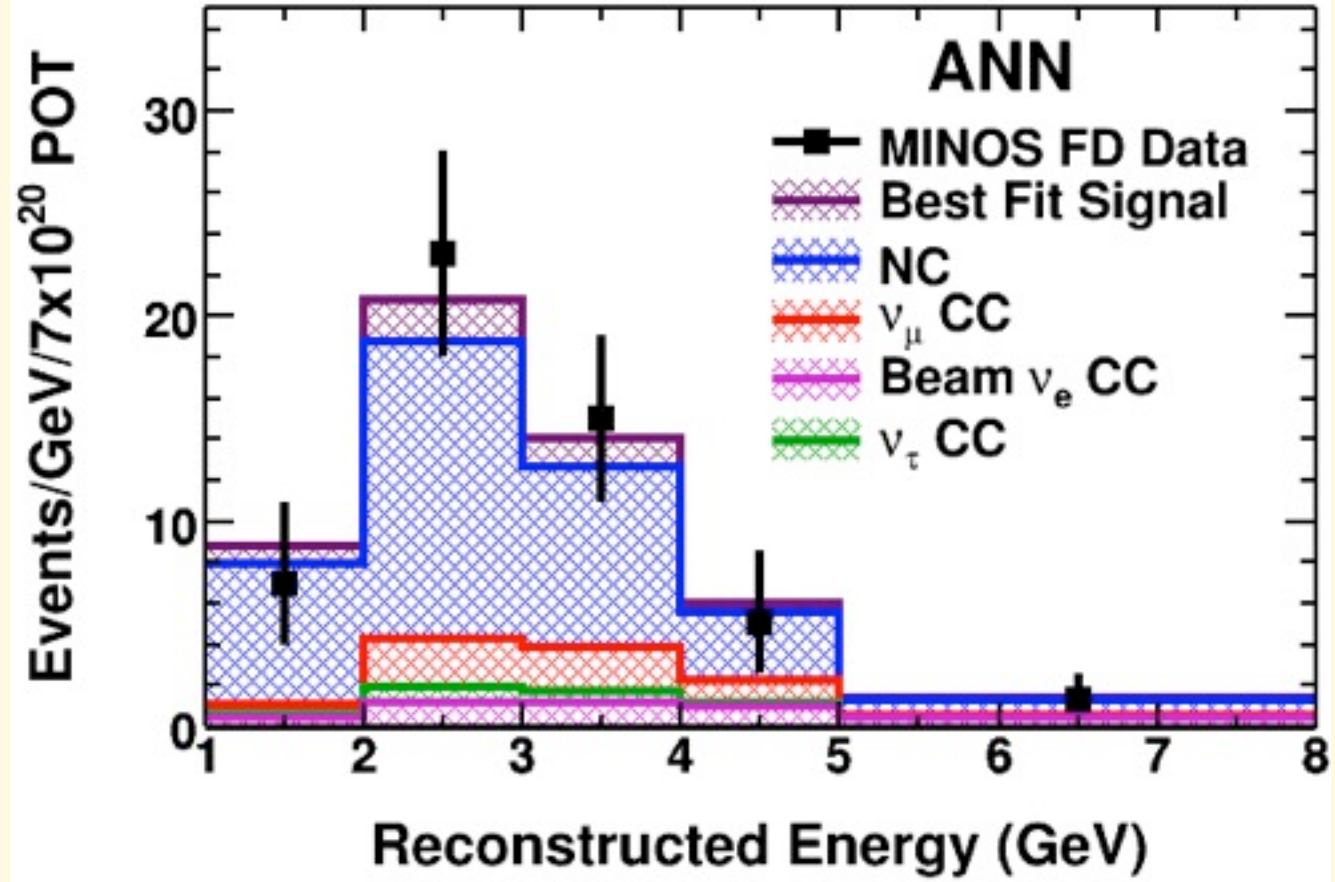
ν_e Appearance Results





ν_e Appearance Results





The ND analysis predicts:

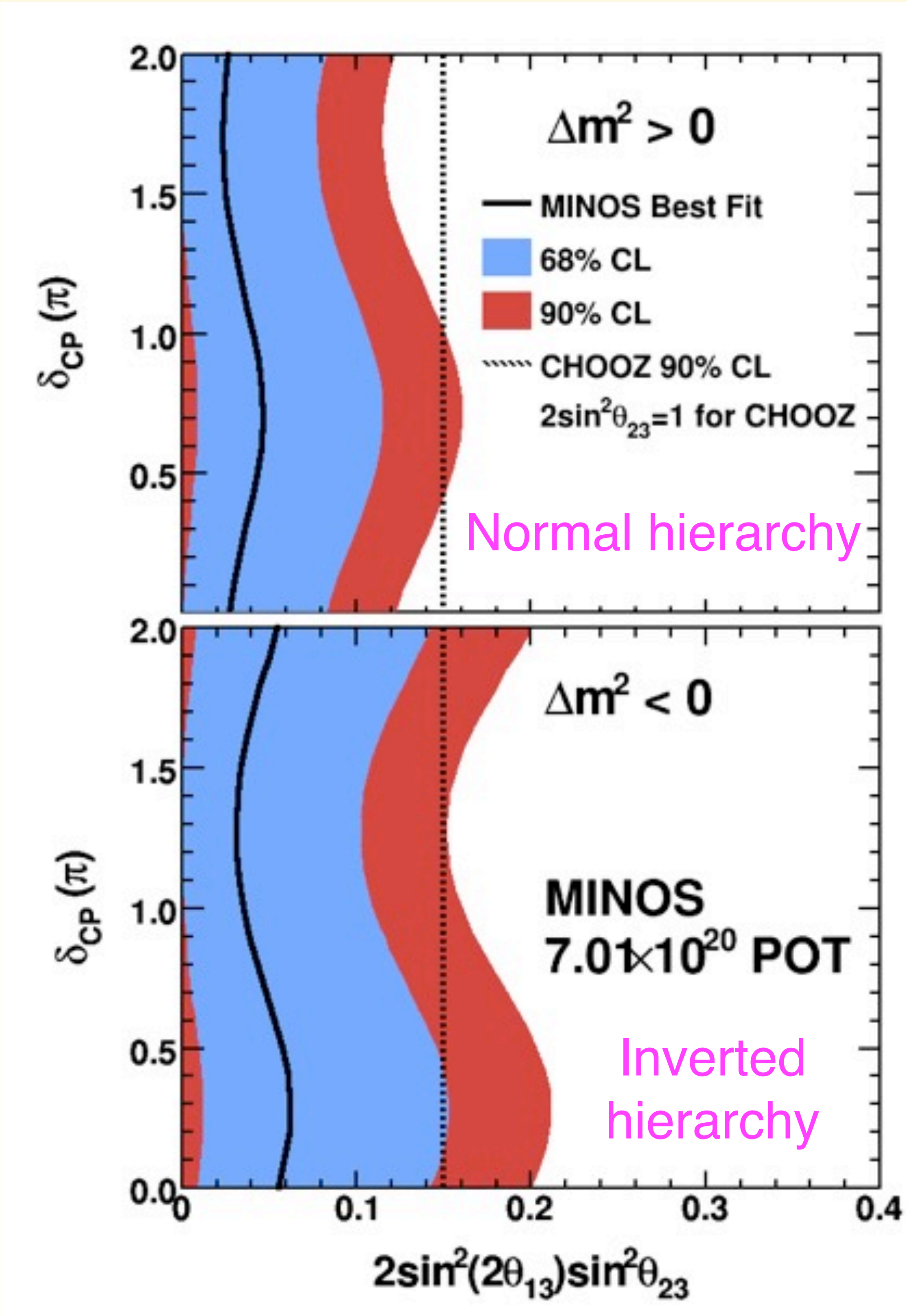
49.1±7.0(stat.)±2.7(syst.)

events in the Far Detector

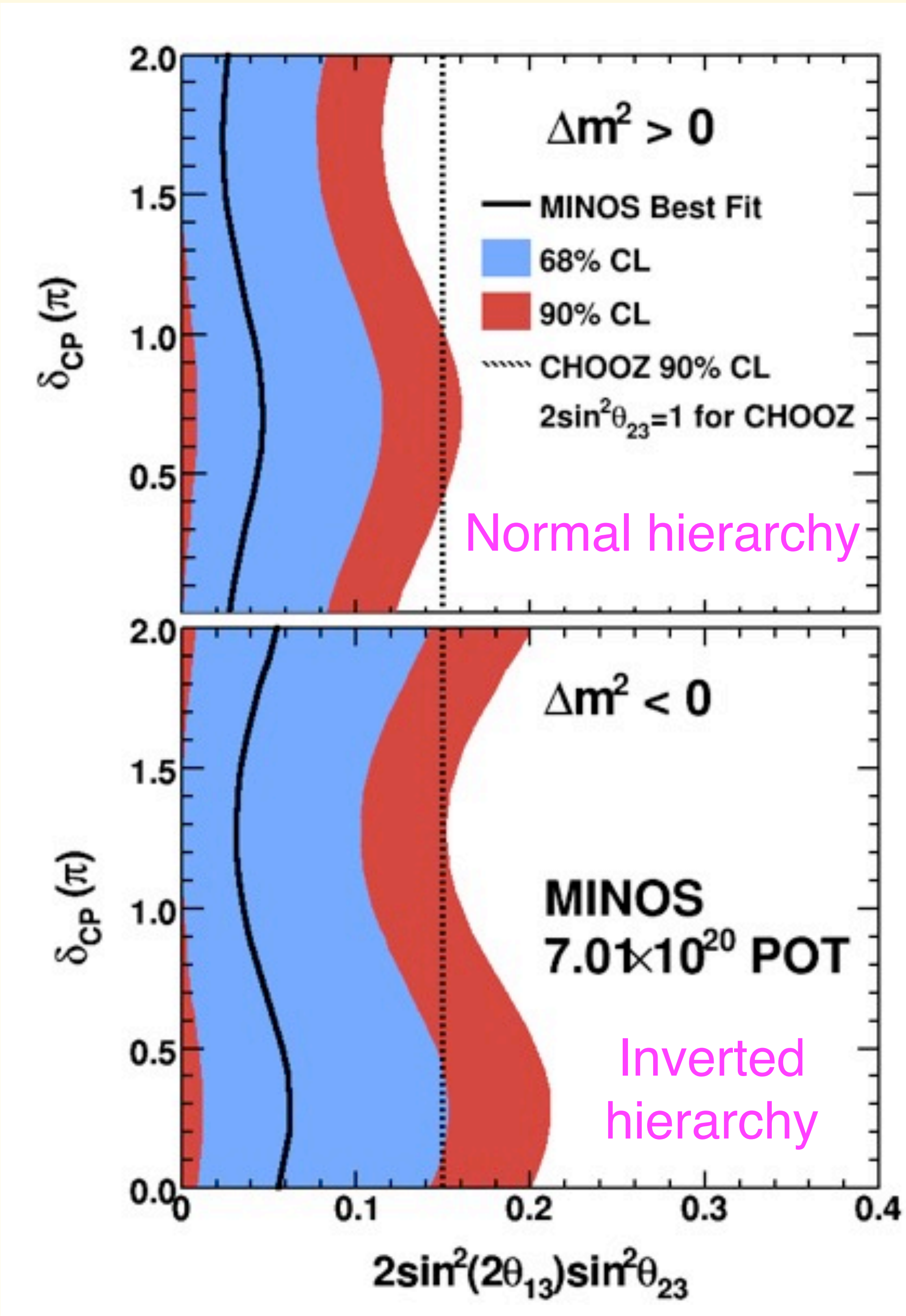
54 observed, **0.7σ** excess

MINOS Result

MINOS Result



MINOS Result



The 90% C.L. limits are:

$\sin^2(2\theta_{13}) < 0.12$ (normal)

$\sin^2(2\theta_{13}) < 0.20$ (inverse)

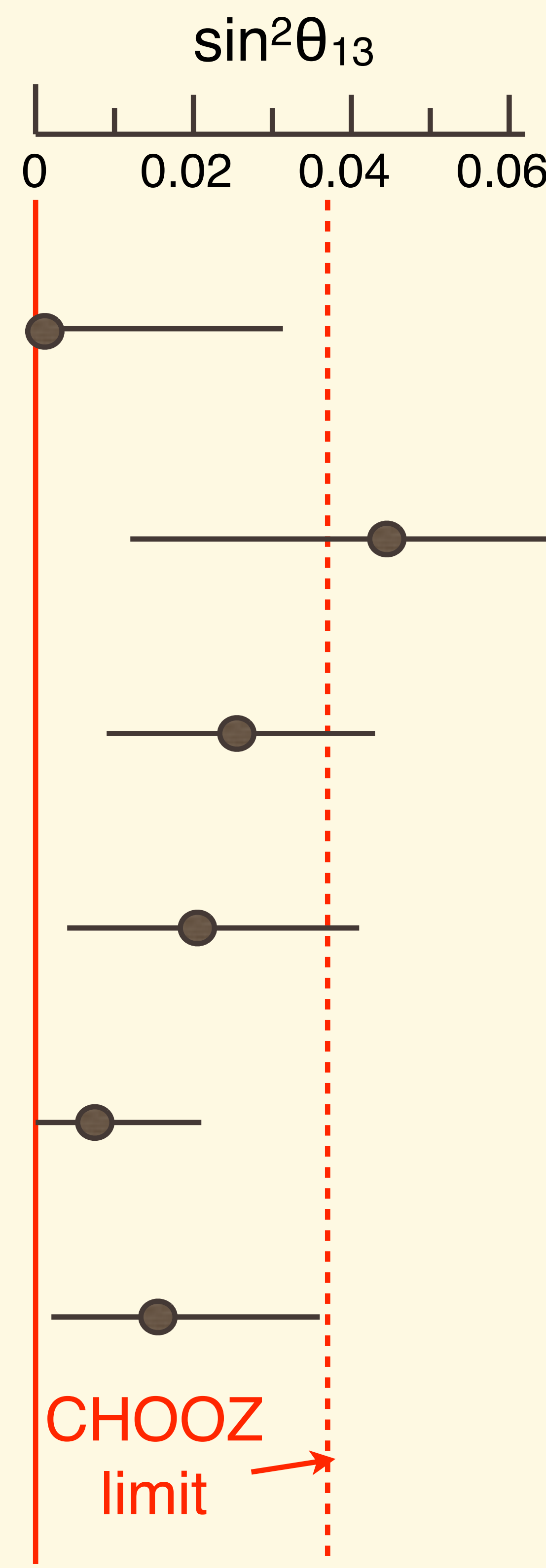
for

$\sin^2(2\theta_{23}) = 1$, $\delta_{CP} = 0$,

$|\Delta m^2_{31}| = 2.43 \times 10^{-3}$ eV^2

Summary (Mixed)

Oscillation analysis	$\sin^2\theta_{13}$ (value)	$\sin^2\theta_{13}$ (90% CL)	$\sin^2\theta_{13}$ (95% CL)
SuperK (atmospheric,norm)	$0.006^{+.030}_{-.006}$	<0.066	
SuperK (atmospheric,inv)	$0.044^{+.041}_{-.032}$	<0.122	
SuperK (solar,global)	$0.025^{+.018}_{-.016}$		<0.059
SNO (solar,global)	$0.020^{+.021}_{-.016}$		<0.057
MINOS (normal) at $\delta_{CP}=0$	$0.007^{+.014}_{-.007}$	<0.03	
MINOS (inverted) at $\delta_{CP}=0$	$0.015^{+.021}_{-.013}$	<0.05	
CHOOZ		<0.037	



Anomalies?

LSND Experiment

LSND Experiment

- The experiment uses neutrinos produced in the proton beam dump

LSND Experiment

- The experiment uses neutrinos produced in the proton beam dump
- The relevant steps are as follows:

LSND Experiment

- The experiment uses neutrinos produced in the proton beam dump
- The relevant steps are as follows:

$$p + Cu \rightarrow \pi^-, \pi^+, \ldots$$

π^- stops and is captured by a nucleus; no neutrinos

LSND Experiment

- The experiment uses neutrinos produced in the proton beam dump
- The relevant steps are as follows:

$$p + Cu \rightarrow \pi^-, \pi^+, \ldots$$

π^- stops and is captured by a nucleus; no neutrinos

π^+ stops; decays: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

μ^+ stops; decays: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

LSND Experiment

- The experiment uses neutrinos produced in the proton beam dump
- The relevant steps are as follows:

$$p + Cu \to \pi^-, \pi^+, \ldots$$

π^- stops and is captured by a nucleus; no neutrinos

π^+ stops; decays: $\pi^+ \to \mu^+ + \nu_\mu$

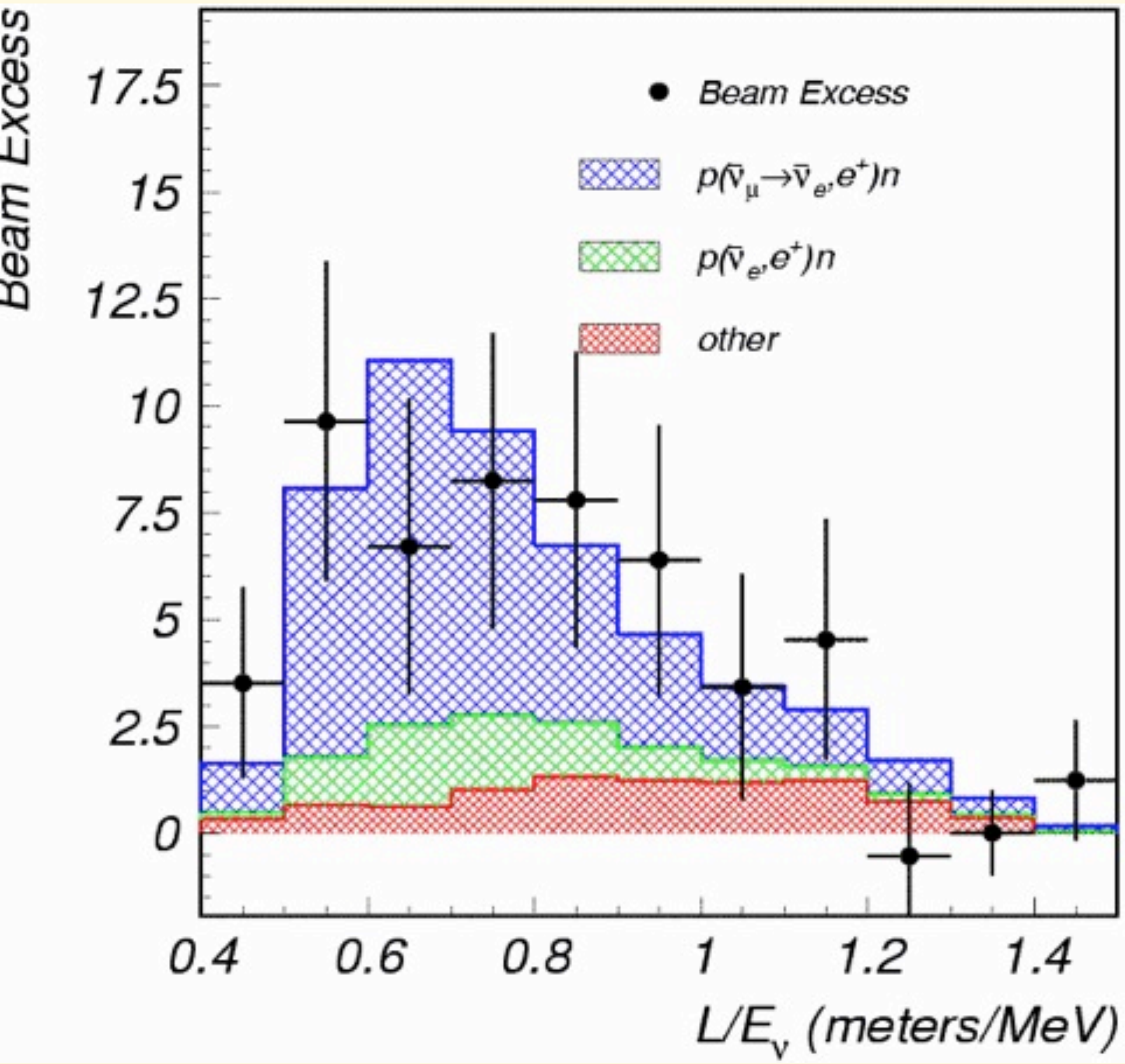
μ^+ stops; decays: $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$

Note that no $\bar{\nu}_e$ are produced in these processes

LSND Effect

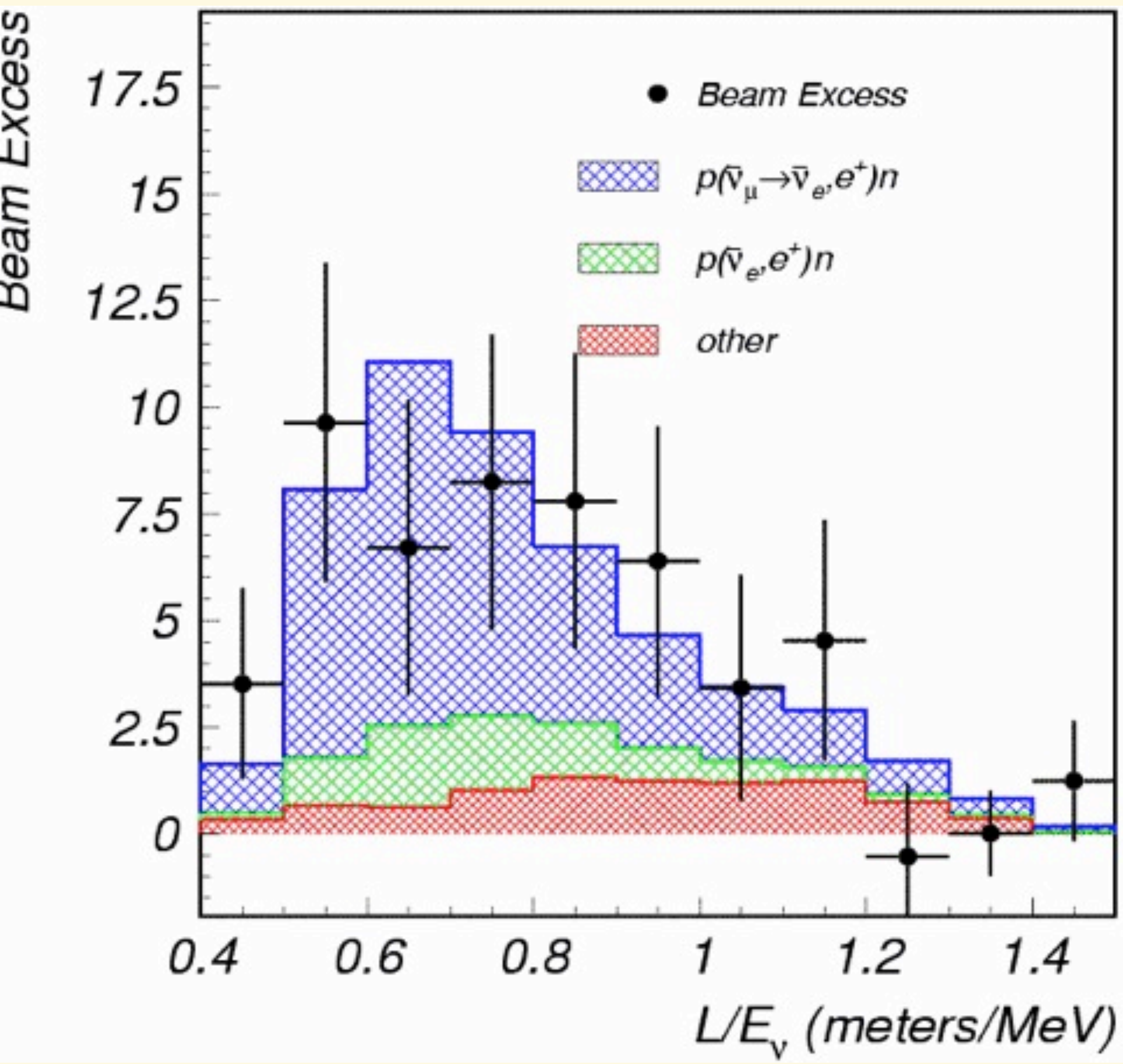
LSND Effect

Apparent $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ transition

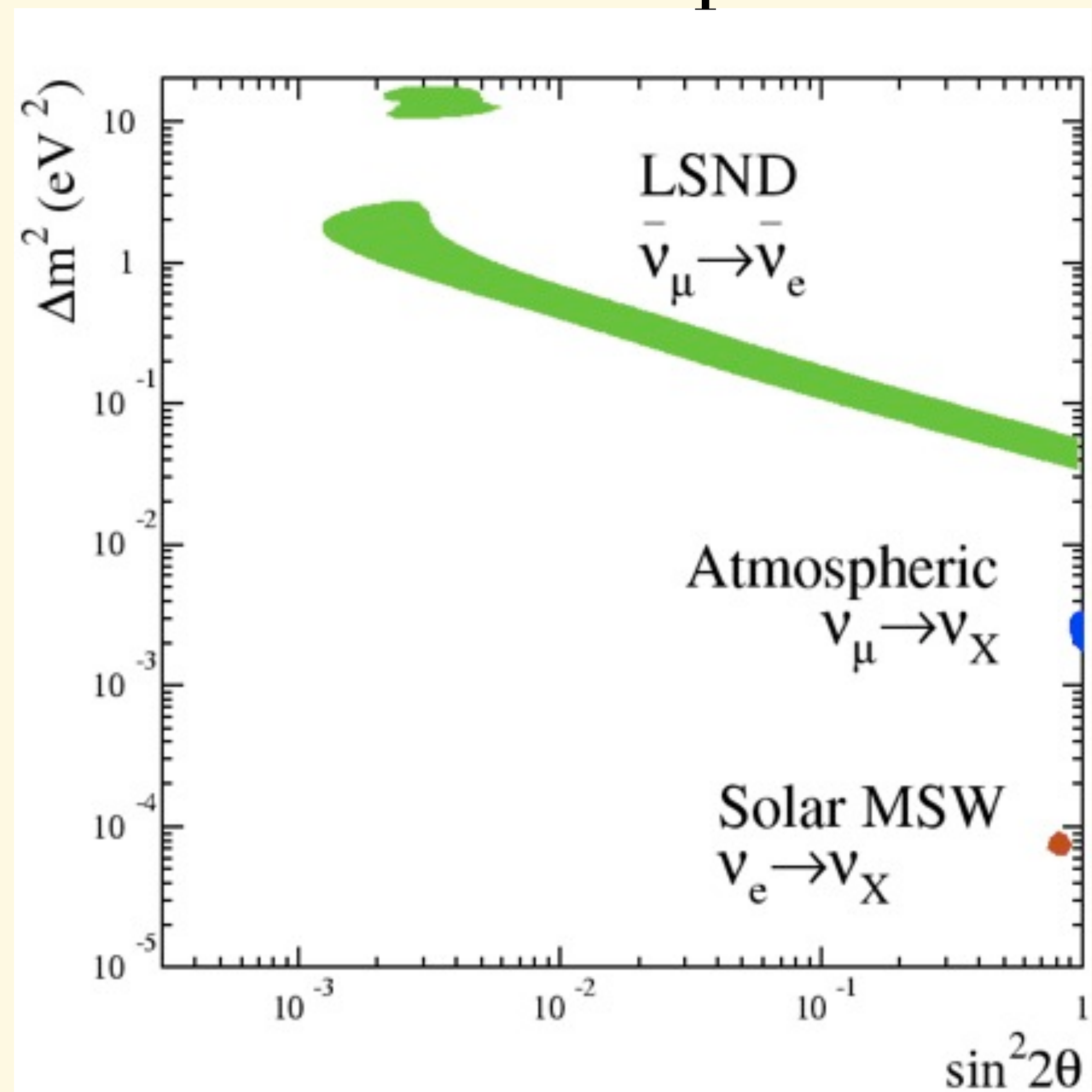


LSND Effect

Apparent $\overline{\nu_\mu}$ -> $\overline{\nu_e}$ transition

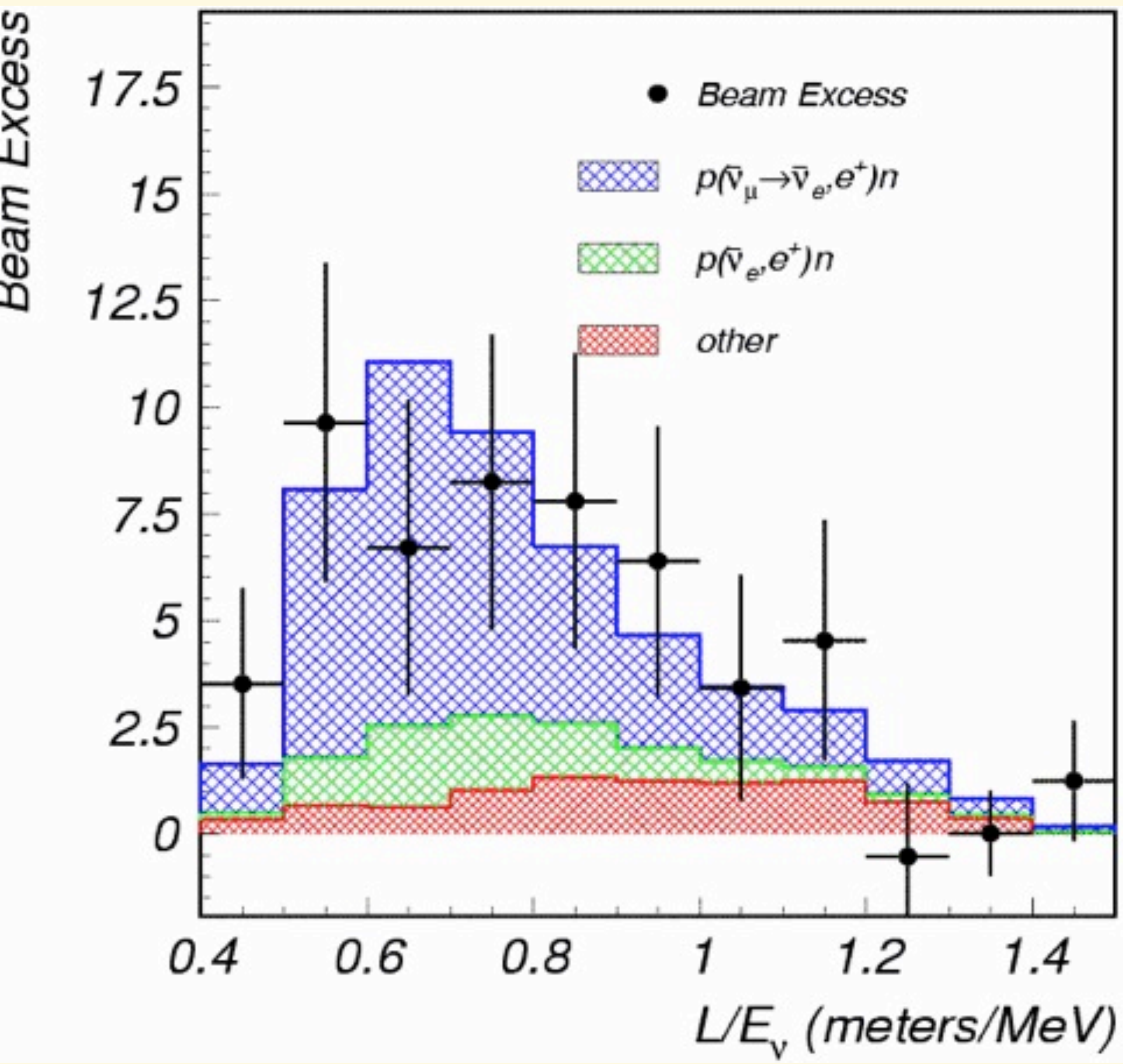


Oscillation interpretation

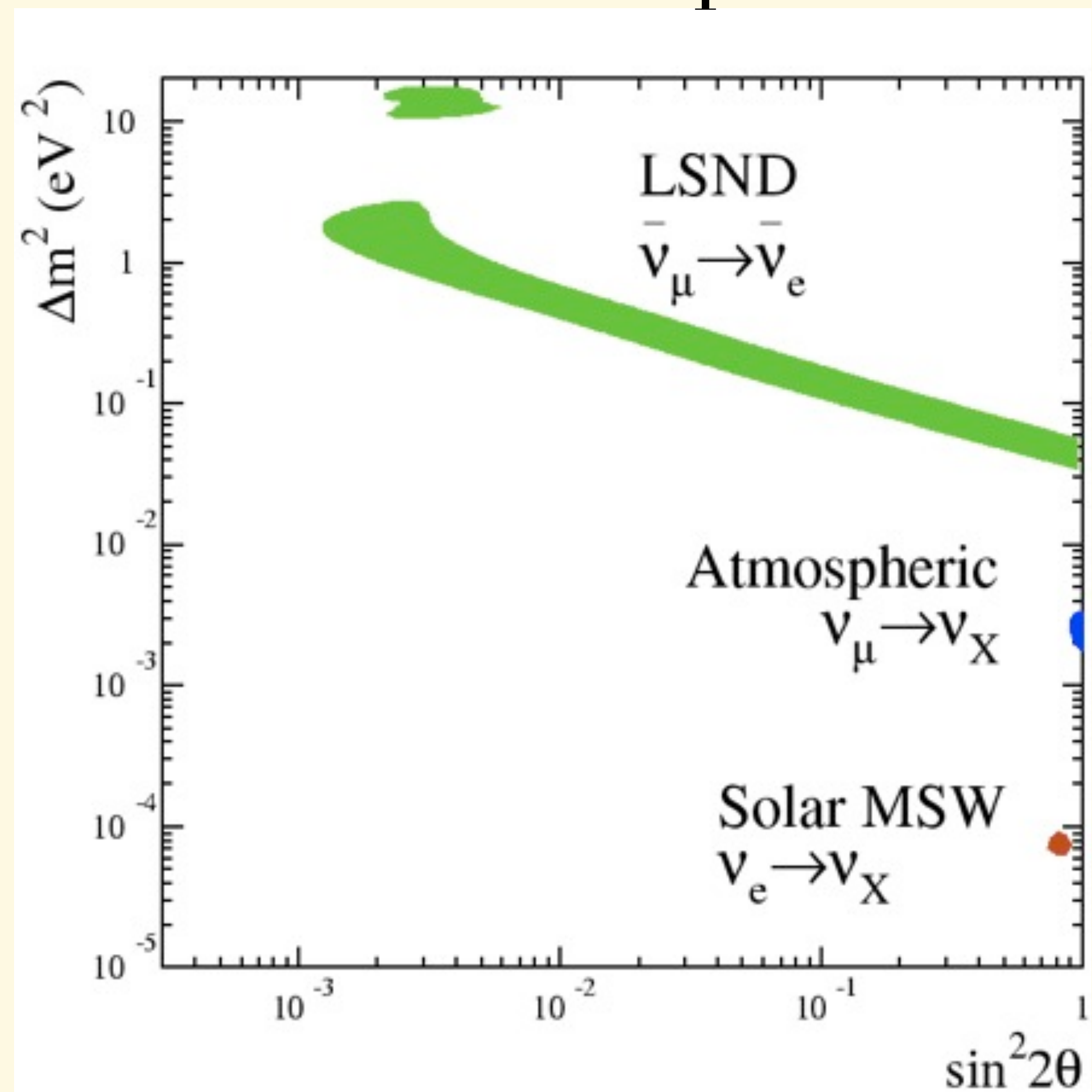


LSND Effect

Apparent $\bar{\nu}_\mu \to \bar{\nu}_e$ transition



Oscillation interpretation



If effect is due to oscillations, there must be a 4th, sterile, neutrino

MiniBooNE

MiniBooNE was designed to test the LSND result

It uses a neutrino beam produced by Fermilab Booster

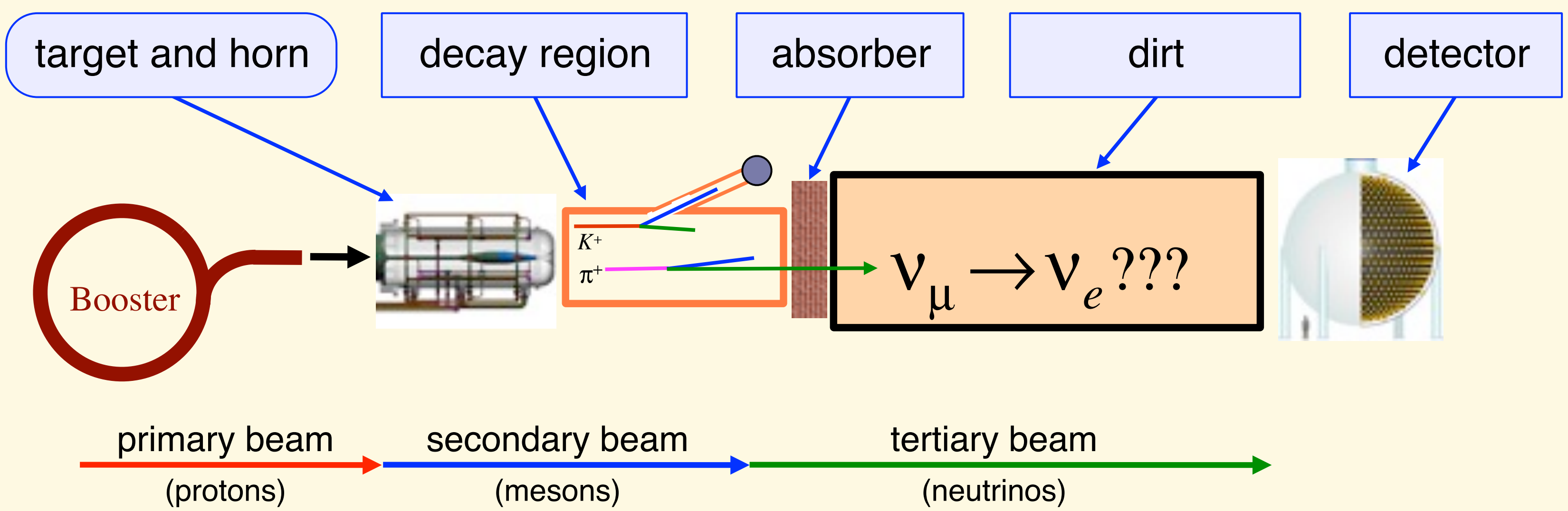
L/E is similar to that in LSND but L and E are roughly an order of magnitude larger; different systematics

MiniBooNE

MiniBooNE was designed to test the LSND result

It uses a neutrino beam produced by Fermilab Booster

L/E is similar to that in LSND but L and E are roughly an order of magnitude larger; different systematics

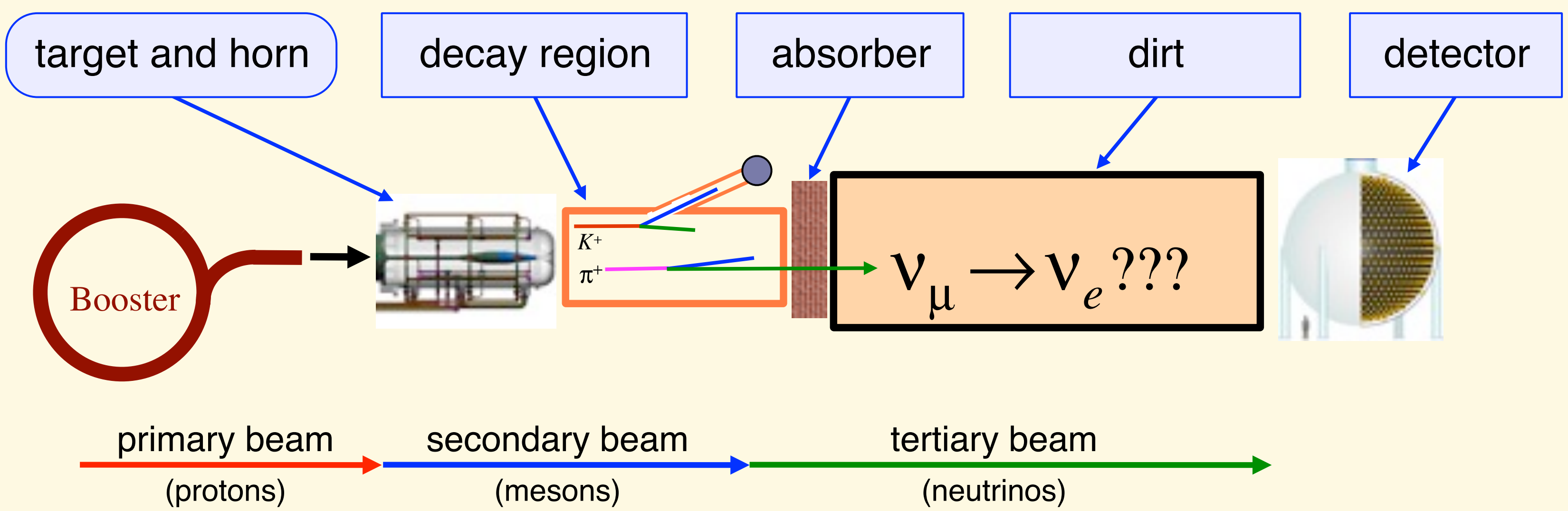


MiniBooNE

MiniBooNE was designed to test the LSND result

It uses a neutrino beam produced by Fermilab Booster

L/E is similar to that in LSND but L and E are roughly an order of magnitude larger; different systematics



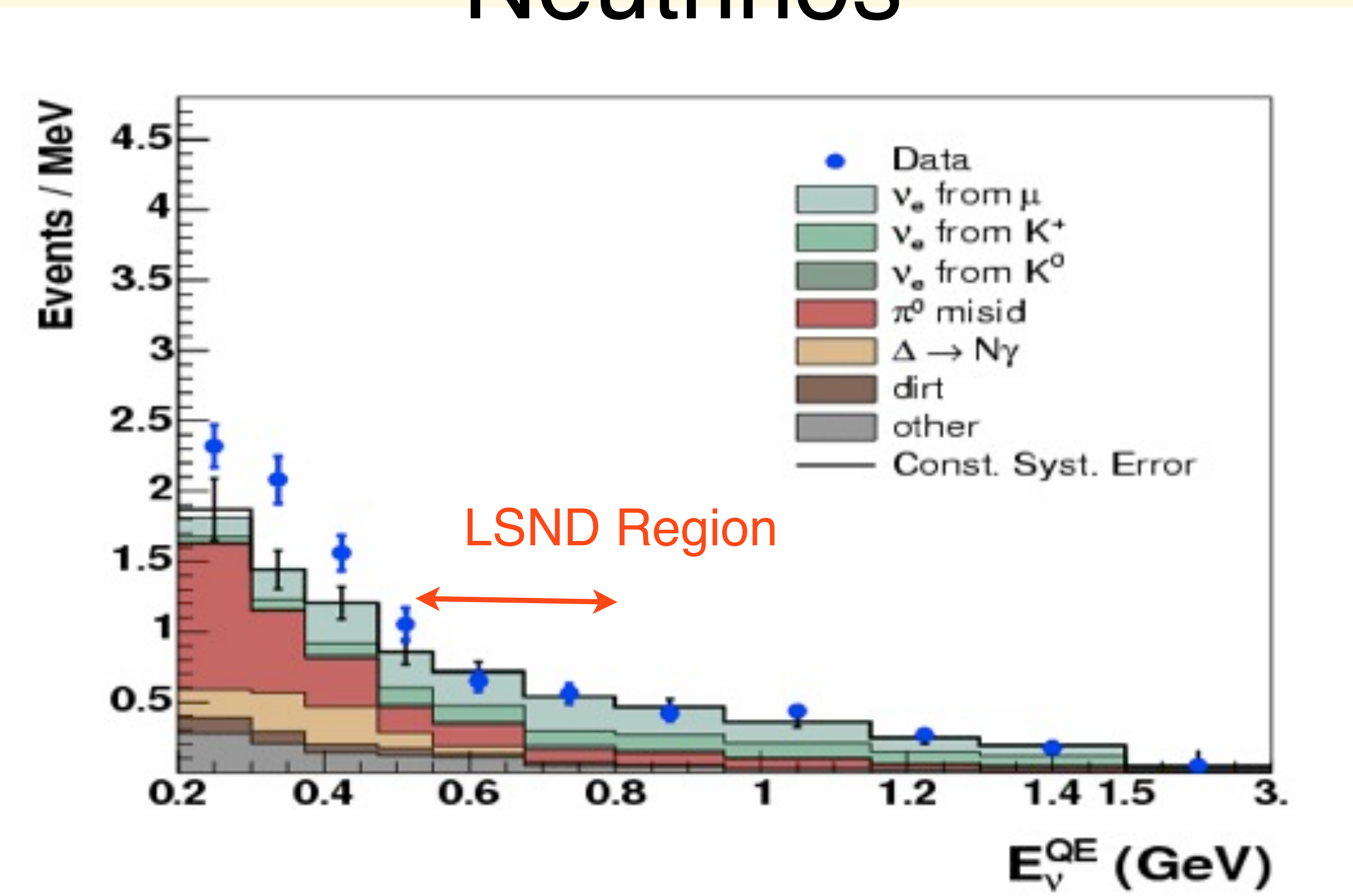
Both neutrino and antineutrino exposures were obtained

Antineutrino run tests the LSND directly

MiniBooNE Results

MiniBooNE Results

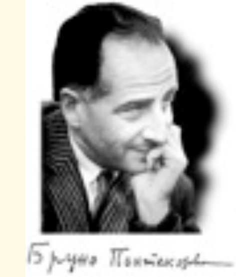
Neutrinos



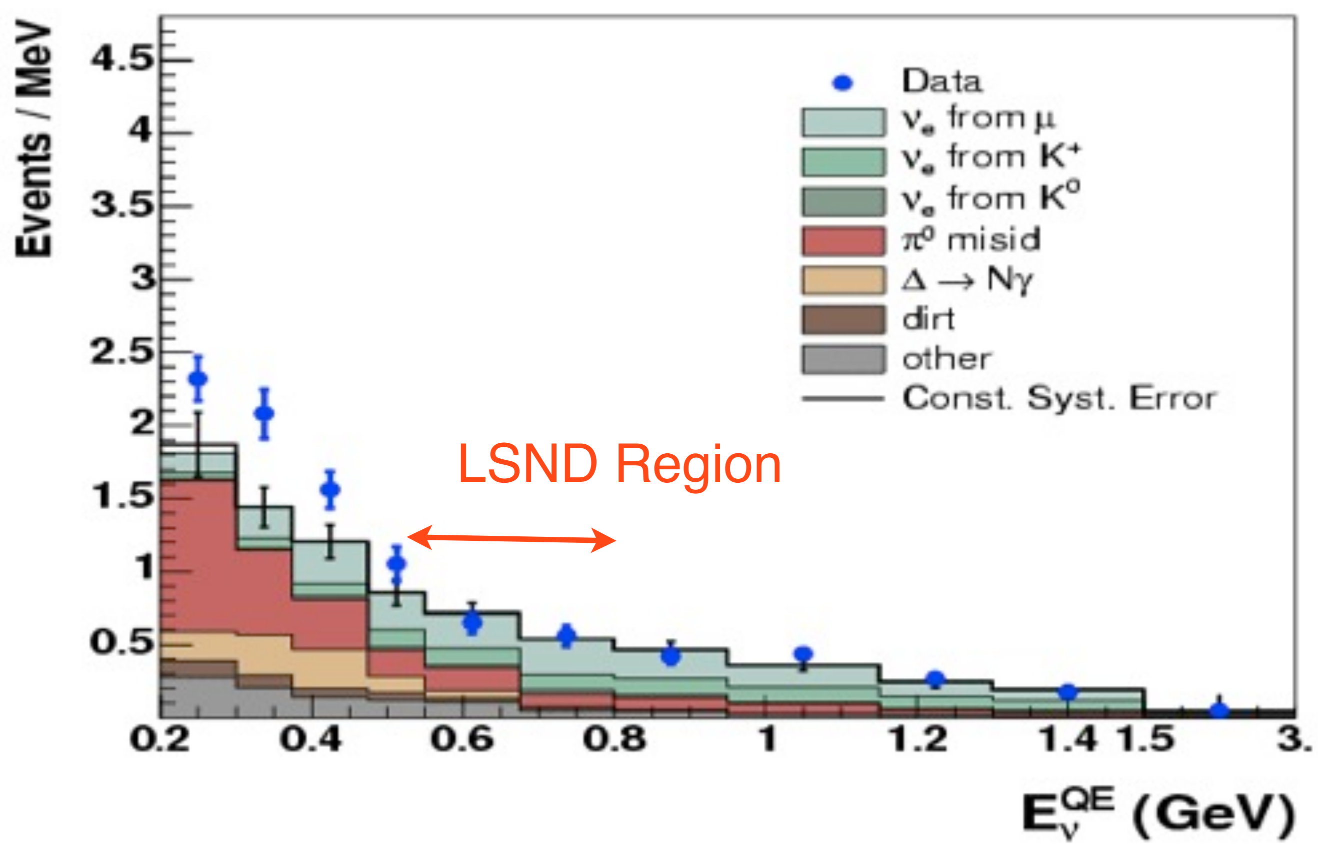
Neutrinos: Excess of electrons (γ's?) below 475 MeV

No excess of events in the LSND region

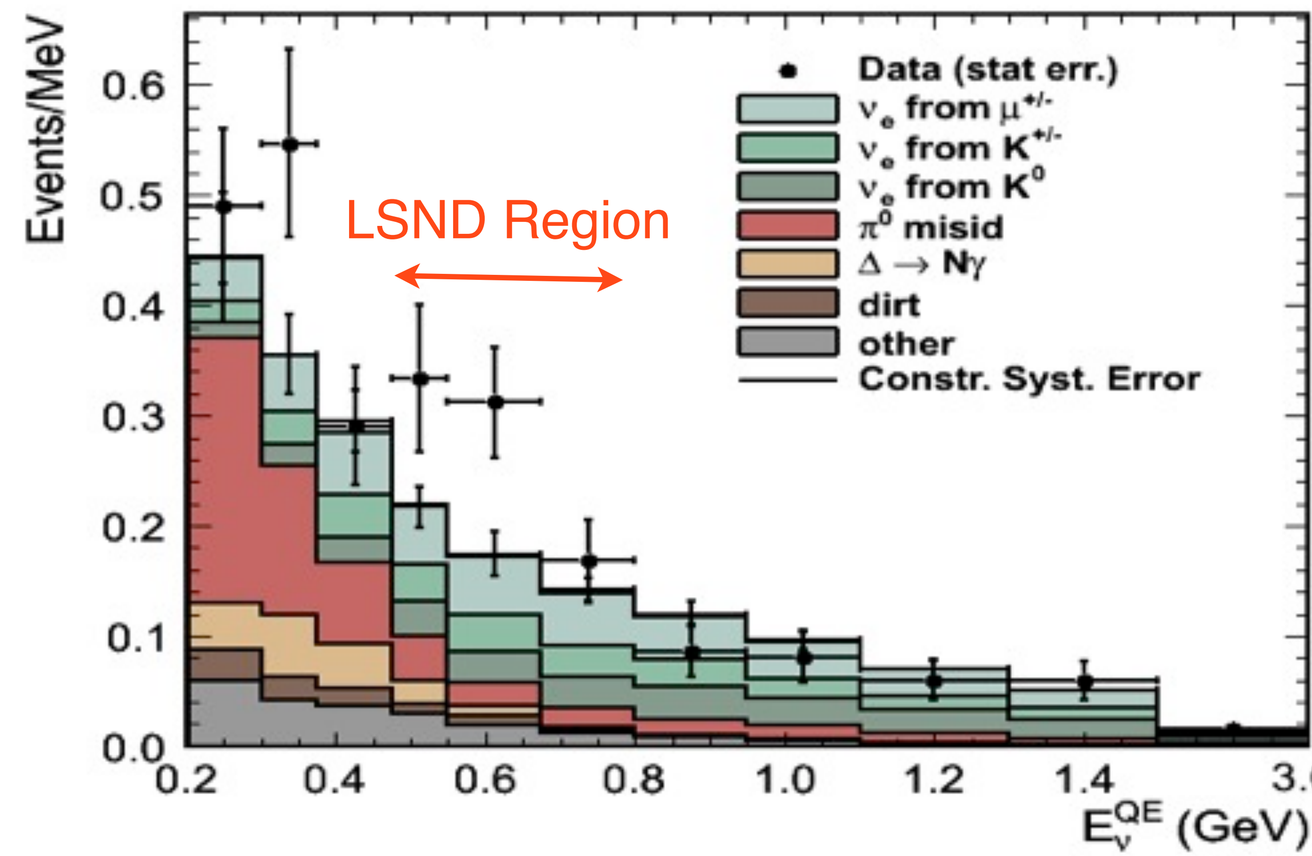
MiniBooNE Results



Neutrinos



Antineutrinos



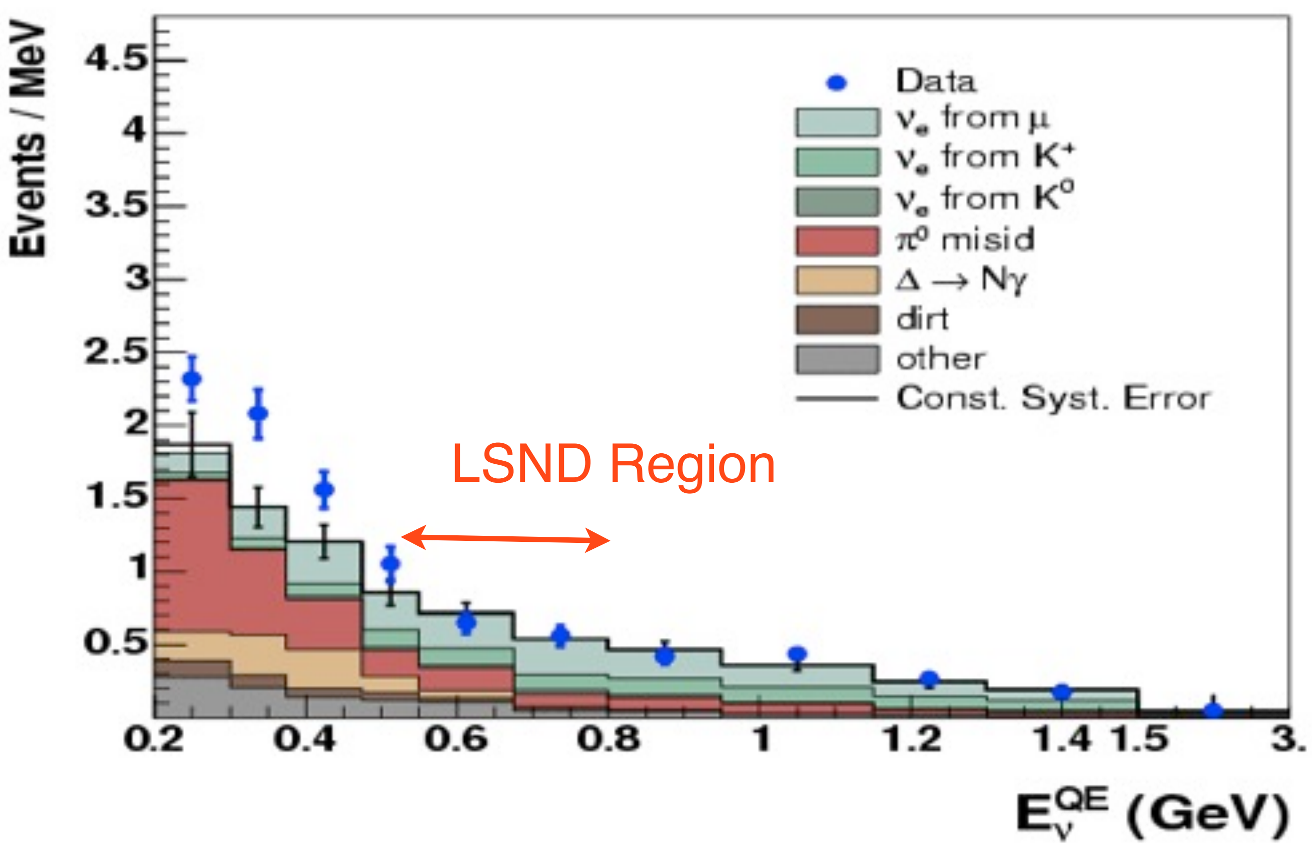
Neutrinos: Excess of electrons (γ's?) below 475 MeV

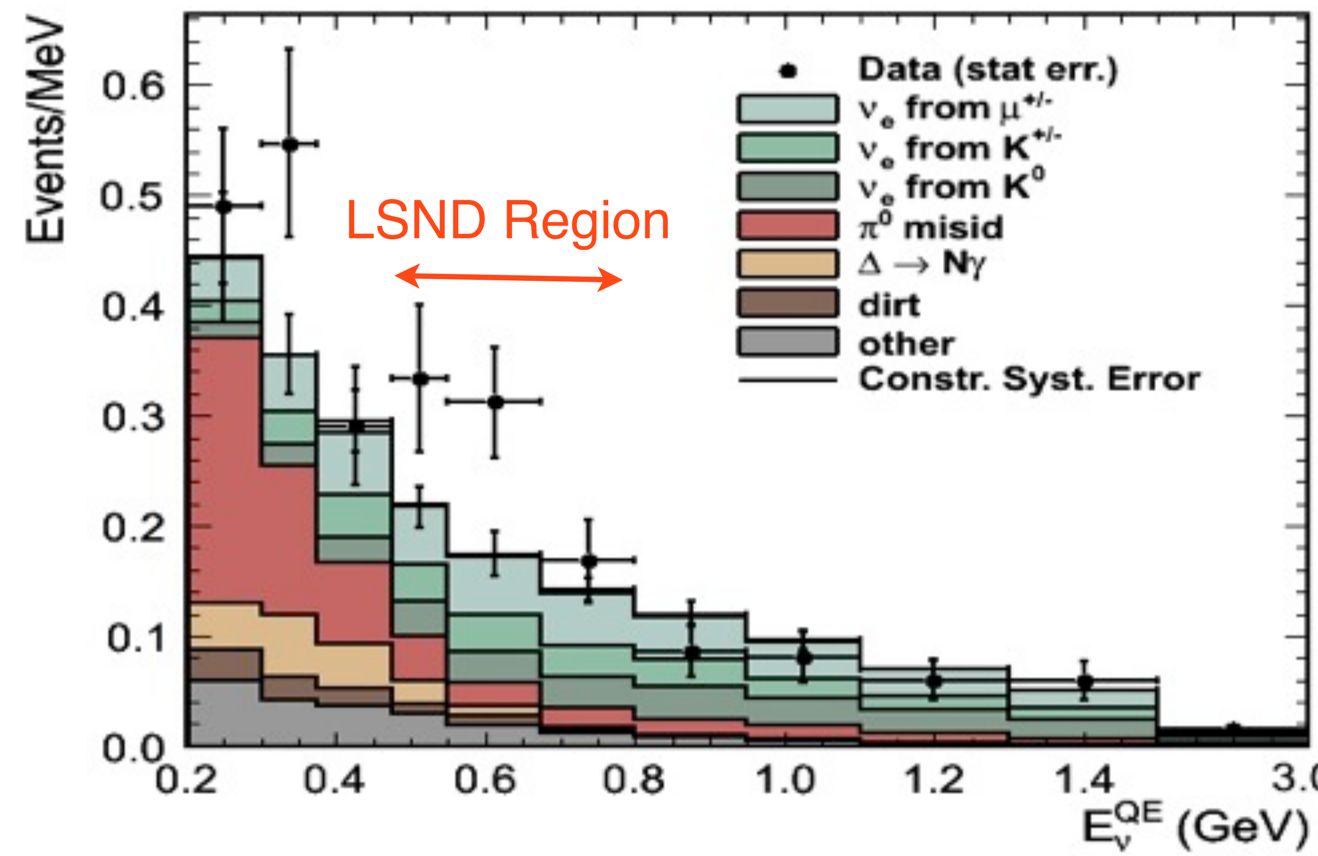
No excess of events in the LSND region

Antineutrinos: Small excess below 475 MeV

Excess of events in LSND region

MiniBooNE Results





Neutrinos: Excess of electrons (γ's?) below 475 MeV

No excess of events in the LSND region

Antineutrinos: Small excess below 475 MeV

Excess of events in LSND region

More data are needed to resolve these issues

MINOS Search

MINOS Search

MINOS can search for sterile neutrinos in a different L/E domain than LSND/MiniBooNE (small Δm^2 and large mixing angle)

MINOS Search

MINOS can search for sterile neutrinos in a different L/E domain than LSND/MiniBooNE (small Δm^2 and large mixing angle)

MINOS looks for depletion of neutral current (NC) events in the Far Detector compared to prediction from the Near Detector

MINOS Search

MINOS can search for sterile neutrinos in a different L/E domain than LSND/MiniBooNE (small Δm^2 and large mixing angle)

MINOS looks for depletion of neutral current (NC) events in the Far Detector compared to prediction from the Near Detector

In the conventional oscillation picture there should be no depletion of NC events

MINOS Search

MINOS can search for sterile neutrinos in a different L/E domain than LSND/MiniBooNE (small Δm^2 and large mixing angle)

MINOS looks for depletion of neutral current (NC) events in the Far Detector compared to prediction from the Near Detector

In the conventional oscillation picture there should be no depletion of NC events

The result has a mild dependence on the assumption regarding θ_{13} since ν_e events would be classified as NC

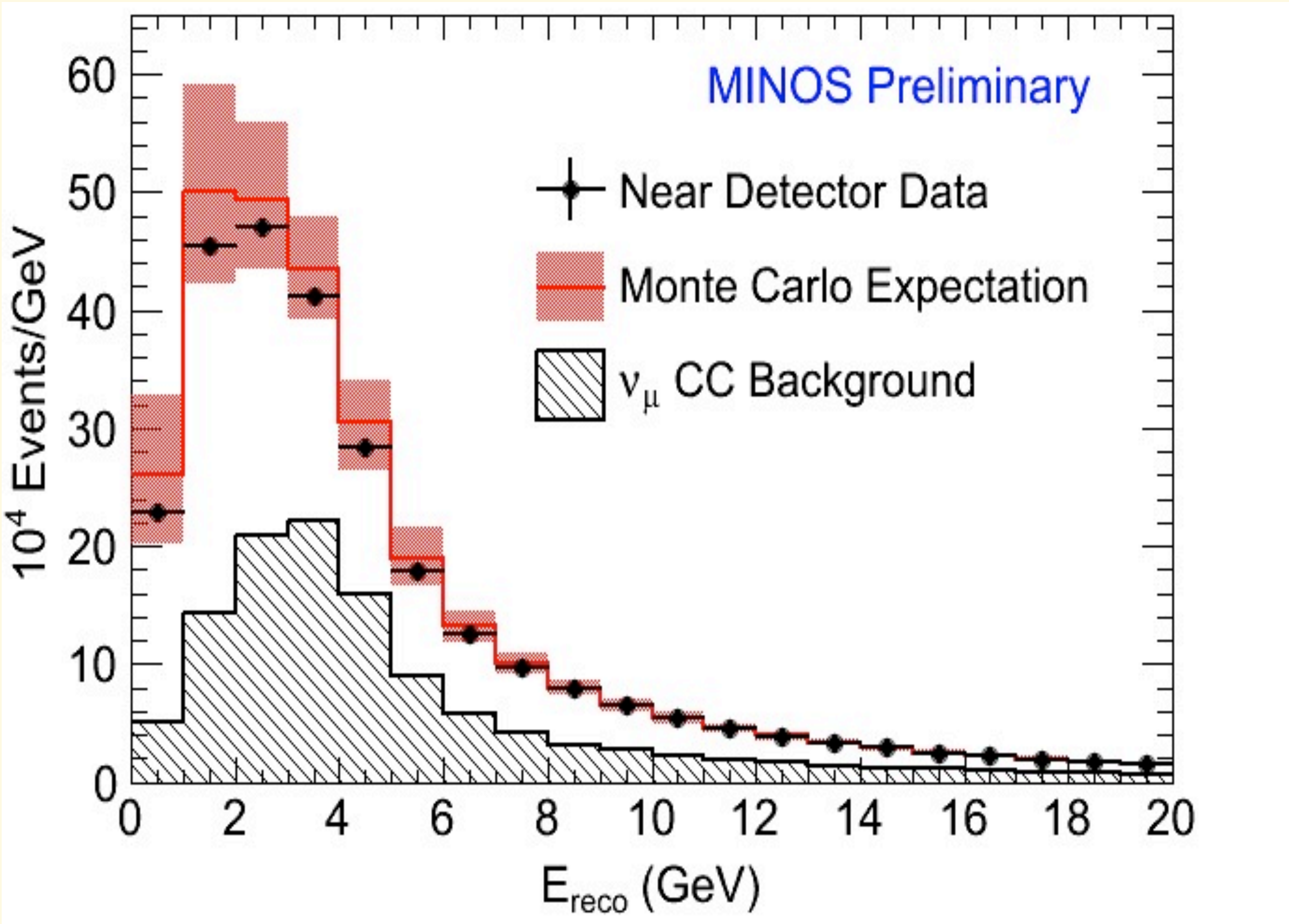
Neutral Current Data

Neutral Current Data

The NC spectrum is measured in ND, extrapolated to FD

Neutral Current Data

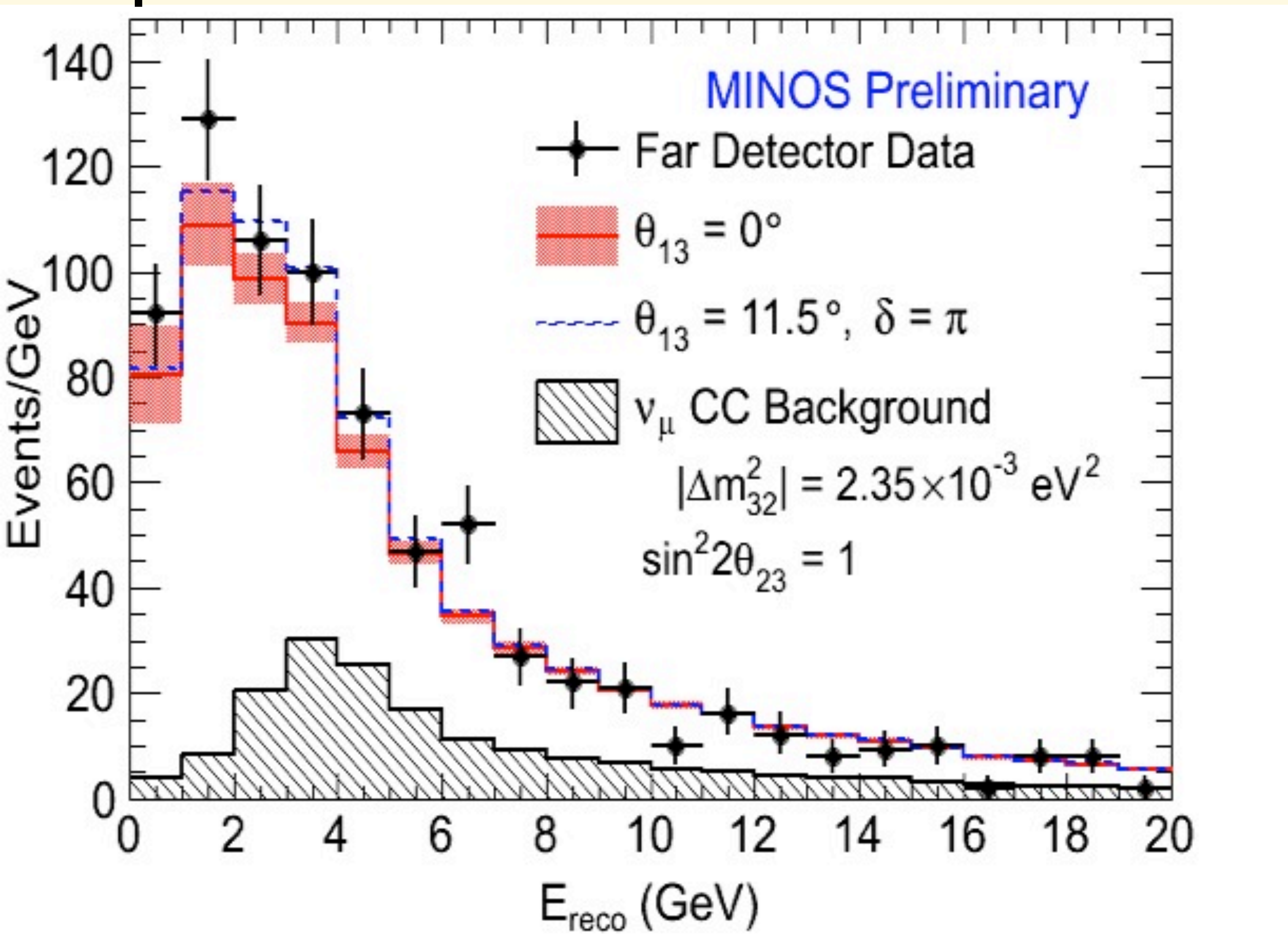
The NC spectrum is measured in ND, extrapolated to FD



MINOS Result

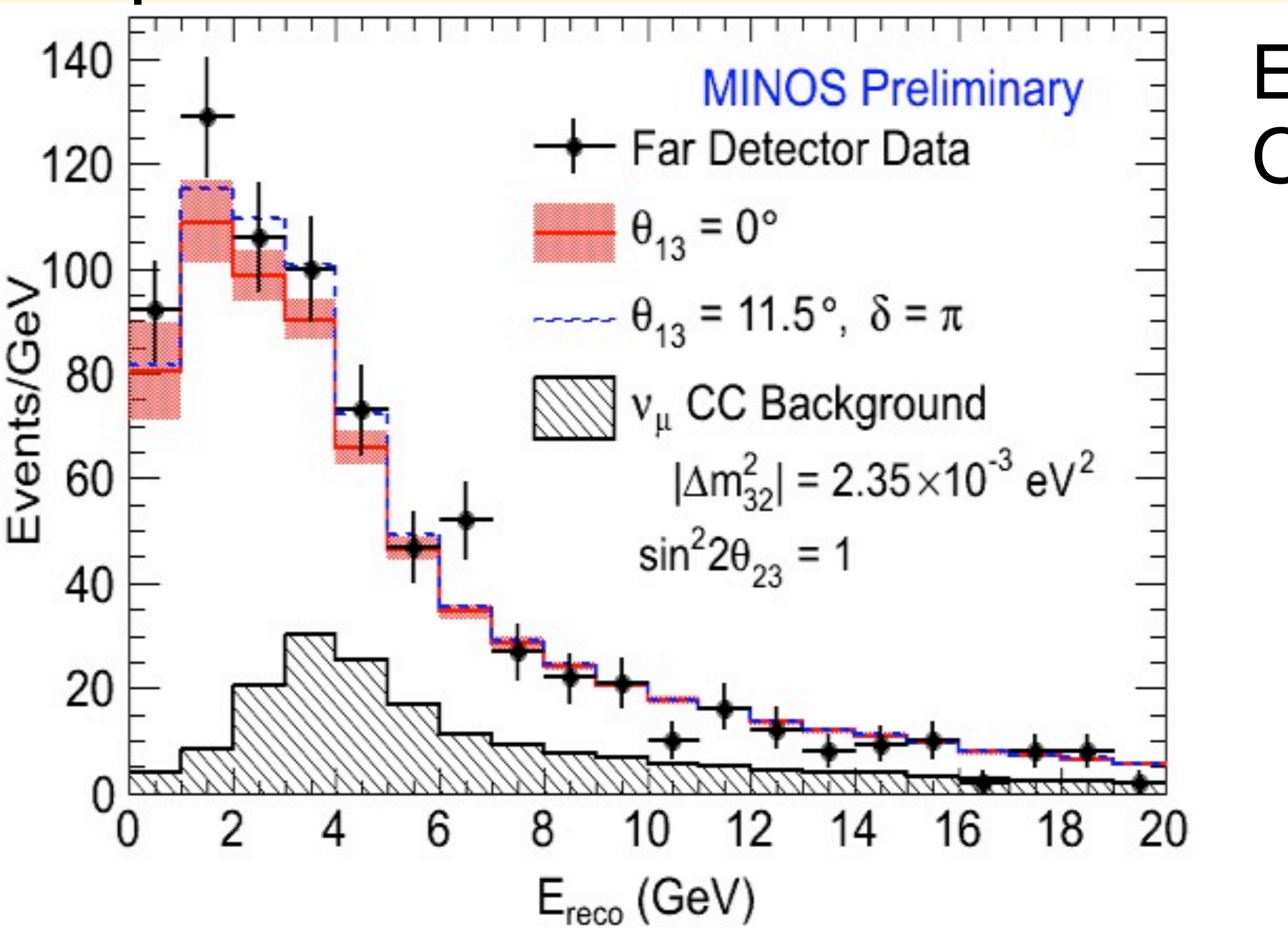
MINOS Result

Spectrum of NC events in FD



MINOS Result

Spectrum of NC events in FD

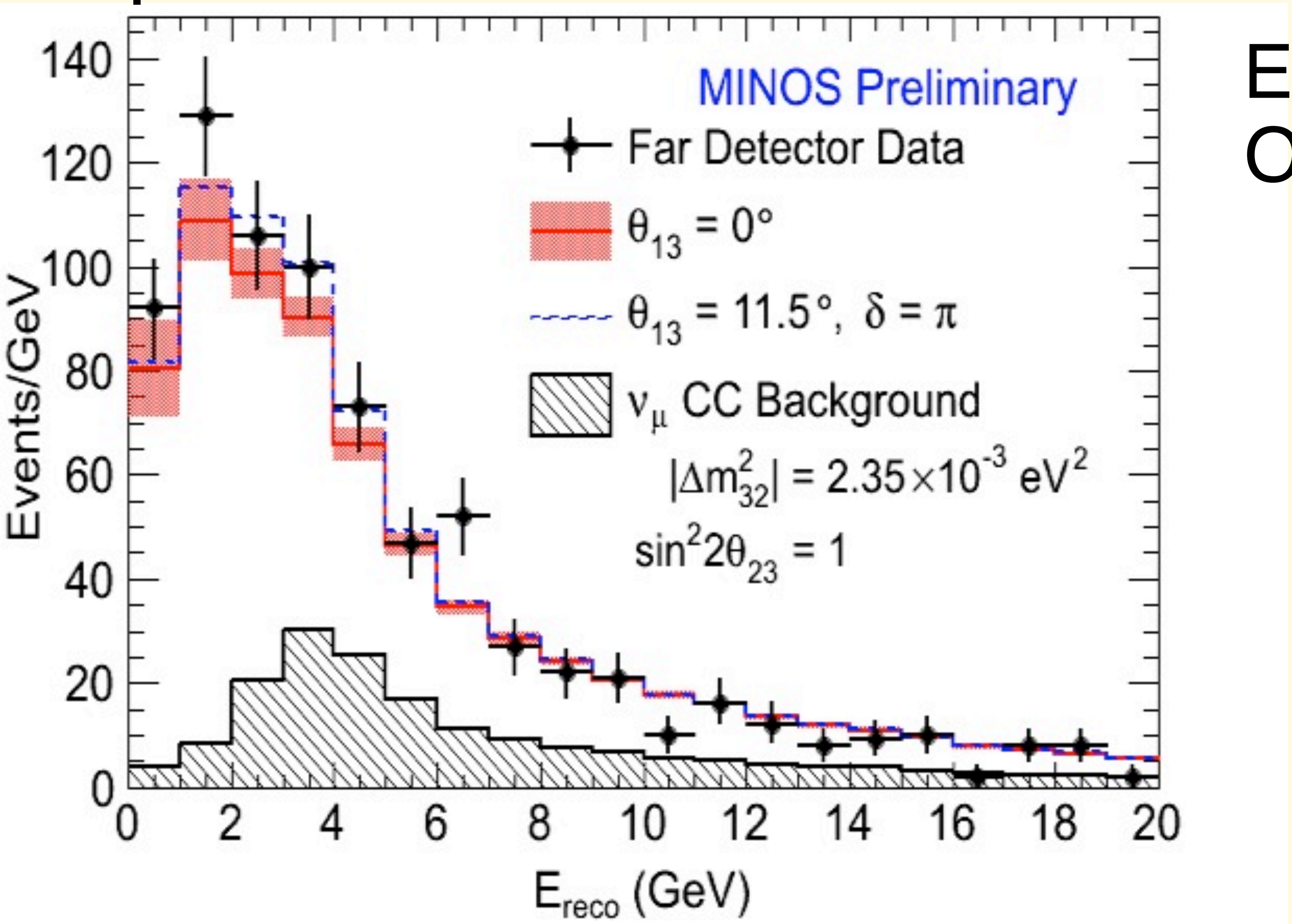


Expect (no ν_e): 757 events
Observe: 802 events

No depletion seen

MINOS Result

Spectrum of NC events in FD



Expect (no ν_e): 757 events
Observe: 802 events

No depletion seen

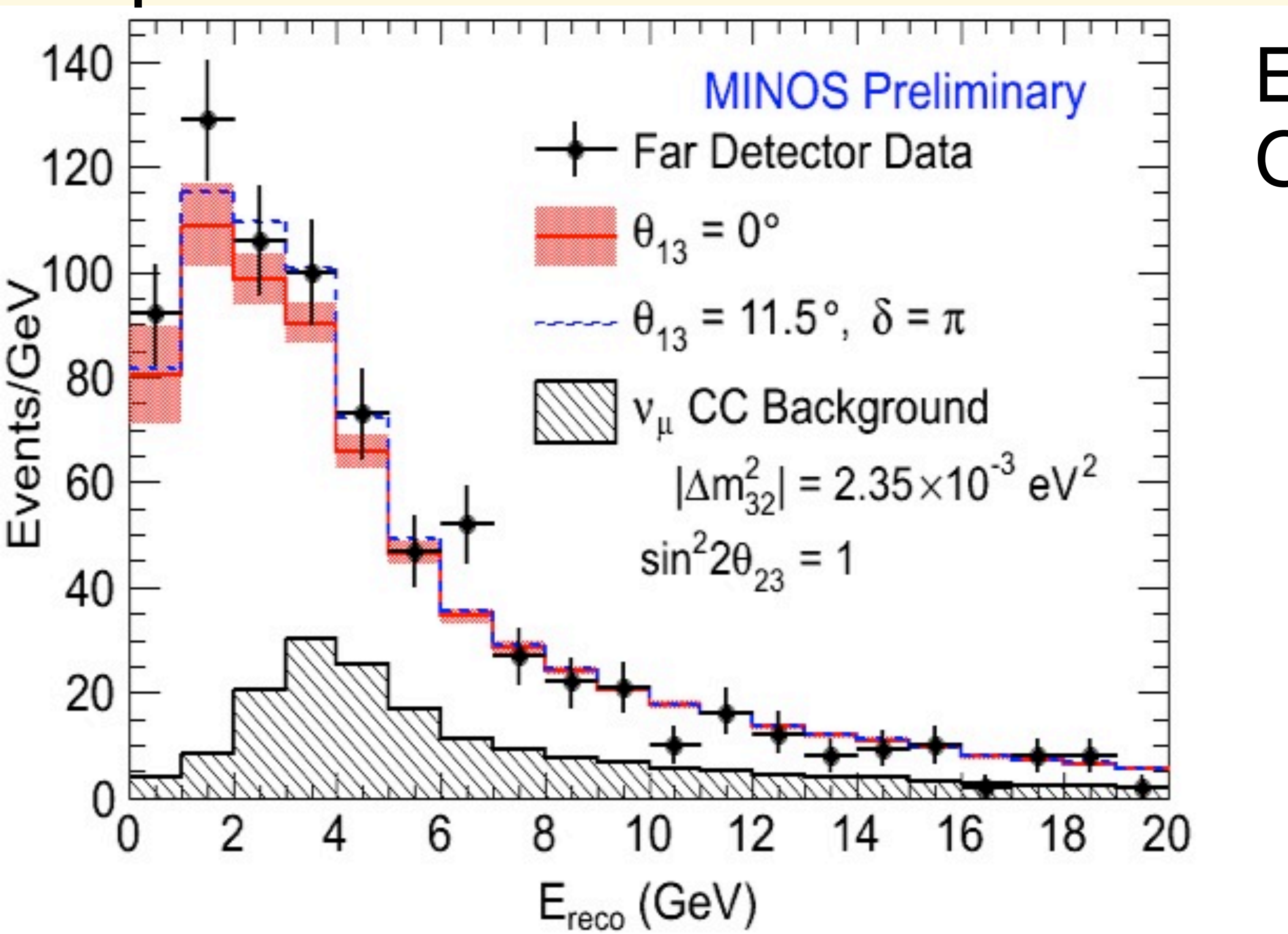
Define: $$R = \frac{N_{data} - BG}{S_{NC}}$$

1.09 ± 0.06 (stat.) ± 0.05 (syst.)
(no ν_e appearance)

1.01 ± 0.06 (stat.) ± 0.05 (syst.)
(with ν_e appearance)

MINOS Result

Spectrum of NC events in FD



Expect (no ν_e): 757 events
Observe: 802 events

No depletion seen

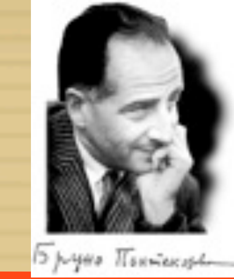
Define: $R = \dfrac{N_{data} - BG}{S_{NC}}$

1.09 ± 0.06 (stat.) ± 0.05 (syst.)
(no ν_e appearance)

1.01 ± 0.06 (stat.) ± 0.05 (syst.)
(with ν_e appearance)

Limit on fraction, f_s, of oscillated ν_μ converting to ν_s:

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22 \ (0.40) \text{ at } 90\% \text{ C.L.}$$



Neutrino/Antineutrino Comparison

Antineutrino Beam

Antineutrino Beam

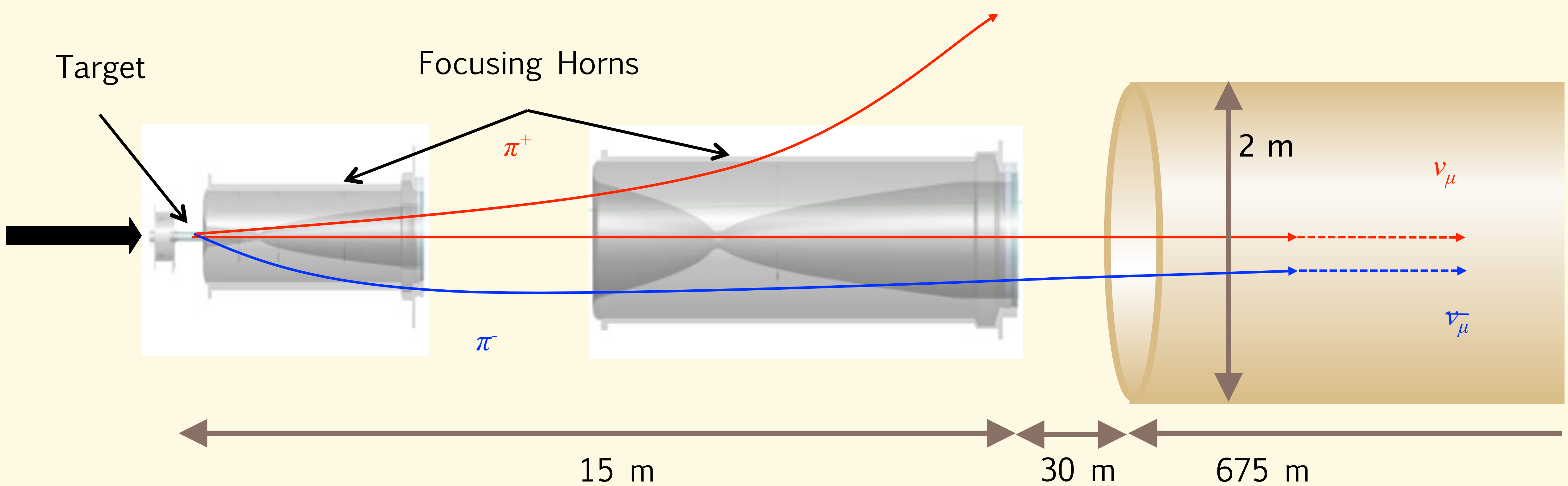
- To obtain antineutrino beam, one changes the direction of the current in the focusing horn(s)

Antineutrino Beam

- To obtain antineutrino beam, one changes the direction of the current in the focusing horn(s)
- This results in π^- being focused

Antineutrino Beam

- To obtain antineutrino beam, one changes the direction of the current in the focusing horn(s)
- This results in π^- being focused



Background issues

Background issues

- The neutrino background in an antineutrino beam is higher than in the opposite situation

Background issues

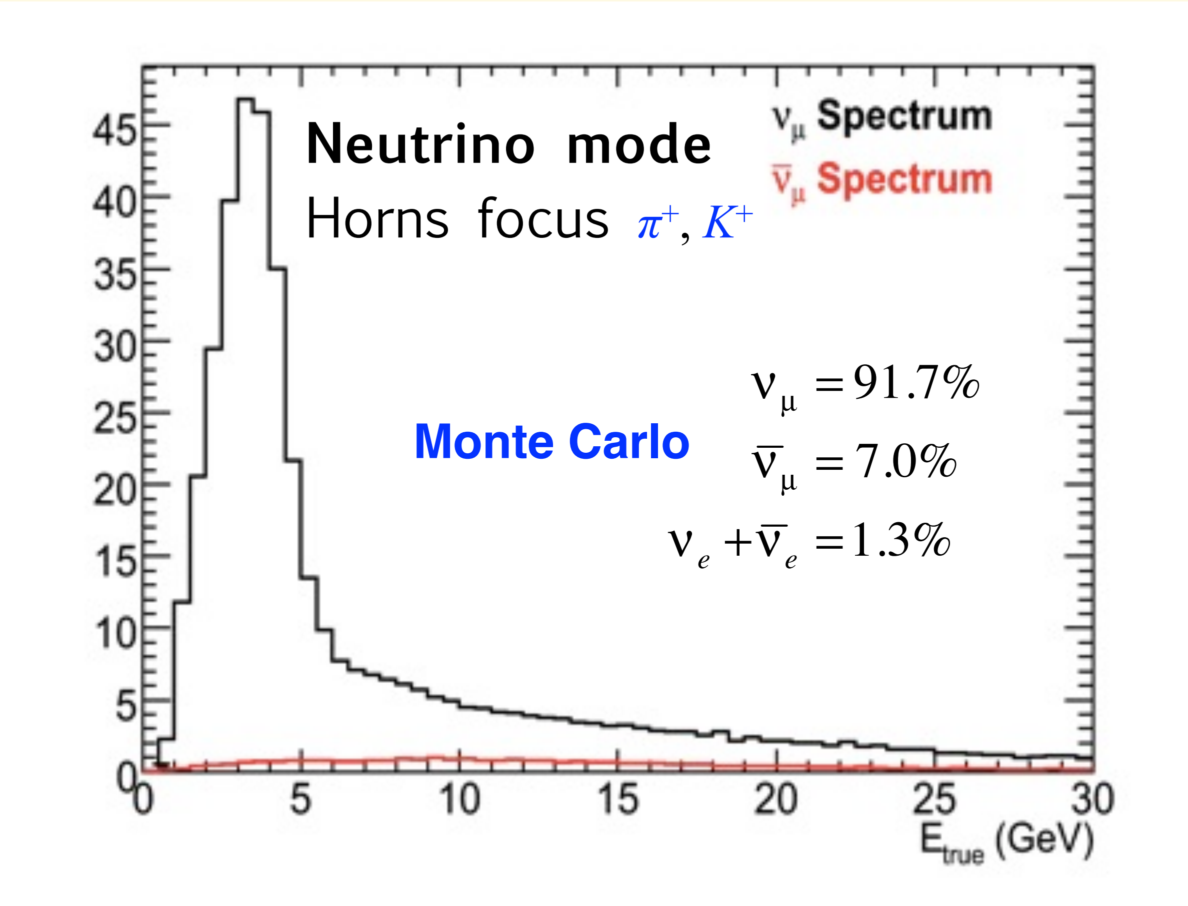
- The neutrino background in an antineutrino beam is higher than in the opposite situation
- This is due to the higher production of π^+ and higher cross section of ν

Background issues

- The neutrino background in an antineutrino beam is higher than in the opposite situation
- This is due to the higher production of π^+ and higher cross section of ν
- It helps significantly to have B field in the detector

Background issues

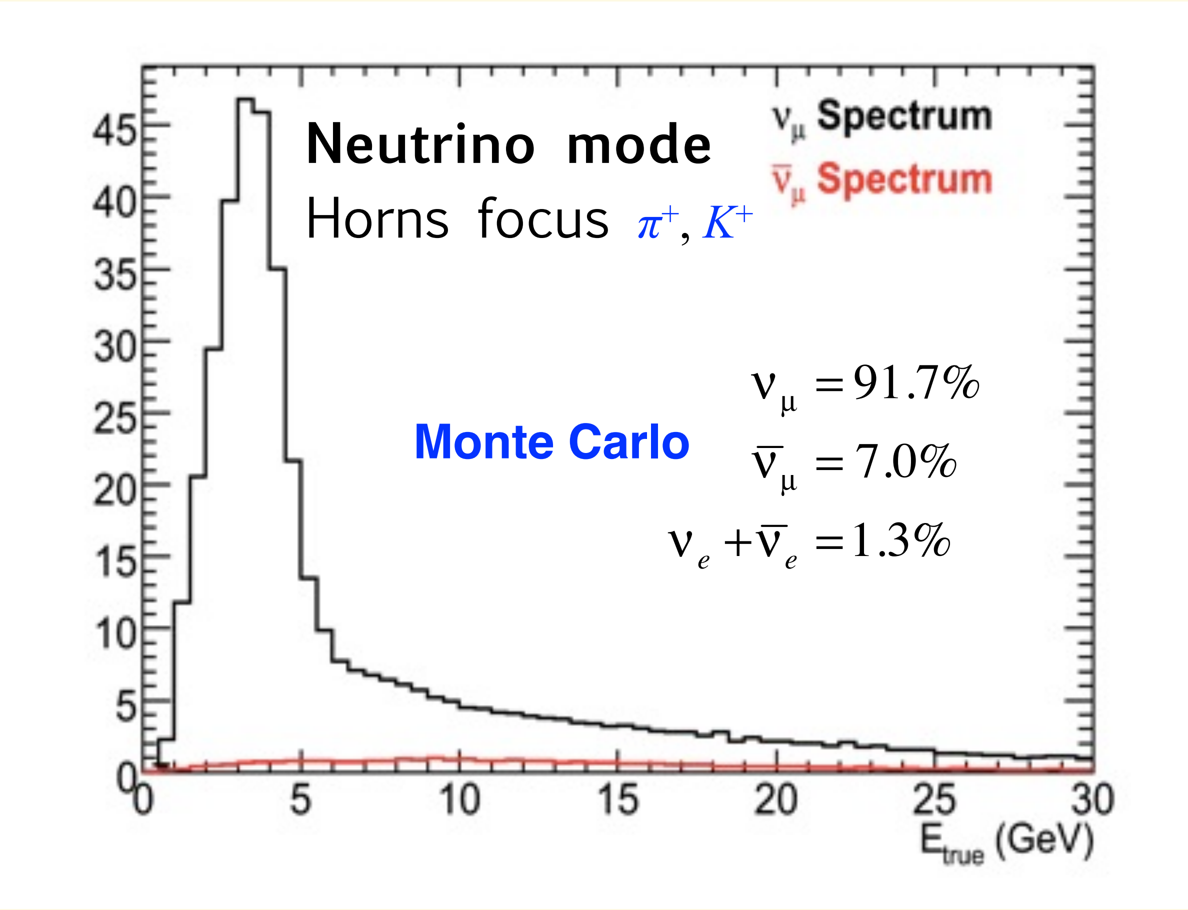
- The neutrino background in an antineutrino beam is higher than in the opposite situation
- This is due to the higher production of π^+ and higher cross section of ν
- It helps significantly to have B field in the detector

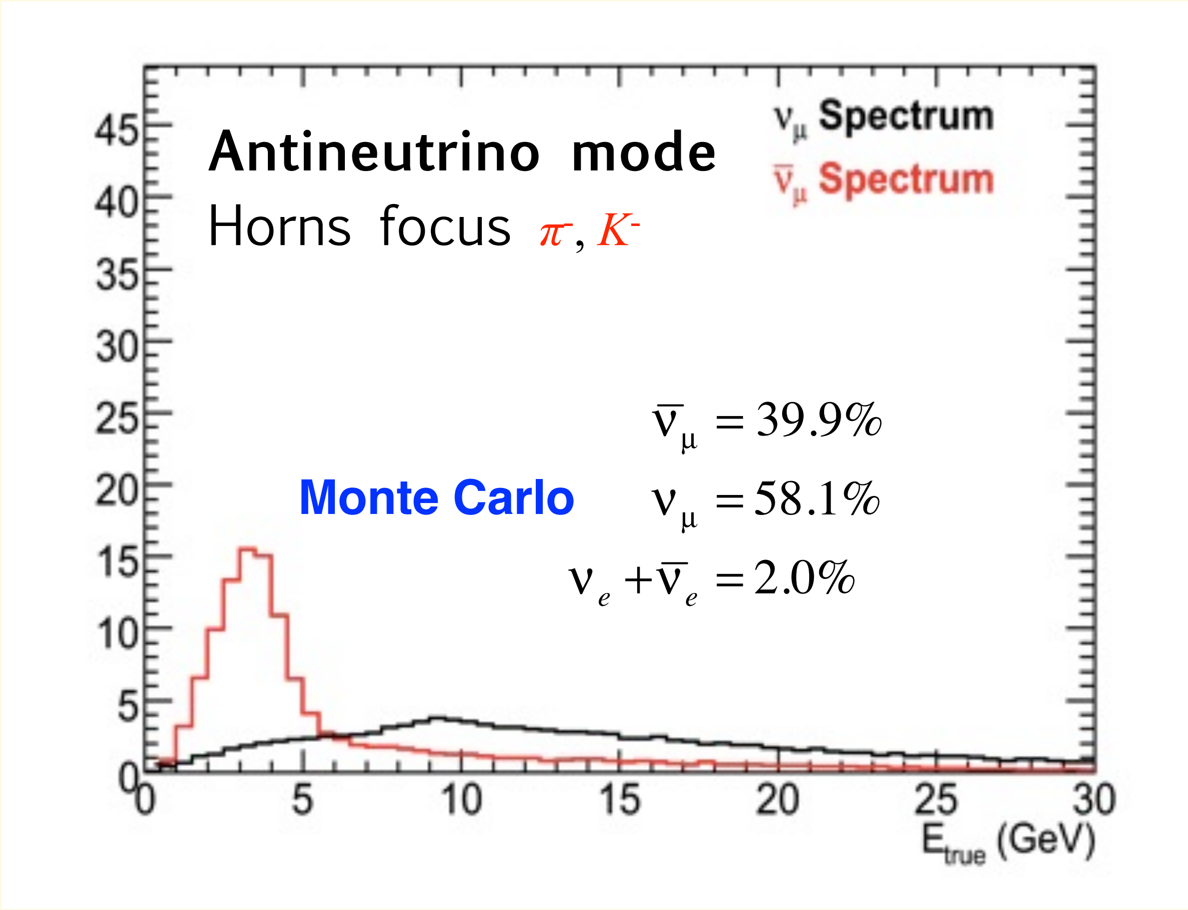


Monday, September 27, 2010

Background issues

- The neutrino background in an antineutrino beam is higher than in the opposite situation
- This is due to the higher production of π^+ and higher cross section of ν
- It helps significantly to have B field in the detector

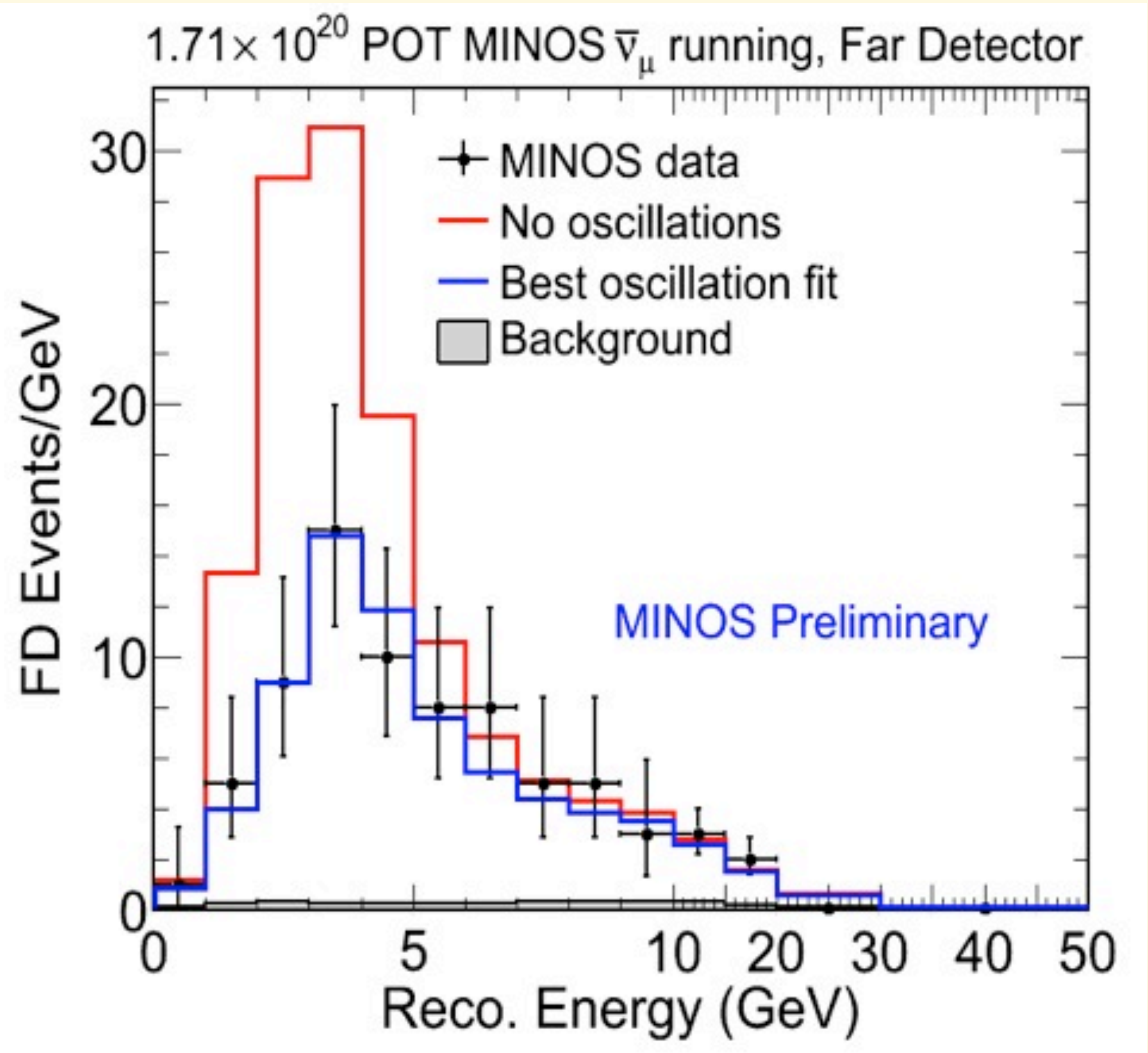




MINOS Result

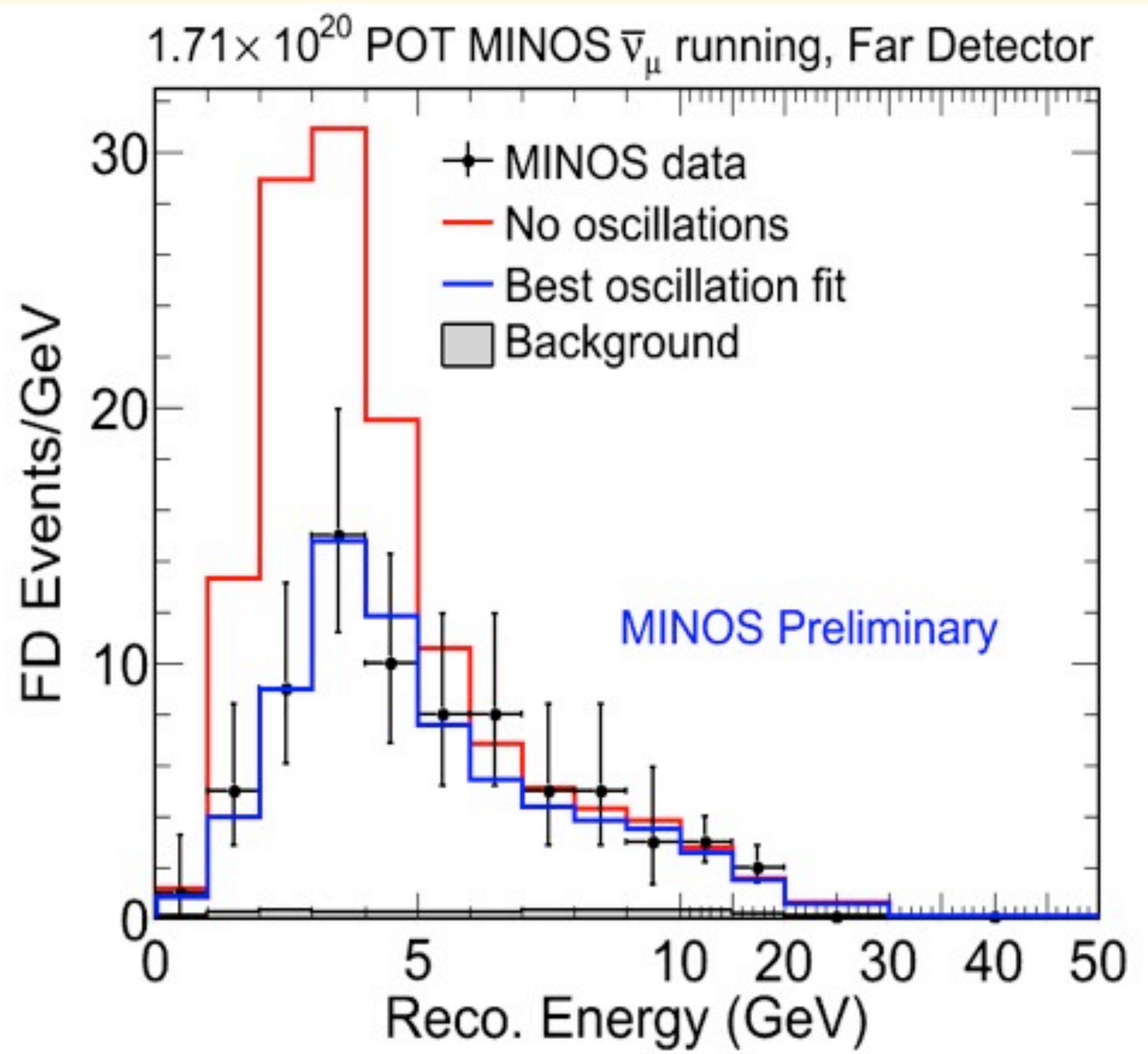
MINOS Result

MINOS took 1.7E20 protons on target in $\overline{\nu_\mu}$ mode



MINOS Result

MINOS took 1.7E20 protons on target in $\overline{\nu_\mu}$ mode

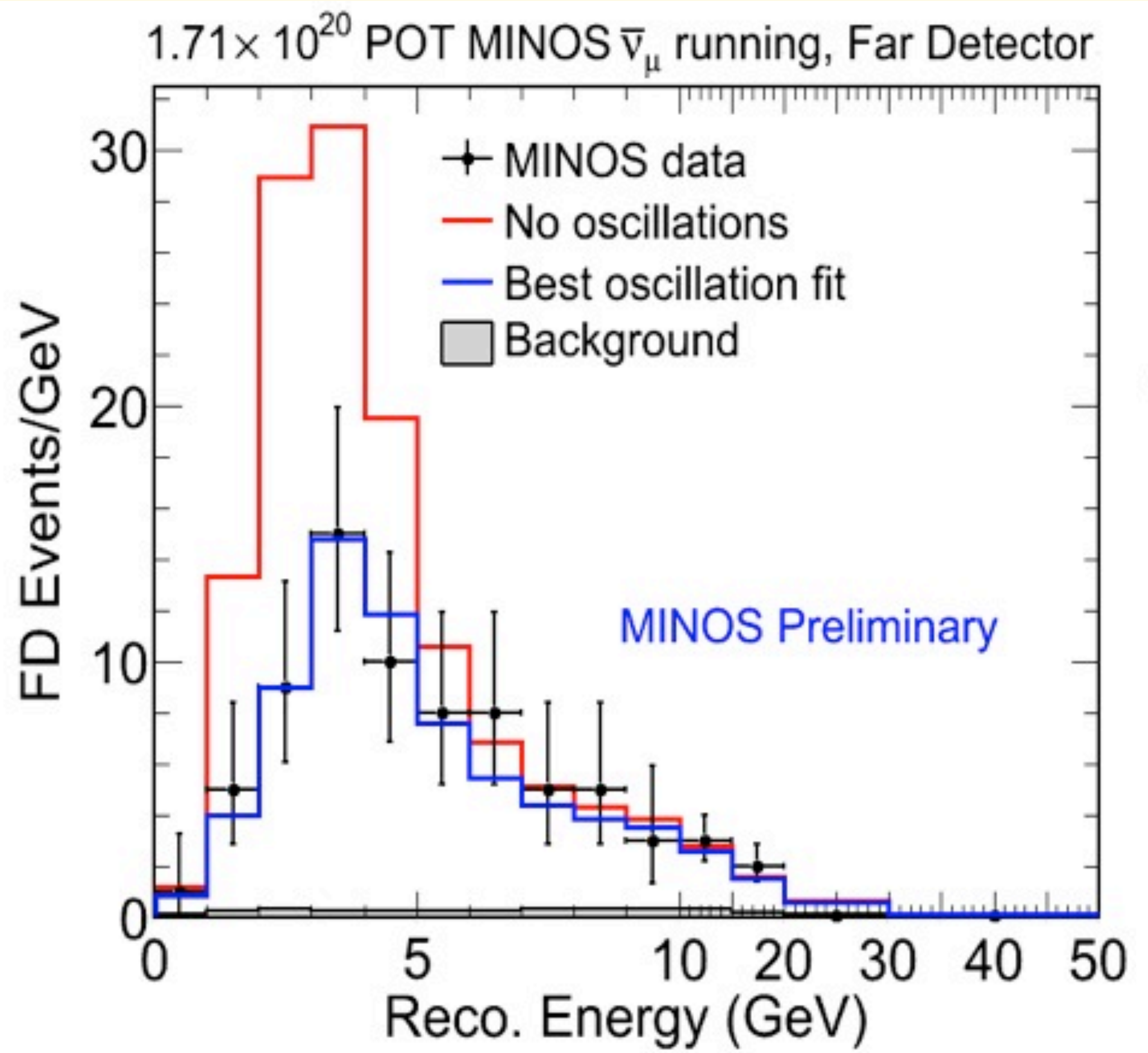


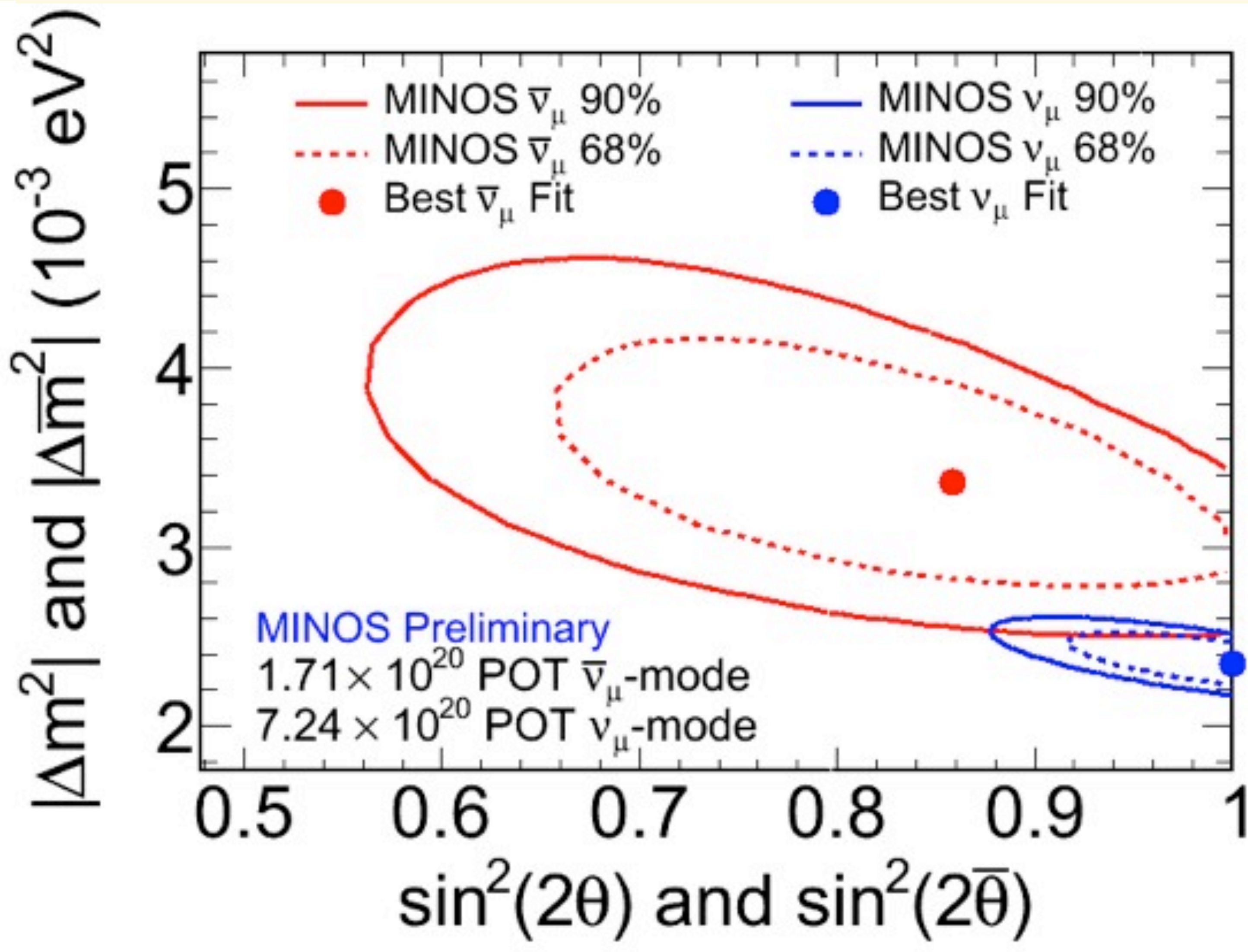
$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

MINOS Result

MINOS took 1.7E20 protons on target in $\overline{\nu_\mu}$ mode



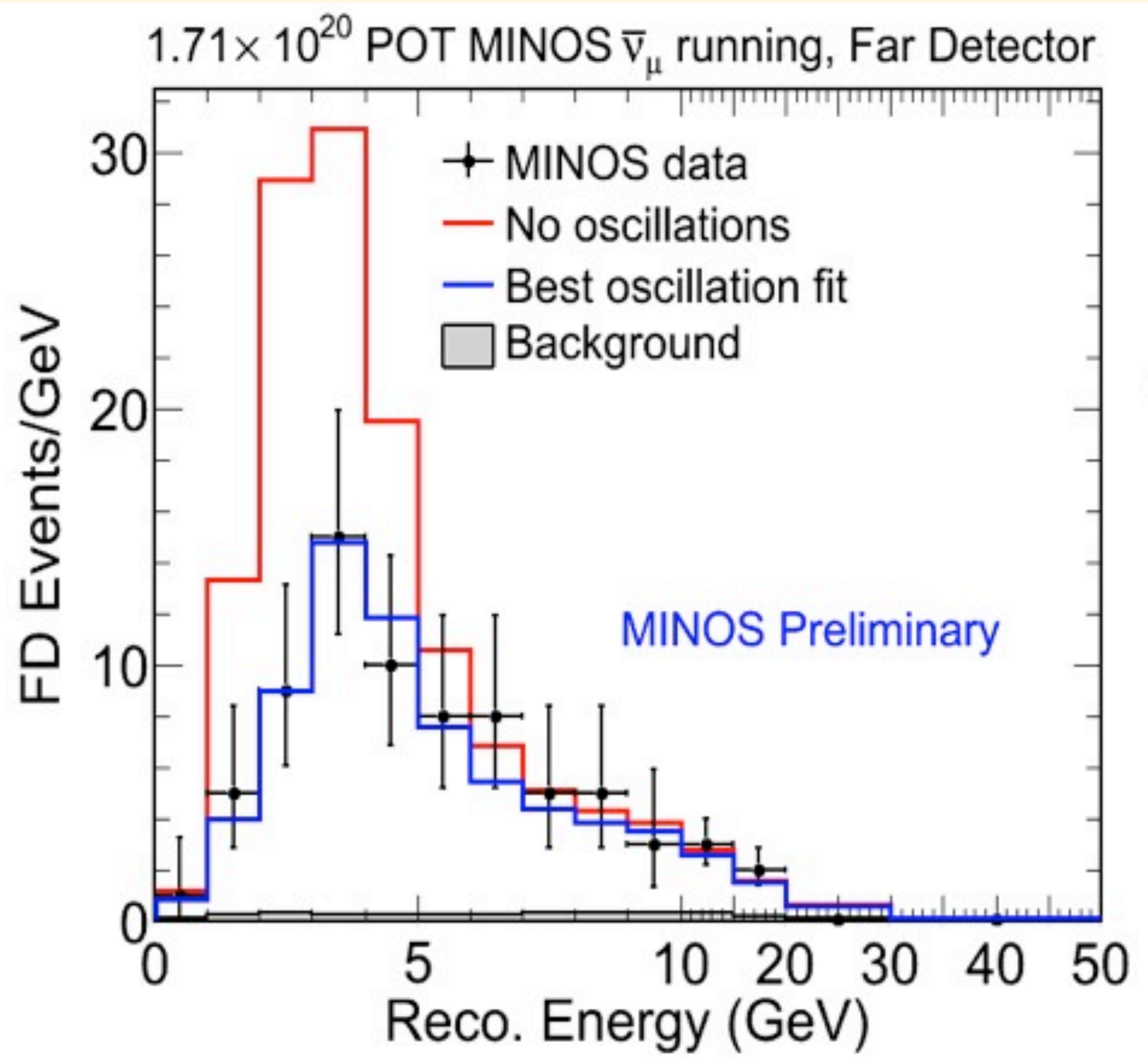


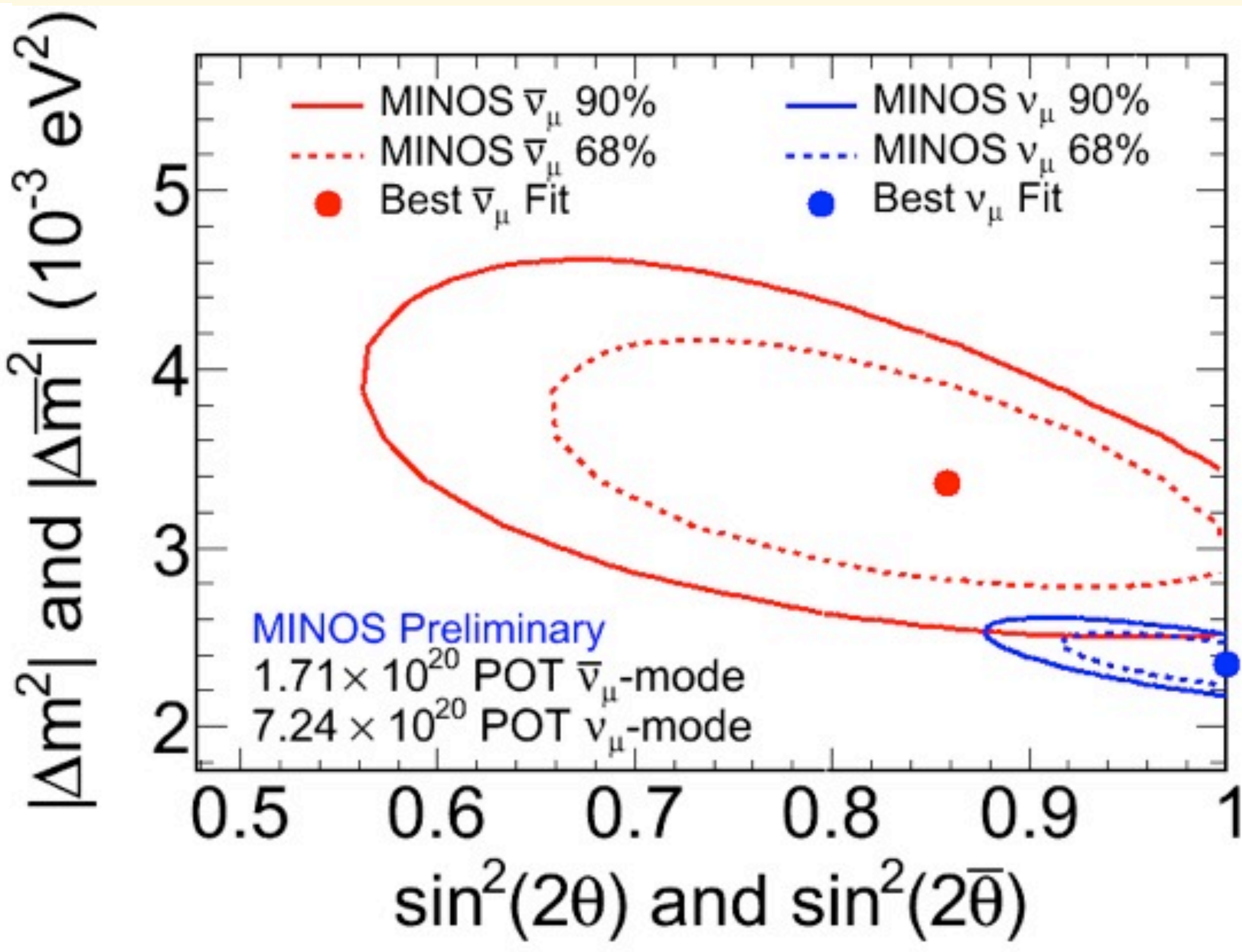
$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40}\times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

MINOS Result

MINOS took 1.7E20 protons on target in $\overline{\nu_\mu}$ mode





$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

There is a plan to increase the data set to 4E20 POT

What Does it Mean?

What Does it Mean?

- The difference could be due to a statistical fluctuation (~2σ)

What Does it Mean?

- The difference could be due to a statistical fluctuation (~2σ)
- The oscillation parameters must be the same in these two cases by CPT

What Does it Mean?

- The difference could be due to a statistical fluctuation (~2σ)
- The oscillation parameters must be the same in these two cases by CPT
- But the two situation are not related by the CPT transformation (no anti-earth)

What Does it Mean?

- The difference could be due to a statistical fluctuation (~2σ)
- The oscillation parameters must be the same in these two cases by CPT
- But the two situation are not related by the CPT transformation (no anti-earth)
- Neutrinos and antineutrinos could have different <u>anomalous</u> interactions in the earth

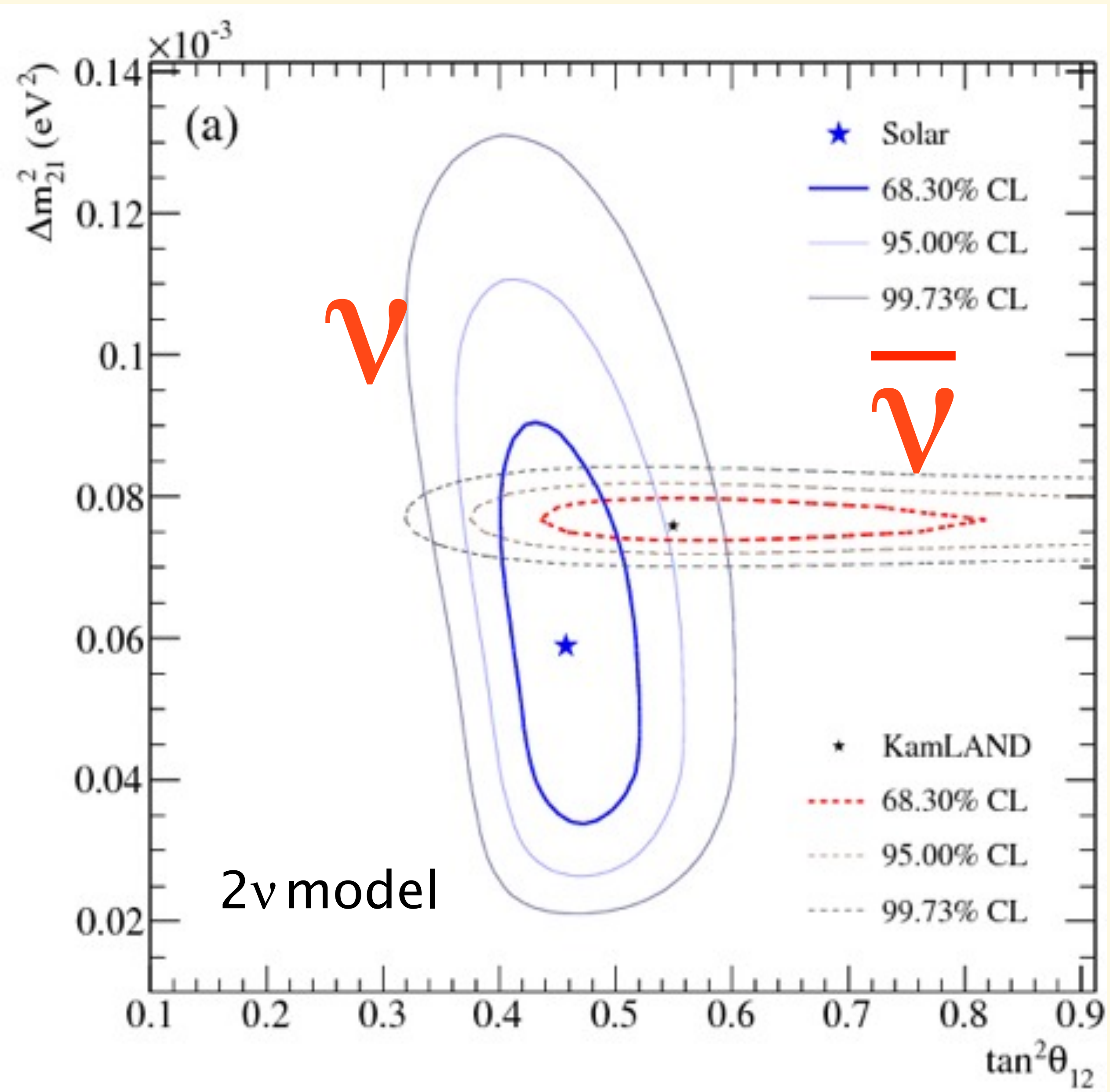
$\nu / \bar{\nu}$ in the Solar Sector

$\nu / \bar{\nu}$ in the Solar Sector

Solar includes all solar experiments (3 phases of SNO, SuperKamiokande, Chlorine, Gallium and Borexino)

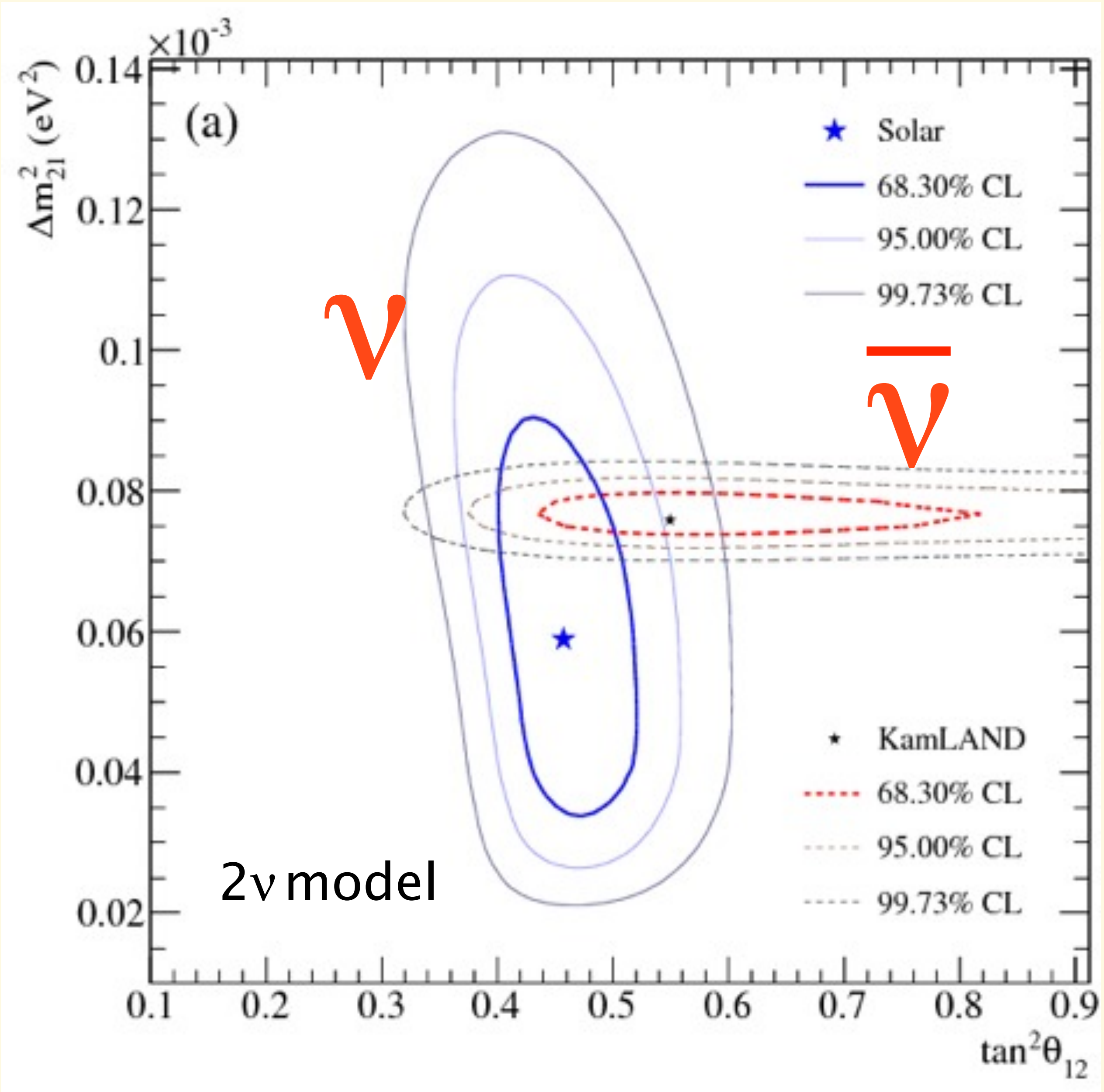
$\nu / \bar{\nu}$ in the Solar Sector

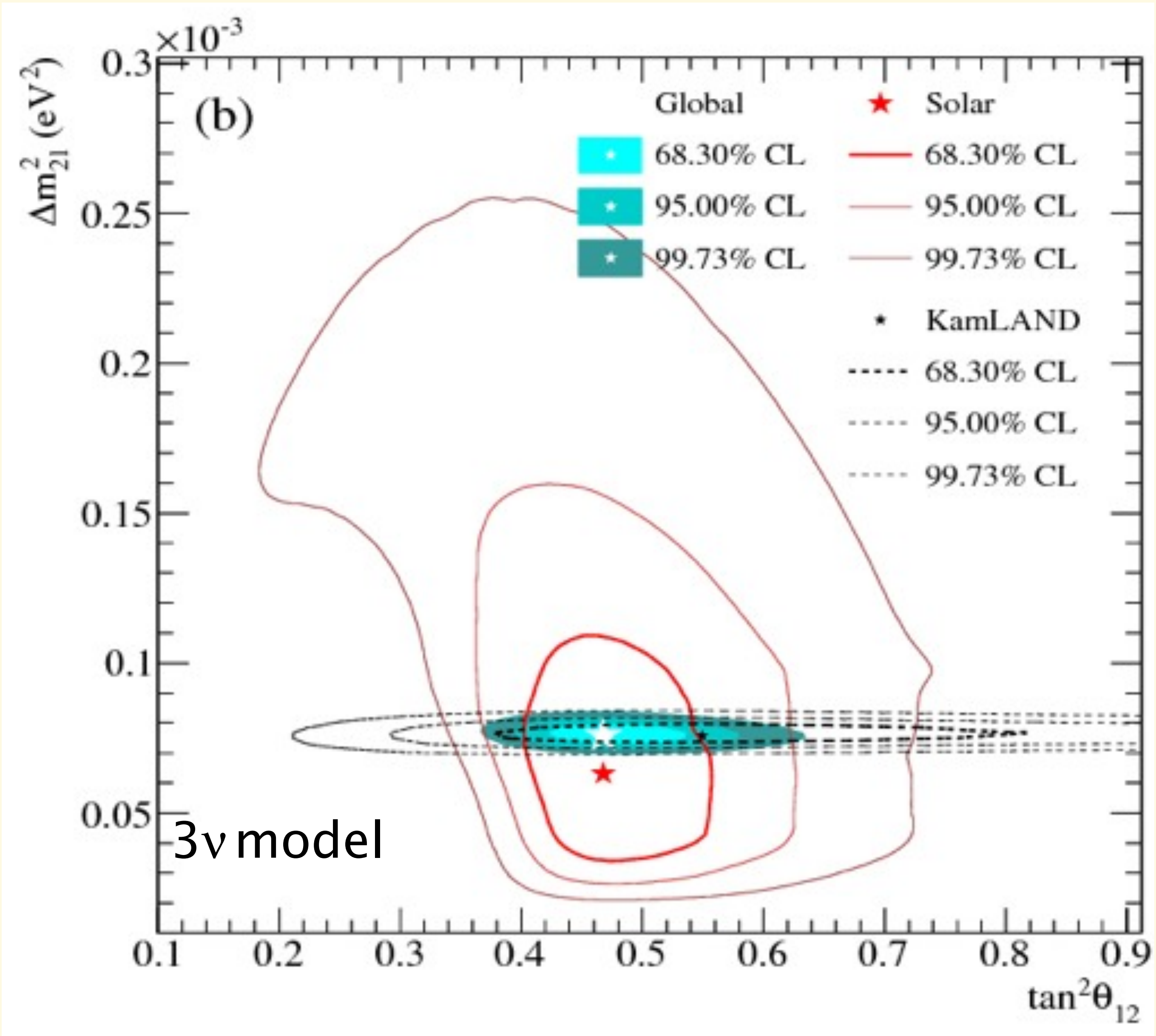
Solar includes all solar experiments (3 phases of SNO, SuperKamiokande, Chlorine, Gallium and Borexino)



$\nu / \bar{\nu}$ in the Solar Sector

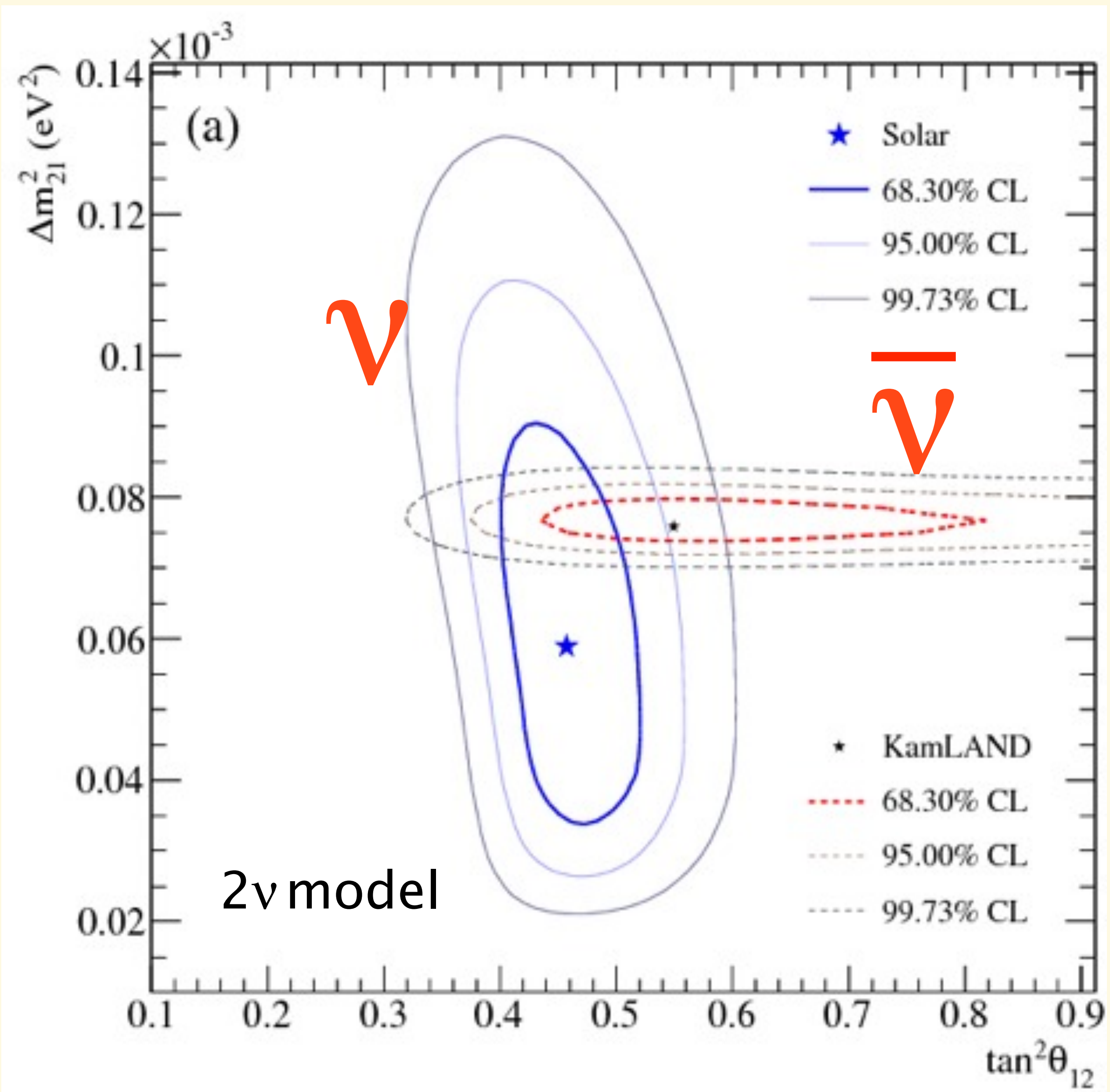
Solar includes all solar experiments (3 phases of SNO, SuperKamiokande, Chlorine, Gallium and Borexino)

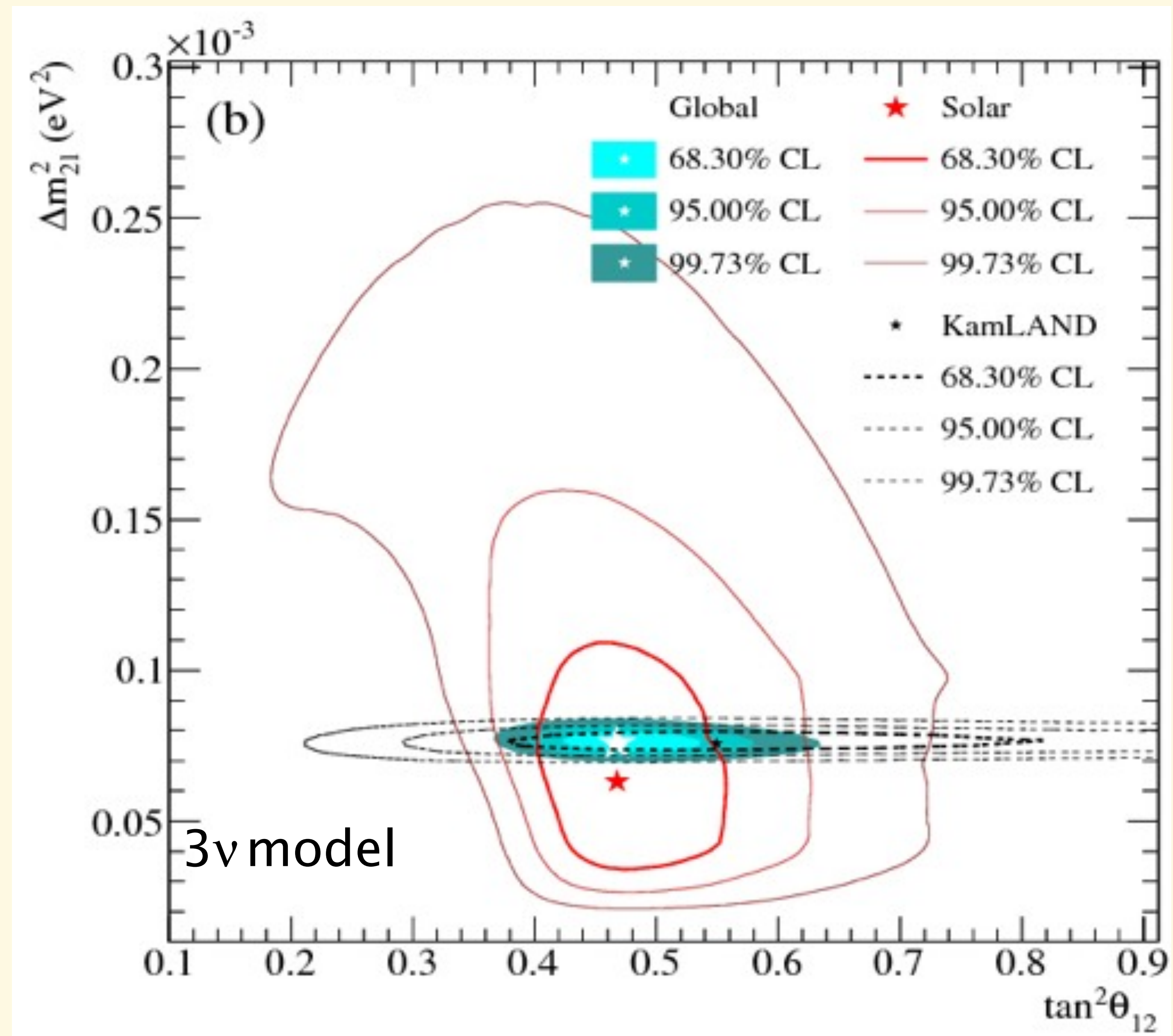




$\nu / \bar{\nu}$ in the Solar Sector

Solar includes all solar experiments (3 phases of SNO, SuperKamiokande, Chlorine, Gallium and Borexino)





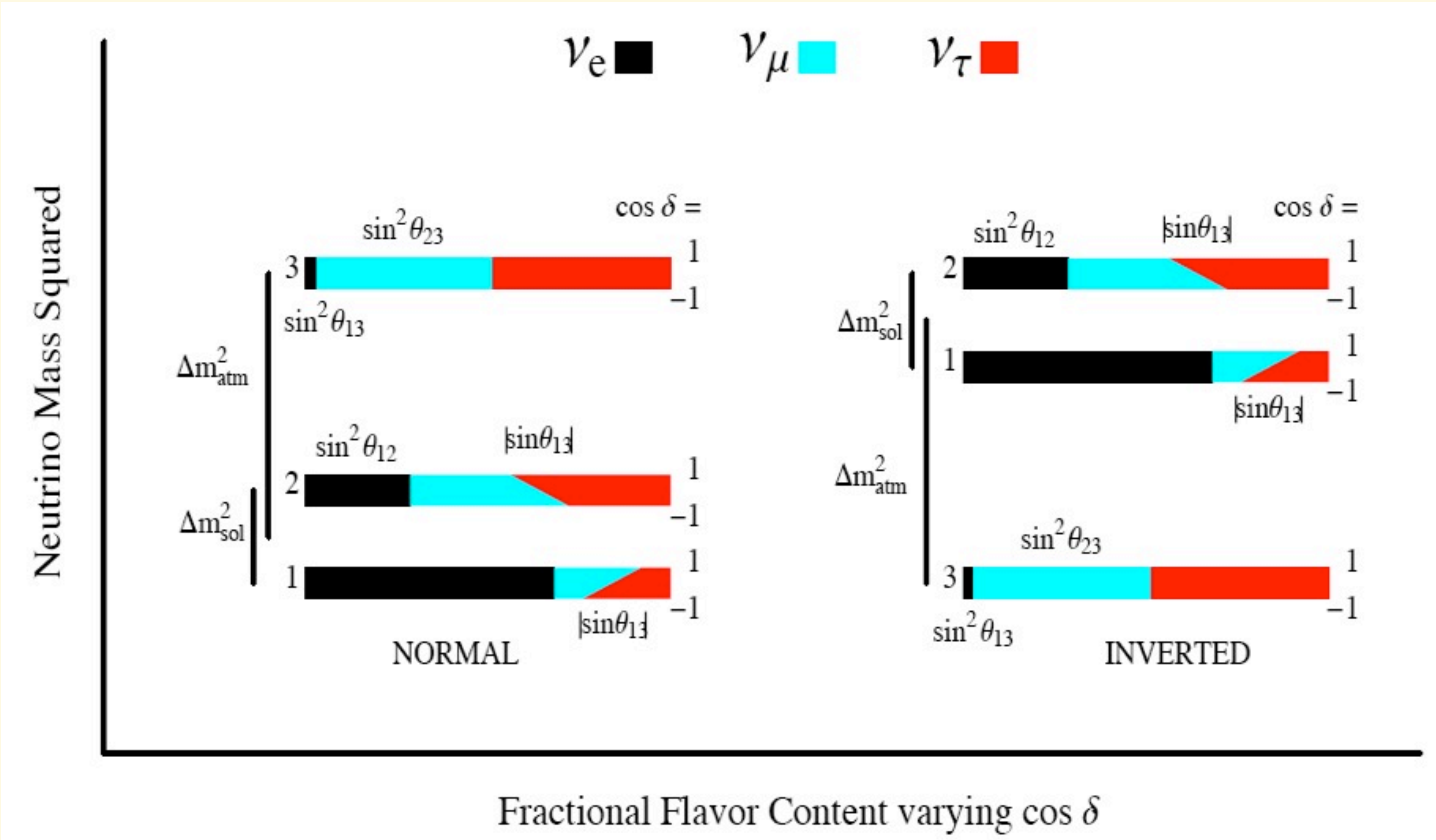
Thus identity is only verified to a factor of 2 (at 1σ level)

Future Accelerator Efforts (Near Term)

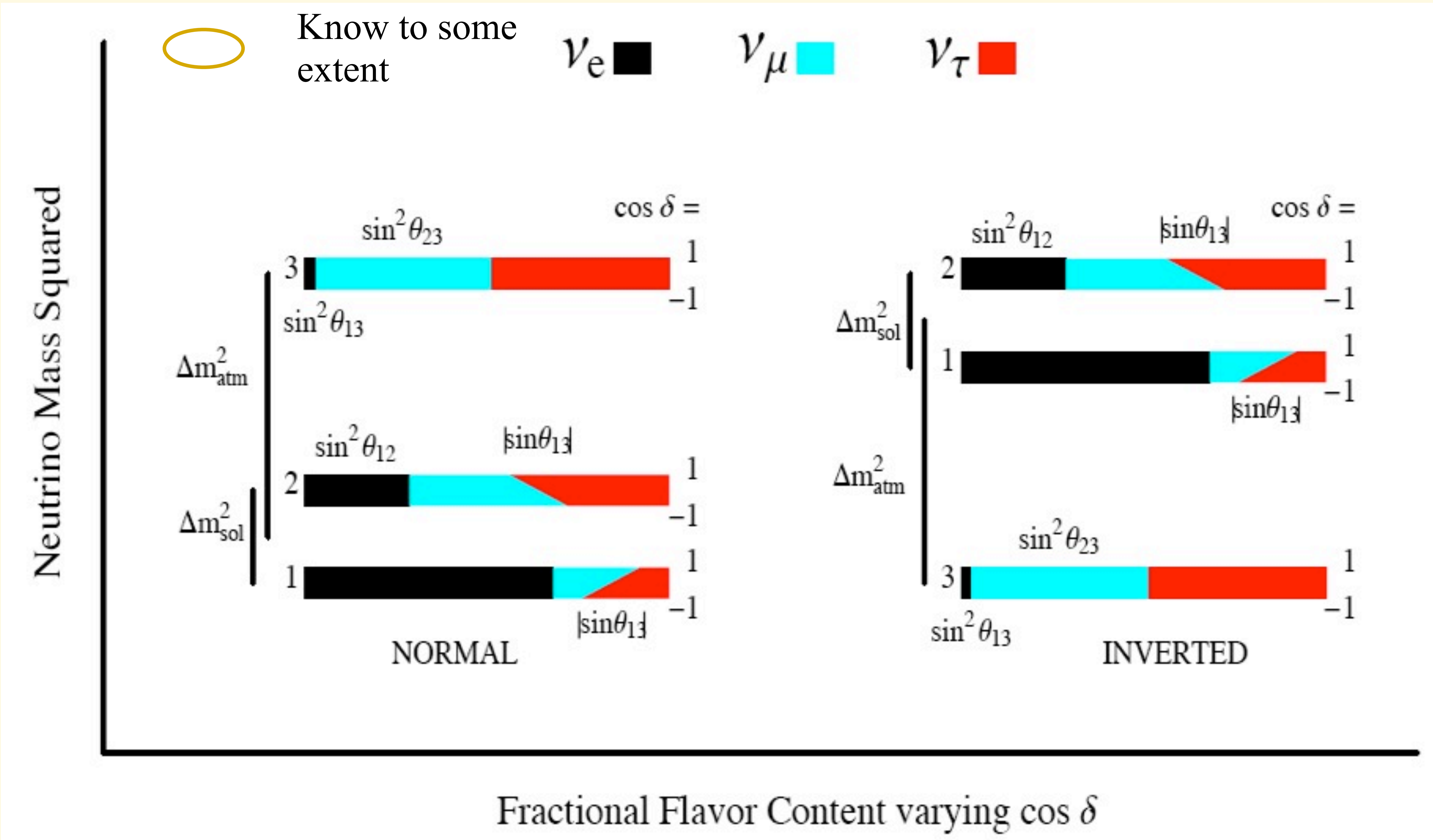
Current Status

O. Mena and S. Parke, hep-ph/0312131

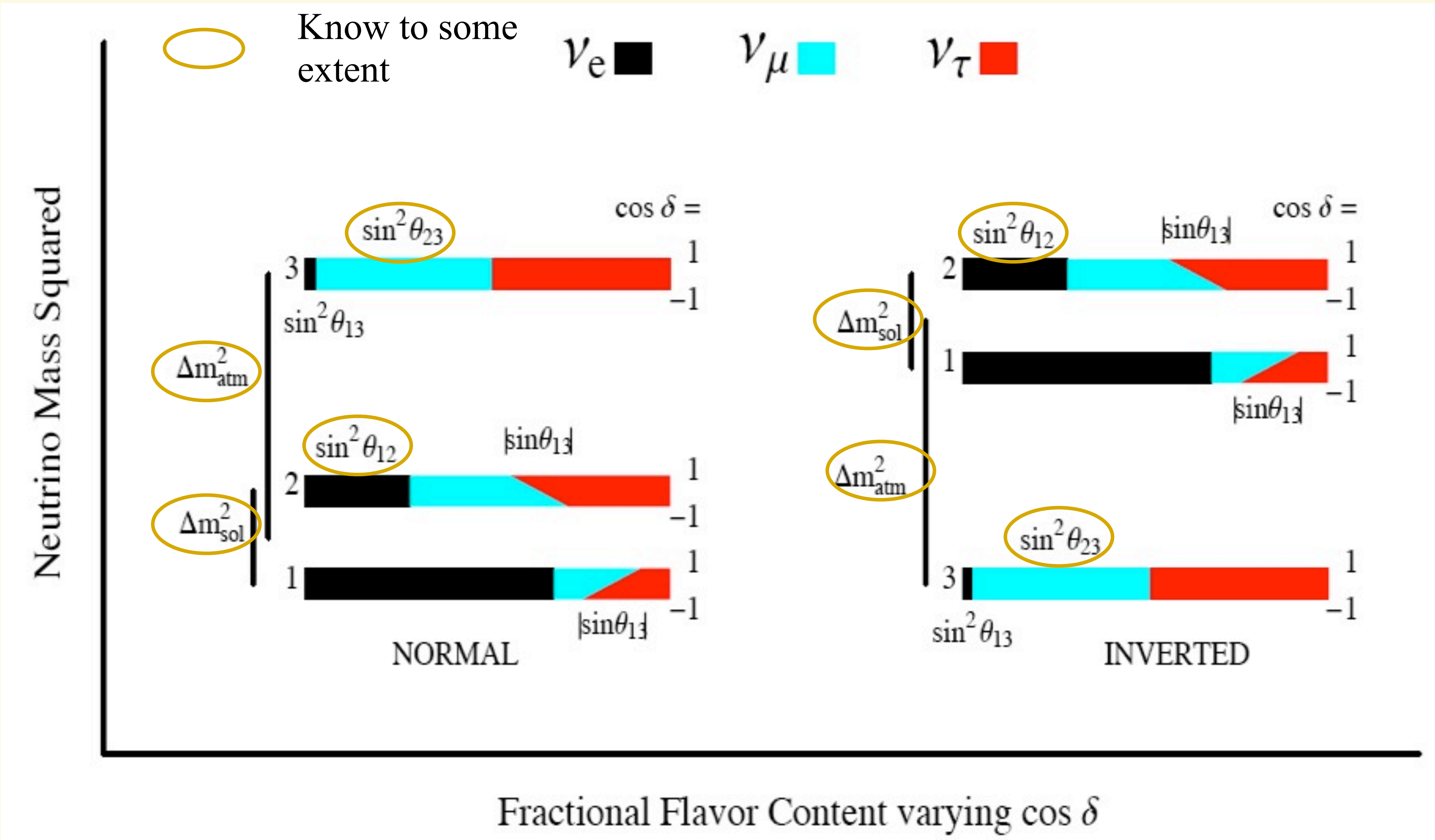
Current Status



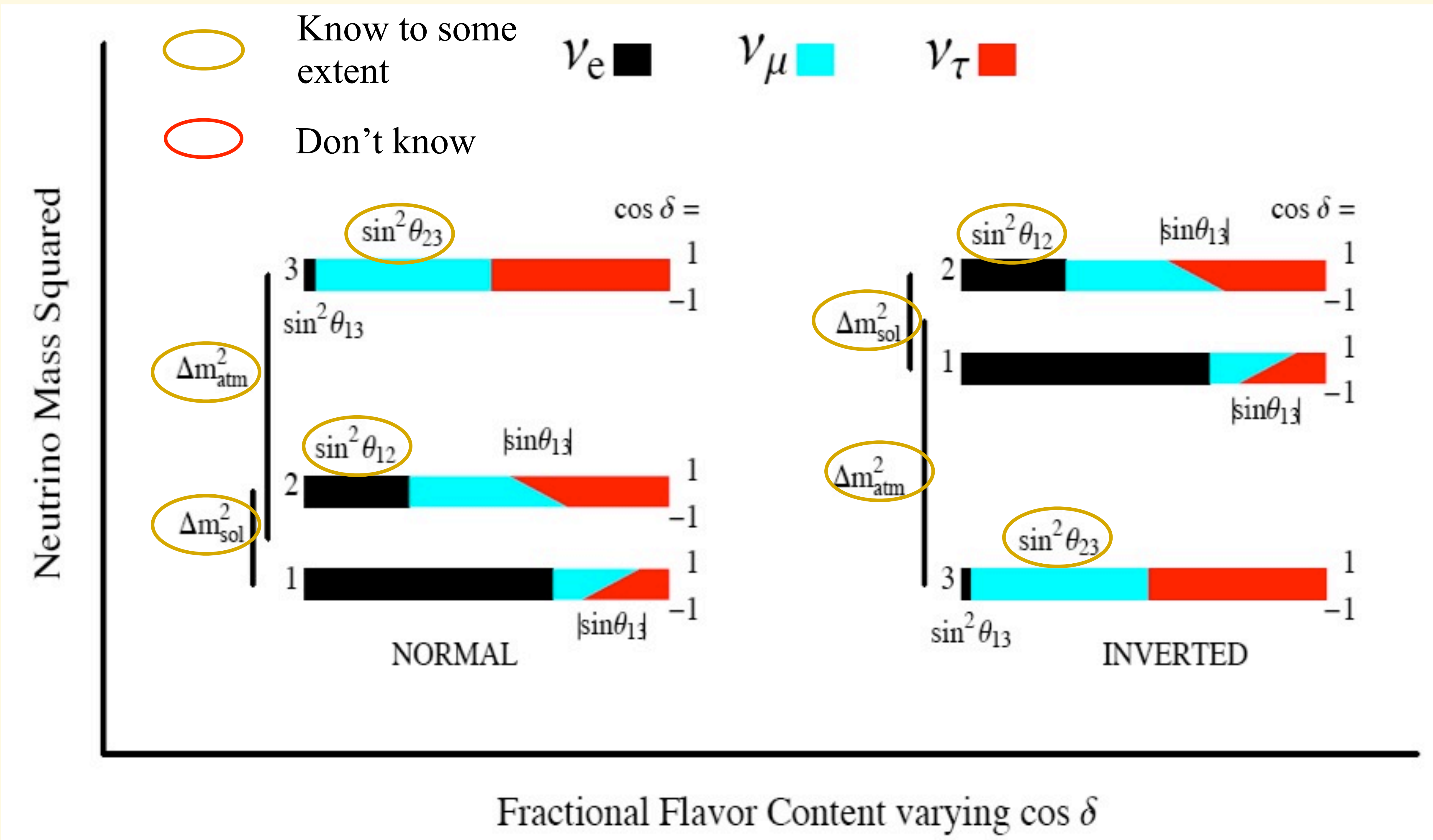
Current Status



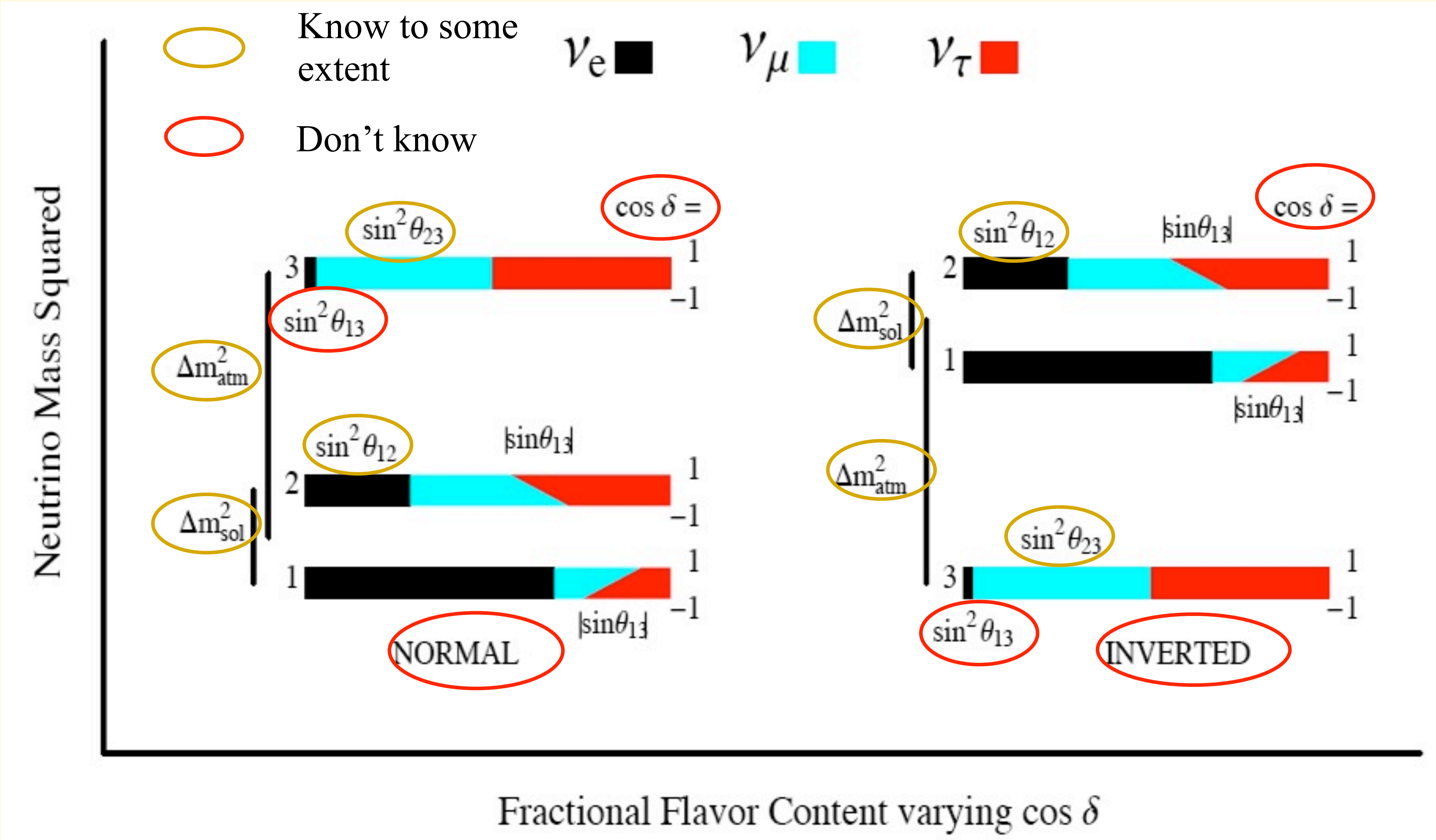
Current Status



Current Status

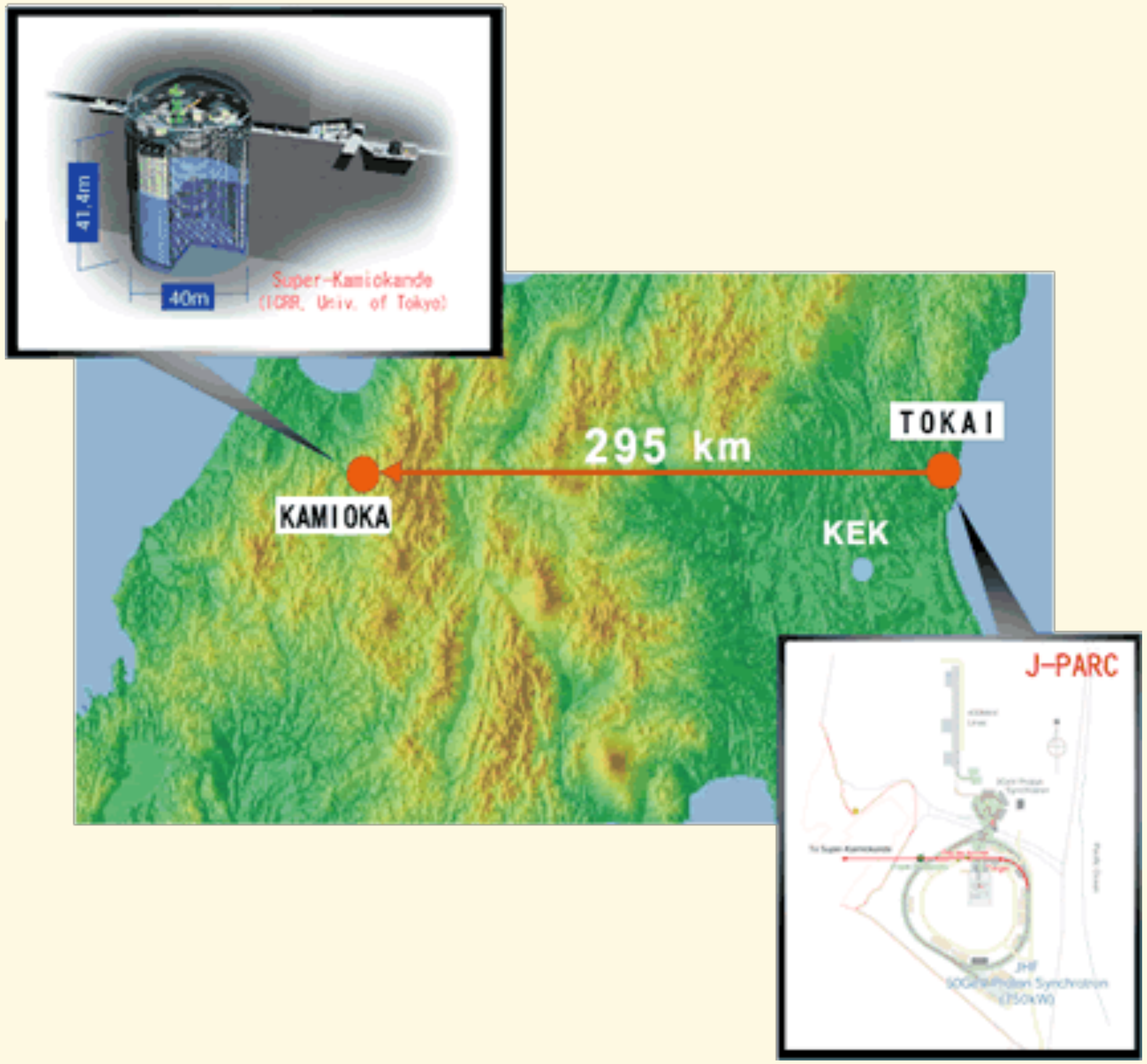


Current Status



Accelerator Efforts

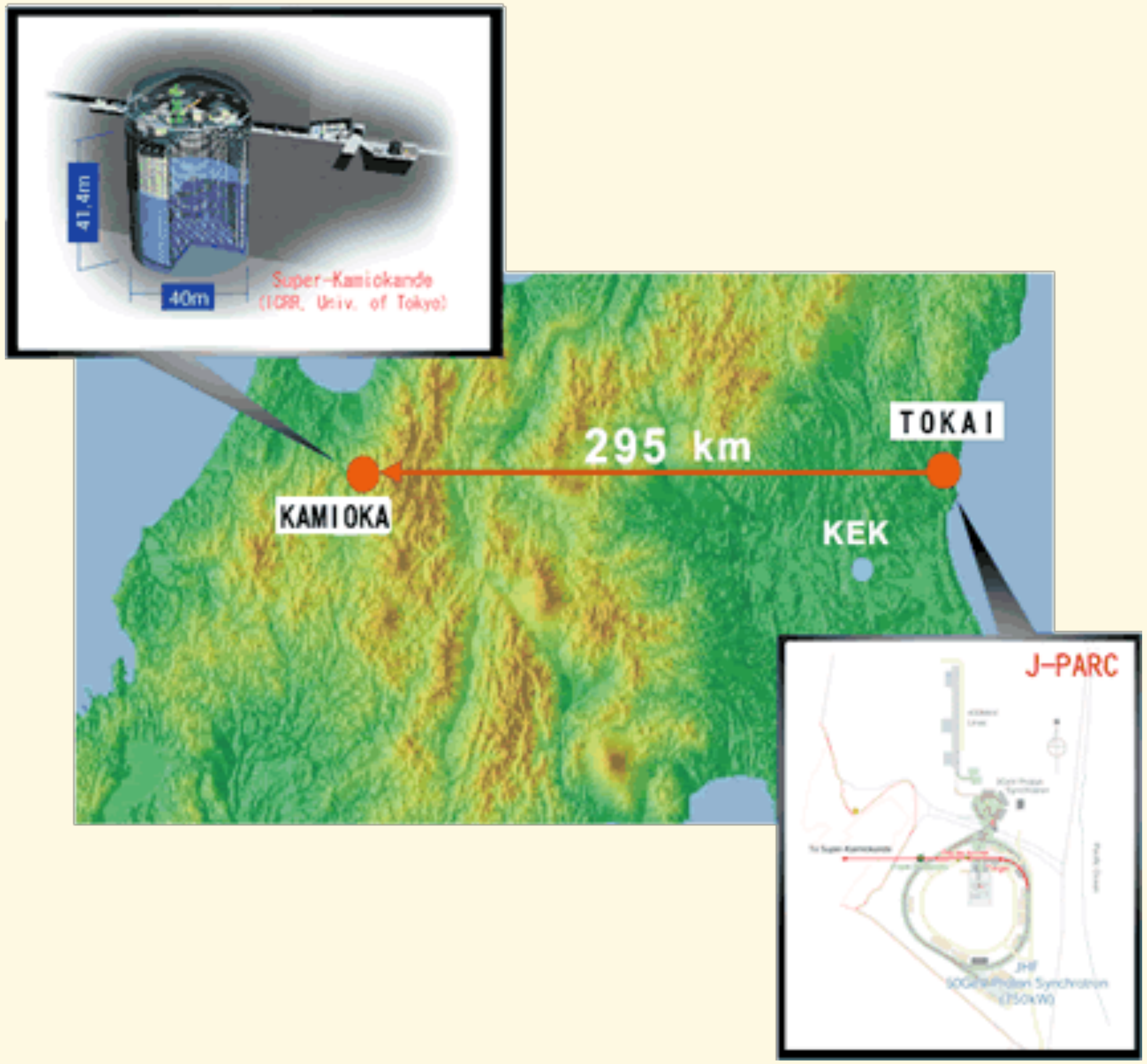
Accelerator Efforts



New accelerator (JPARC) and new beamline
Existing detector (SuperKamiokande)

Data taking stated in spring of 2010 with reduced (50 kW) intensity

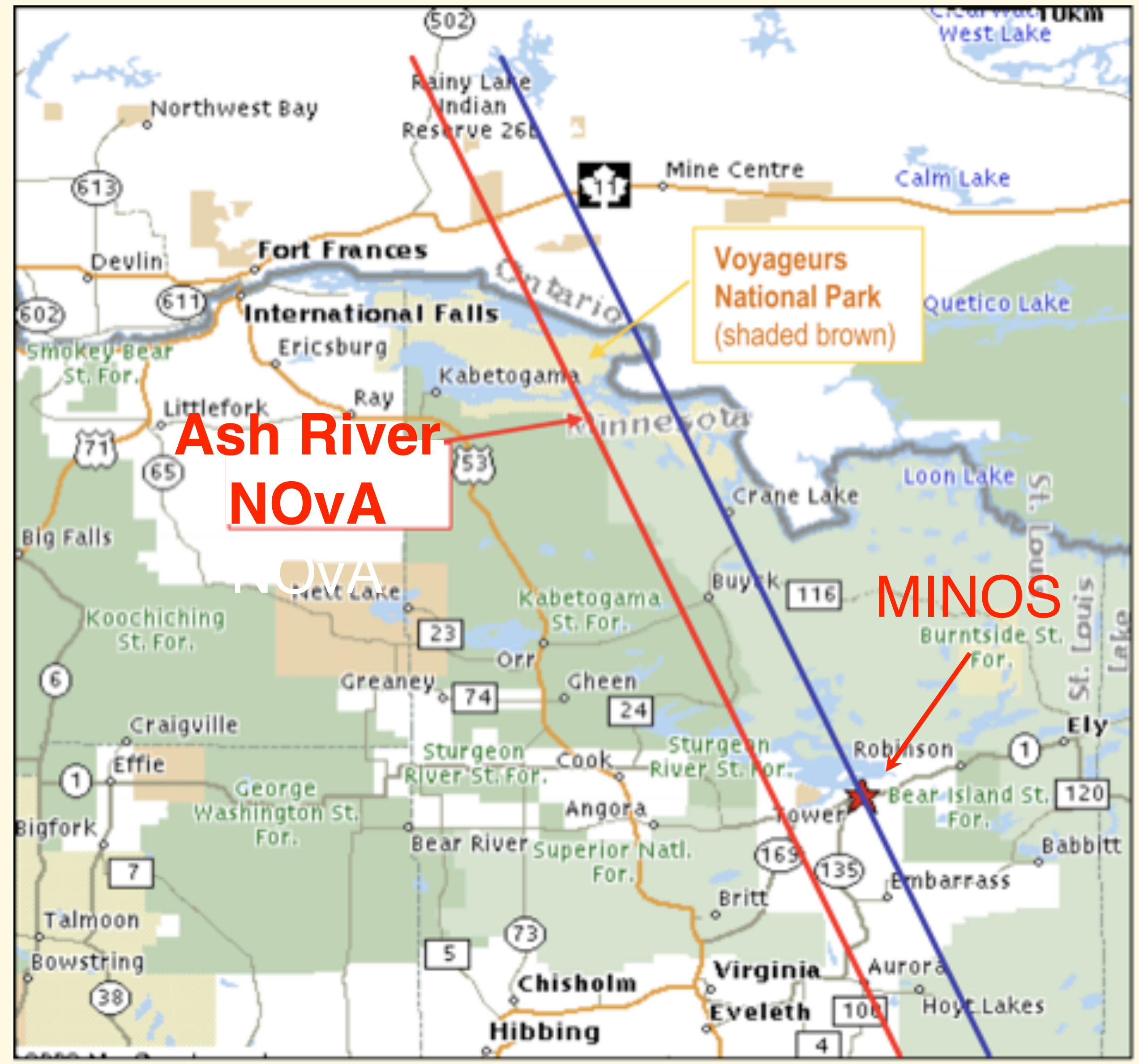
Accelerator Efforts



New accelerator (JPARC) and new beamline
Existing detector (SuperKamiokande)

Data taking stated in spring of 2010 with reduced (50 kW) intensity

NOvA Beamline and Location



Existing beamline (NuMI) at Fermilab
New Detector on a new site

Data taking might start in early 2013 with partial detector

The Goals

The Goals

- The principal goal of these next generation of experiments is to improve on our knowledge of $\sin^2(2\theta_{13})$ with a sensitivity ~0.01

The Goals

- The principal goal of these next generation of experiments is to improve on our knowledge of $\sin^2(2\theta_{13})$ with a sensitivity ~0.01
- Both neutrino and antineutrino runs are contemplated

The Goals

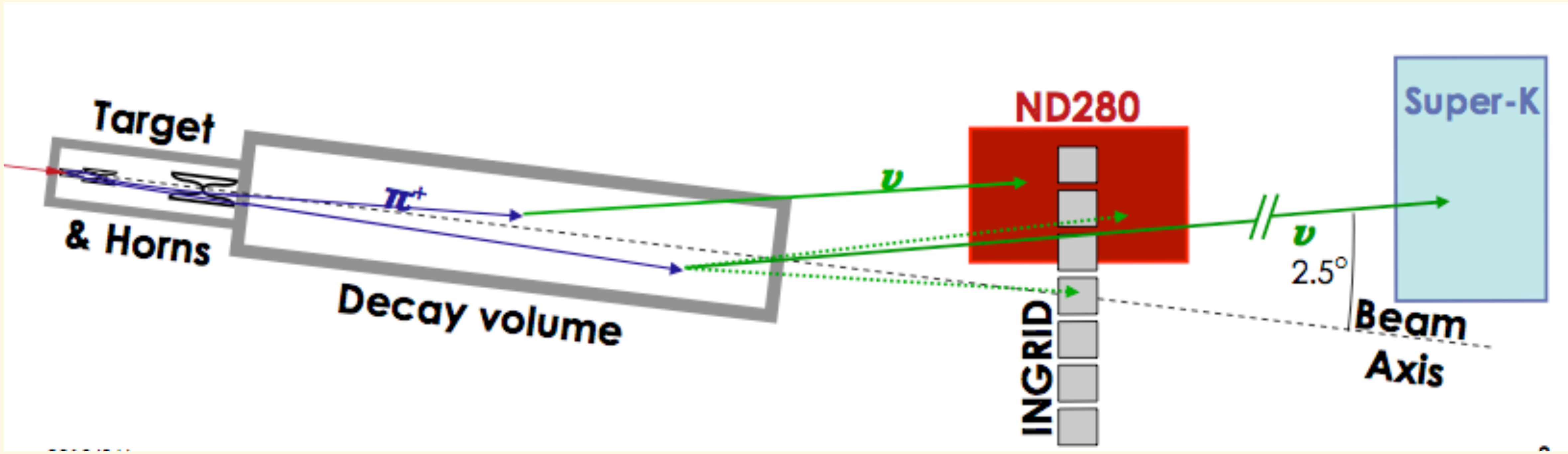
- The principal goal of these next generation of experiments is to improve on our knowledge of $\sin^2(2\theta_{13})$ with a sensitivity ~0.01
- Both neutrino and antineutrino runs are contemplated
- By combining the results of these experiments with those of the reactor experiments one can also obtain information on other parameters.

The Goals

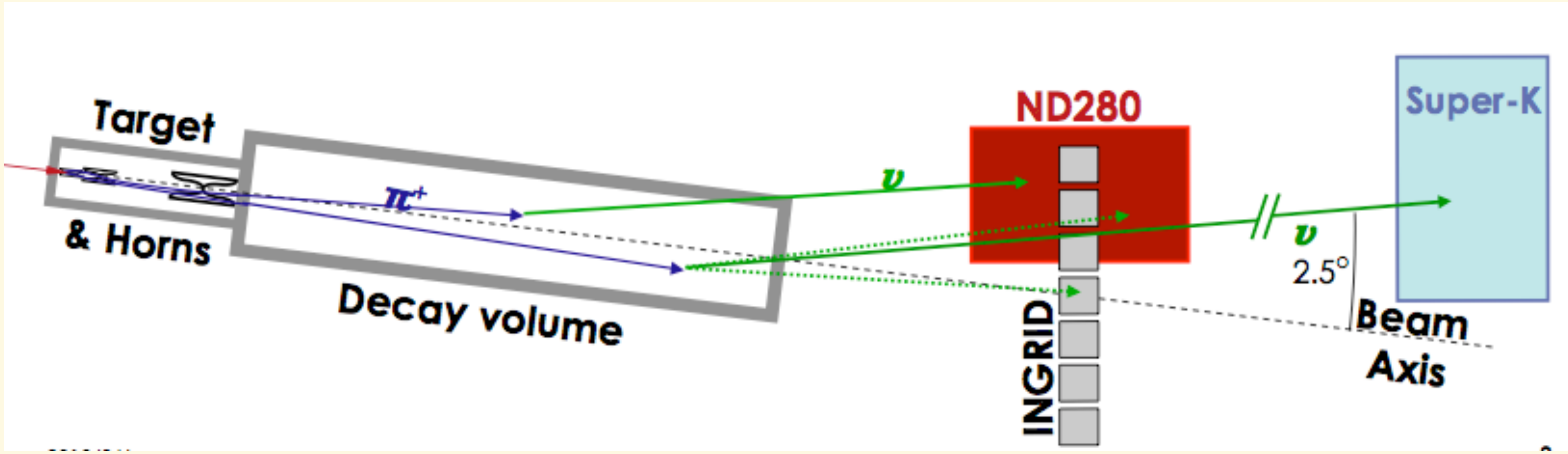
- The principal goal of these next generation of experiments is to improve on our knowledge of $\sin^2(2\theta_{13})$ with a sensitivity ~0.01
- Both neutrino and antineutrino runs are contemplated
- By combining the results of these experiments with those of the reactor experiments one can also obtain information on other parameters.
- If $\sin^2(2\theta_{13})$ is large enough, NOvA can also determine the mass hierarchy

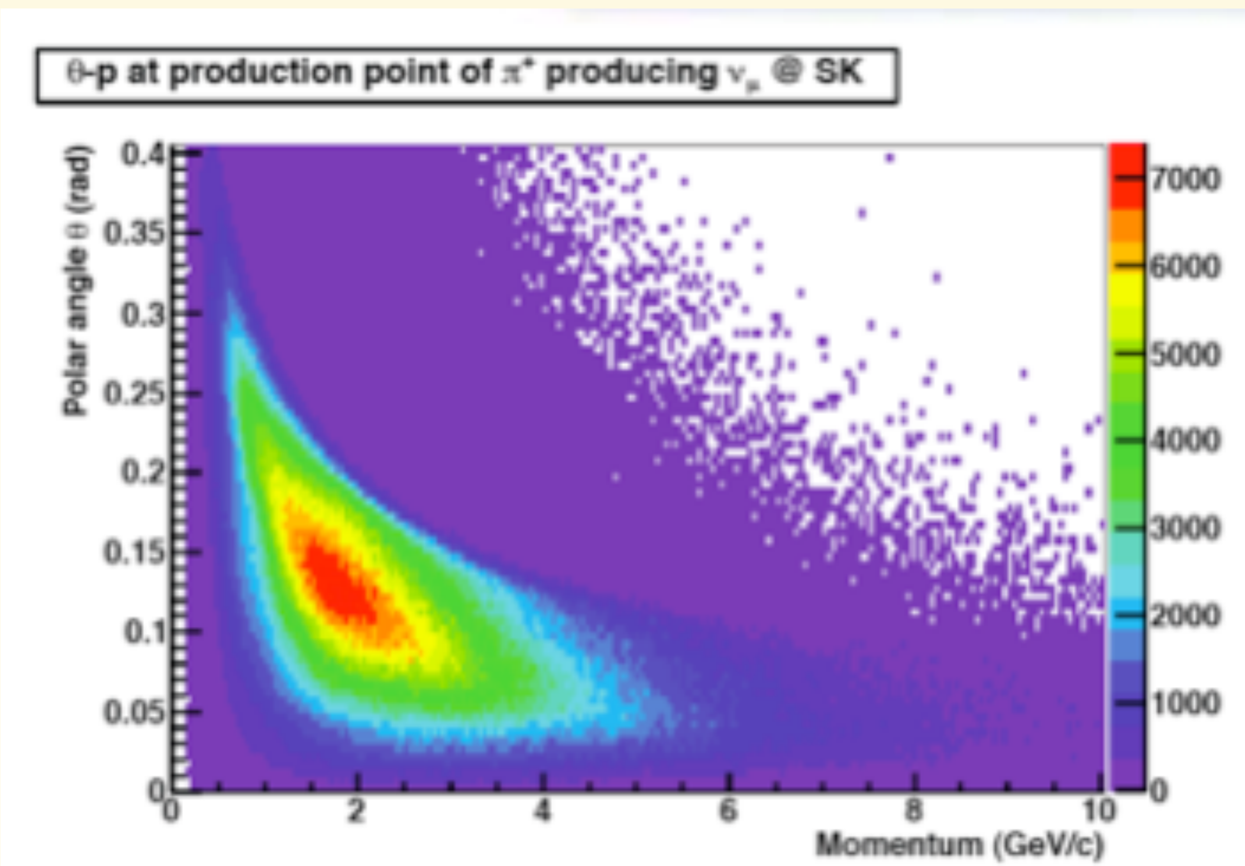
T2K Layout & Spectrum

T2K Layout & Spectrum

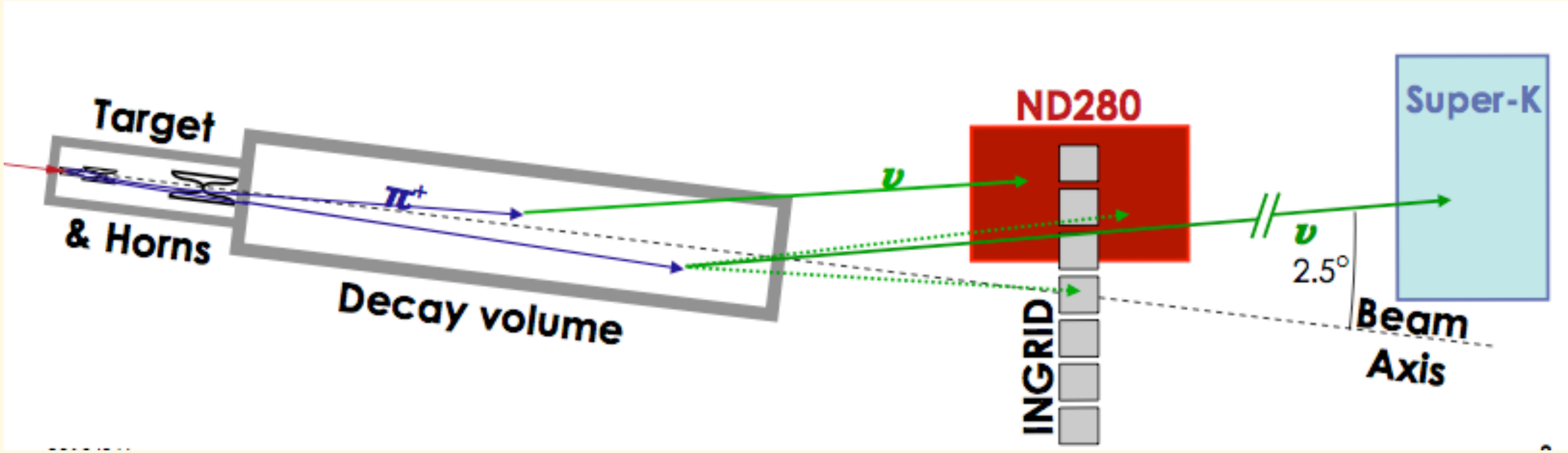


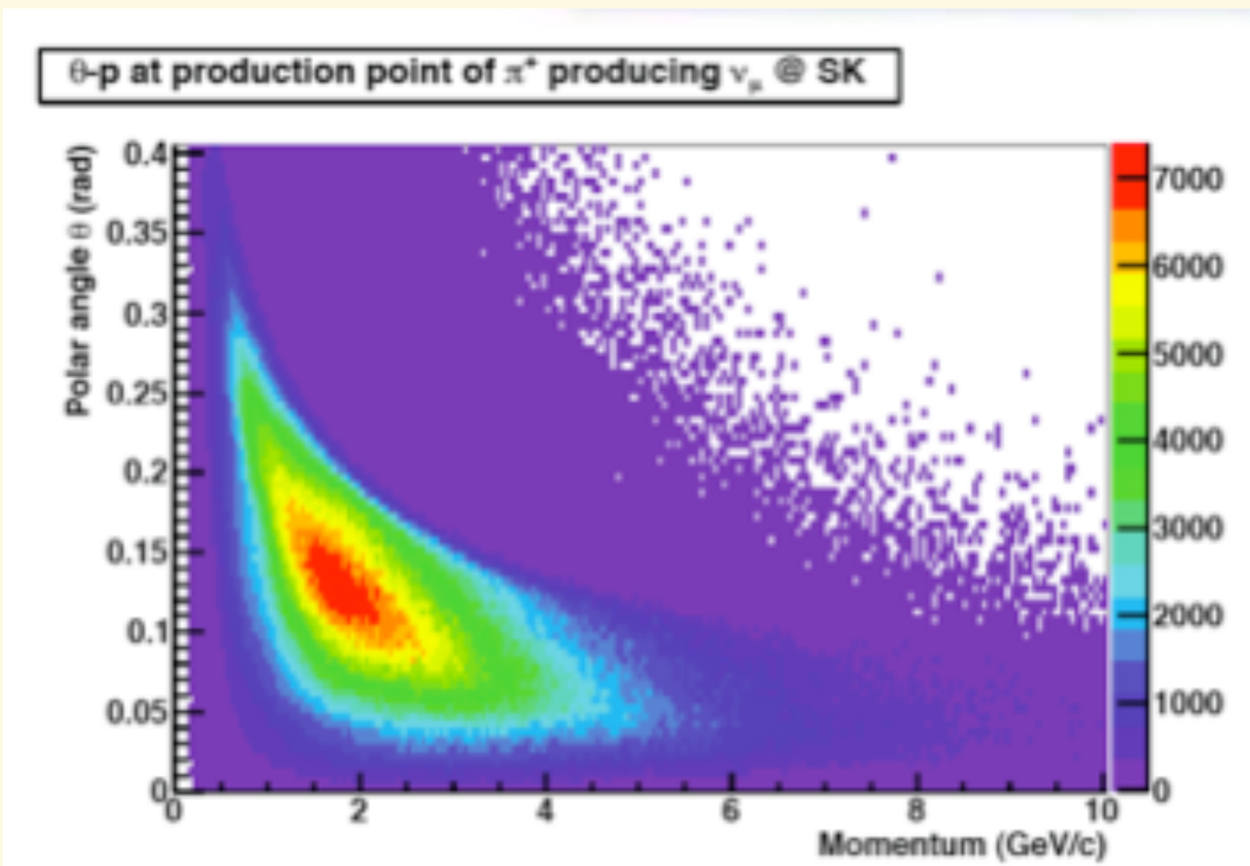
T2K Layout & Spectrum

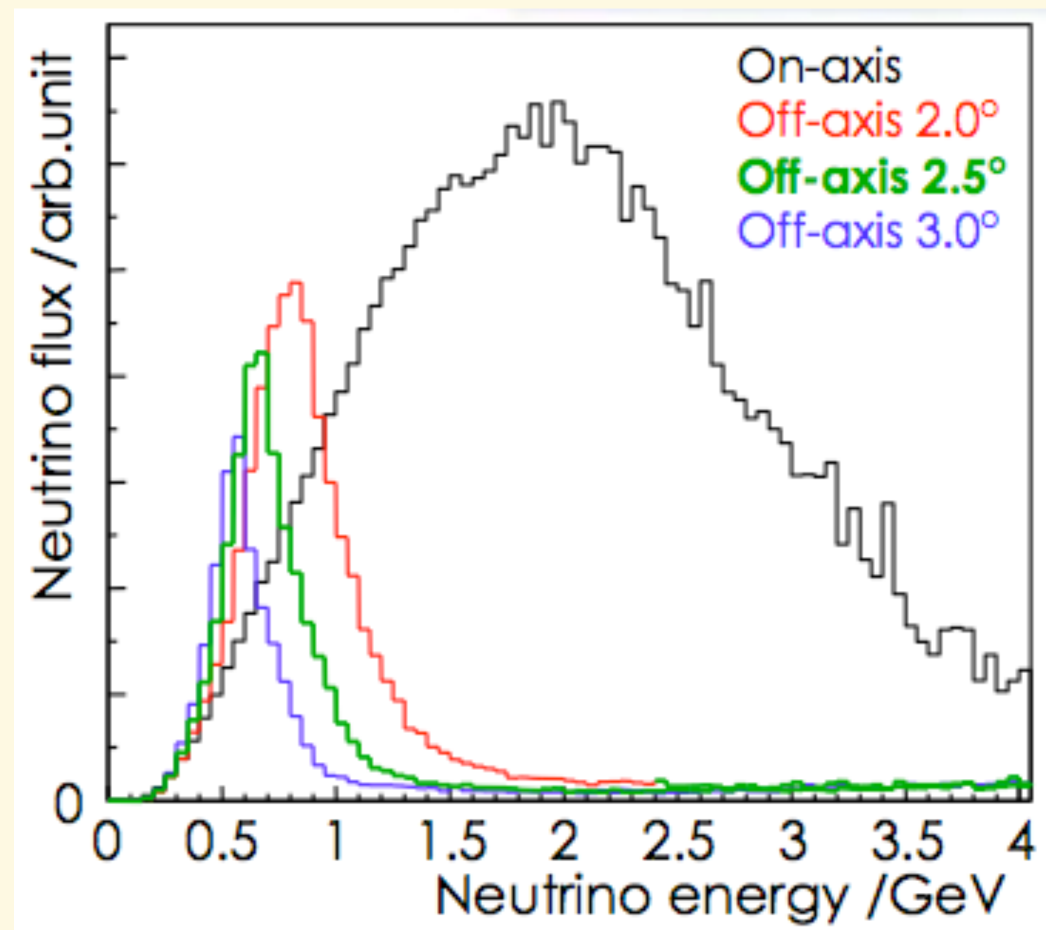




T2K Layout & Spectrum

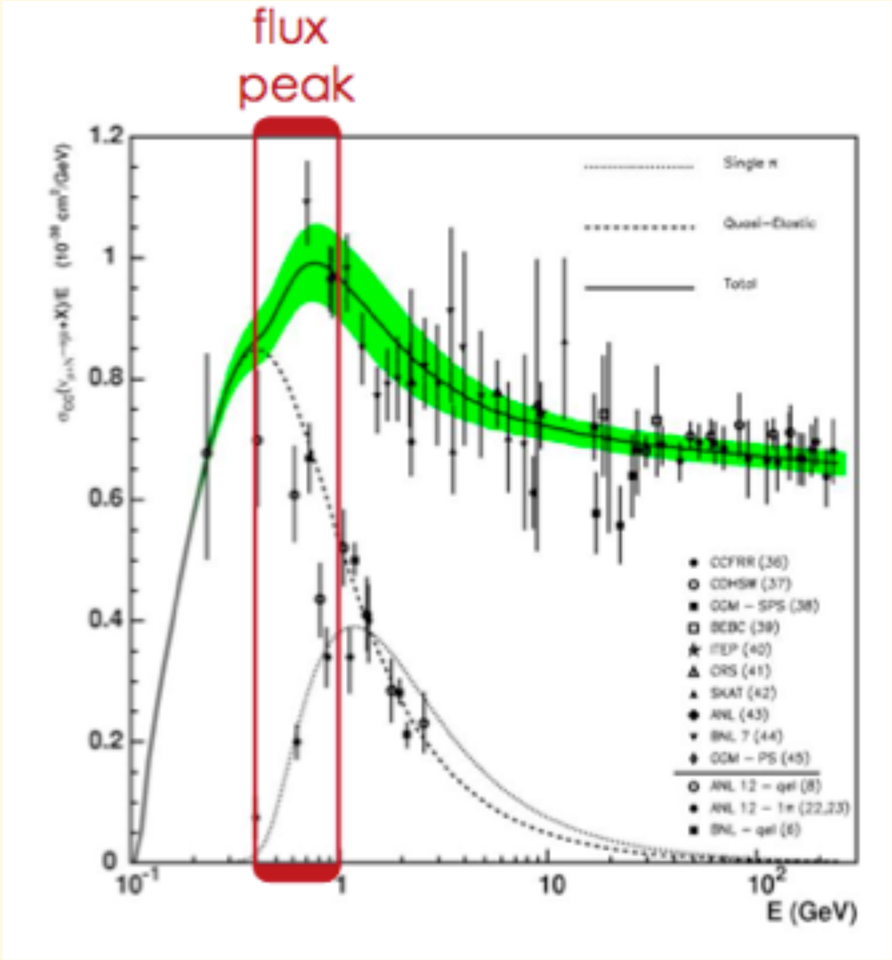




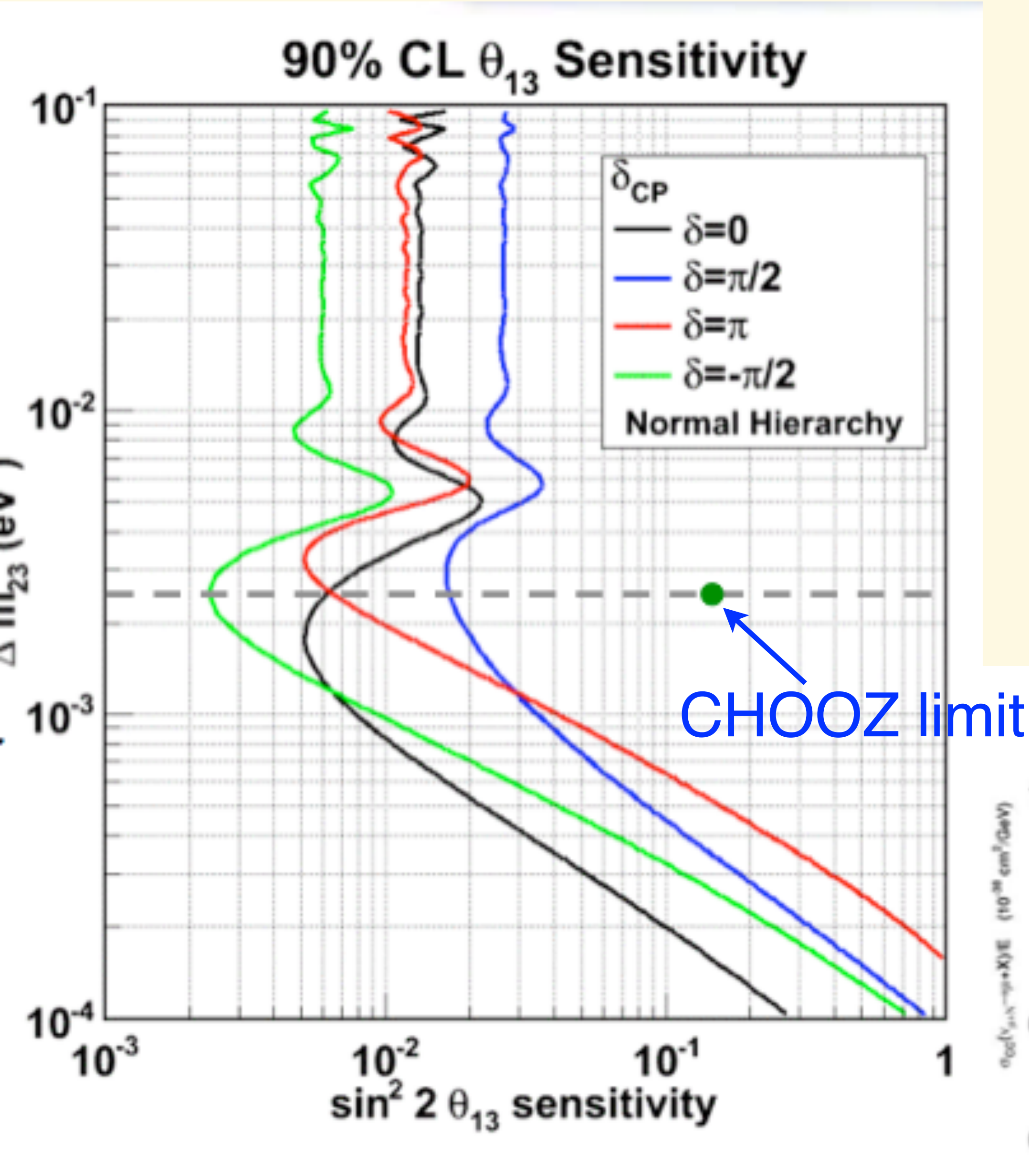


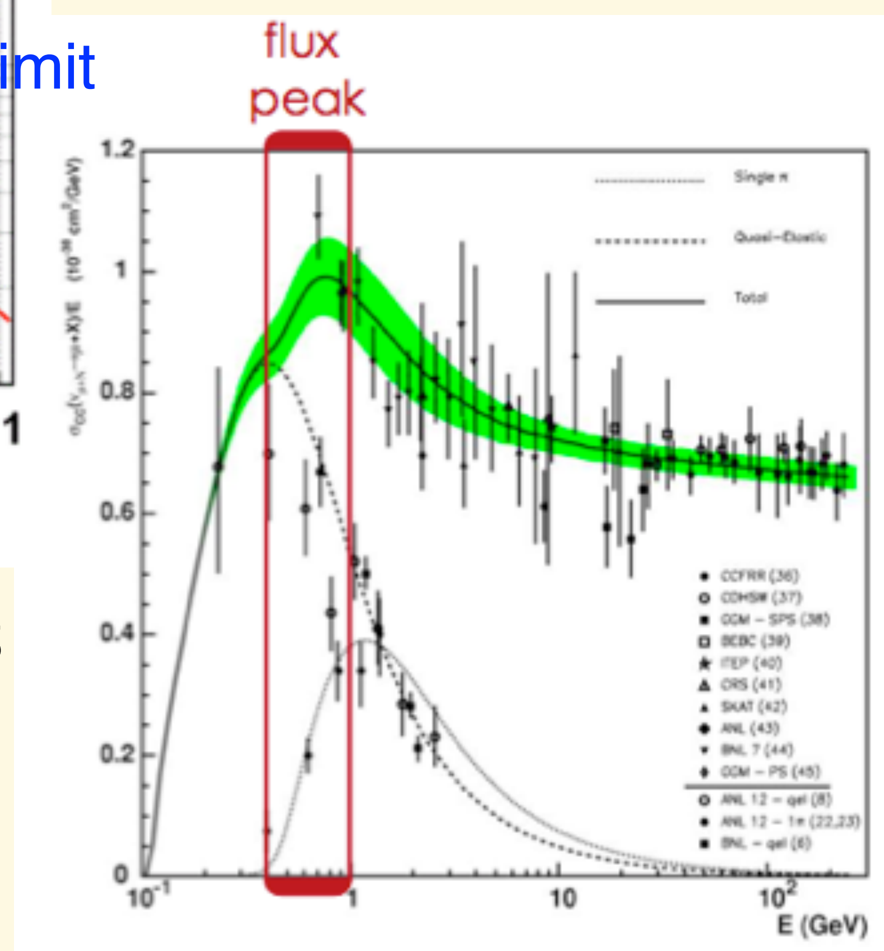
T2K Sensitivities

T2K Sensitivities



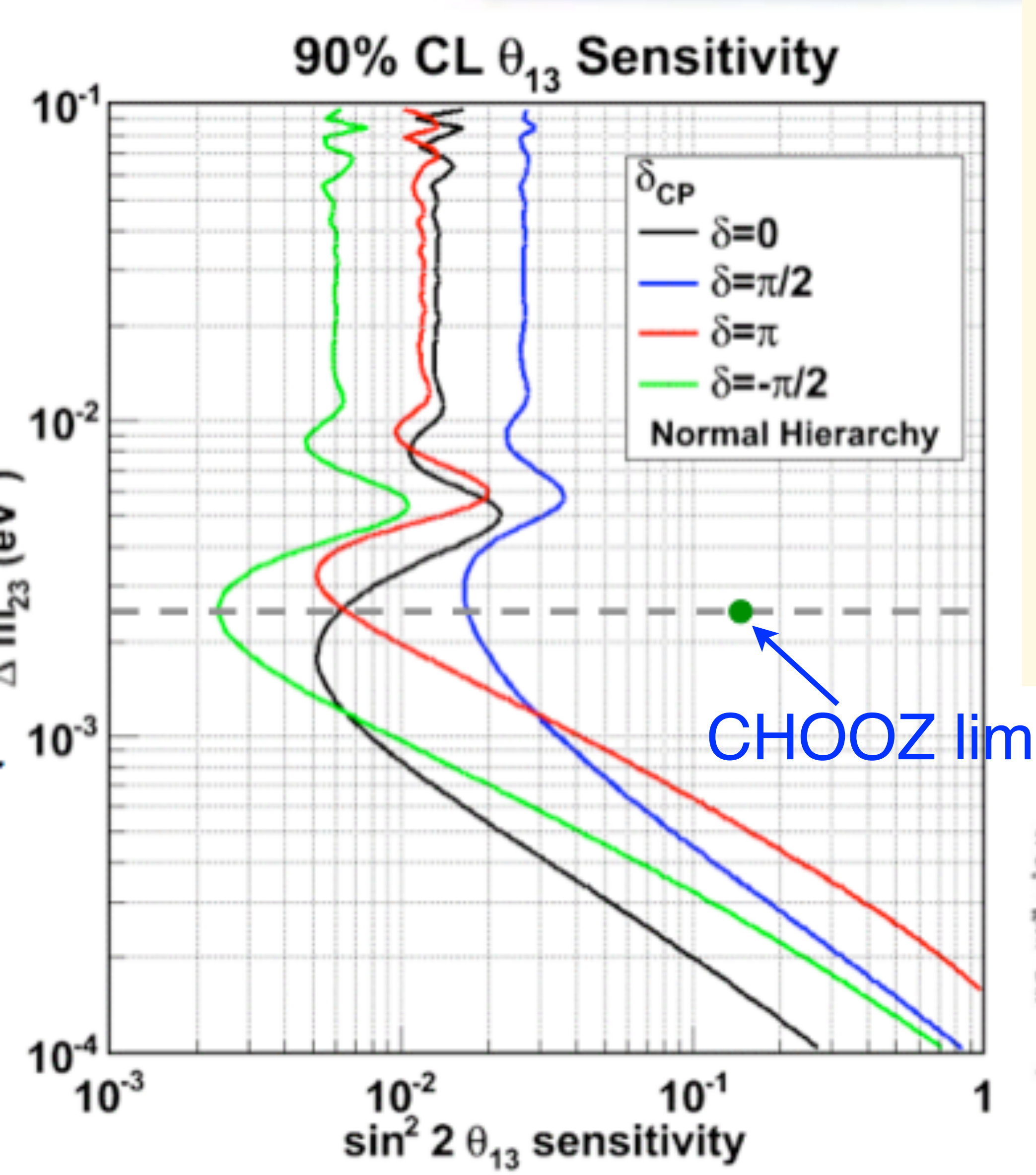
T2K Sensitivities

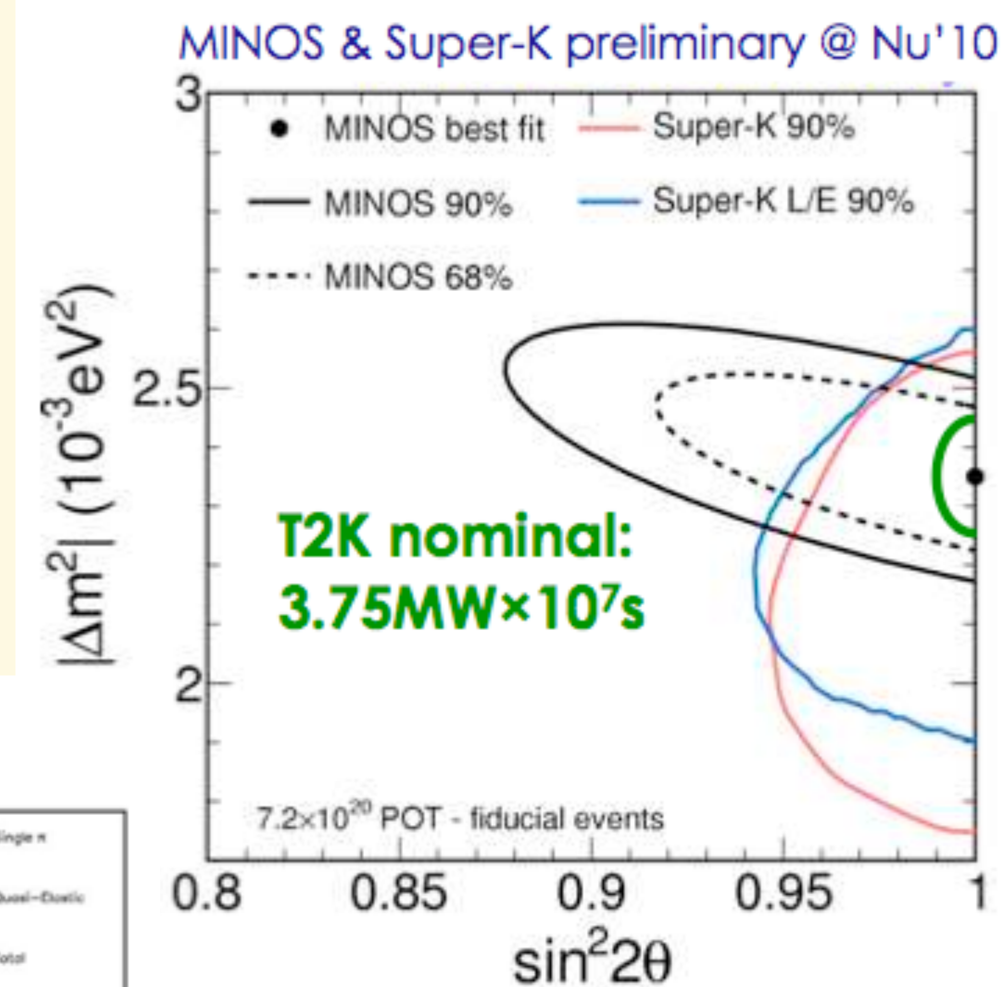


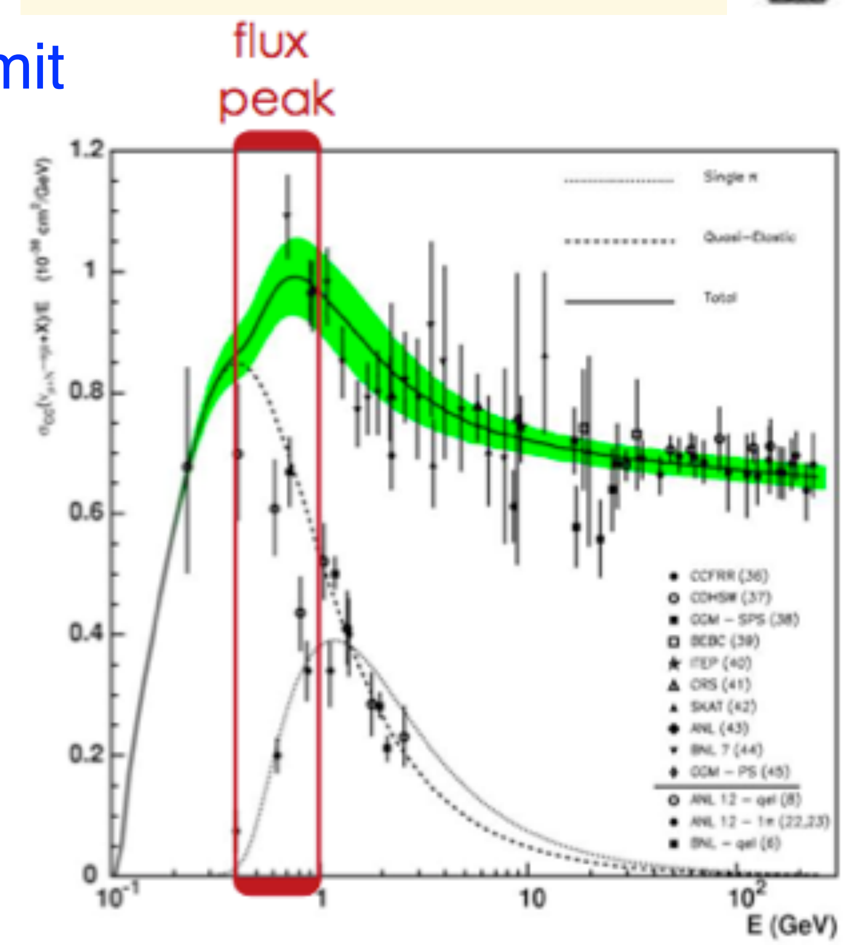


T2K: Assumes 5 years at 750 kW, 22.5 kton fiducial volume

T2K Sensitivities



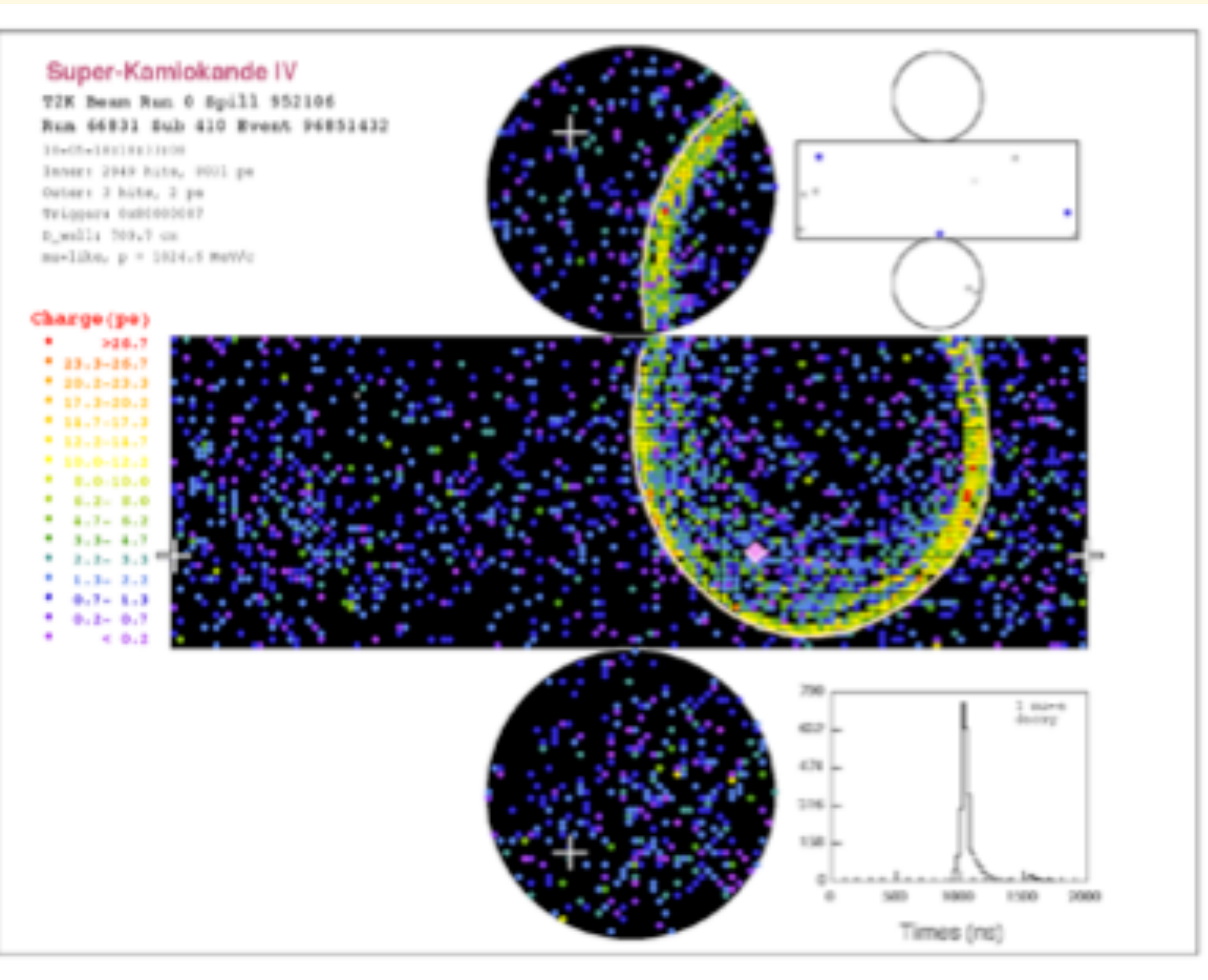




T2K: Assumes 5 years at 750 kW, 22.5 kton fiducial volume

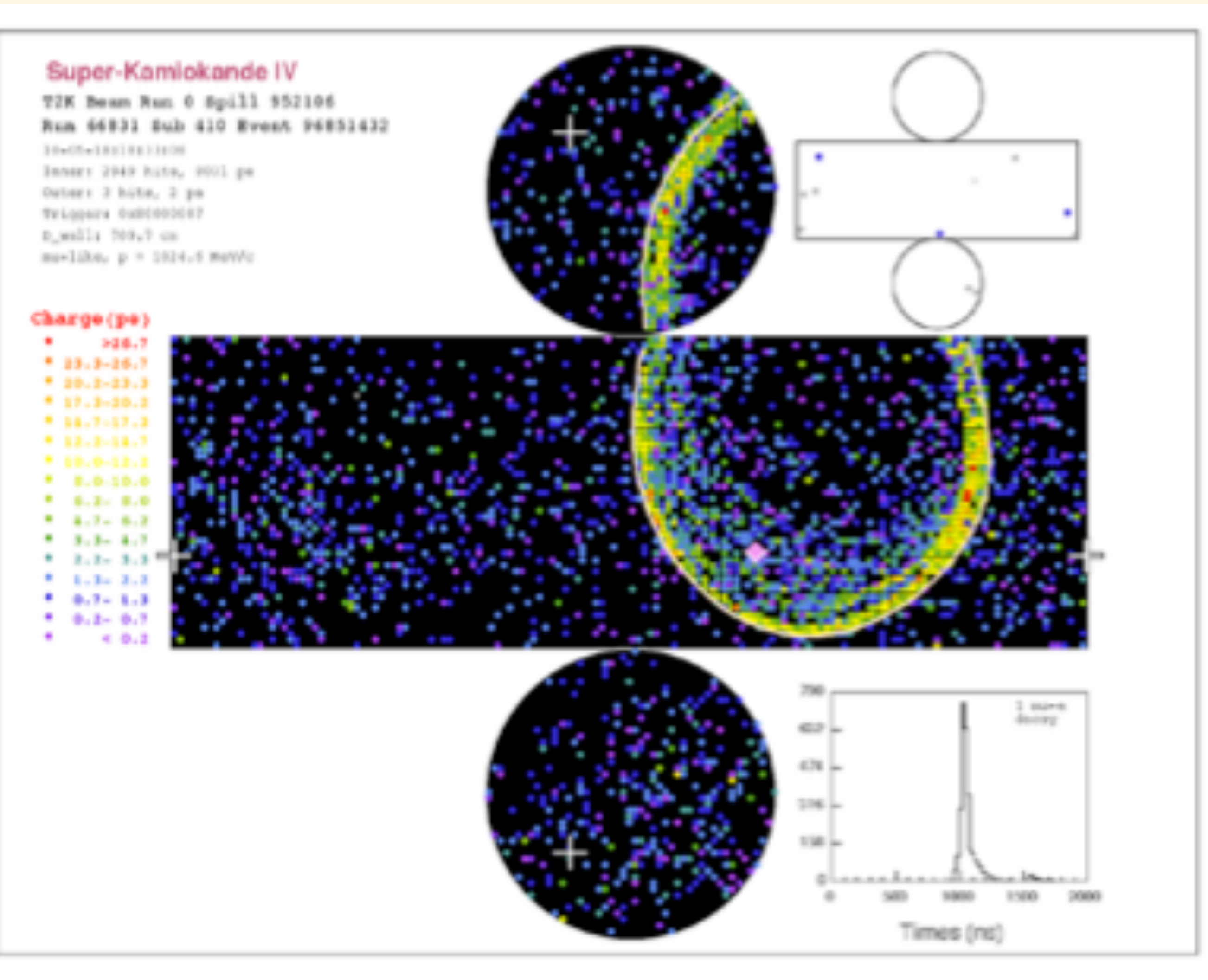
T2K First Events

T2K First Events

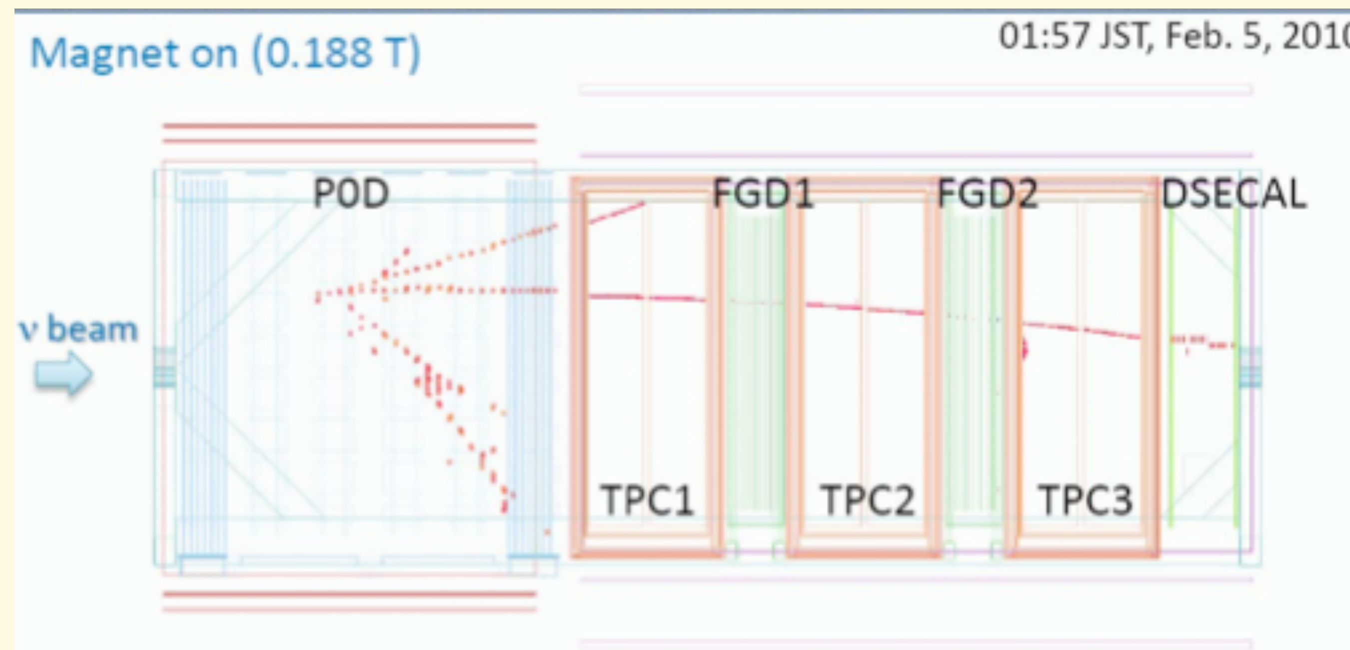


One of first events - ν_μ

T2K First Events



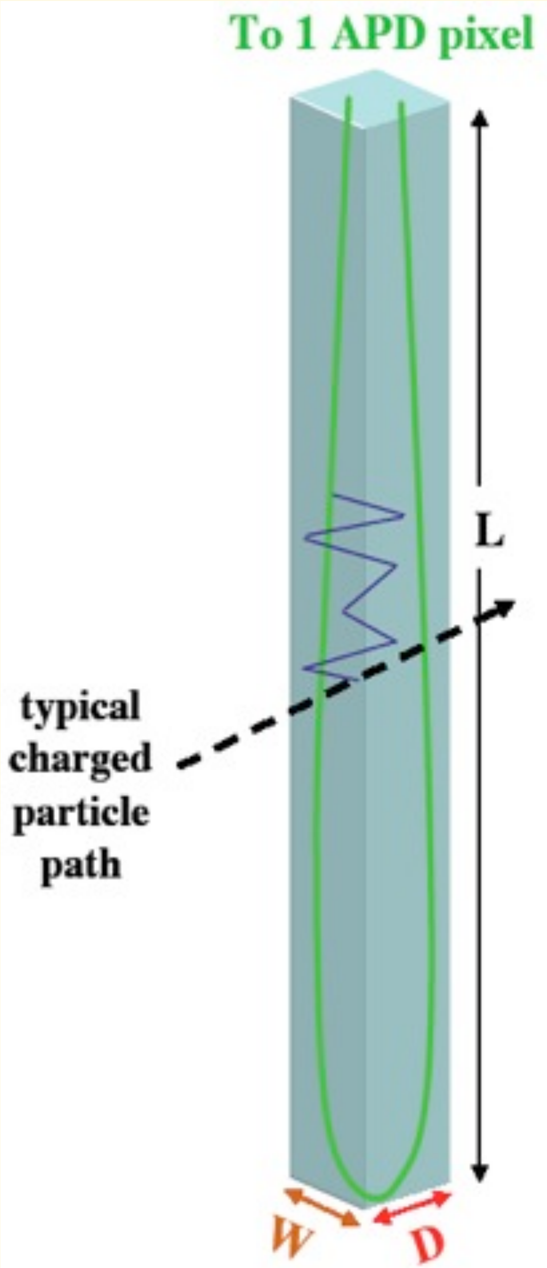
One of first events - ν_μ



Event in the fine grained Near Detector at 280m

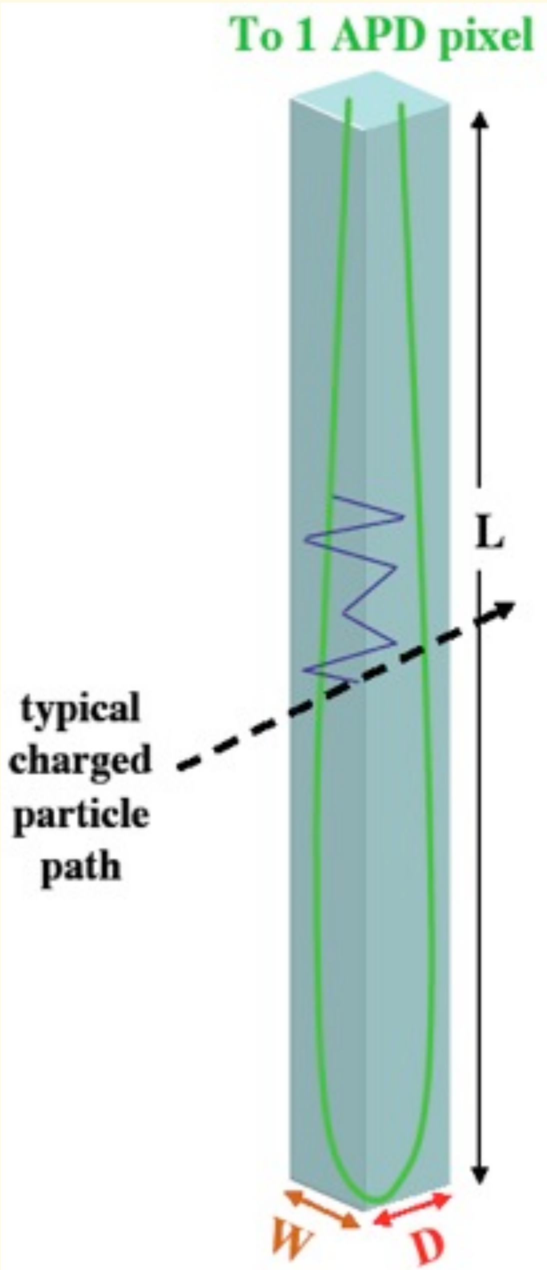
NOvA Detector

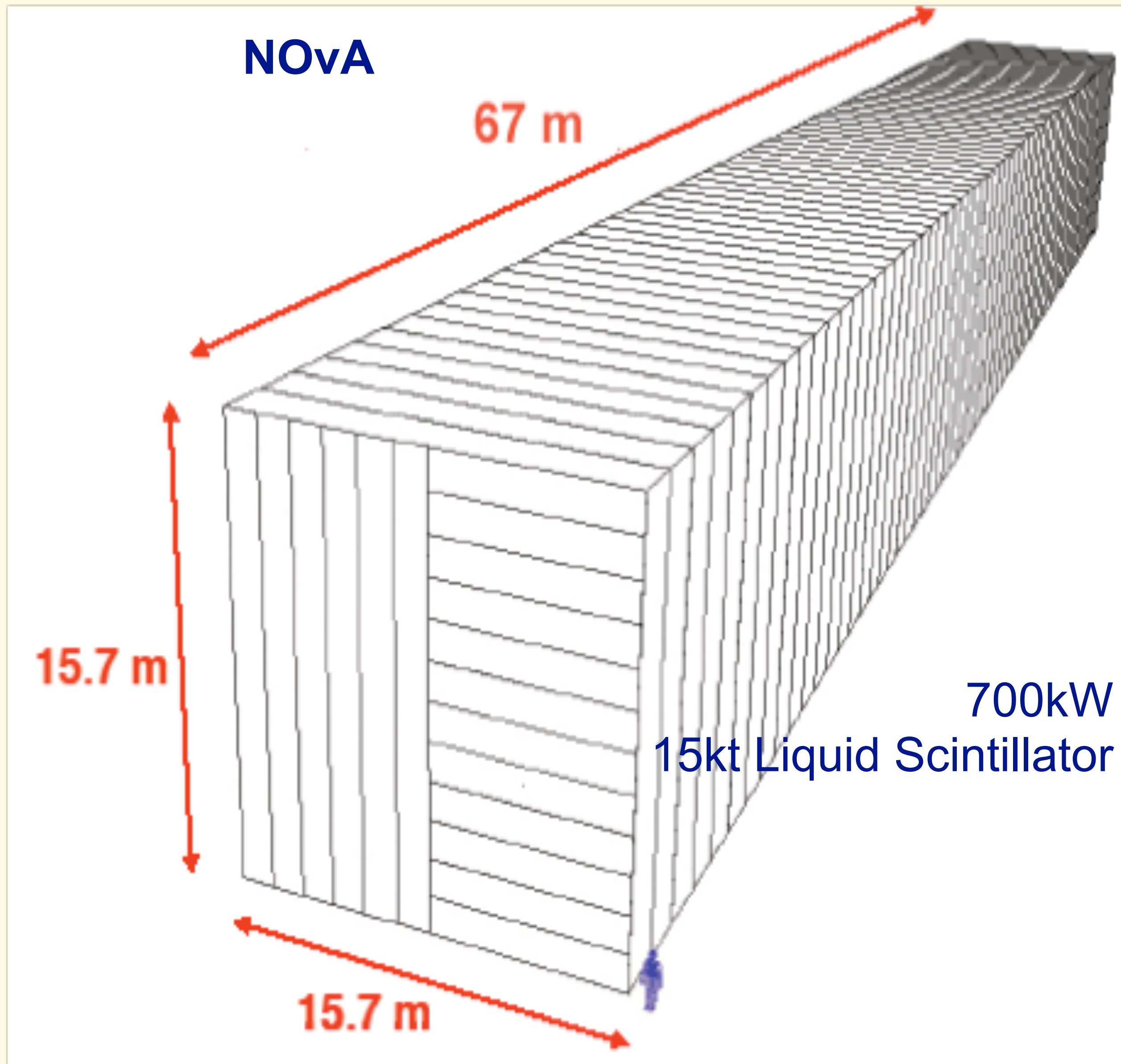
NOvA Detector



1 cell
L=15.7 m, W=4 cm, D=6 cm

NOvA Detector

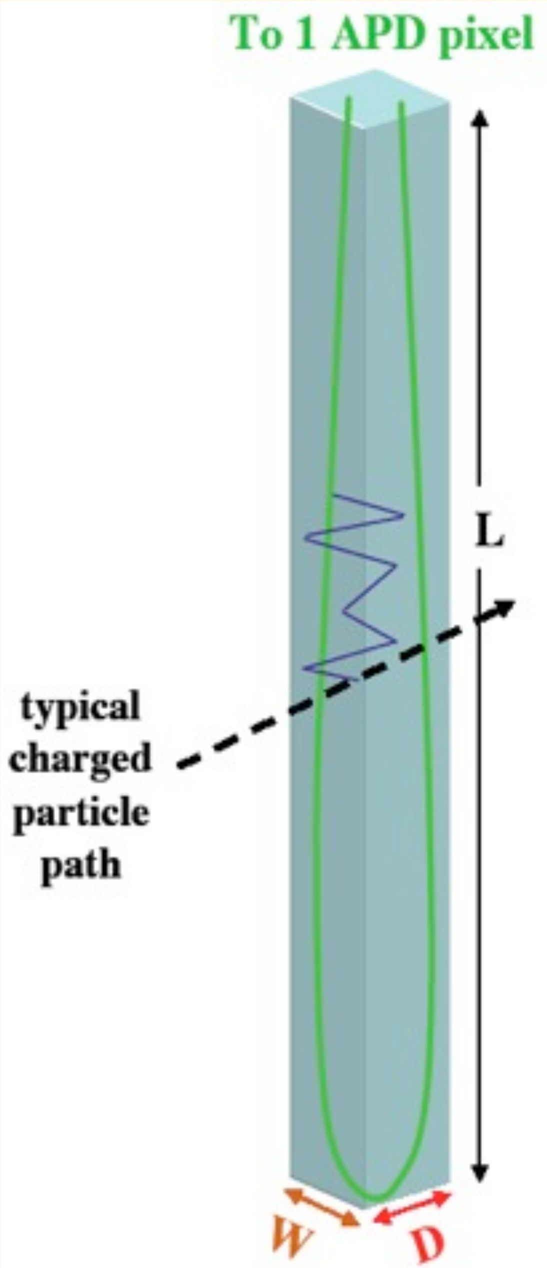


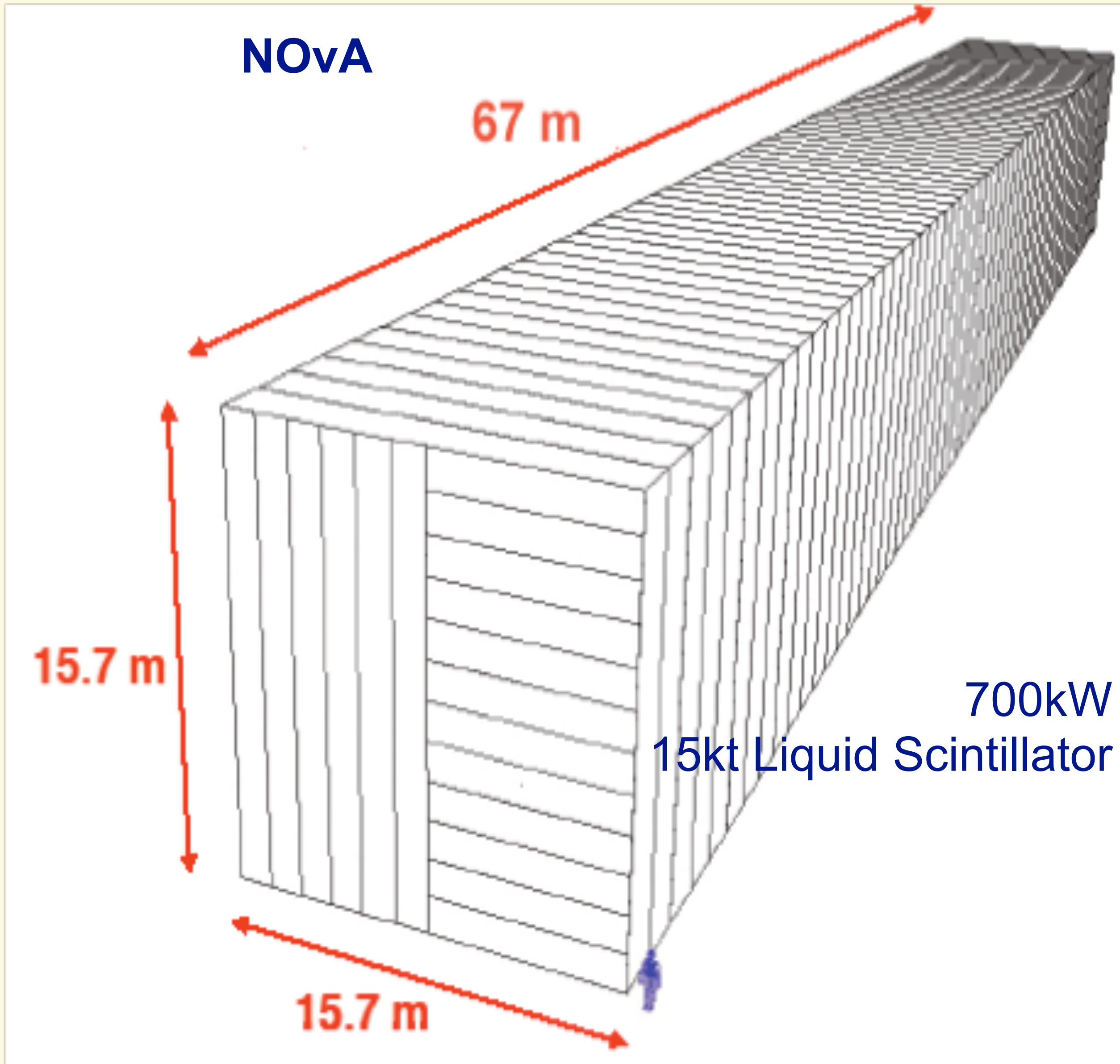


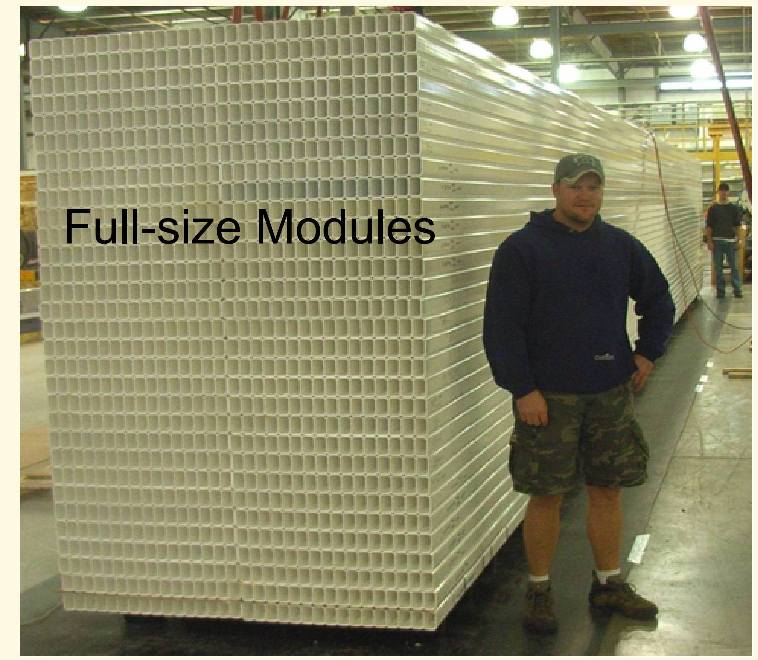
1 cell
L=15.7 m, W=4 cm, D=6 cm

1 module = 32 cells
12 modules make a plane
Vertical and horizontal planes alternate

NOvA Detector





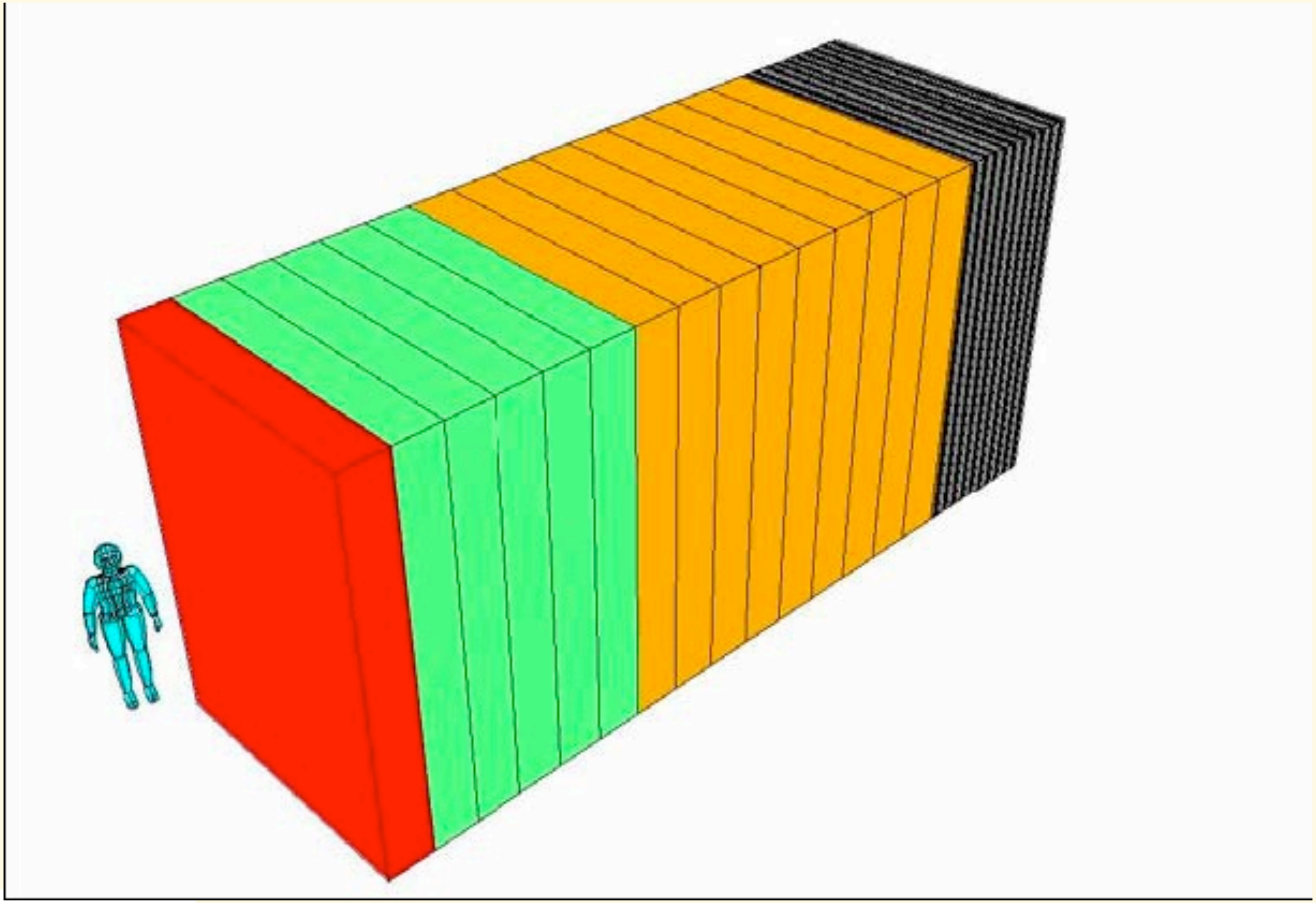


1 cell
L=15.7 m, W=4 cm, D=6 cm

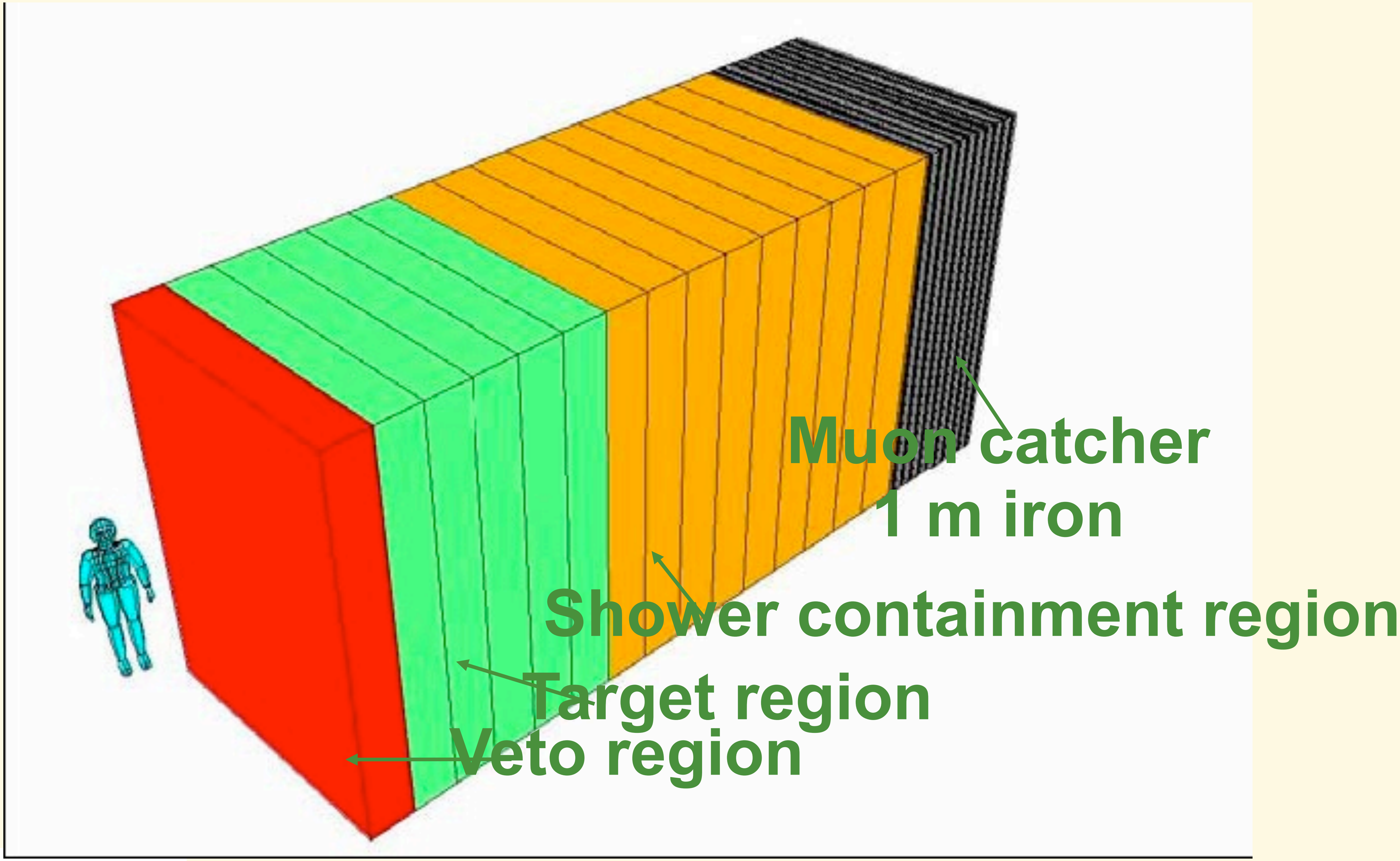
1 module = 32 cells
12 modules make a plane
Vertical and horizontal planes alternate

The Near Detector

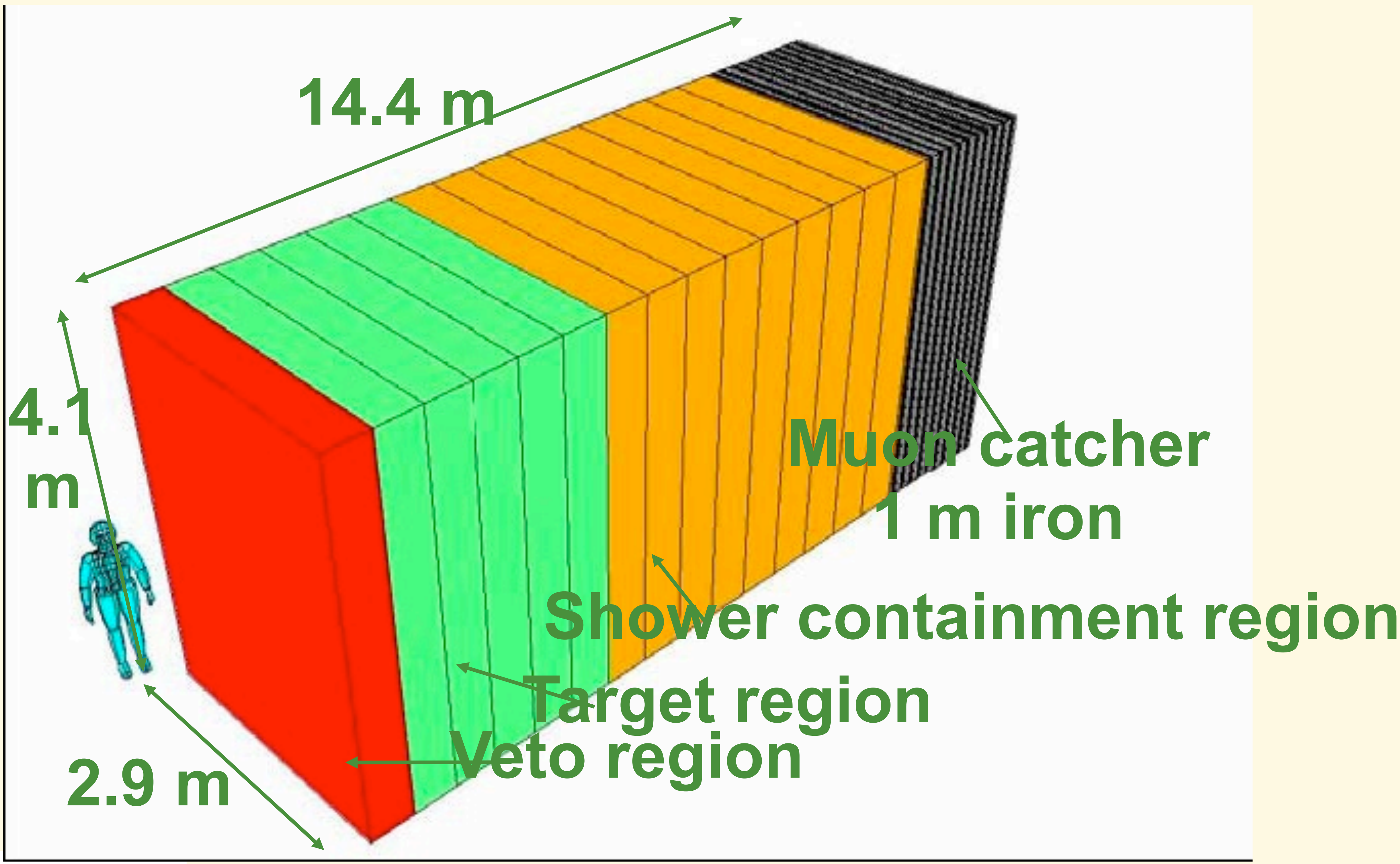
The Near Detector



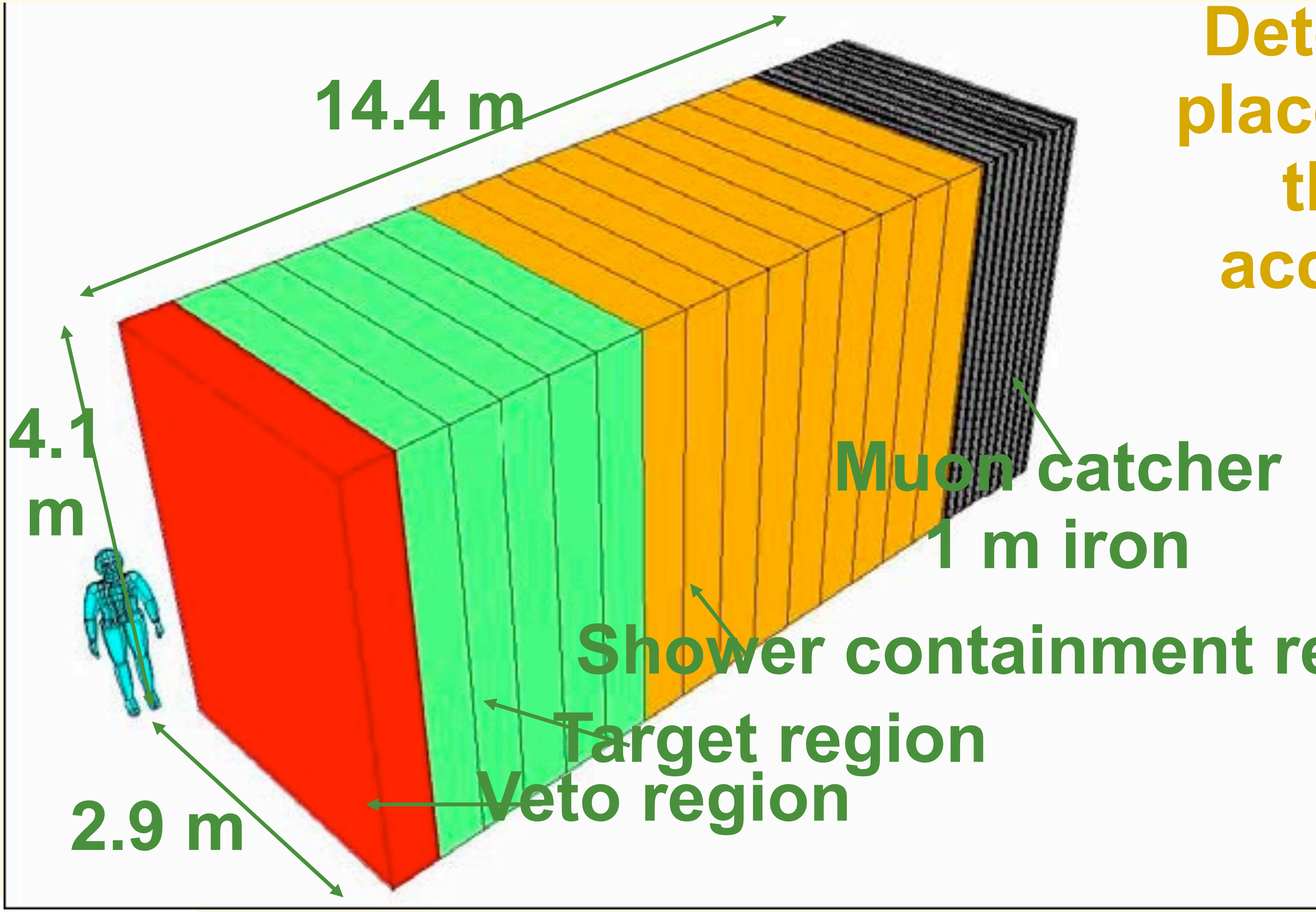
The Near Detector



The Near Detector



The Near Detector



The Near Detector will be placed off-axis in the MINOS access tunnel.

209 T
126 T totally active
23 T fiducial

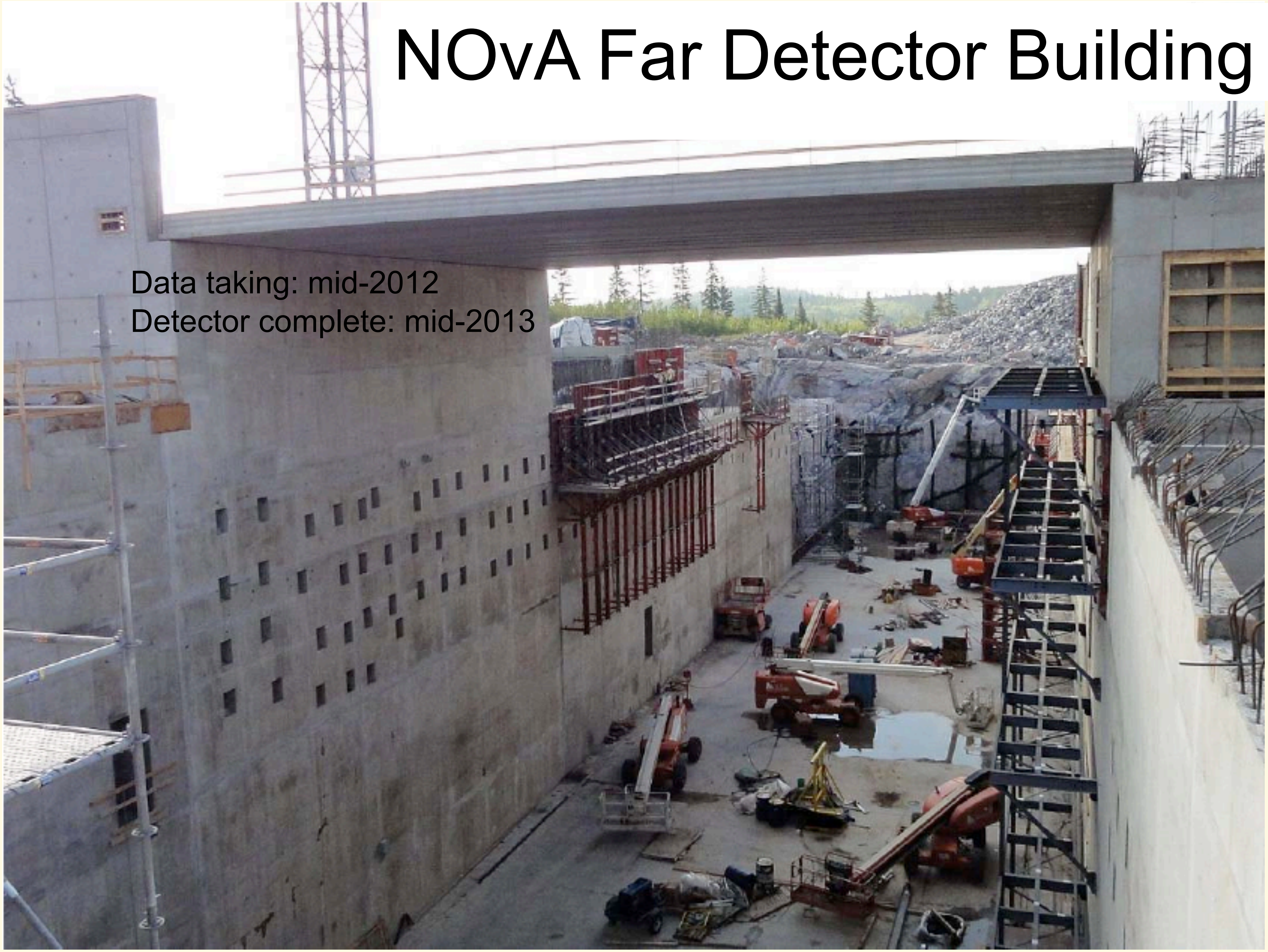
NOvA FD Status

NOvA FD Status

NOvA Far Detector Site - ~3 months ago

NOvA More Recently

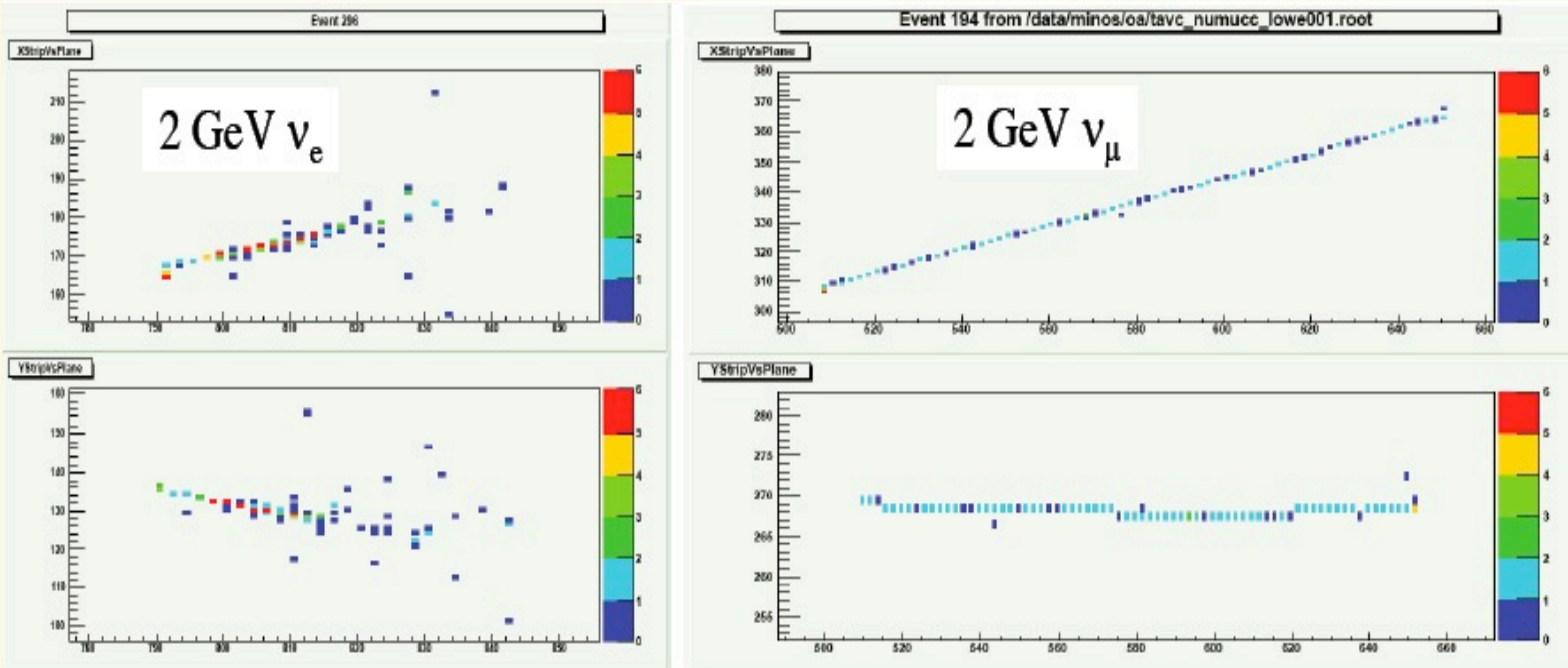
NOvA Far Detector Building



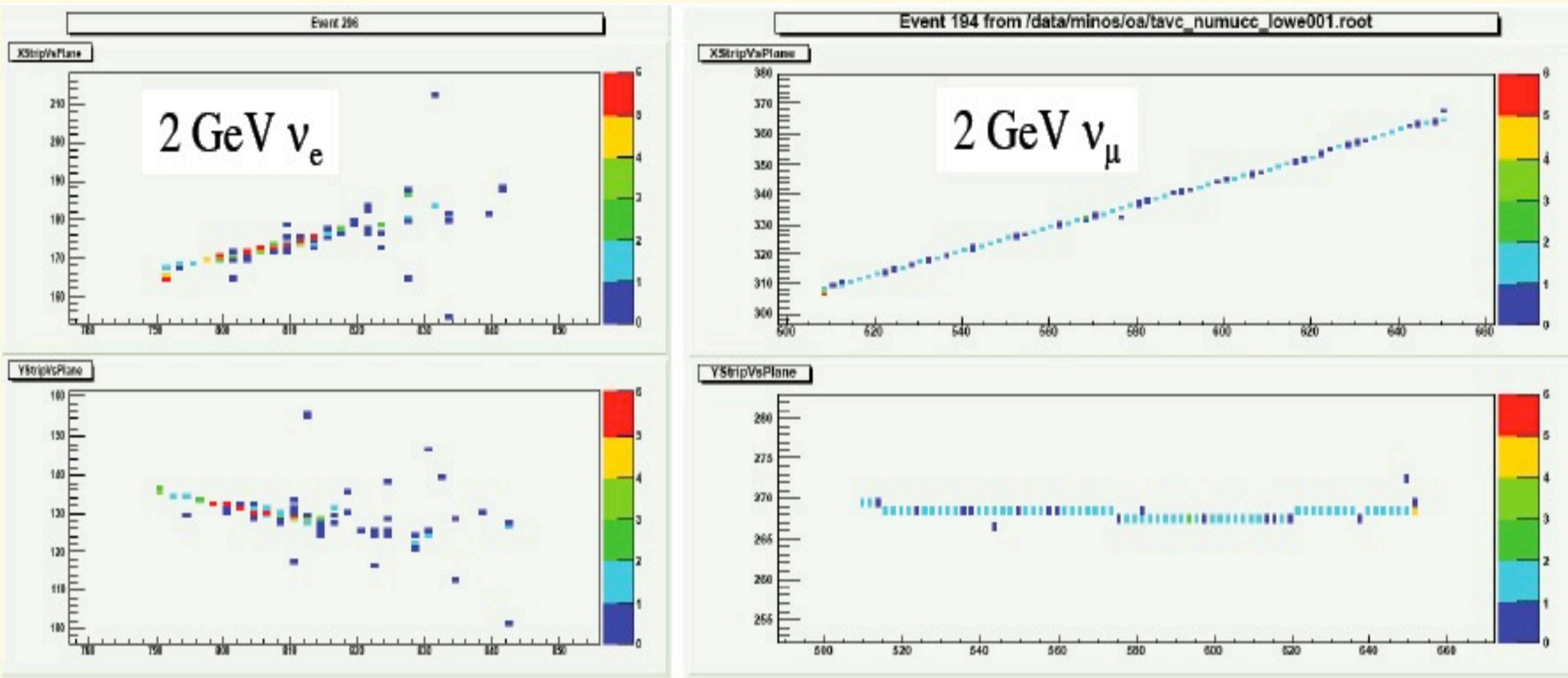
Data taking: mid-2012
Detector complete: mid-2013

NOvA Events (MC)

NOvA Events (MC)



NOvA Events (MC)



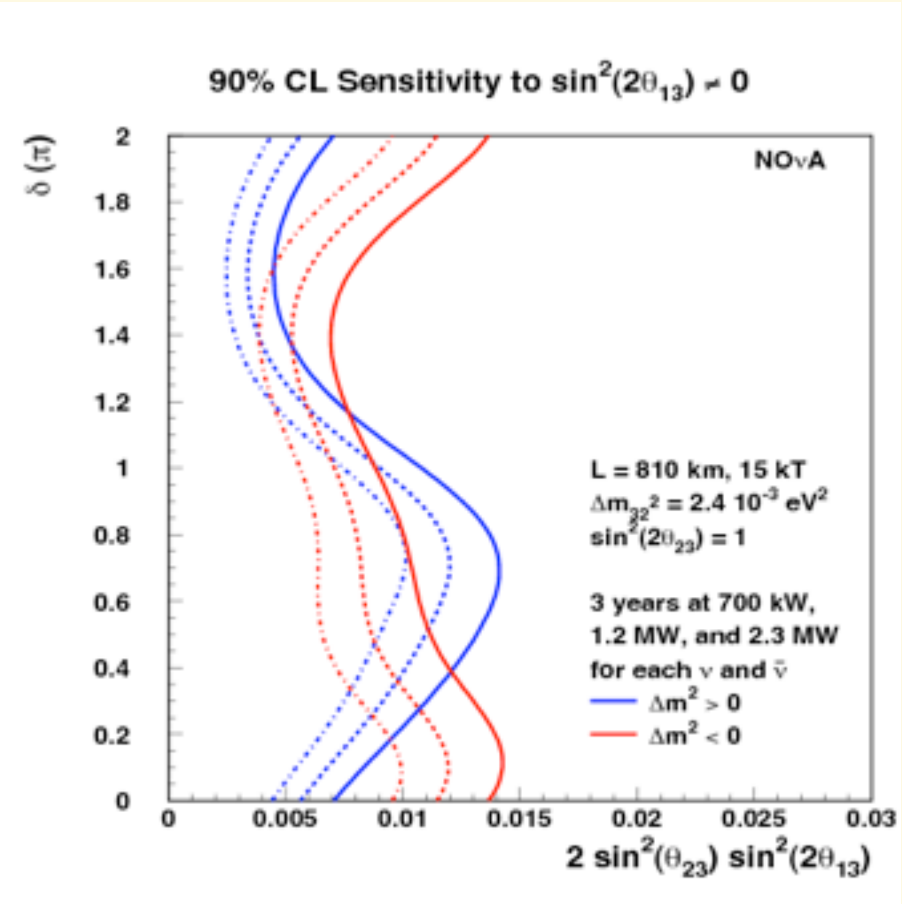
Longitudinal sampling is 0.2 X_0

A 2 GeV muon goes through 60 planes

Sensitivities

Sensitivities

NOvA: Assumes 3 years ν+ 3 years anti-ν, 10% systematic

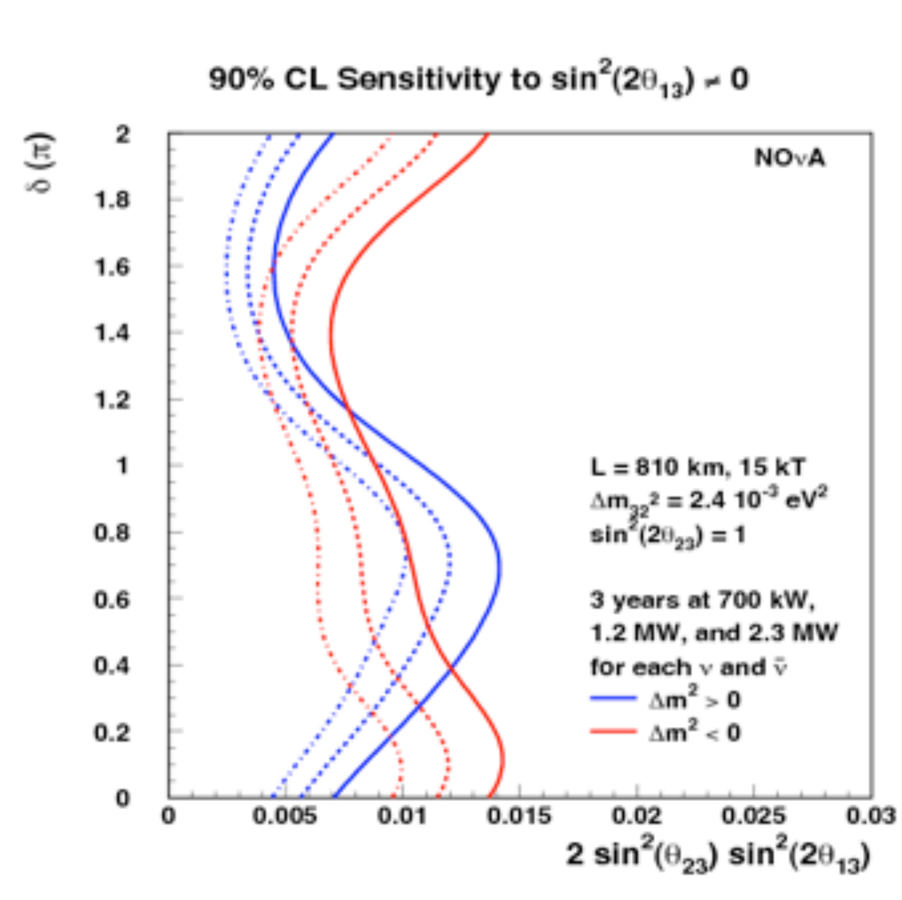


The long distance (810 km) gives it some sensitivity to mass hierarchy

Sensitivities

95% Resolution of Mass Ordering NOvA and T2K combined

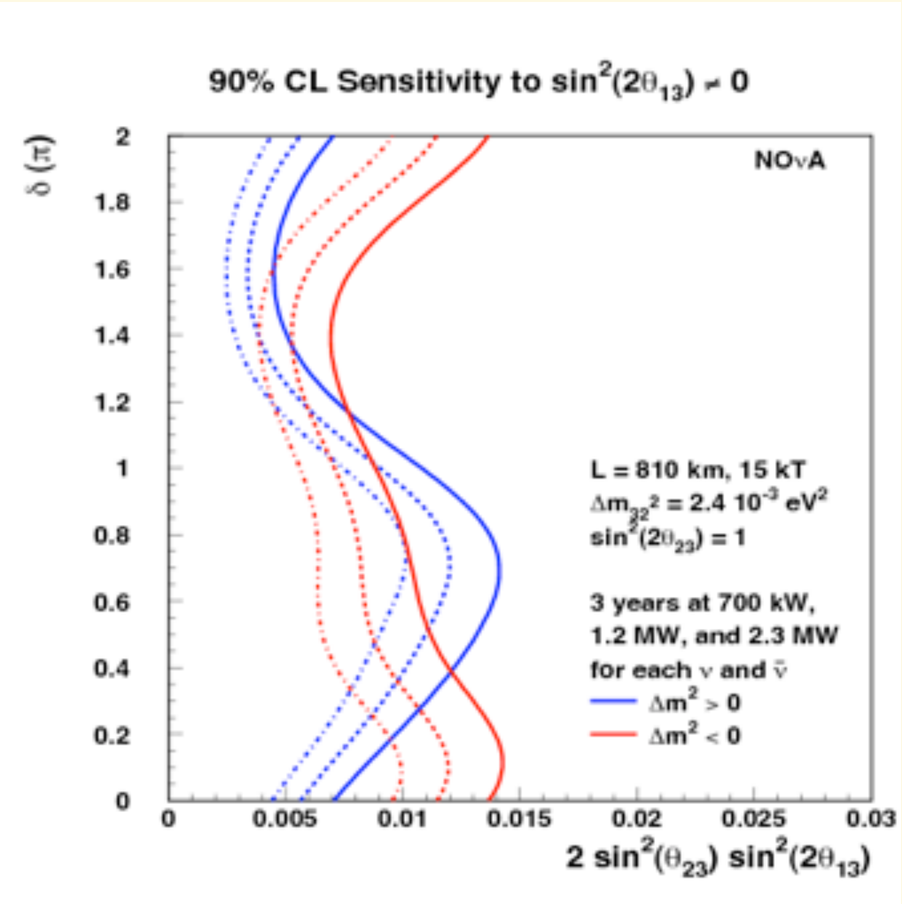
NOvA: Assumes 3 years ν+ 3 years anti-ν, 10% systematic

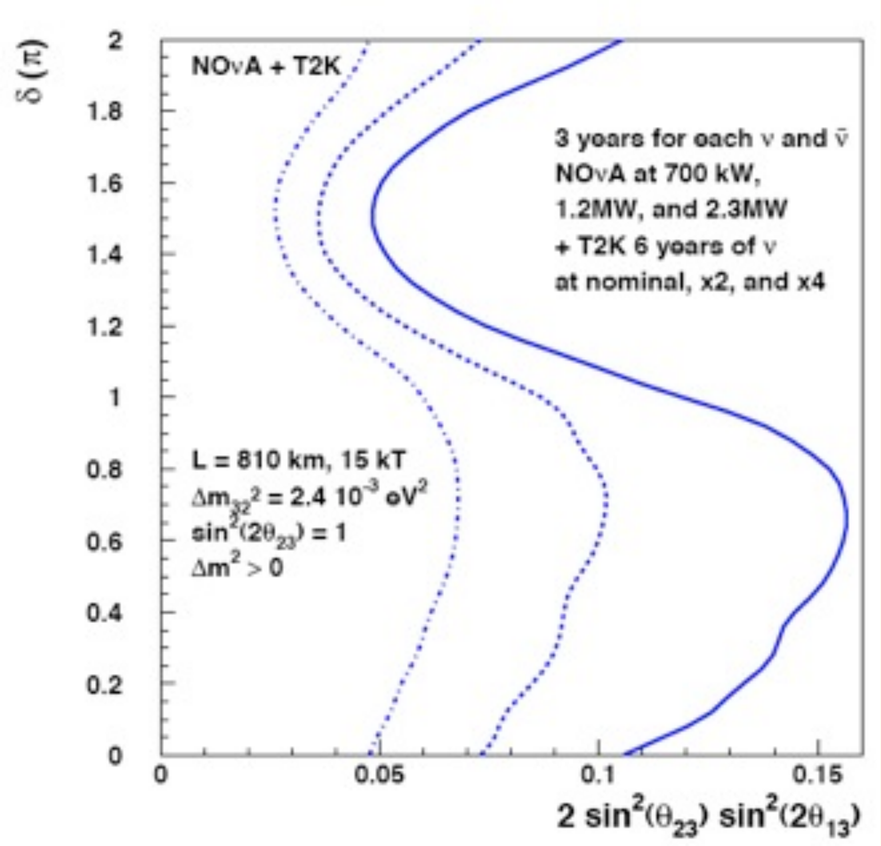


The long distance (810 km) gives it some sensitivity to mass hierarchy

95% Resolution of Mass Ordering NOvA and T2K combined

NOvA: Assumes 3 years ν+ 3 years anti-ν, 10% systematic





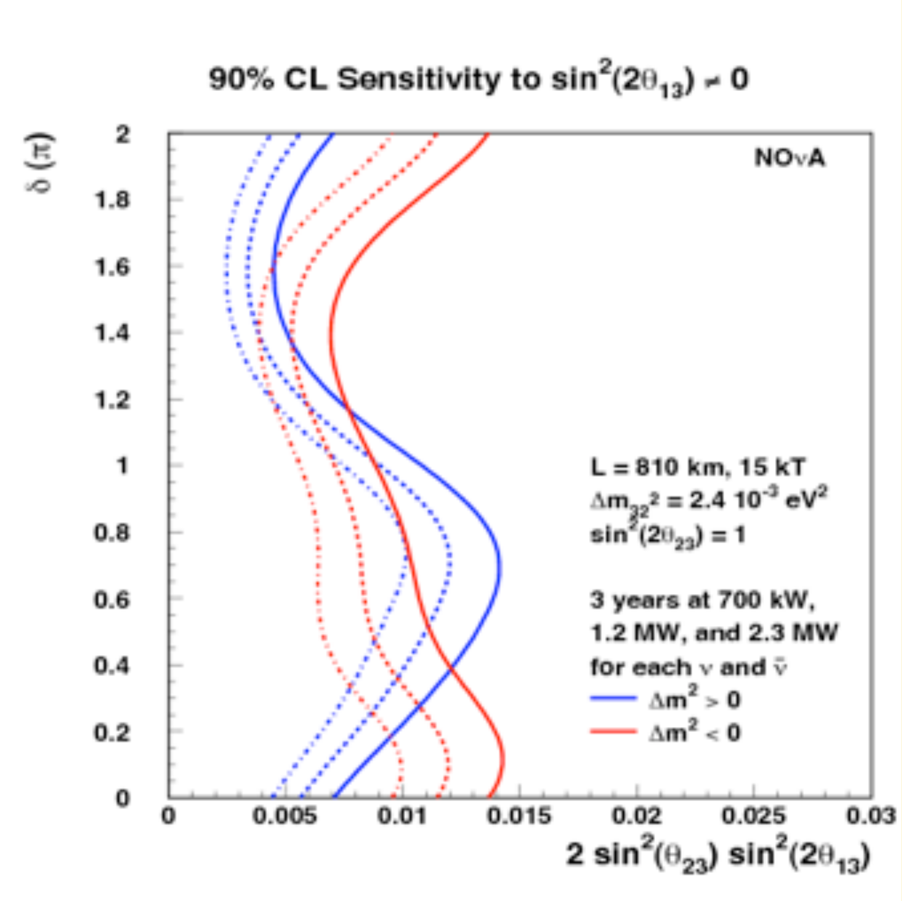
The long distance (810 km) gives it some sensitivity to mass hierarchy

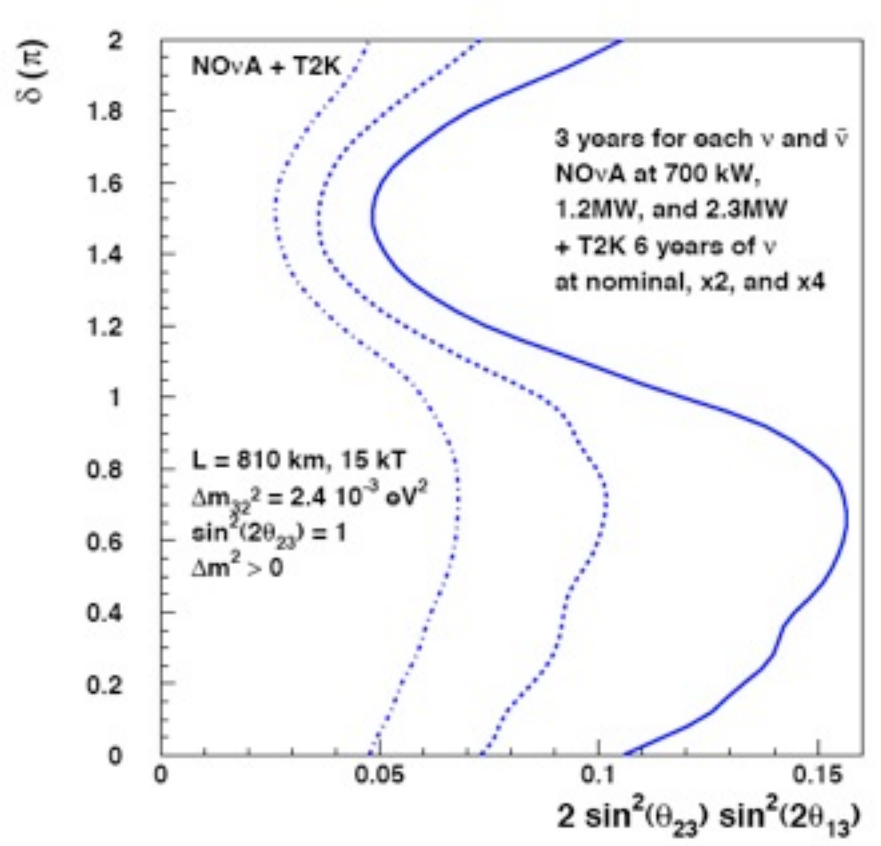
Normal Hierarchy

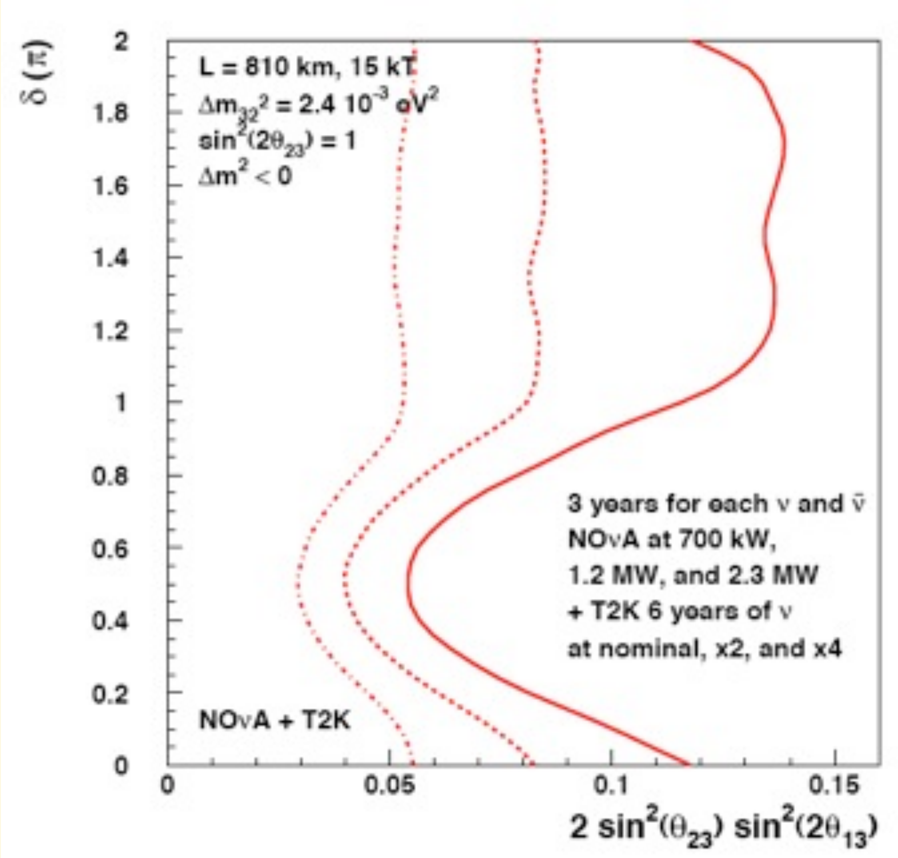
Sensitivities

NOvA: Assumes 3 years ν+ 3 years anti-ν, 10% systematic

95% Resolution of Mass Ordering NOvA and T2K combined







The long distance (810 km) gives it some sensitivity to mass hierarchy

Normal Hierarchy

Inverted hierarchy

Further Future

Further Future

- Next US step?

Further Future

- Next US step?
  - Upgrade off the accelerator complex (Project X?)

Further Future

- Next US step?
  - Upgrade off the accelerator complex (Project X?)
  - New underground laboratory (DUSEL)

Further Future

- Next US step?
  - Upgrade off the accelerator complex (Project X?)
  - New underground laboratory (DUSEL)
  - New neutrino beam

Further Future

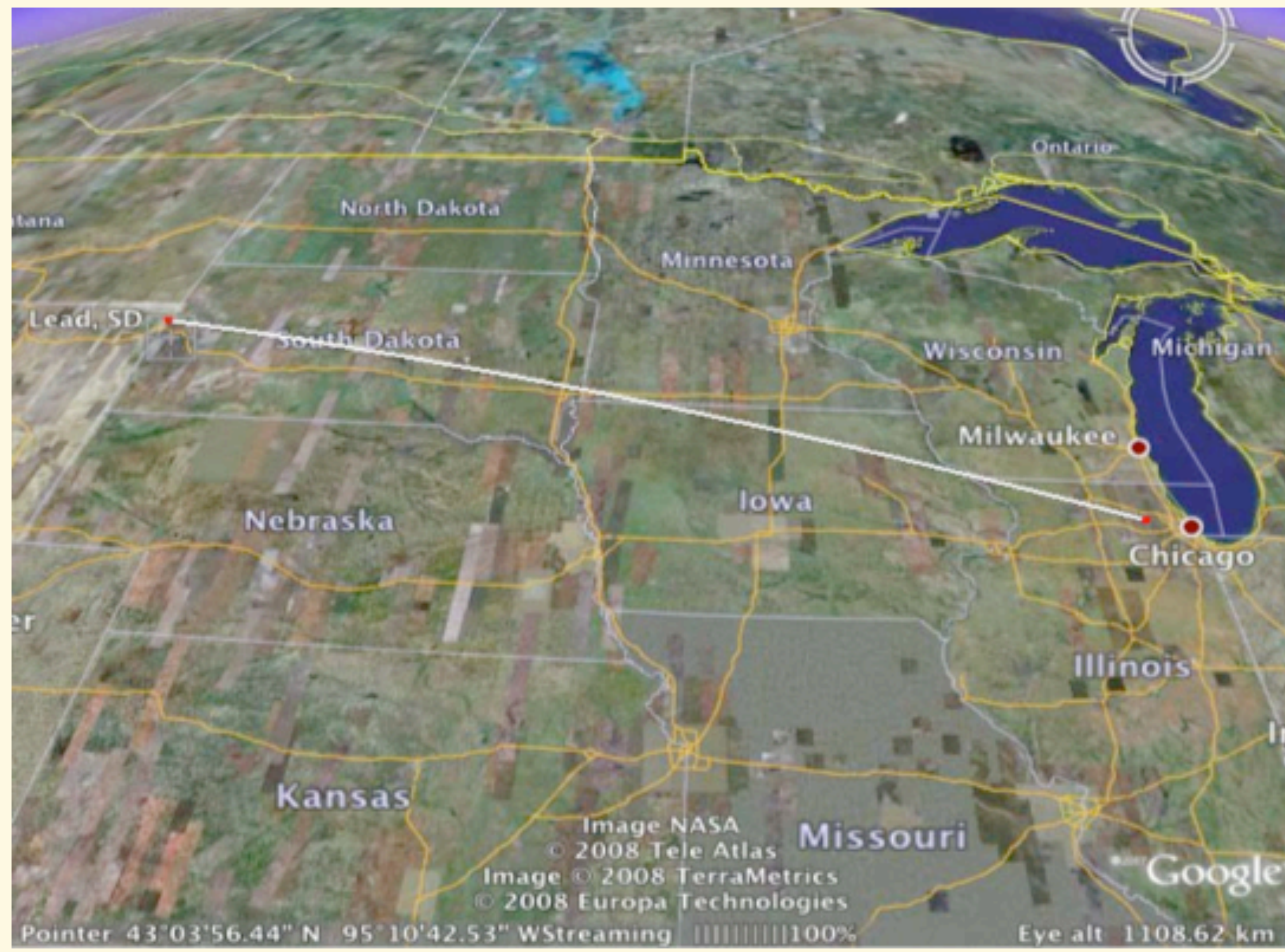
- Next US step?
  - Upgrade off the accelerator complex (Project X?)
  - New underground laboratory (DUSEL)
  - New neutrino beam
  - New detector(s)

Further Future

- Next US step?
  - Upgrade off the accelerator complex (Project X?)
  - New underground laboratory (DUSEL)
  - New neutrino beam
  - New detector(s)
- Emphasis on longer baseline

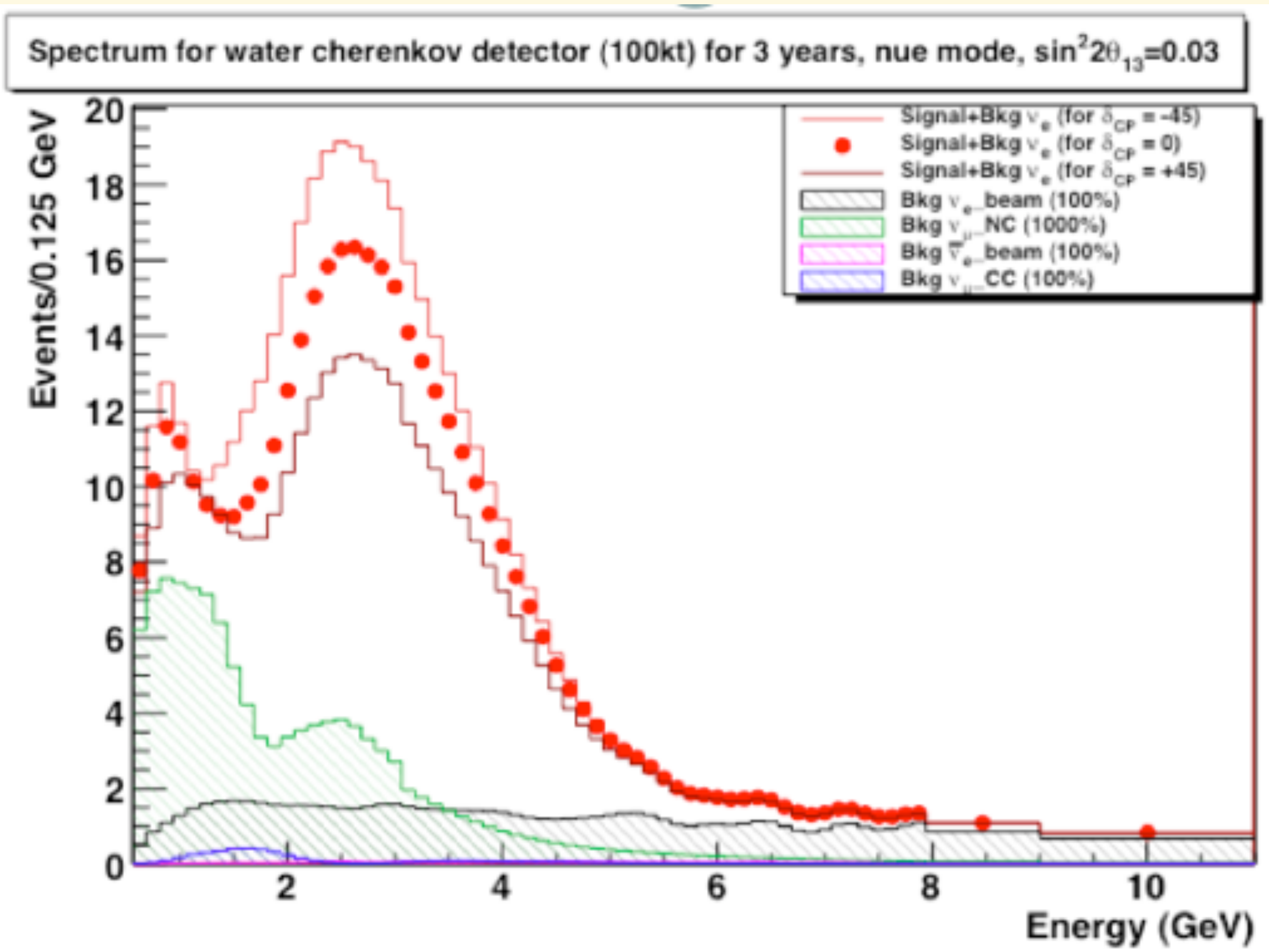
Further Future

- Next US step?
  - Upgrade off the accelerator complex (Project X?)
  - New underground laboratory (DUSEL)
  - New neutrino beam
  - New detector(s)
- Emphasis on longer baseline

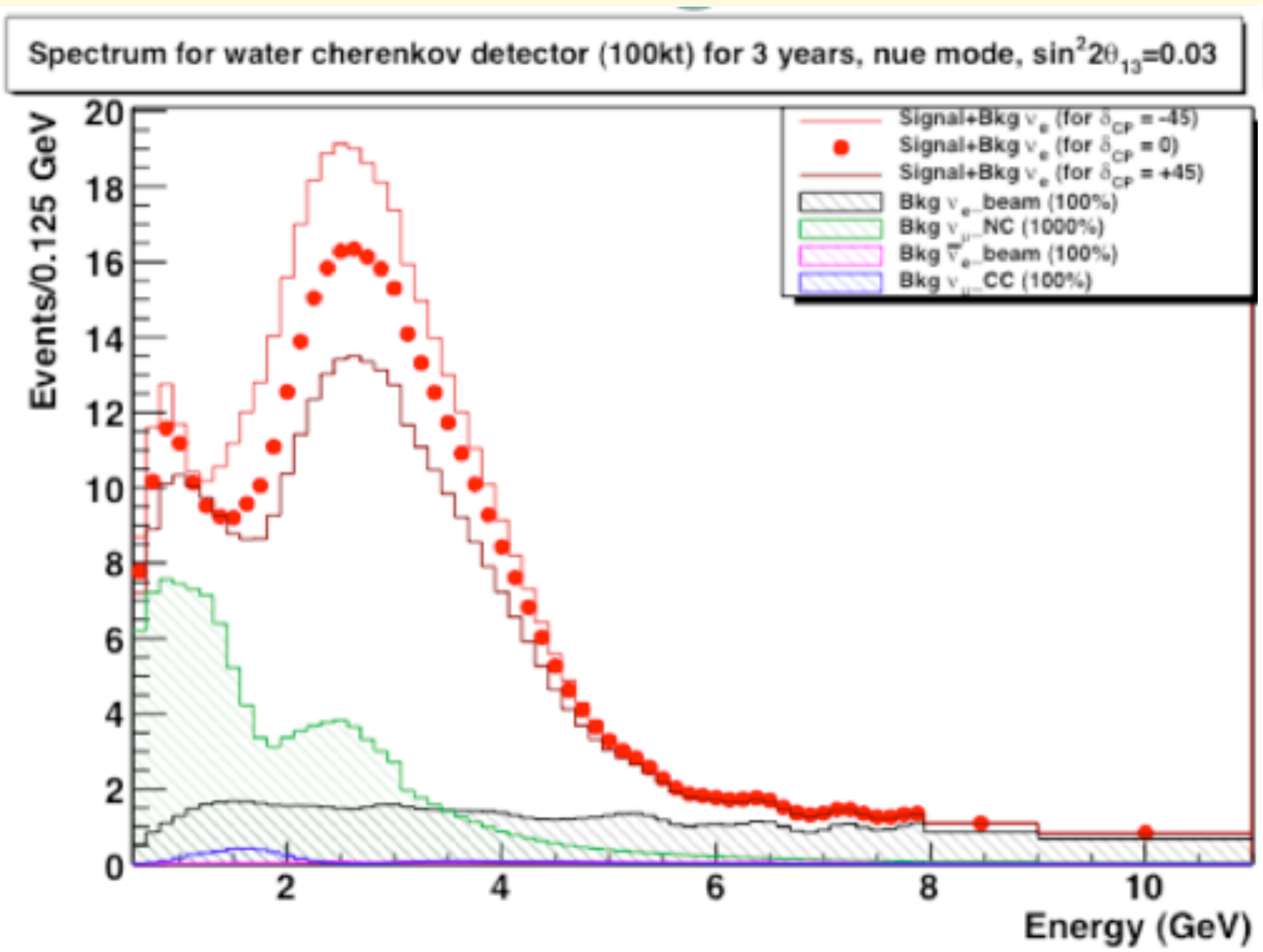


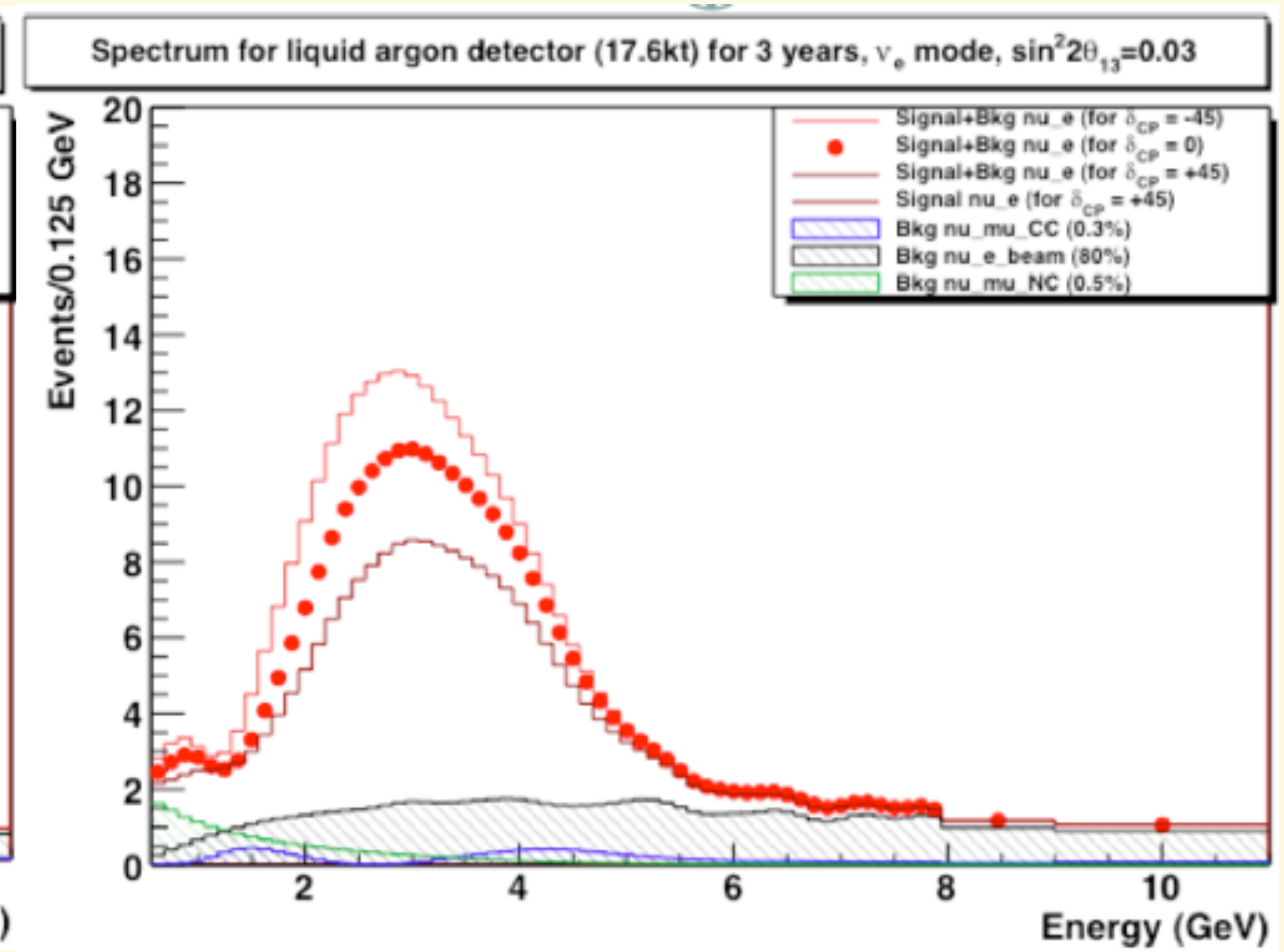
Water or Argon?

Water or Argon?

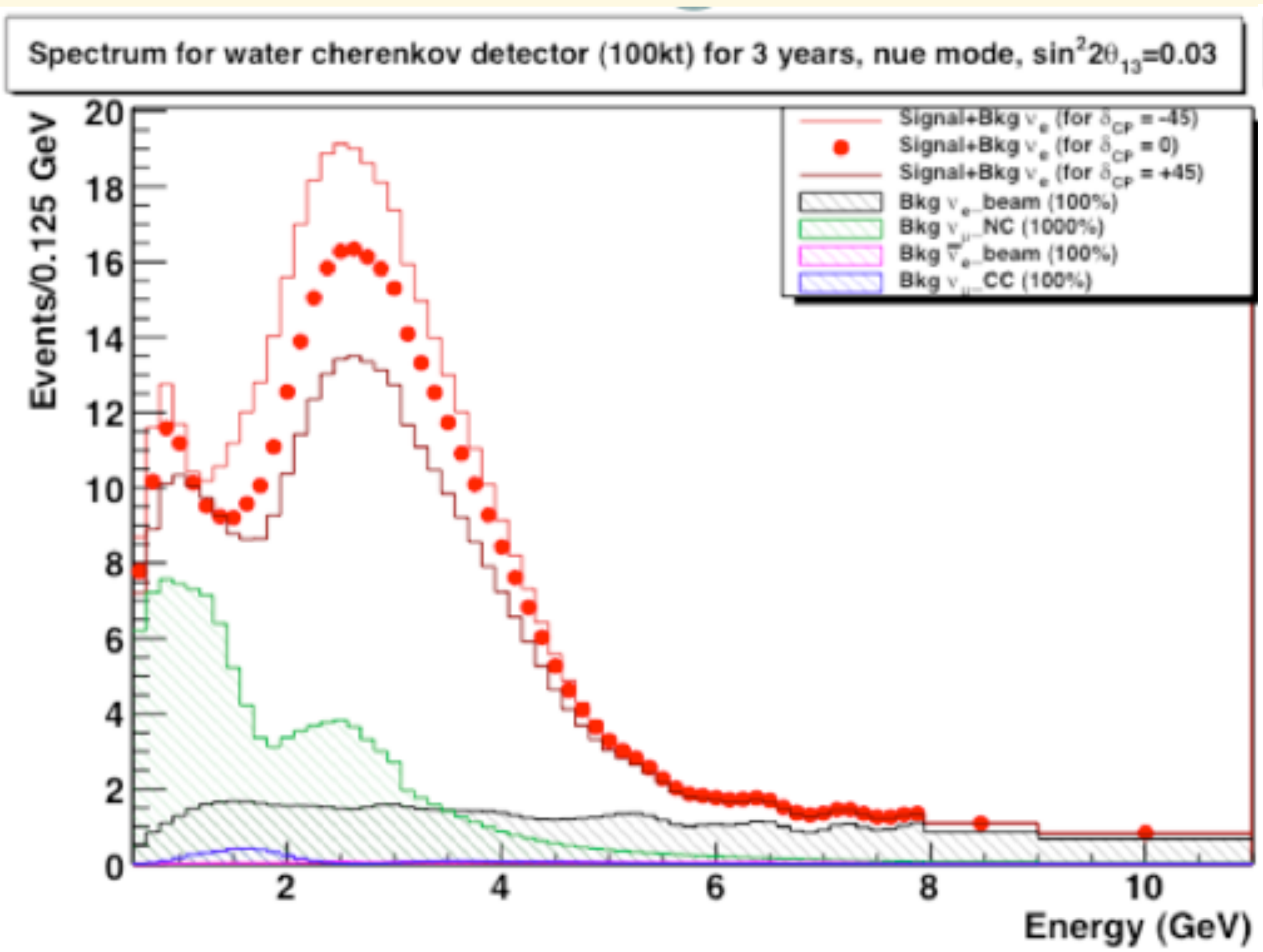


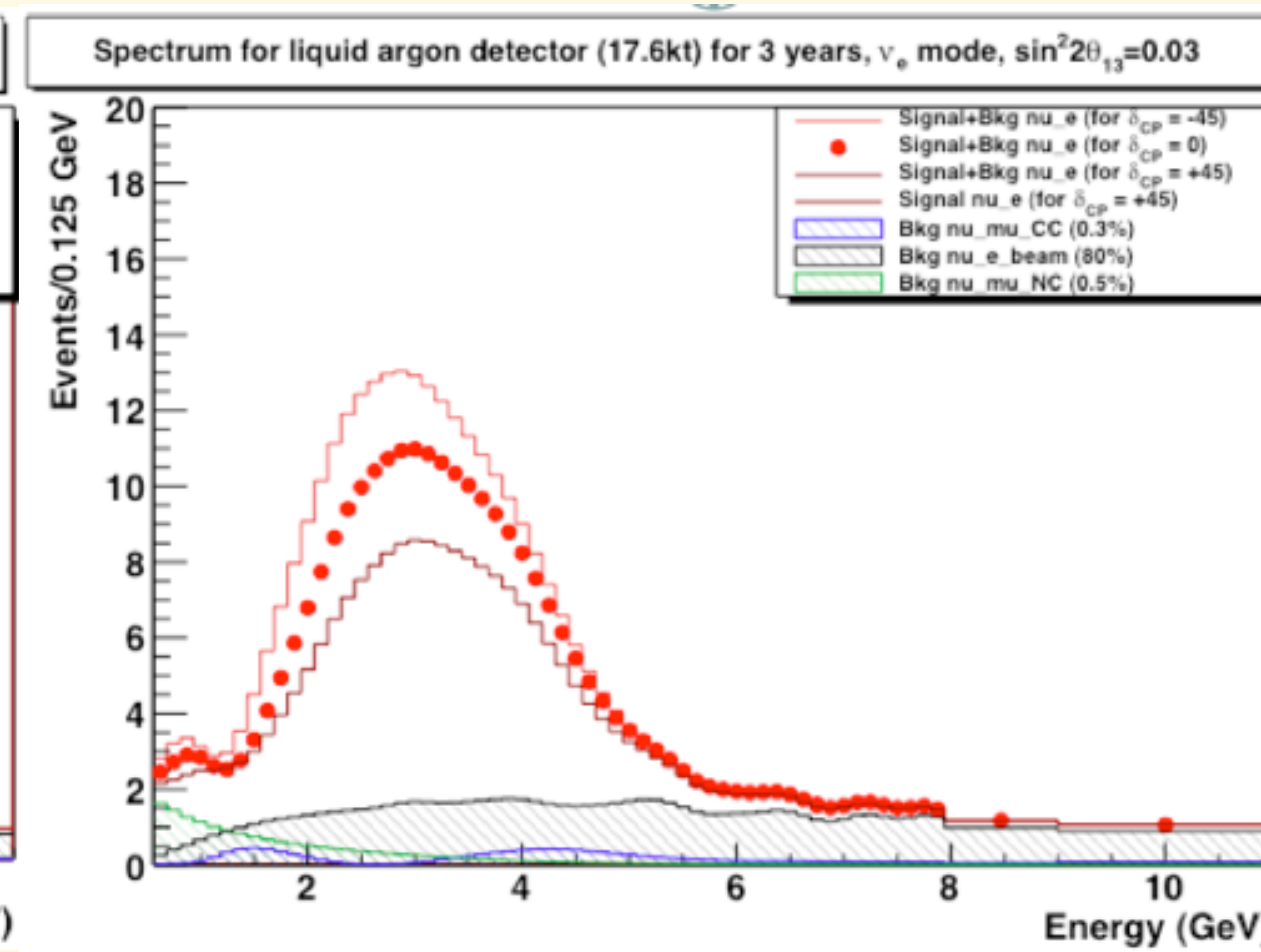
Water or Argon?





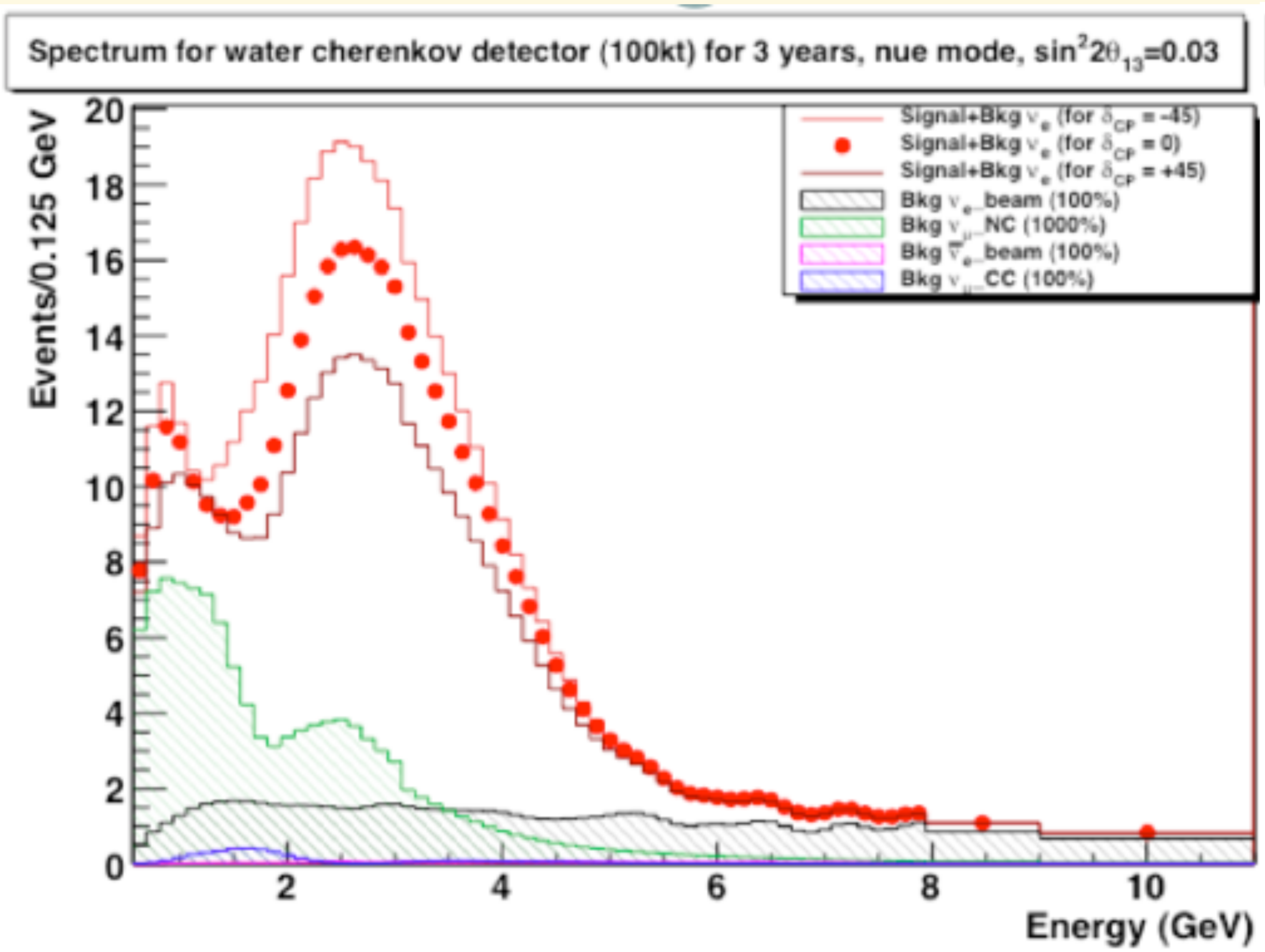
Water or Argon?

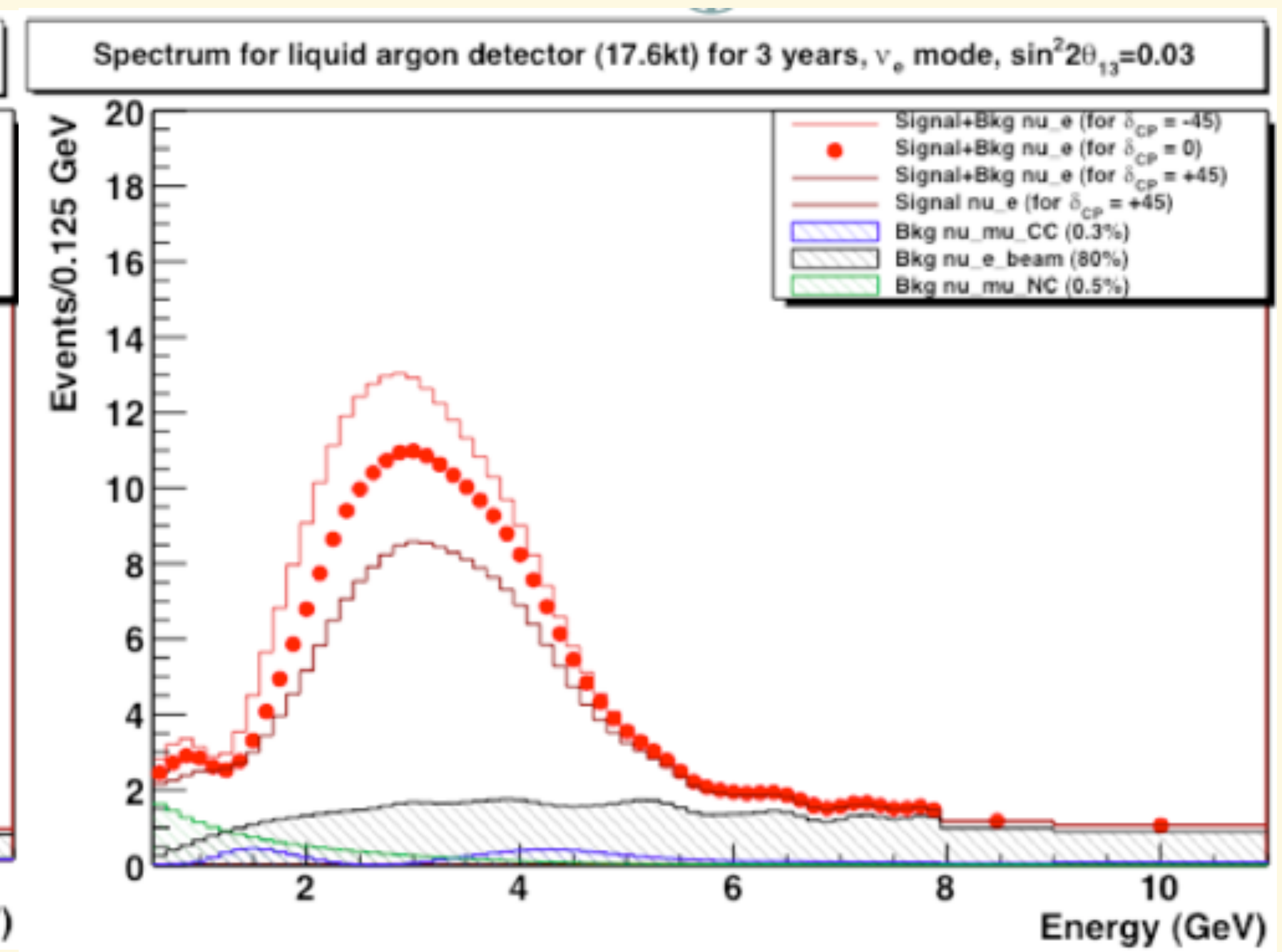




Argon detection efficiency about 5-6 times higher because of much better background rejection

Water or Argon?





Argon detection efficiency about 5-6 times higher because of much better background rejection

A variety of issues need to be considered before an informed decision can be made

Neutrino Cross Sections

Why Cross Sections?

Why Cross Sections?

- Study of neutrino cross sections is important for its own (physics) sake but also for interpretation of other experiments

Why Cross Sections?

- Study of neutrino cross sections is important for its own (physics) sake but also for interpretation of other experiments
- Physics arguments
  - Verification of Standard Model
  - Determination of structure functions
  - Determination of fundamental parameters
  - Study of intra-nuclear interactions

Why Cross Sections?

- Study of neutrino cross sections is important for its own (physics) sake but also for interpretation of other experiments
- Physics arguments
  - Verification of Standard Model
  - Determination of structure functions
  - Determination of fundamental parameters
  - Study of intra-nuclear interactions
- Interpretation of other experiments
  - Understanding of backgrounds
  - Determination of neutrino flux

Ingredients

Ingredients

No signal events α x-section x flux x target mass

No signal events = $(N_{obs}-N_{bknd})$/efficiency

Ingredients

No signal events α x-section x flux x target mass

No signal events = $(N_{obs}-N_{bknd})$/efficiency

Flux measurement of a neutrino beam is hard

Here are some possibilities:

Ingredients

No signal events α x-section *x* flux *x* target mass

No signal events = $(N_{obs} - N_{bknd})$/efficiency

Flux measurement of a neutrino beam is hard
Here are some possibilities:

1) Measure hadronic production; count protons on target
2) Normalize to a known neutrino cross section
3) Measure flux of muons (or hadrons in decay pipe)

Ingredients

No signal events α x-section *x* flux *x* target mass

No signal events = $(N_{obs} - N_{bknd})$/efficiency

Flux measurement of a neutrino beam is hard
Here are some possibilities:

1) Measure hadronic production; count protons on target
2) Normalize to a known neutrino cross section
3) Measure flux of muons (or hadrons in decay pipe)

None of these is easy; they all present some difficulties

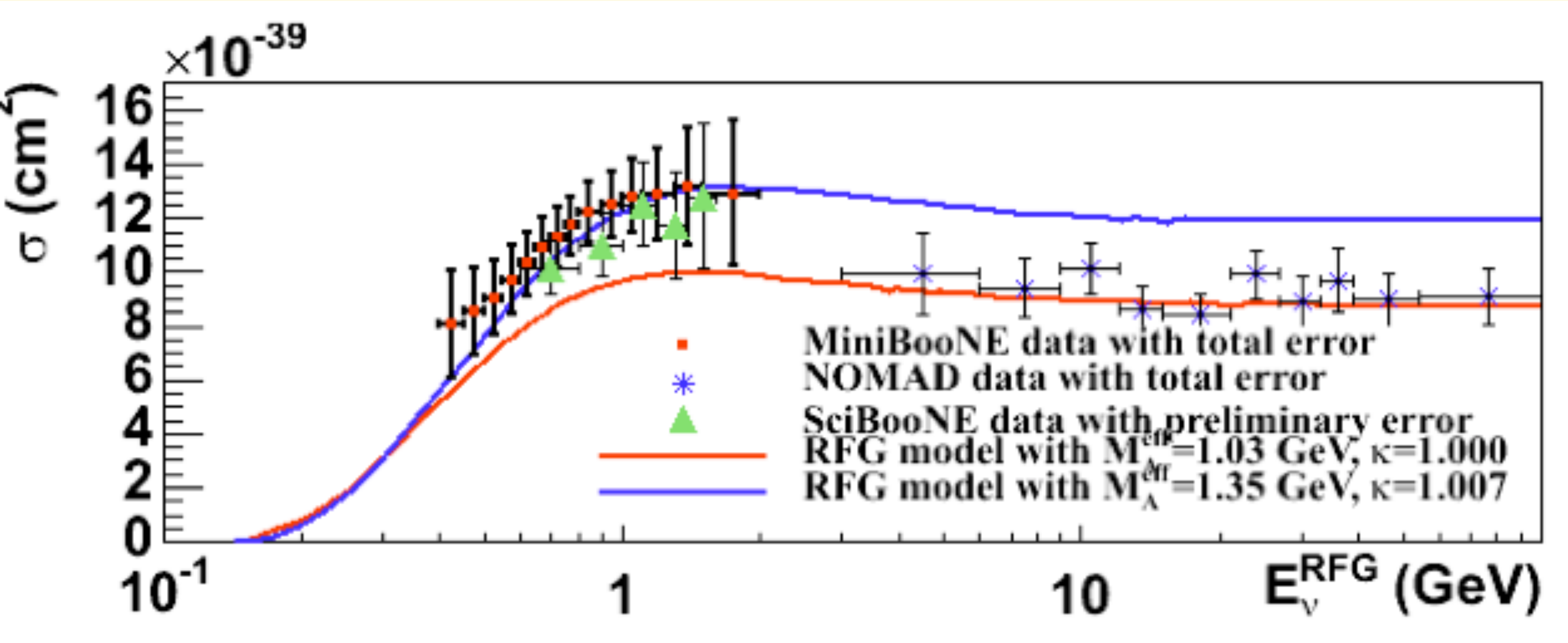
Two Examples

Two Examples

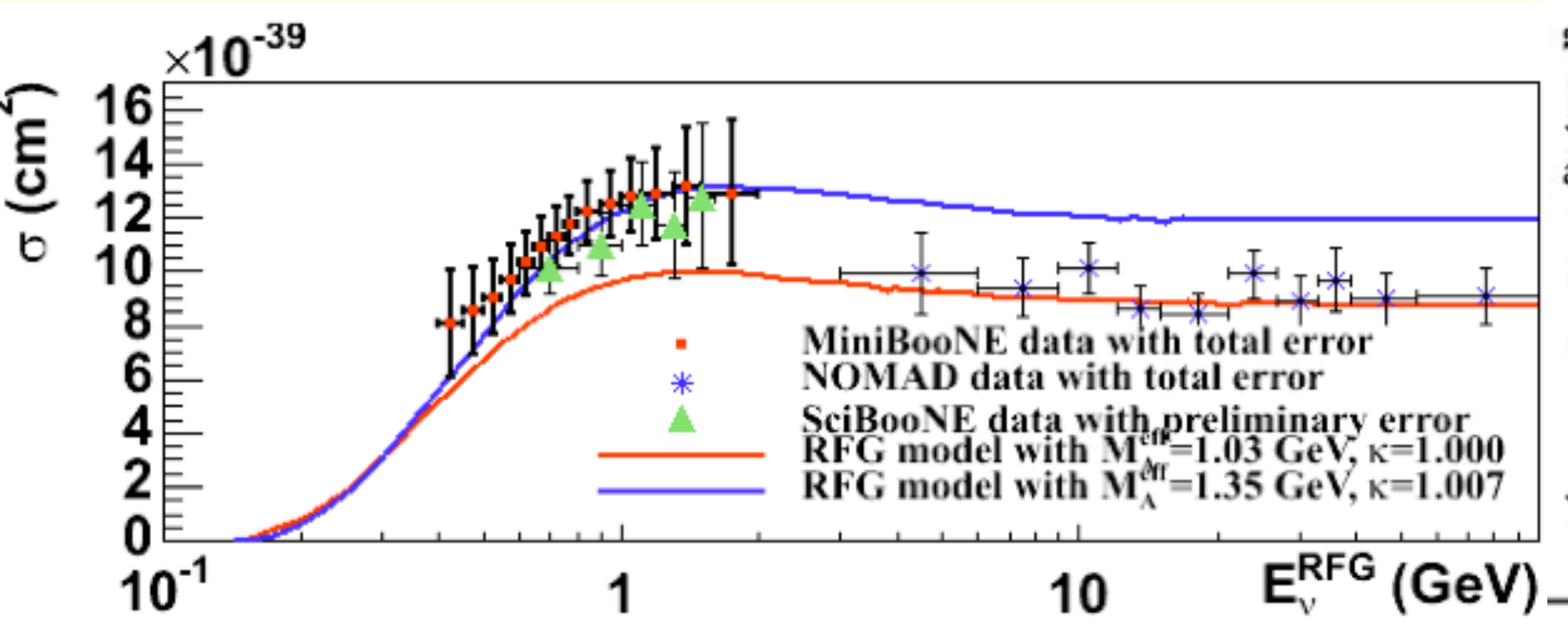
Examples of possible normalization problems

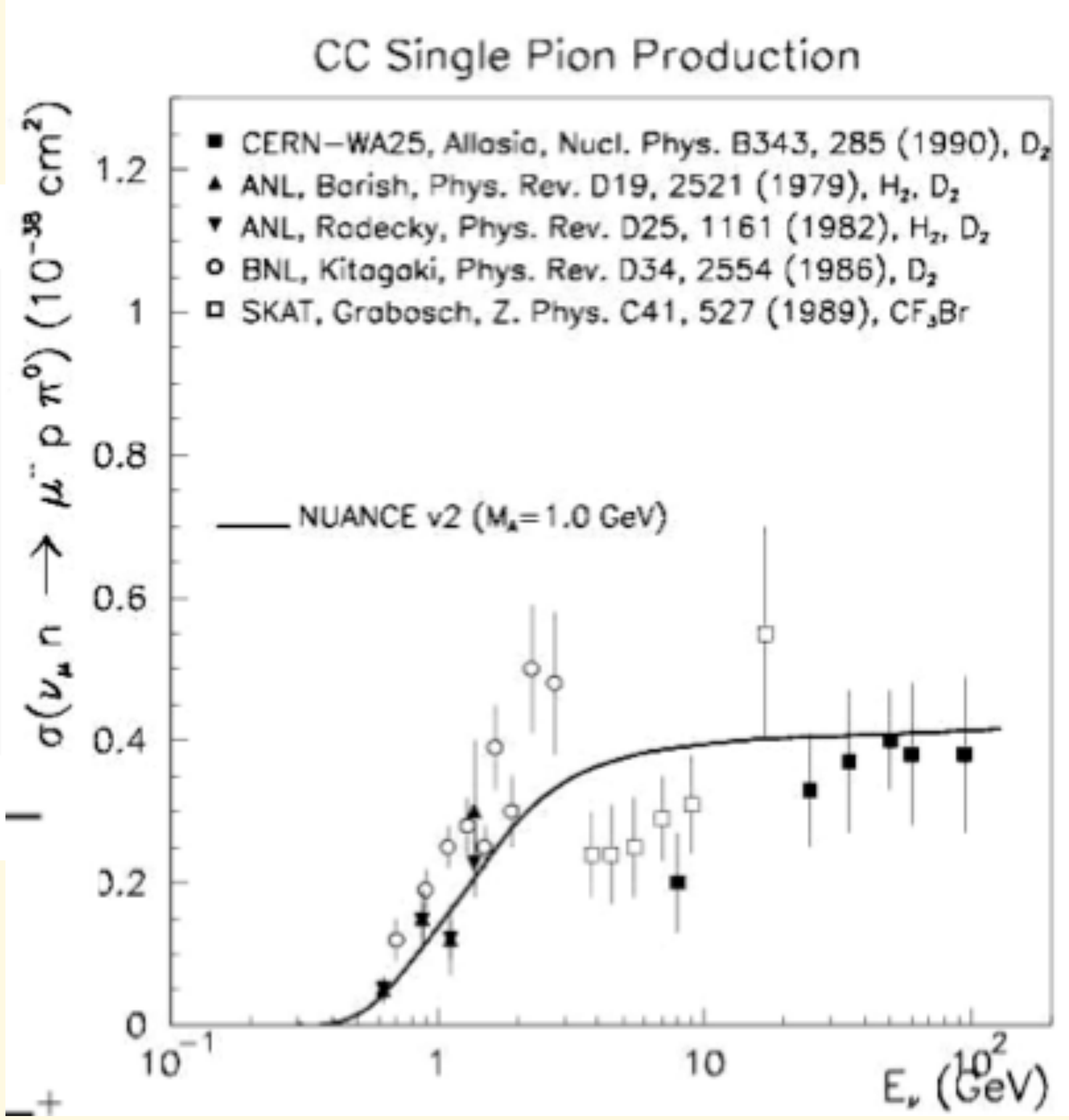
Two Examples

Examples of possible normalization problems



Examples of possible normalization problems





Exclusive X-sections

Exclusive X-sections

- For some purposes it is important to measure exclusive x-sections and/or their differential distributions

Exclusive X-sections

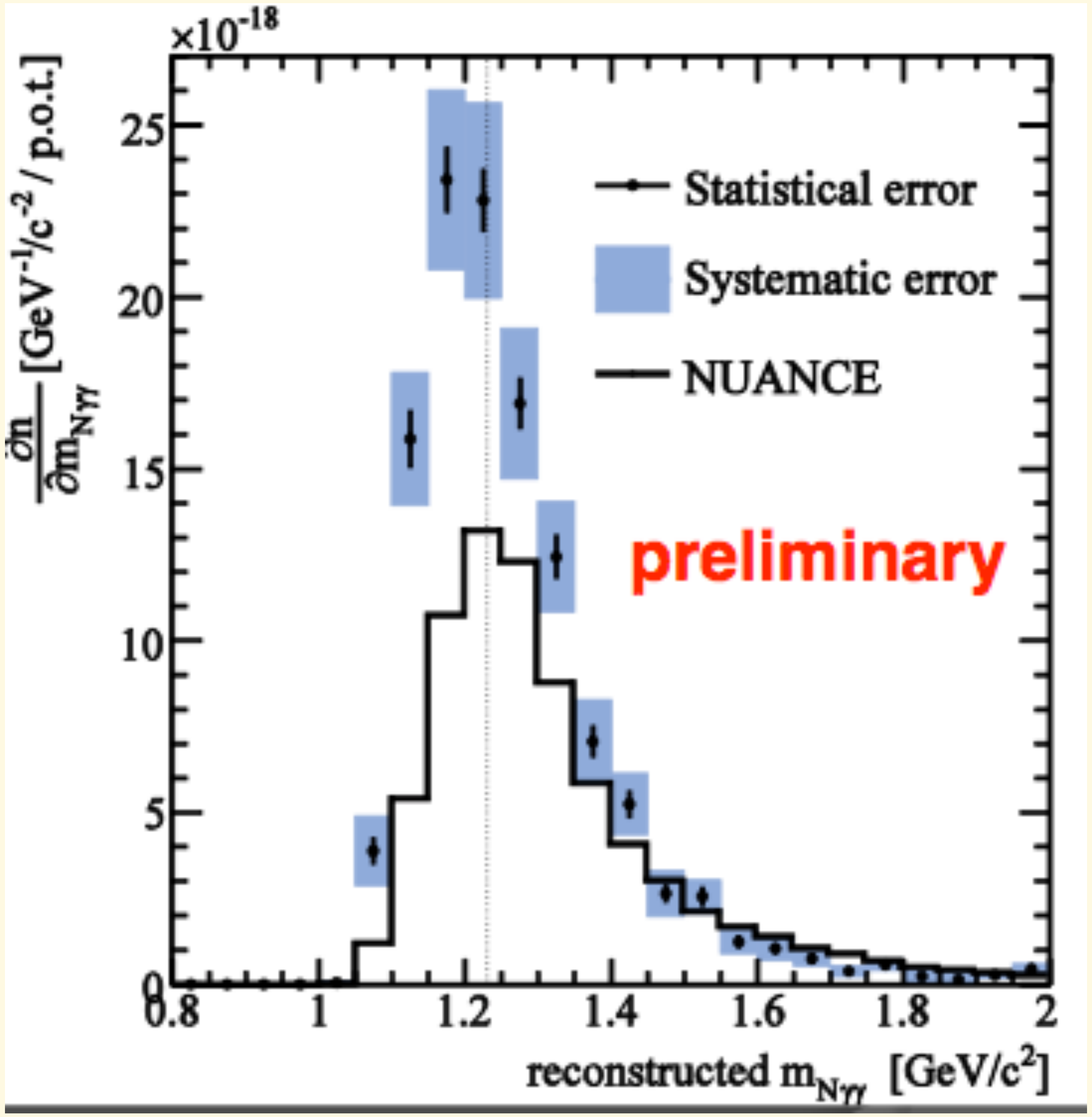
- For some purposes it is important to measure exclusive x-sections and/or their differential distributions
    - Measurement of differential distributions of π^0's. Important for understanding backgrounds in ν_e appearance experiments

Exclusive X-sections

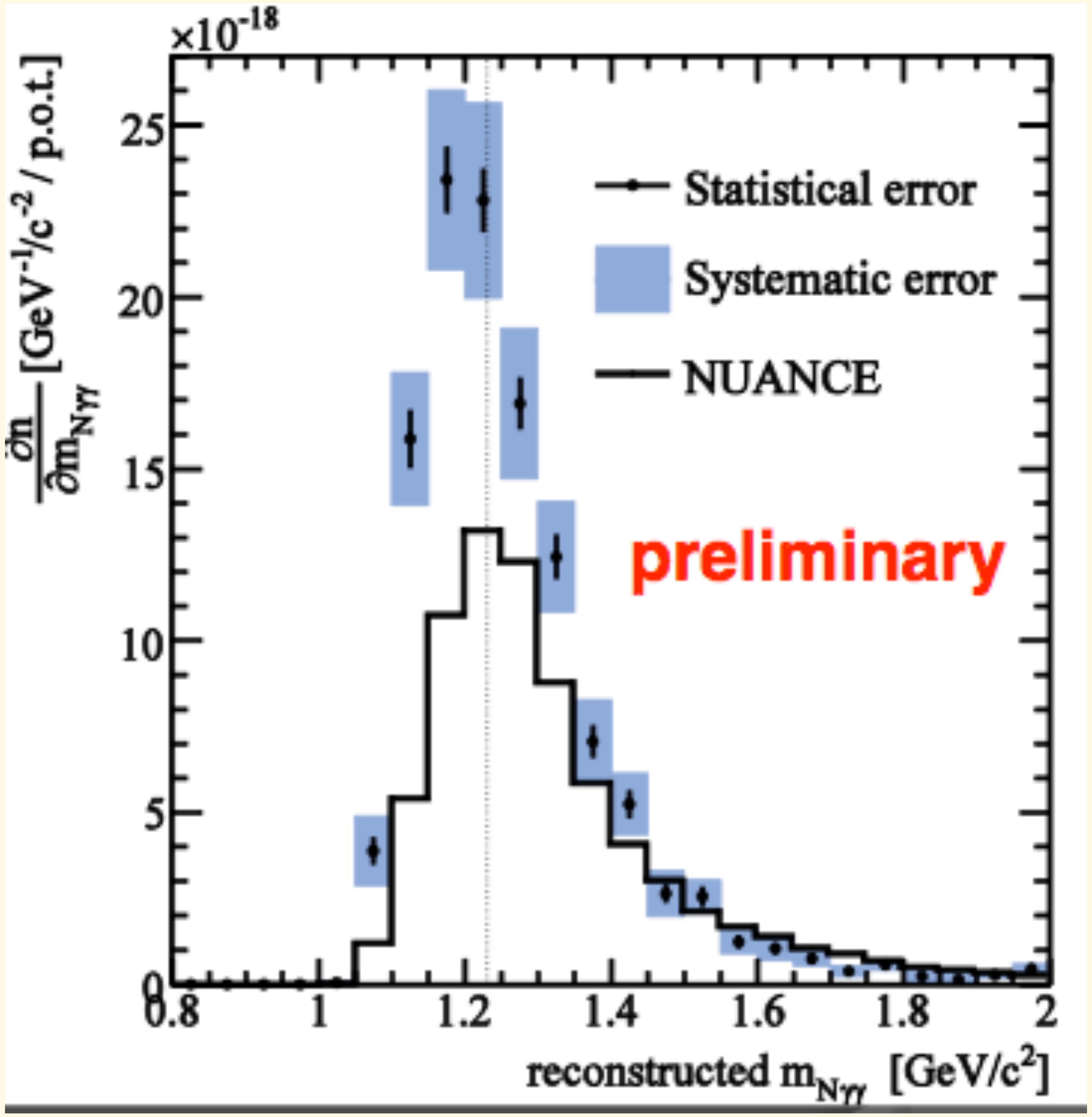
- For some purposes it is important to measure exclusive x-sections and/or their differential distributions
  - Measurement of differential distributions of π^0's. Important for understanding backgrounds in ν_e appearance experiments
  - Resonance production. If one uses kinematics to deduce neutrino energy, misclassifying resonant event as QE leads to a wrong energy assignment

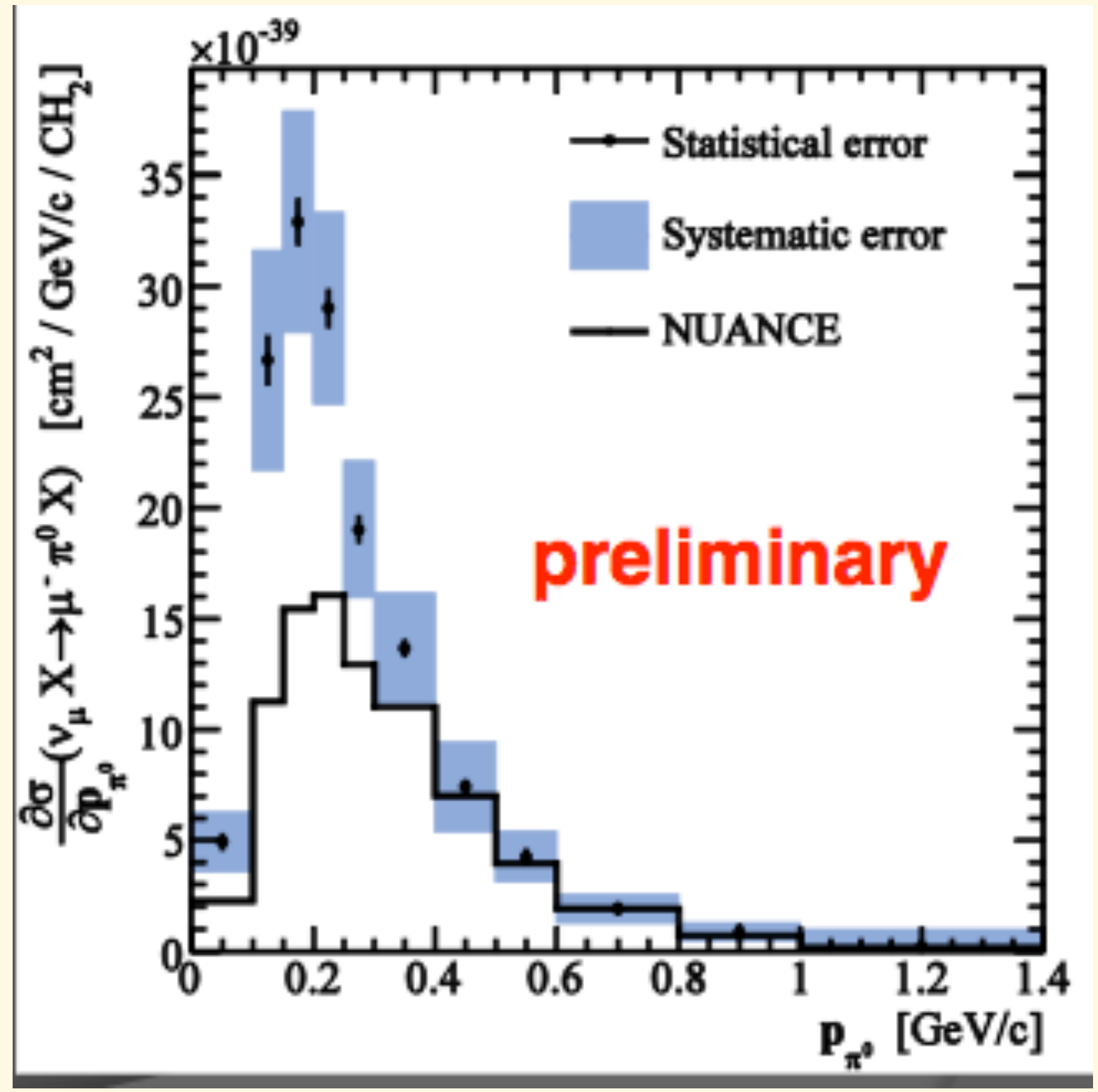
MiniBooNE Results

MiniBooNE Results

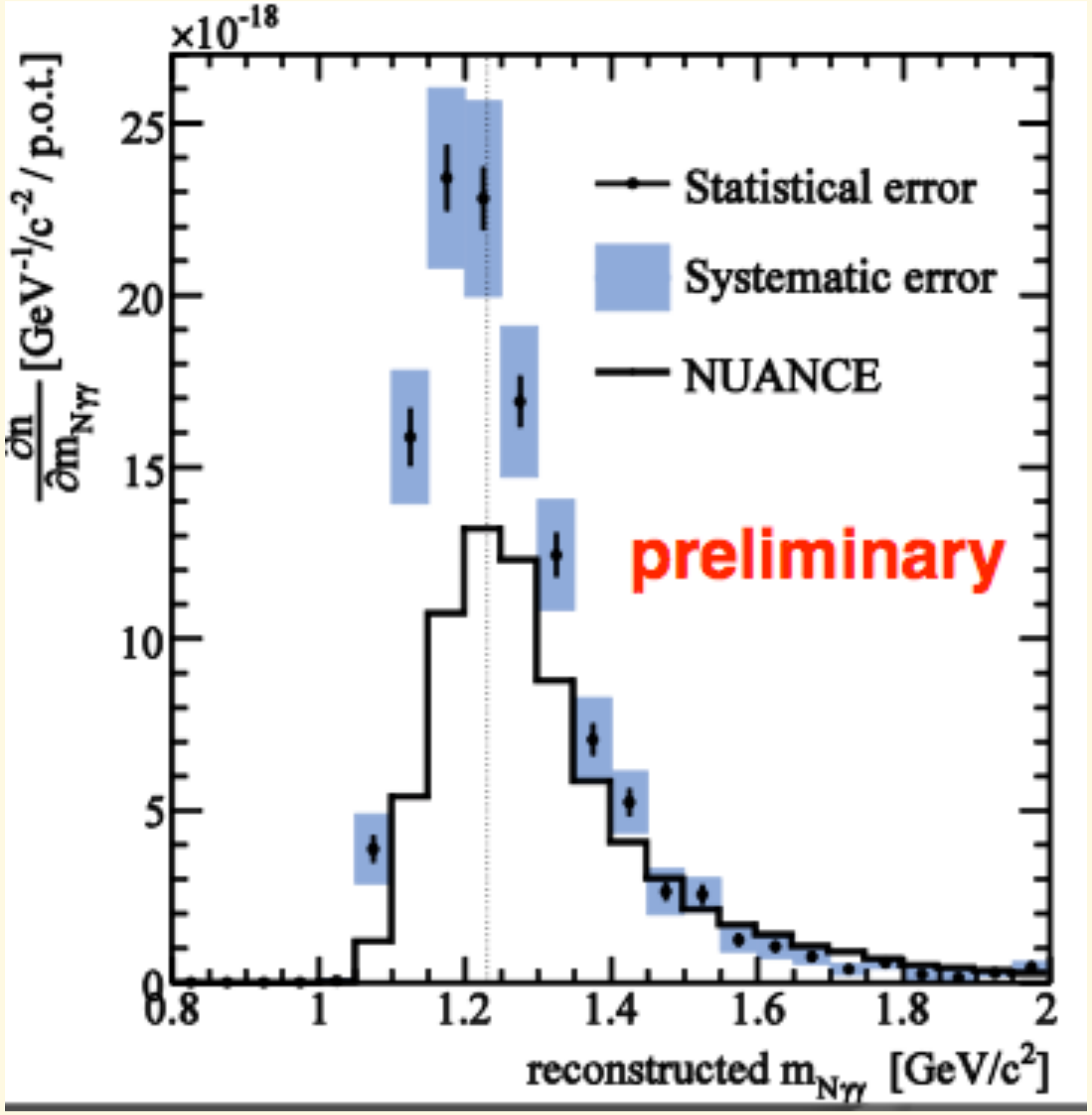


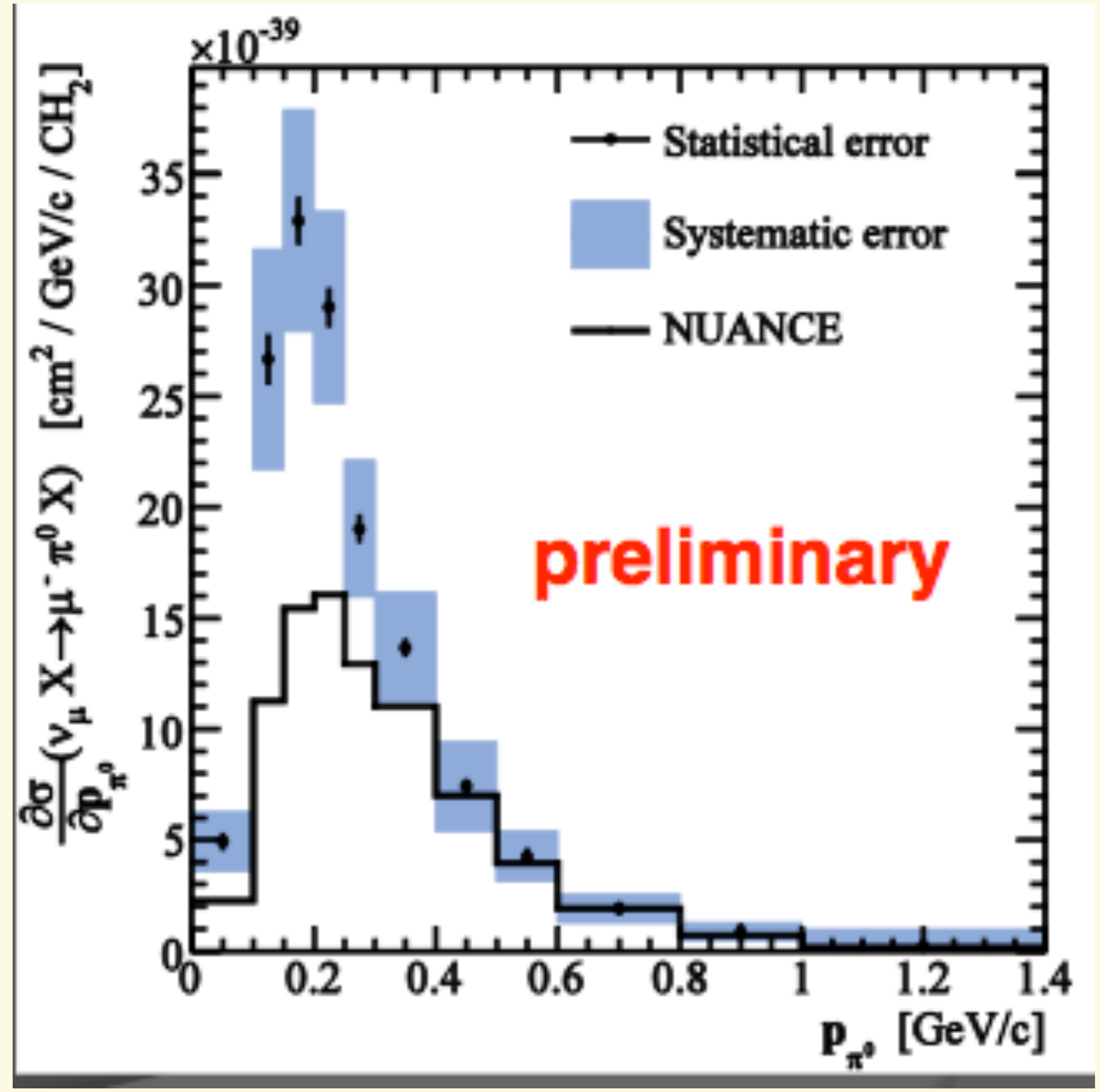
MiniBooNE Results





MiniBooNE Results





Significant differences between the measurements and the original MC simulation

MINERvA Experiment

MINERvA Experiment

- Dedicated experiment to measure neutrino cross sections in the 1-10 GeV range

MINERvA Experiment

- Dedicated experiment to measure neutrino cross sections in the 1-10 GeV range
- Experiment uses NuMI beam

MINERvA Experiment

- Dedicated experiment to measure neutrino cross sections in the 1-10 GeV range
- Experiment uses NuMI beam
- New fine grained main detector; MINOS Near Detector used as muon spectrometer

MINERvA Experiment

- Dedicated experiment to measure neutrino cross sections in the 1-10 GeV range
- Experiment uses NuMI beam
- New fine grained main detector; MINOS Near Detector used as muon spectrometer
- The goal is to measure also individual contributions: QE, single pion, DIS

MINERvA Experiment

- Dedicated experiment to measure neutrino cross sections in the 1-10 GeV range
- Experiment uses NuMI beam
- New fine grained main detector; MINOS Near Detector used as muon spectrometer
- The goal is to measure also individual contributions: QE, single pion, DIS
- The plan is to use different materials as targets to understand A dependence

MINERvA Energy Region

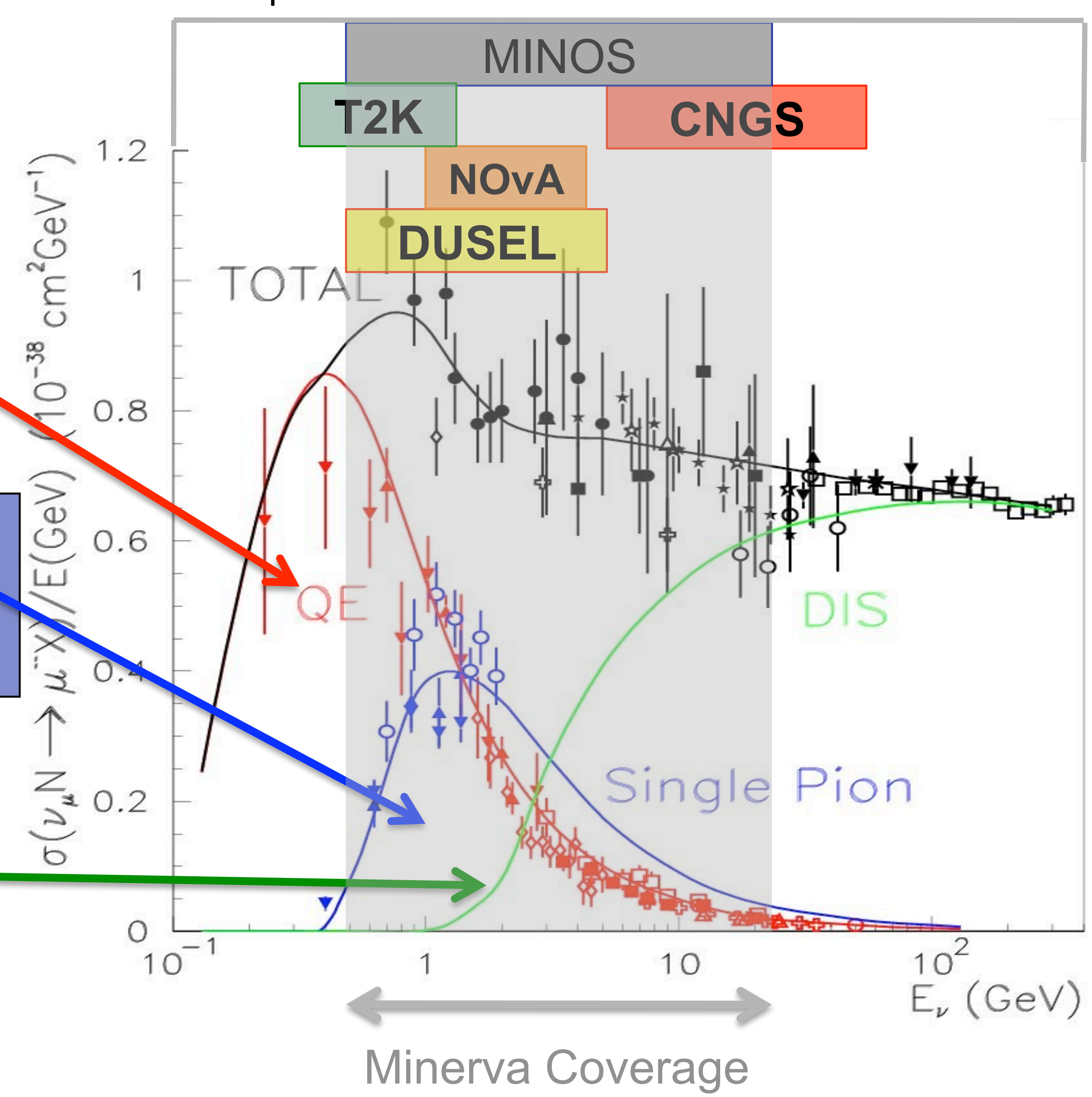
ν_μ charged-current cross-sections

Quasi-Elastic
signal channel in LBL oscillation experiments

NC π^0
background for ν_e appearance

CC π^+
background for ν_μ disappearance

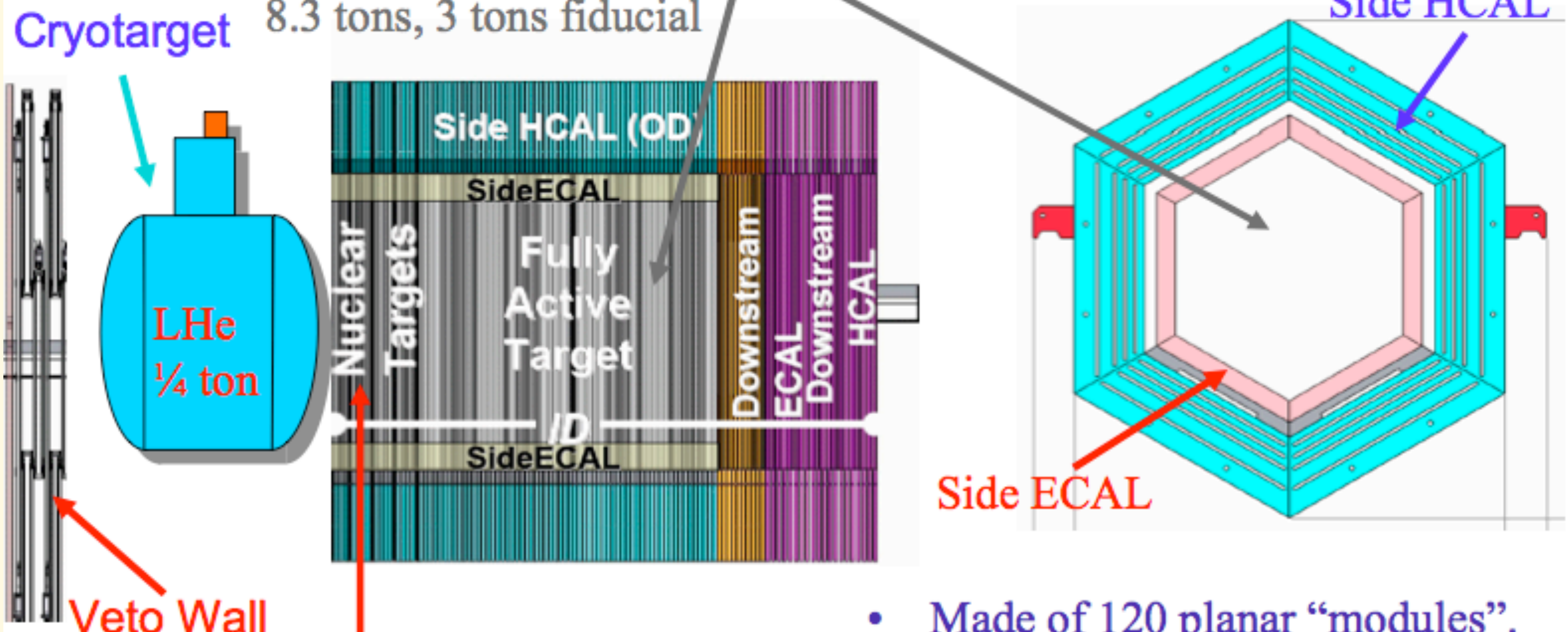
DIS
need to extrapolate into low energy region



Jeff Hartnell, NOW 2010   Dave Schmitz, MSU Seminar   38

MINERvA Detector

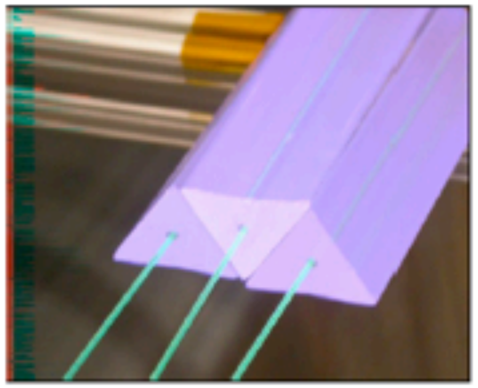
MINERvA Detector



Nuclear Targets with Pb, Fe, C, H_2O,CH
In same experiment reduces systematic errors between nuclei

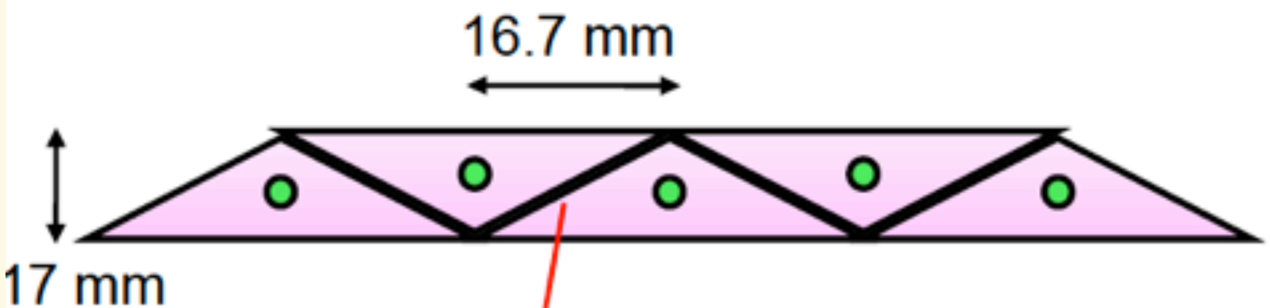
- Made of 120 planar "modules".
  - Total Mass: 200 tons
  - Total channels: ~32K

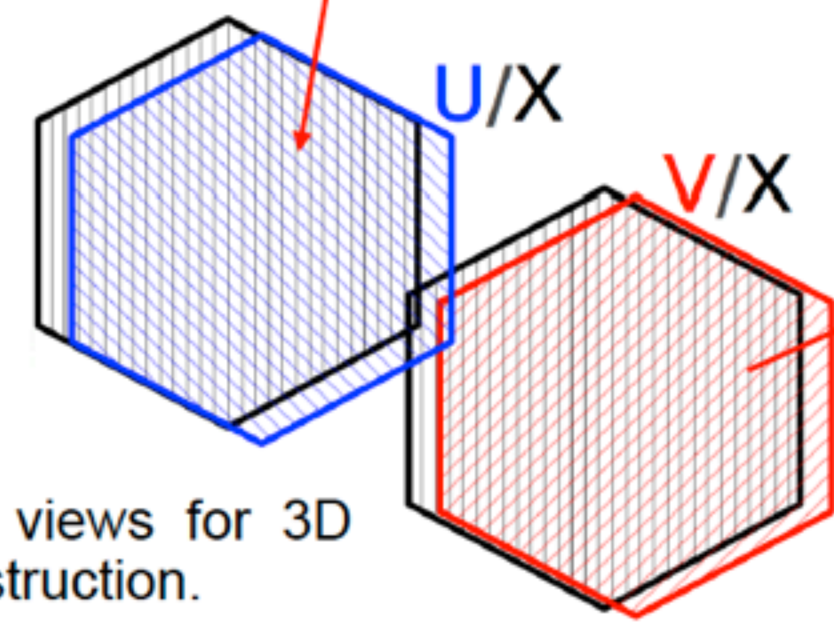
MINERvA Tracking



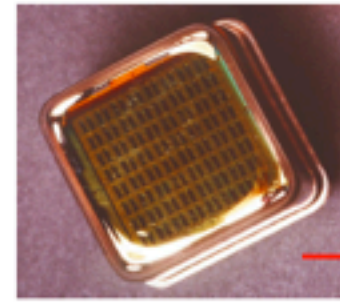
Extruded plastic scintillator
+ wavelength shifters.

Triangular geometry allows charge sharing for better position resolution.

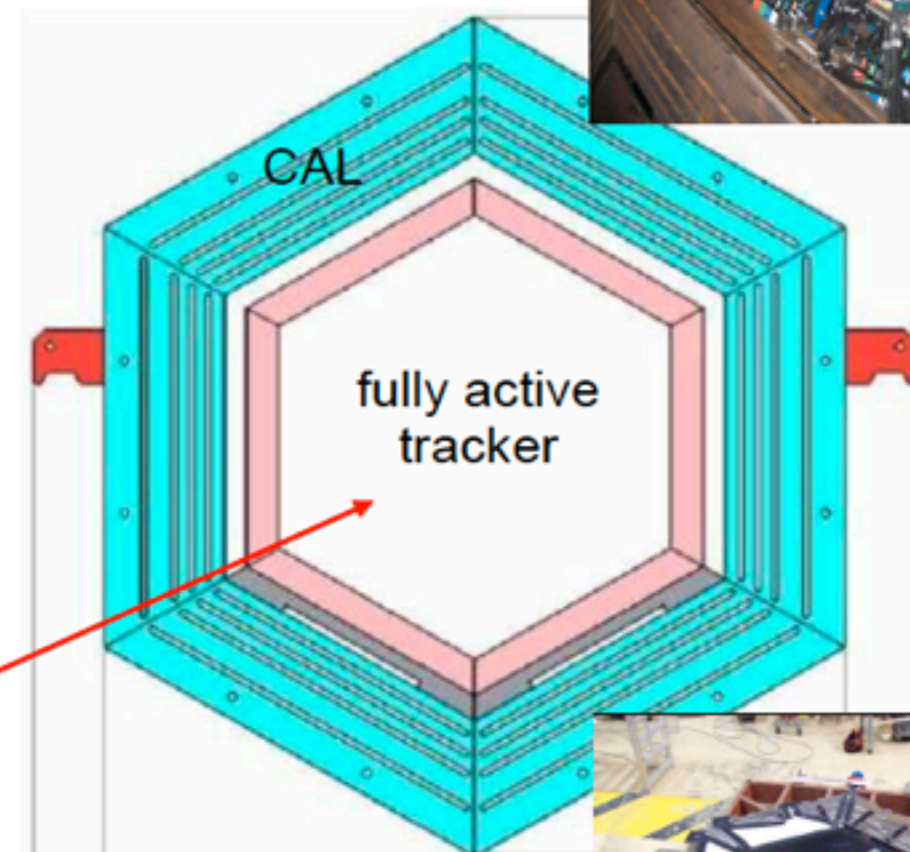


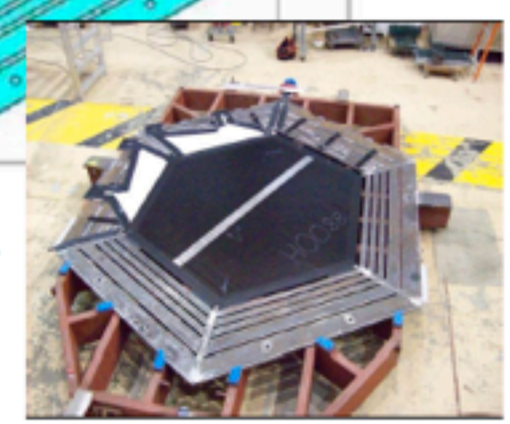


Three views for 3D reconstruction.



64 anode
PMT's

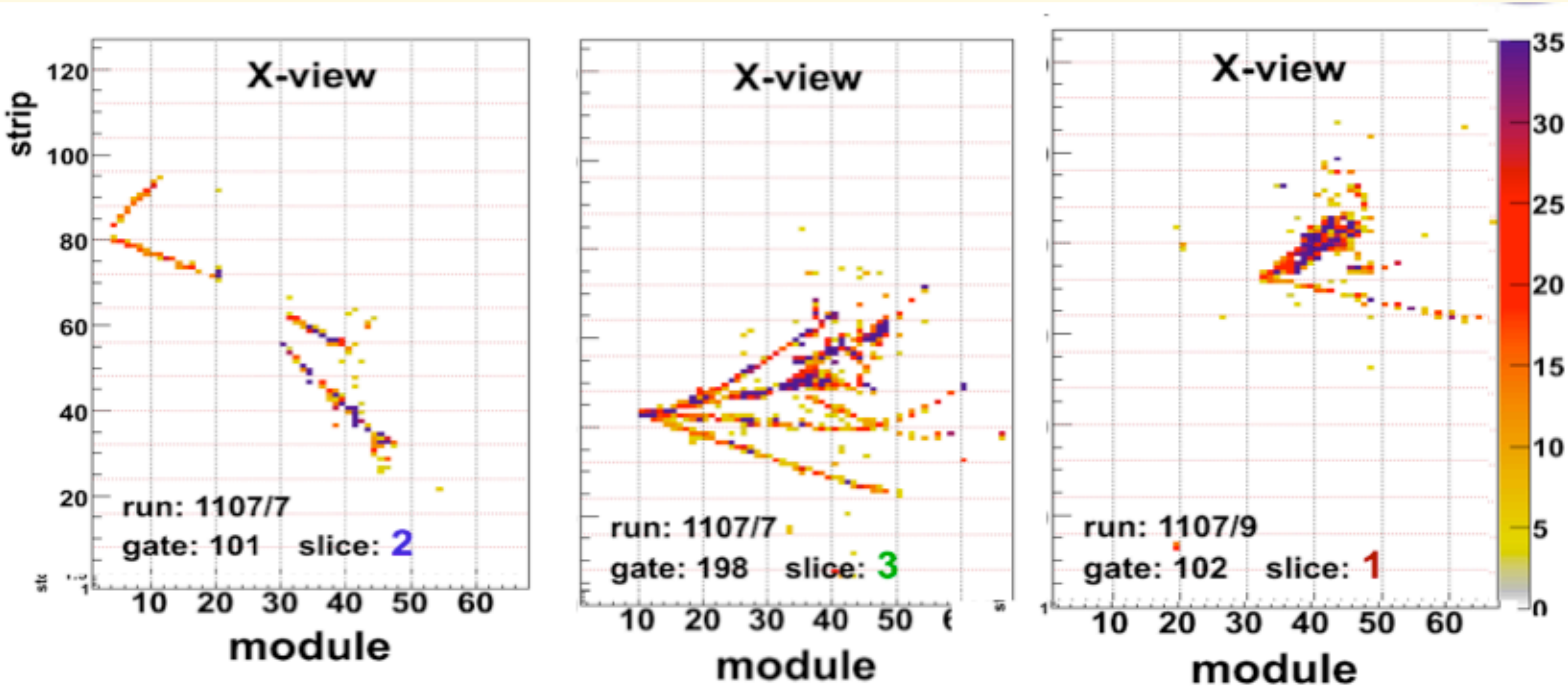




Iron outer detector instrumented for EM calorimetry.

Examples of Events

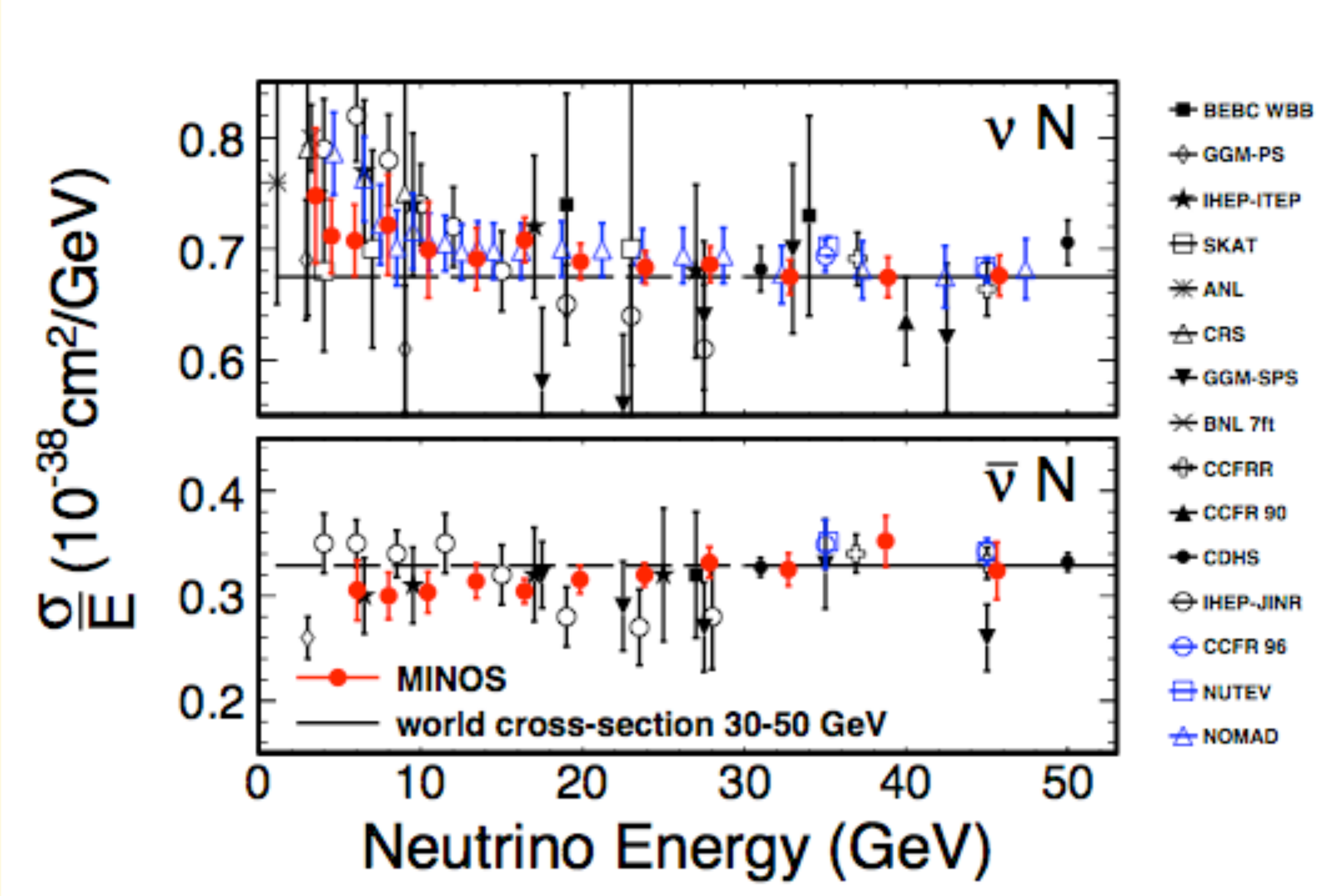
Examples of Events



3 different events; same view

Total x-sections - today

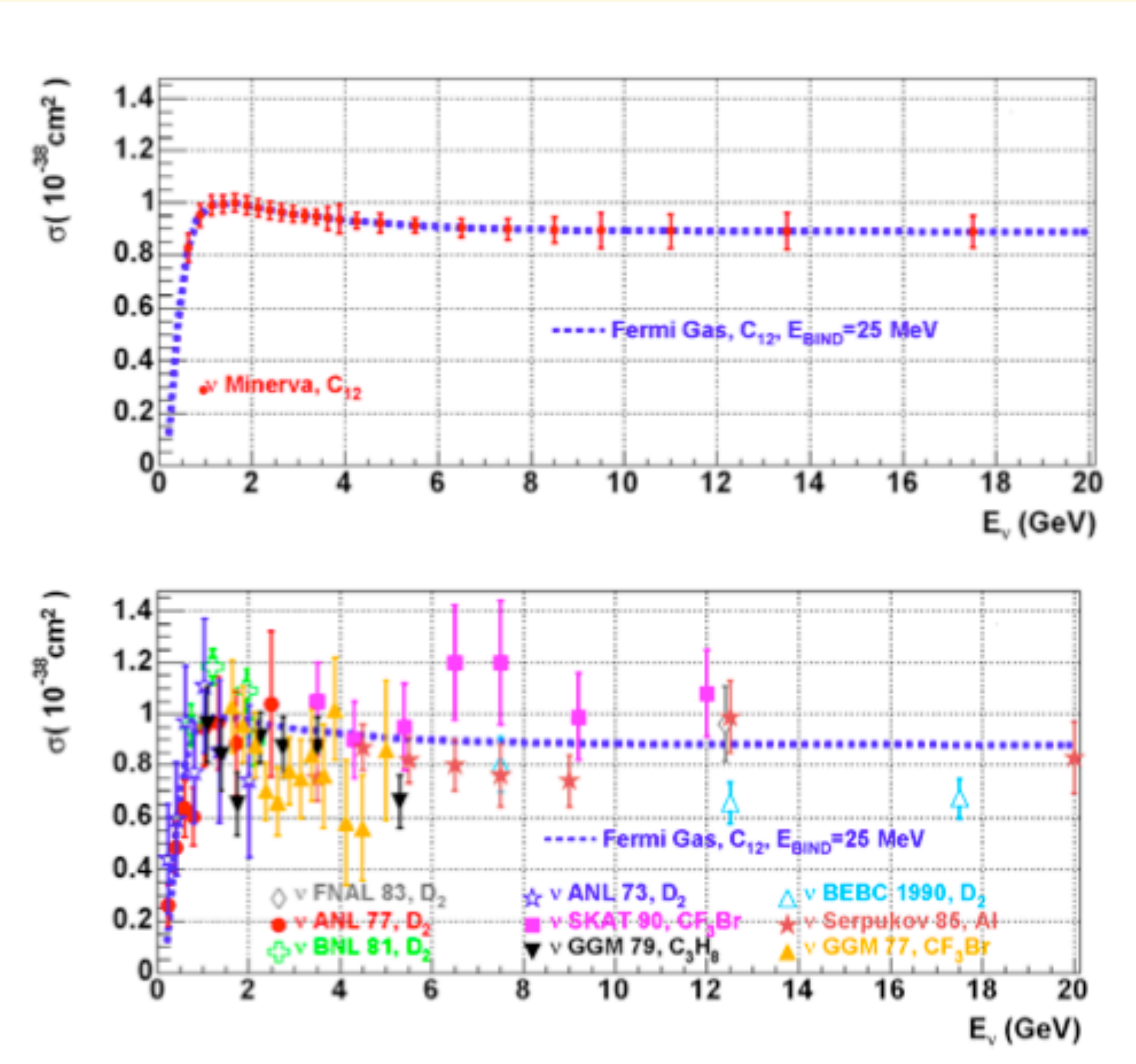
Total x-sections - today



MINOS uses low *y* events to determine the relative flux and normalized to previous high energy (30-50 GeV) measurements

MINERvA Goal

MINERvA Goal



Summary

Summary

- Accelerator conventional beams have been an important element in our study of neutrinos

Summary

- Accelerator conventional beams have been an important element in our study of neutrinos
- In many situations they provided unique information

Summary

- Accelerator conventional beams have been an important element in our study of neutrinos
- In many situations they provided unique information
- They will continue to play that role in the future

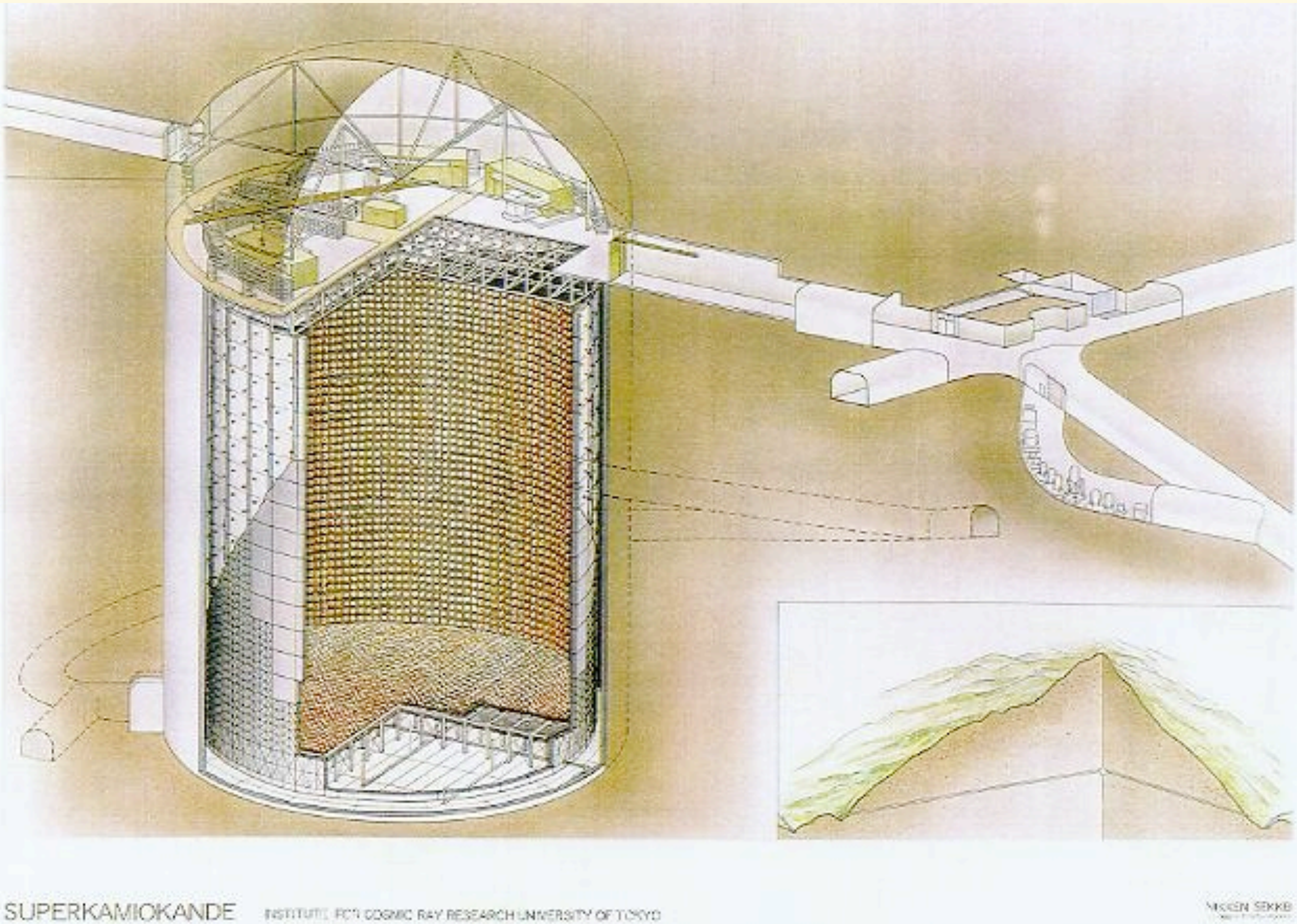
Summary

- Accelerator conventional beams have been an important element in our study of neutrinos
- In many situations they provided unique information
- They will continue to play that role in the future
- Due to technical innovations, their capabilities continue to increase

Backup Slides

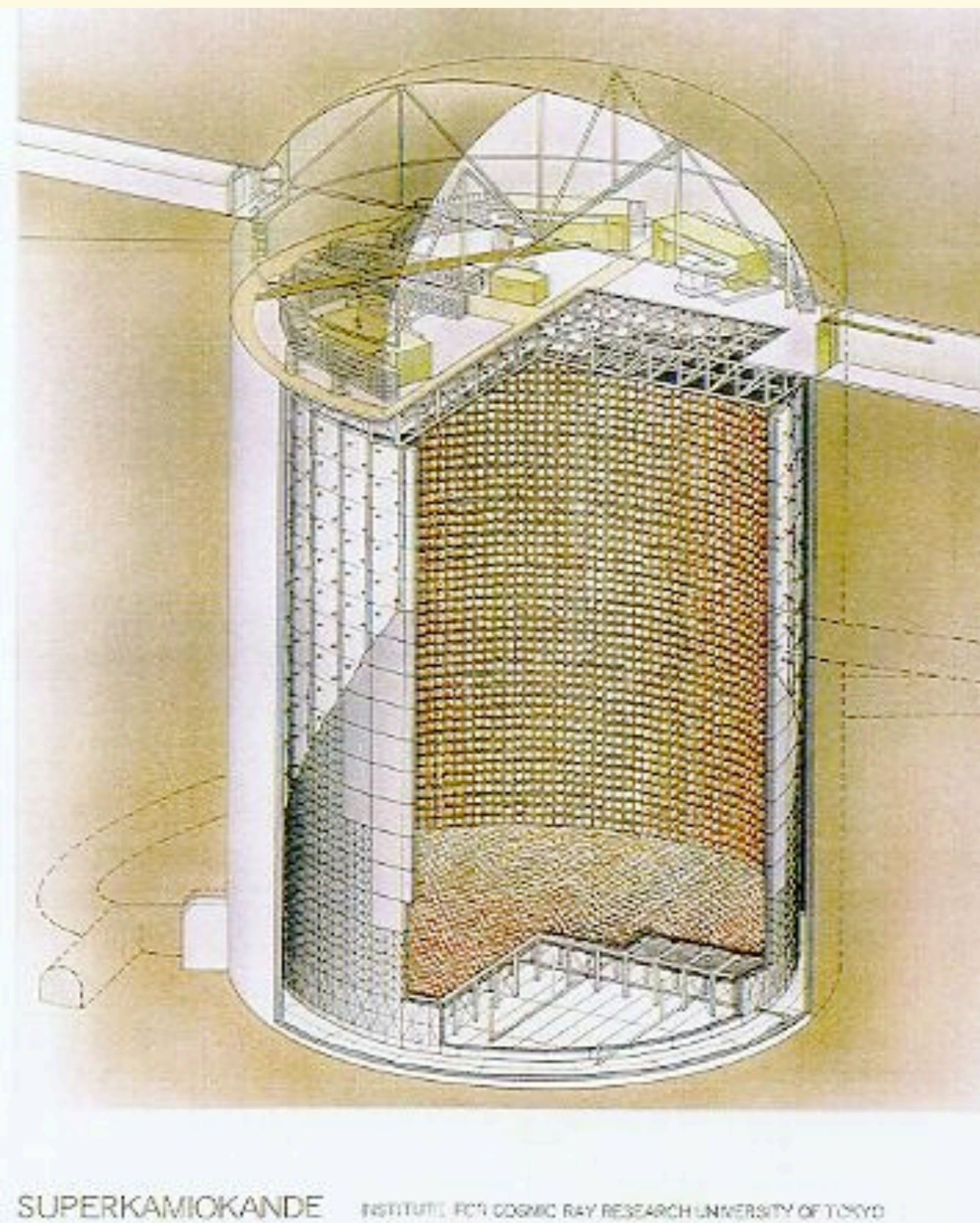
SuperKamiokande

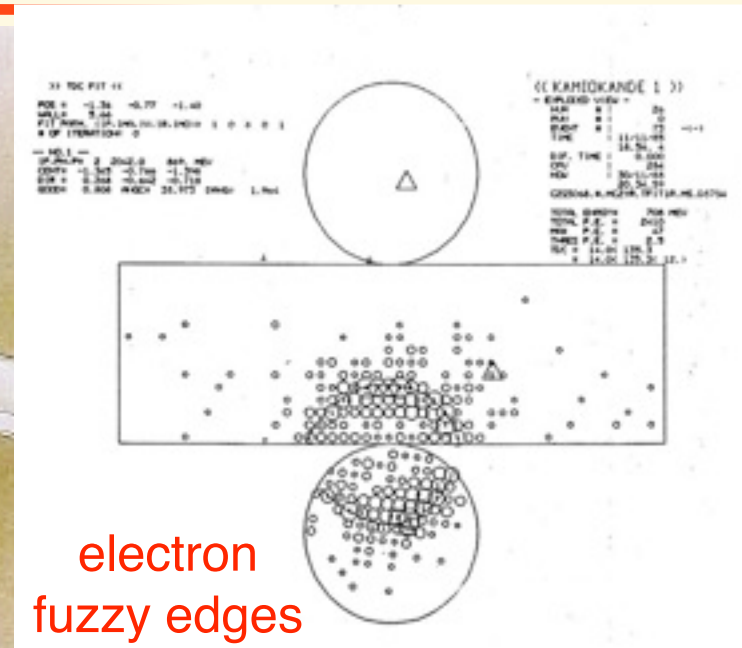
SuperKamiokande

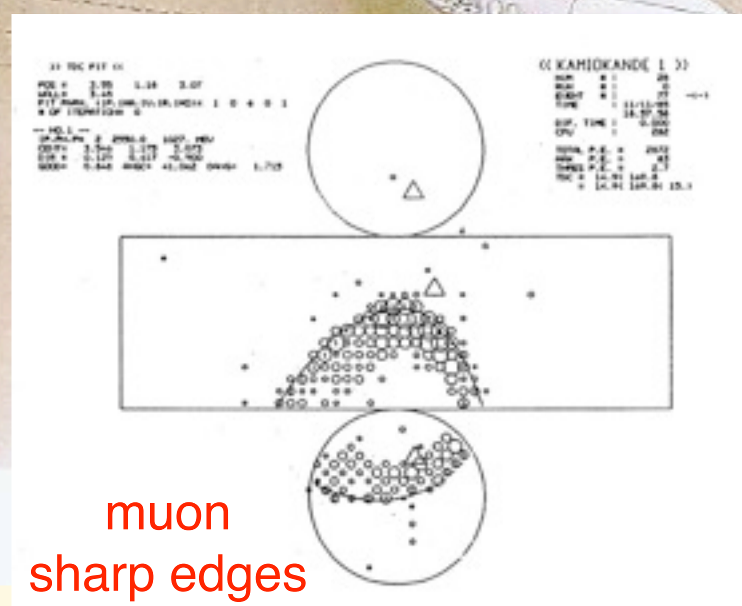


50 kt of water
42m high, 40 m diam
40% PMT coverage
1000m underground

SuperKamiokande

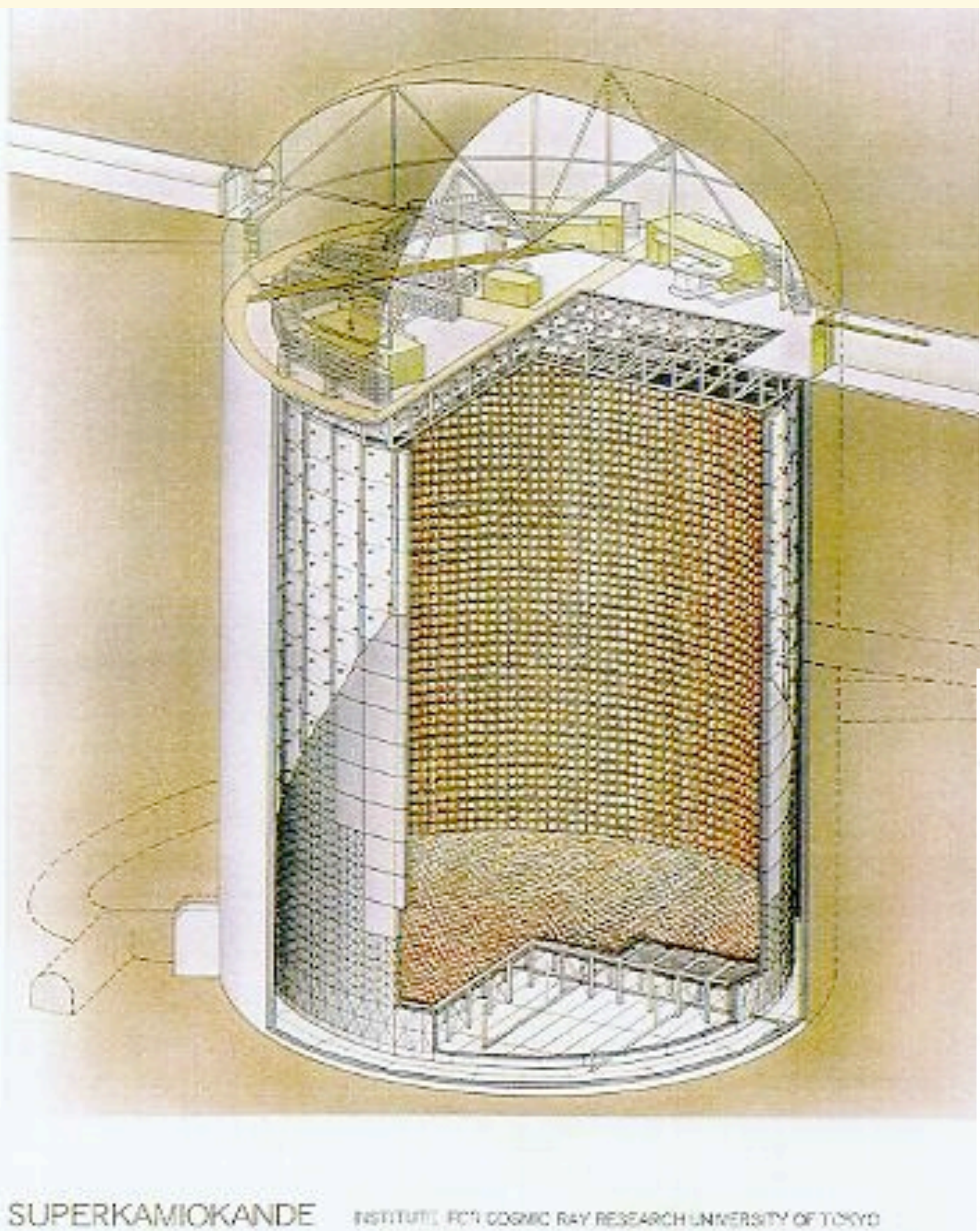


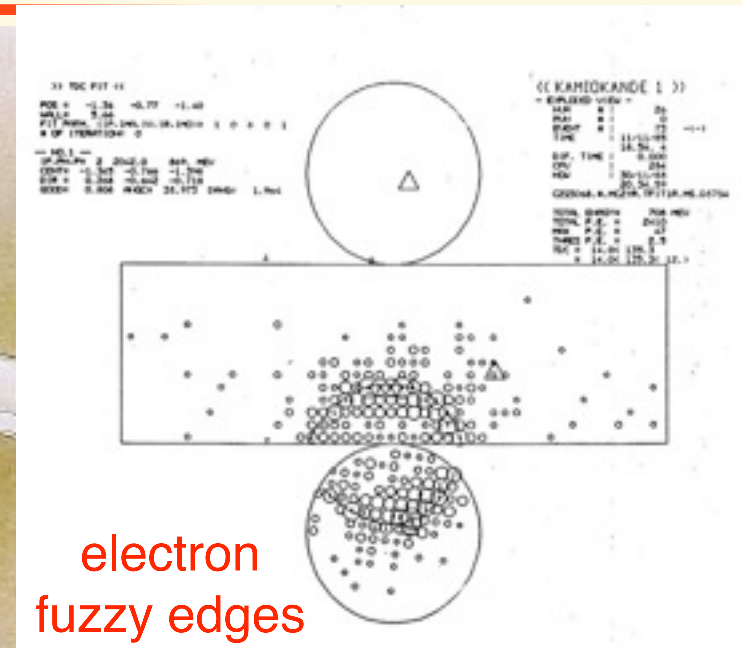


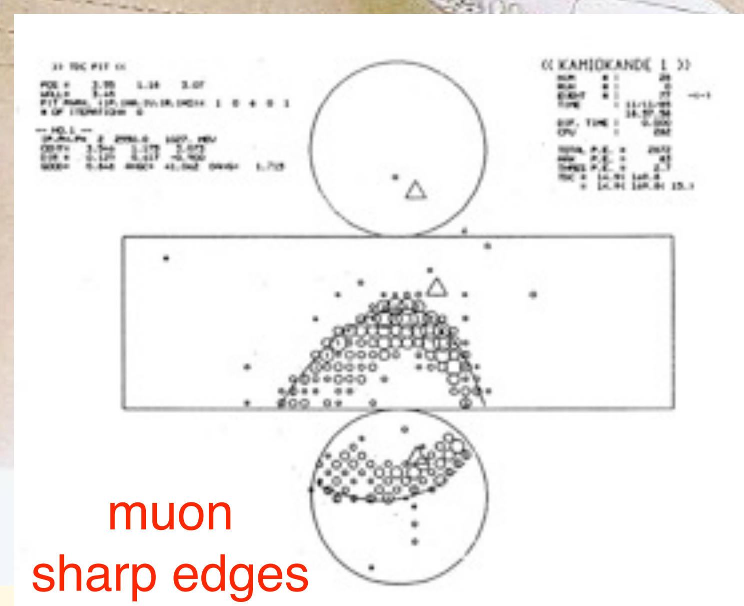


50 kt of water
42m high, 40 m diam
40% PMT coverage
1000m underground

SuperKamiokande



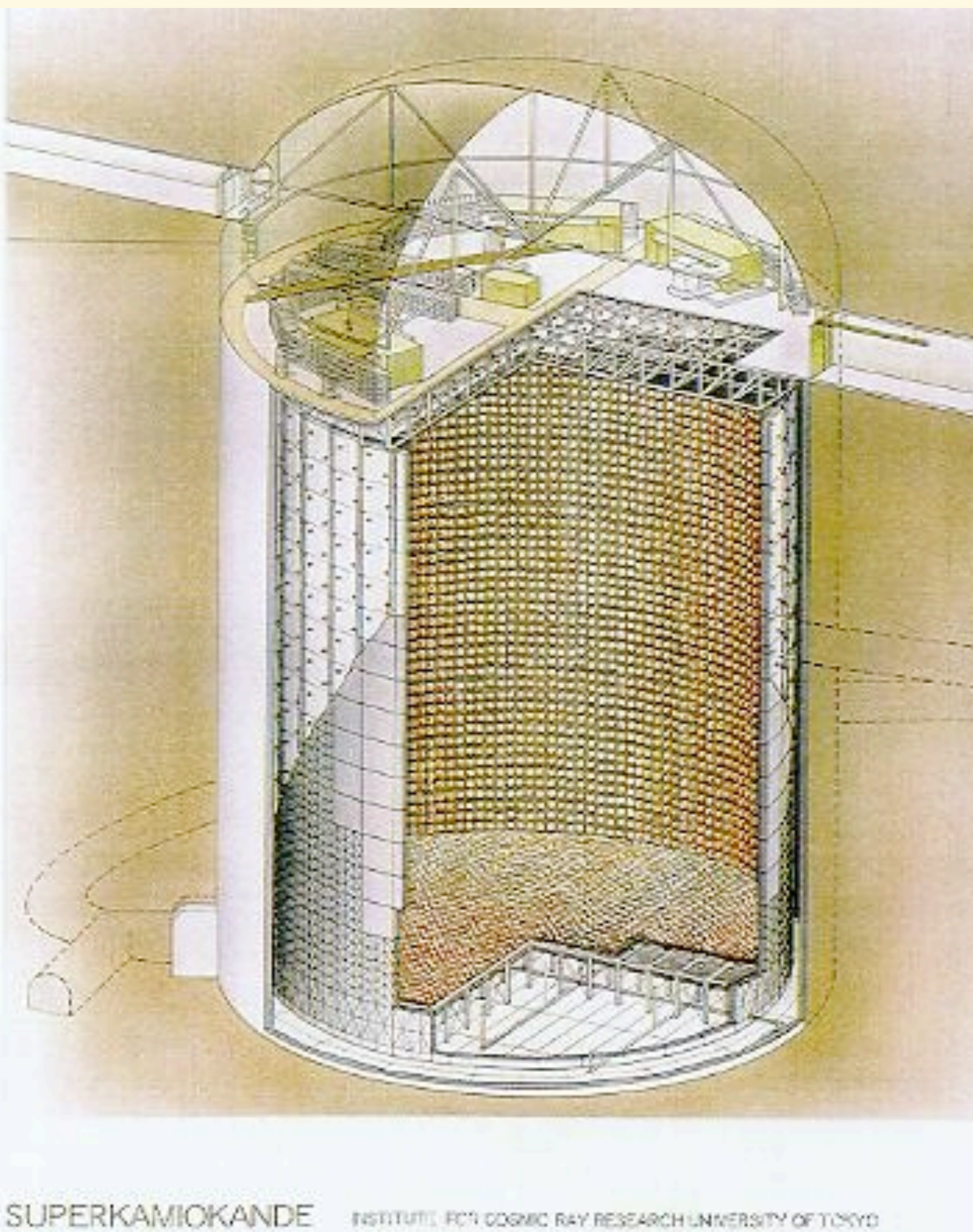


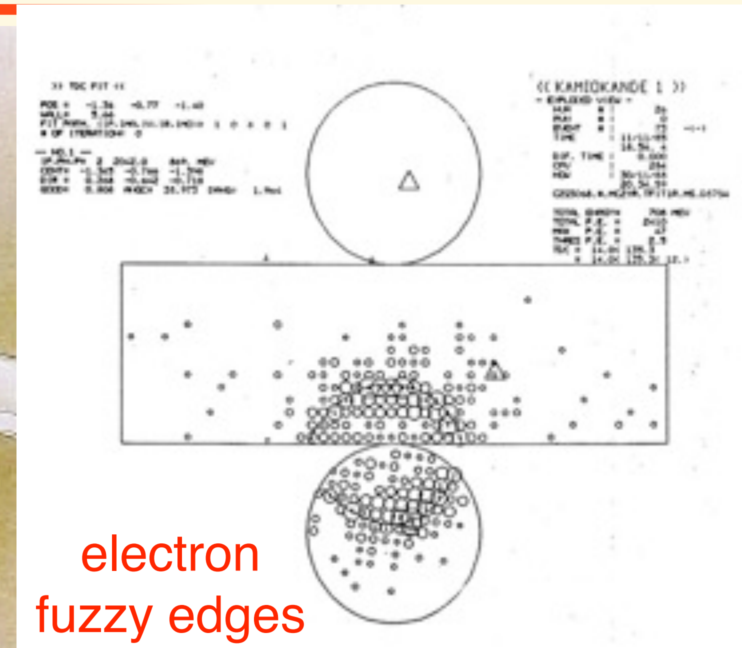


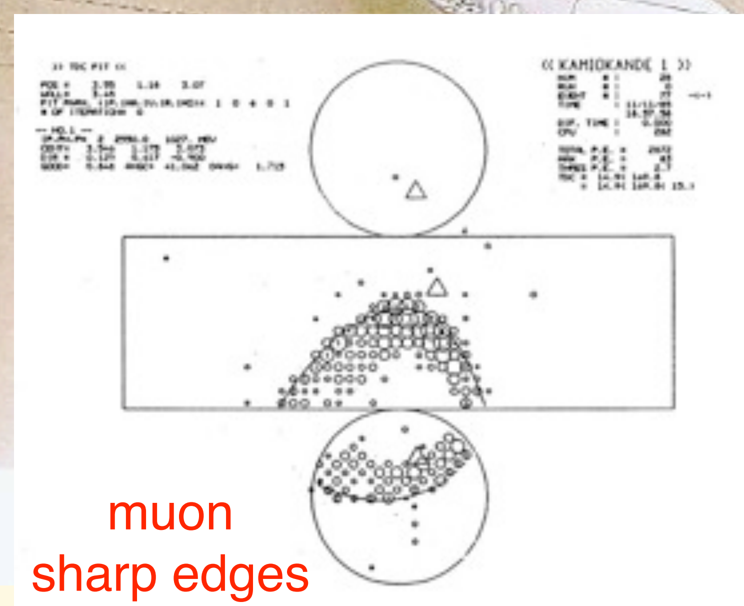
50 kt of water
42m high, 40 m diam
40% PMT coverage
1000m underground

Zenith angle and L/E distributions are used to extract oscillation parameters

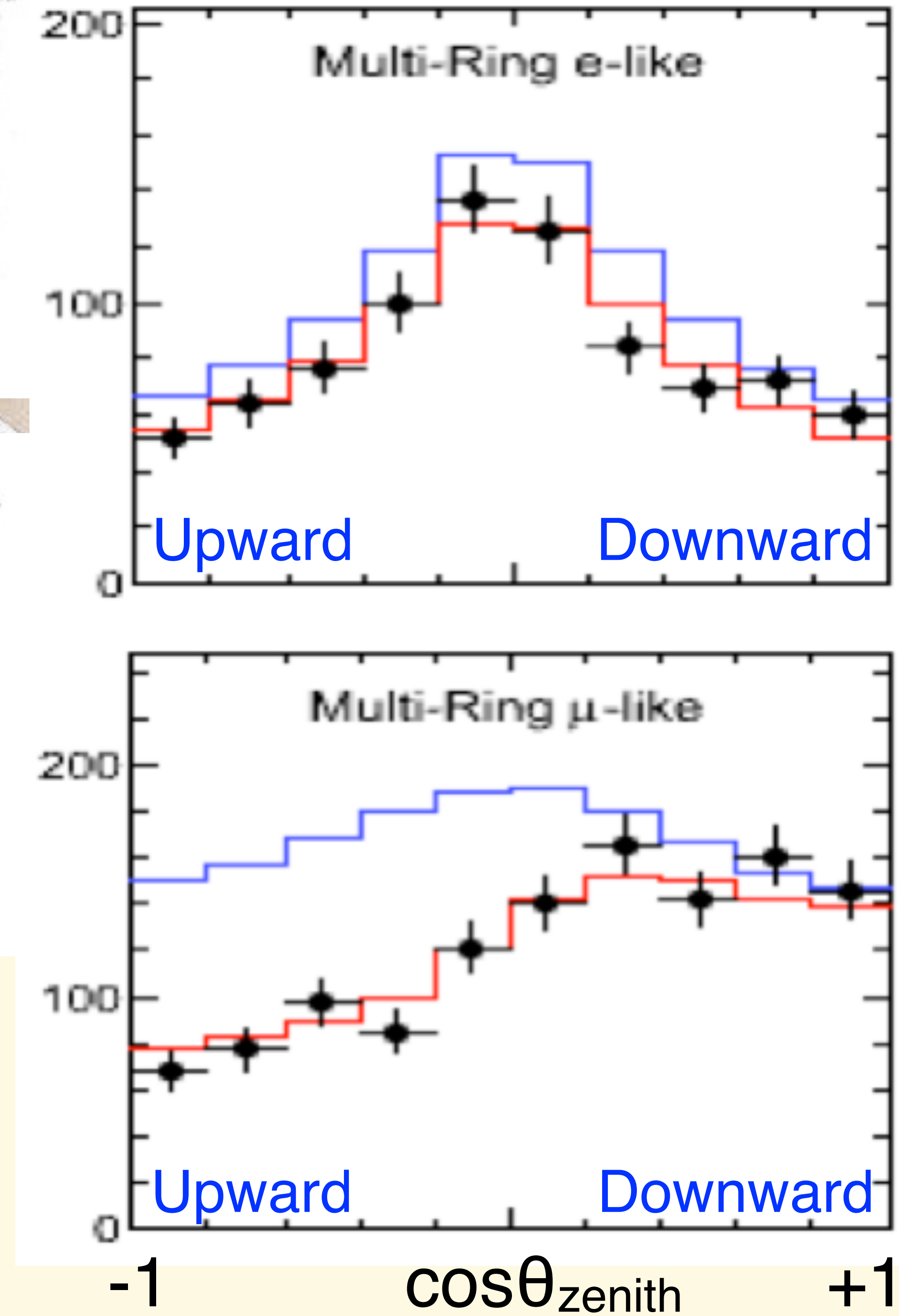
SuperKamiokande







Example distributions



50 kt of water
42m high, 40 m diam
40% PMT coverage
1000m underground

Zenith angle and L/E distributions are used to extract oscillation parameters

Comparison of ν and $\bar{\nu}$

Comparison of ν and $\bar{\nu}$

Parameters of ν and $\bar{\nu}$ have to be equal by CPT

Comparison of ν and $\bar{\nu}$

Parameters of ν and $\bar{\nu}$ have to be equal by CPT

But experiments with ν and $\bar{\nu}$ beams are generally not related by CPT because of passage through matter

Comparison of ν and $\bar{\nu}$

Parameters of ν and $\bar{\nu}$ have to be equal by CPT

But experiments with ν and $\bar{\nu}$ beams are generally not related by CPT because of passage through matter

The current data do not constrain the equality of oscillation parameters in the solar sector to better than ~2

Comparison of ν and $\bar{\nu}$

Parameters of ν and $\bar{\nu}$ have to be equal by CPT

But experiments with ν and $\bar{\nu}$ beams are generally not related by CPT because of passage through matter

The current data do not constrain the equality of oscillation parameters in the solar sector to better than ~2

The situation in the ν_μ sector is made difficult by the fact that ν_μ contamination in a $\bar{\nu}_\mu$ beam is generally rather high. Thus independent verification of muon charge is helpful

Comparison of ν and $\bar{\nu}$

Parameters of ν and $\bar{\nu}$ have to be equal by CPT

But experiments with ν and $\bar{\nu}$ beams are generally not related by CPT because of passage through matter

The current data do not constrain the equality of oscillation parameters in the solar sector to better than ~2

The situation in the ν_μ sector is made difficult by the fact that ν_μ contamination in a $\bar{\nu}_\mu$ beam is generally rather high. Thus independent verification of muon charge is helpful

Magnetic field in its detectors makes MINOS particularly suitable for $\nu_\mu/\bar{\nu}_\mu$ comparison

MINOS Search

MINOS Search

MINOS can search for sterile neutrinos in a different L/E domain than LSND/MiniBooNE (small Δm^2 and large mixing angle)

MINOS Search

MINOS can search for sterile neutrinos in a different L/E domain than LSND/MiniBooNE (small Δm^2 and large mixing angle)

MINOS looks for depletion of neutral current (NC) events in the Far Detector compared to prediction obtained from the measured rate in the Near Detector

MINOS Search

MINOS can search for sterile neutrinos in a different L/E domain than LSND/MiniBooNE (small Δm^2 and large mixing angle)

MINOS looks for depletion of neutral current (NC) events in the Far Detector compared to prediction obtained from the measured rate in the Near Detector

In the conventional oscillation picture there should be no depletion of NC events