Accelerator Neutrino Experiments Status and Prospects

Stanley Wojcicki

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

Outline

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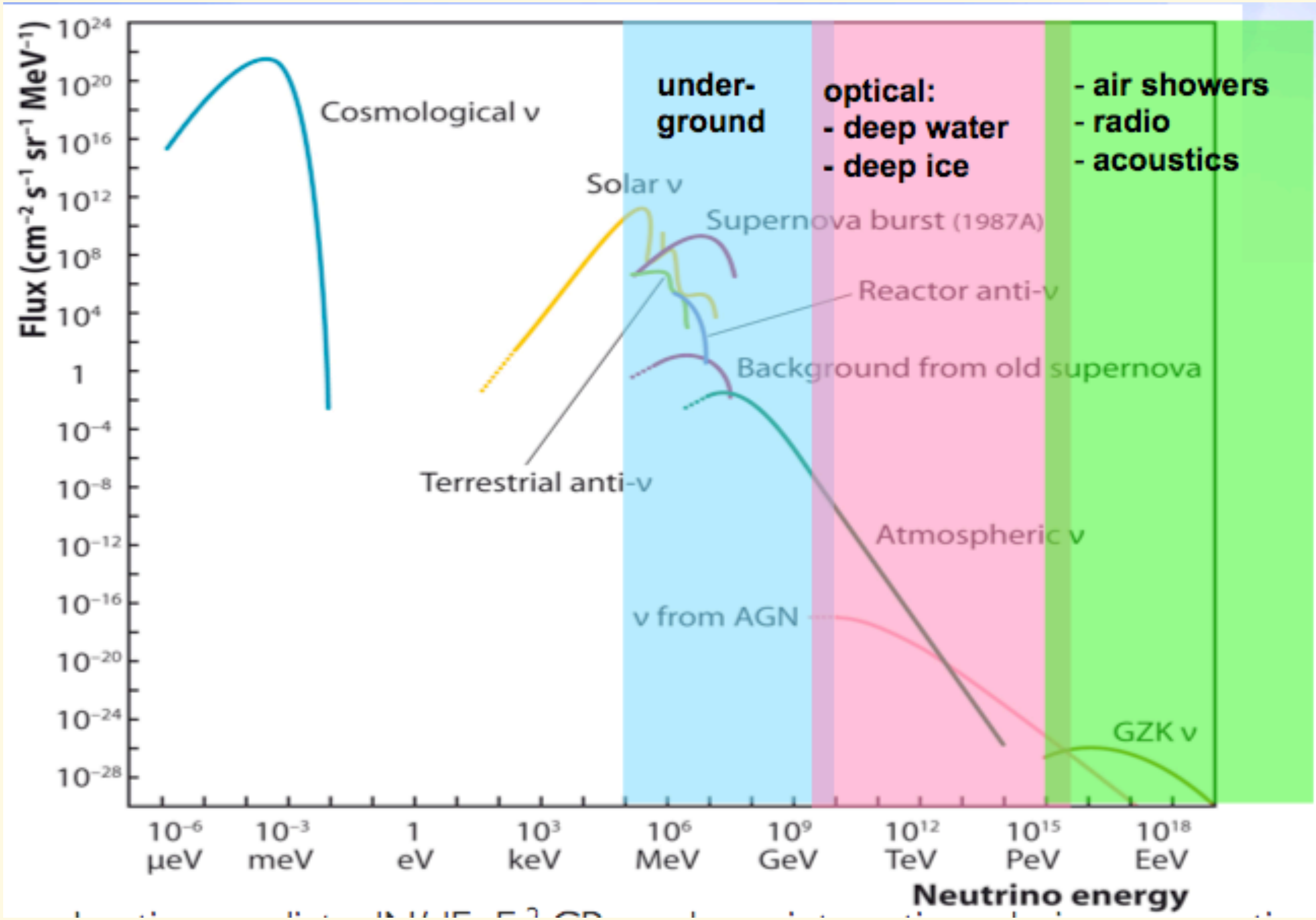

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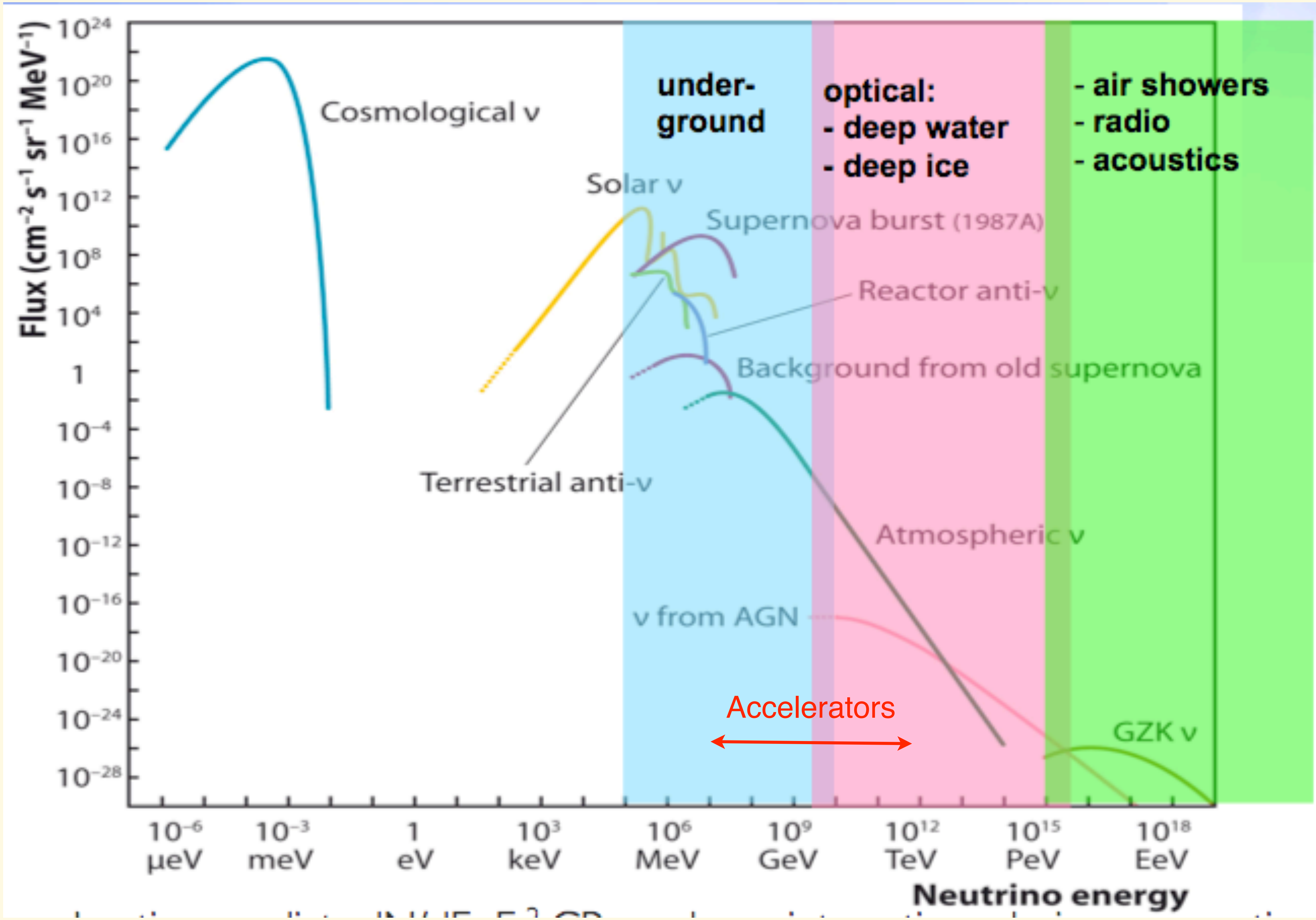

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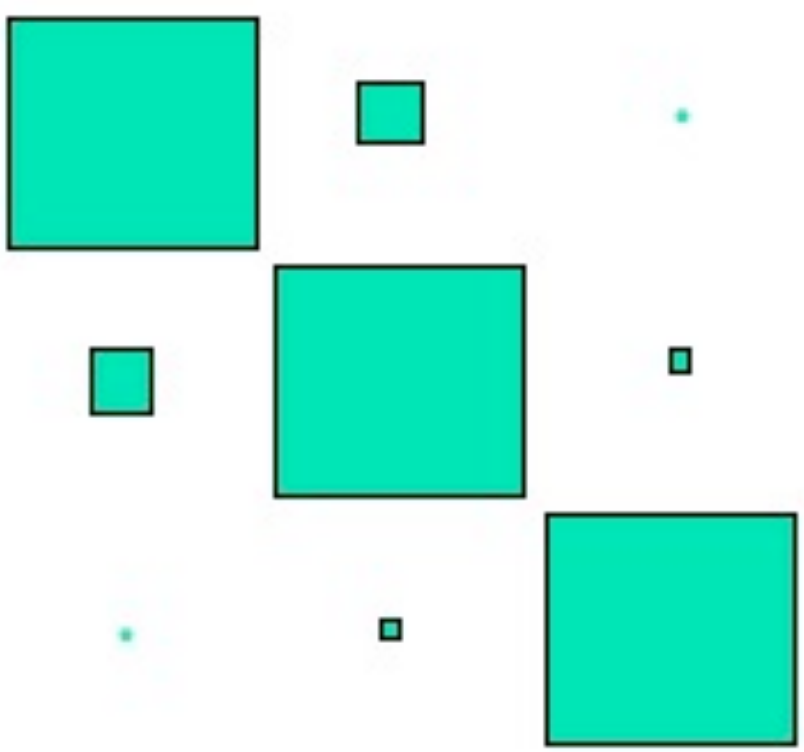

CKM Matrix, graphically

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Theoretical views:

"…angle $\theta_{\tau\mu}$ mixes adjacent generations. It is analogous to θ_{23} in the quark sector…. The pattern of the charged lepton mass ratios is not very much different from that of the quark mass ratios. Most theoretical models expect mixing angles to be somehow related to fermion masses."

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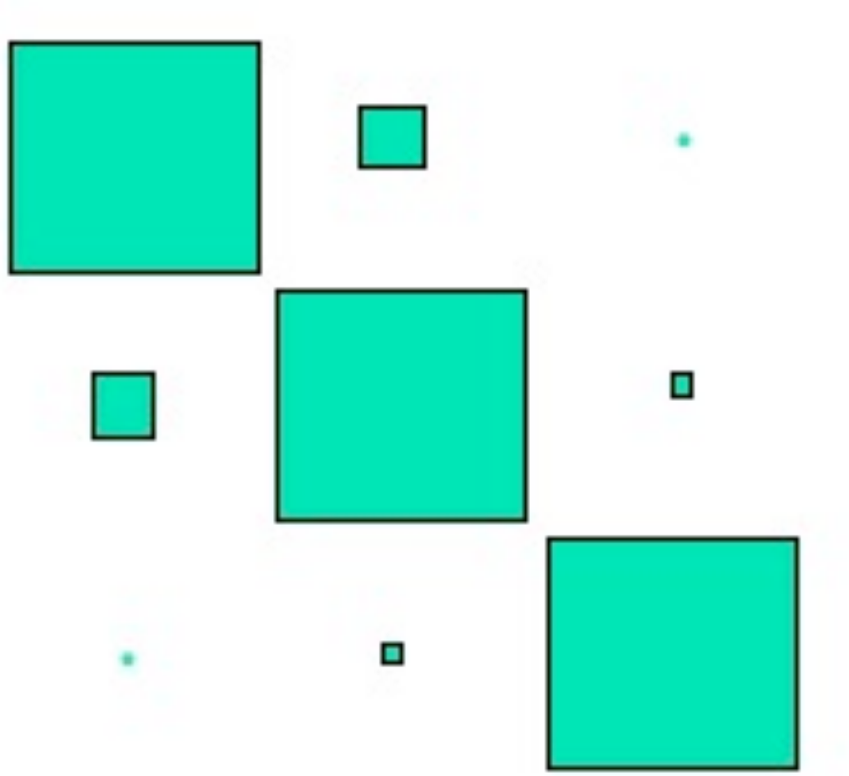

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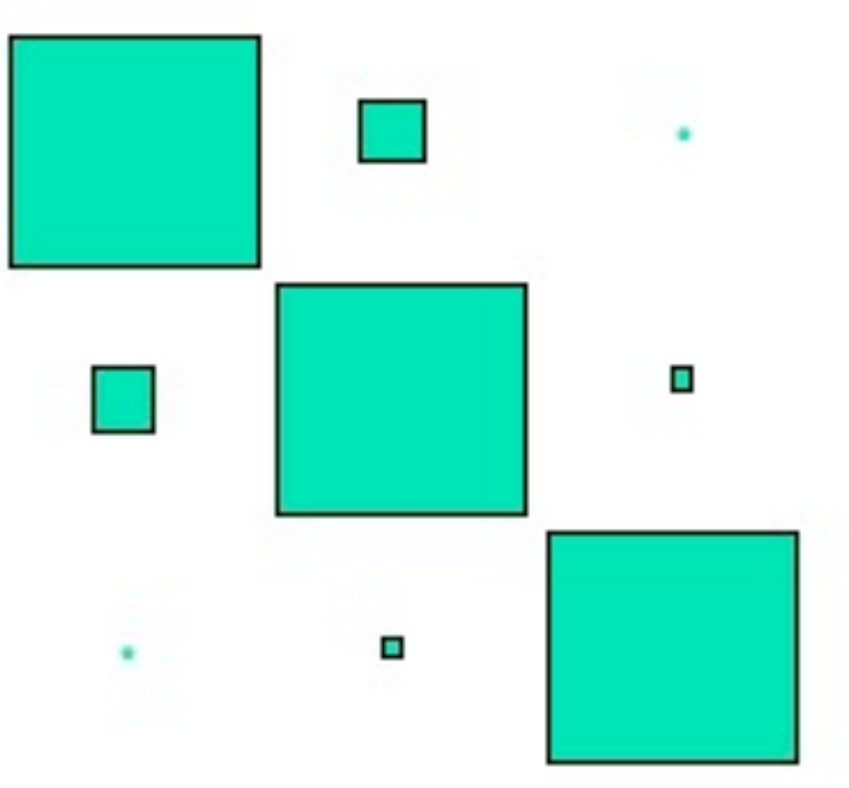

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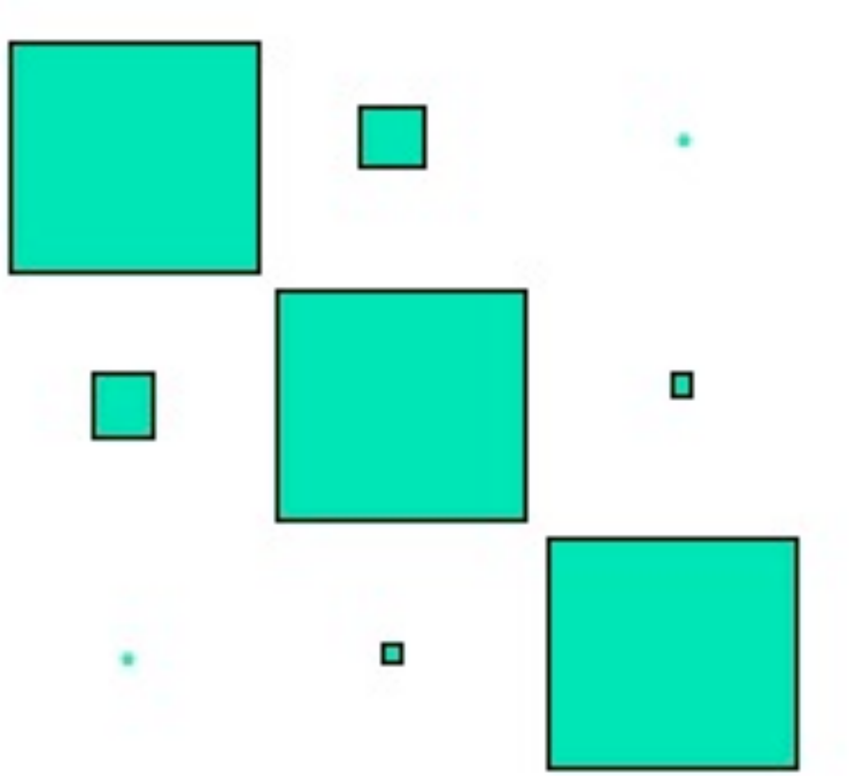

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"Most likely the solar neutrino problem has nothing whatsoever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, within a factor of 2 or 3."

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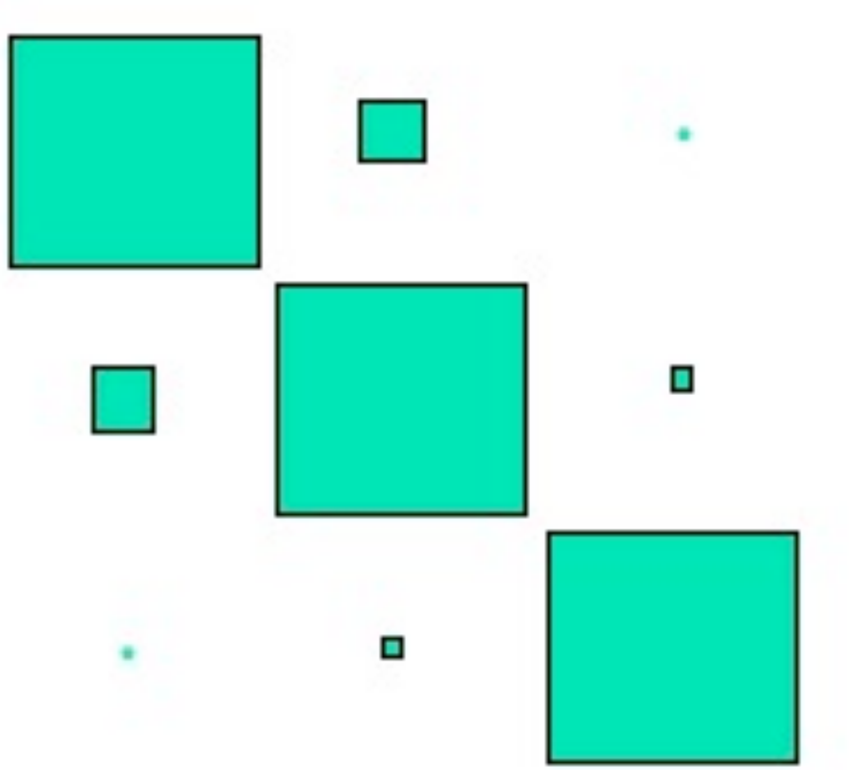

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Initial Ideas

- The idea to use pion decays (produced in accelerators) as source of neutrinos was initially proposed independently by Pontecorvo and Schwartz in the 1950's
- The motivation focused on clean study of weak decays (Schwartz) and also on specific study of studying ν_μ interactions (Pontecorvo)

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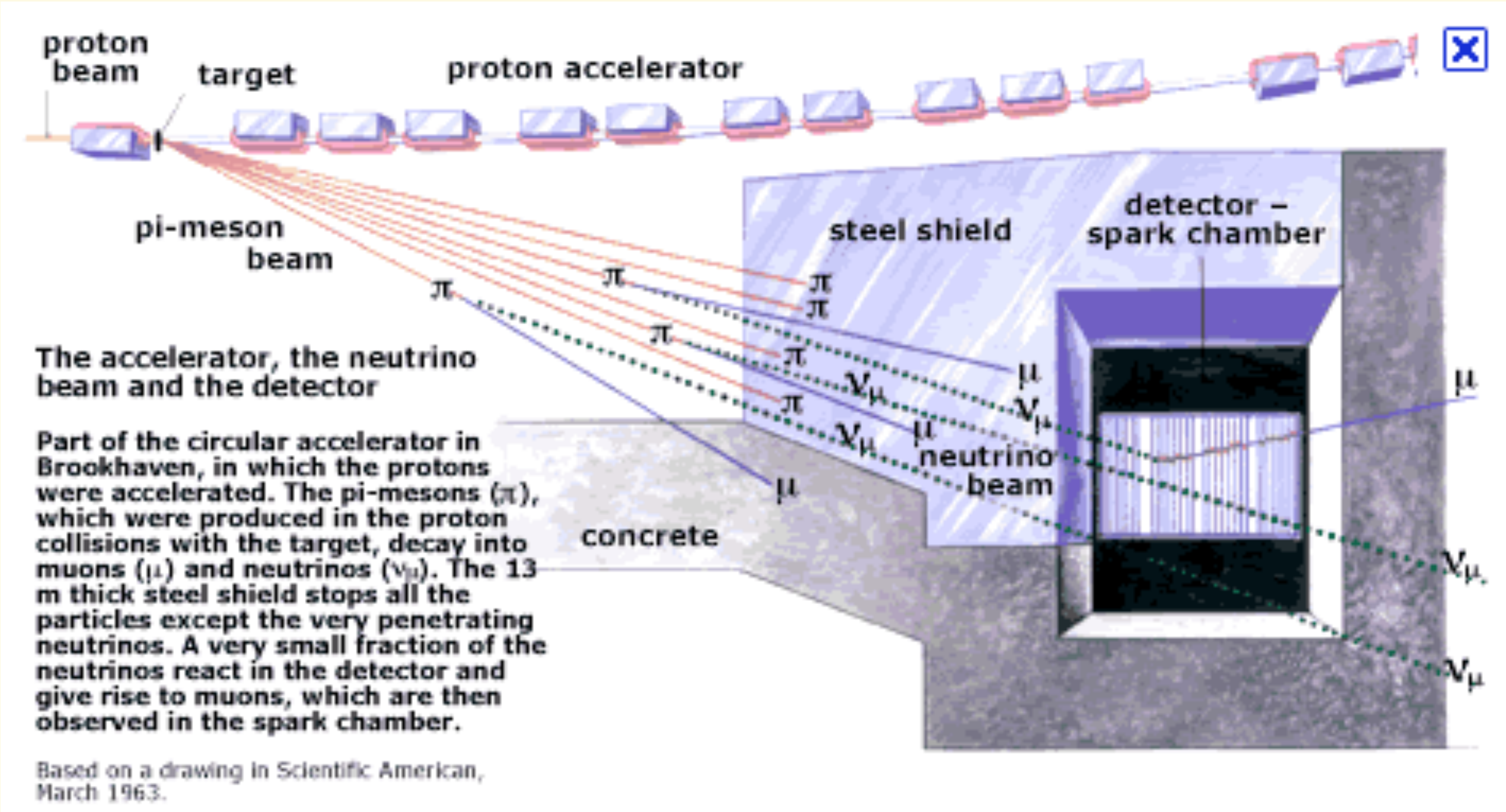

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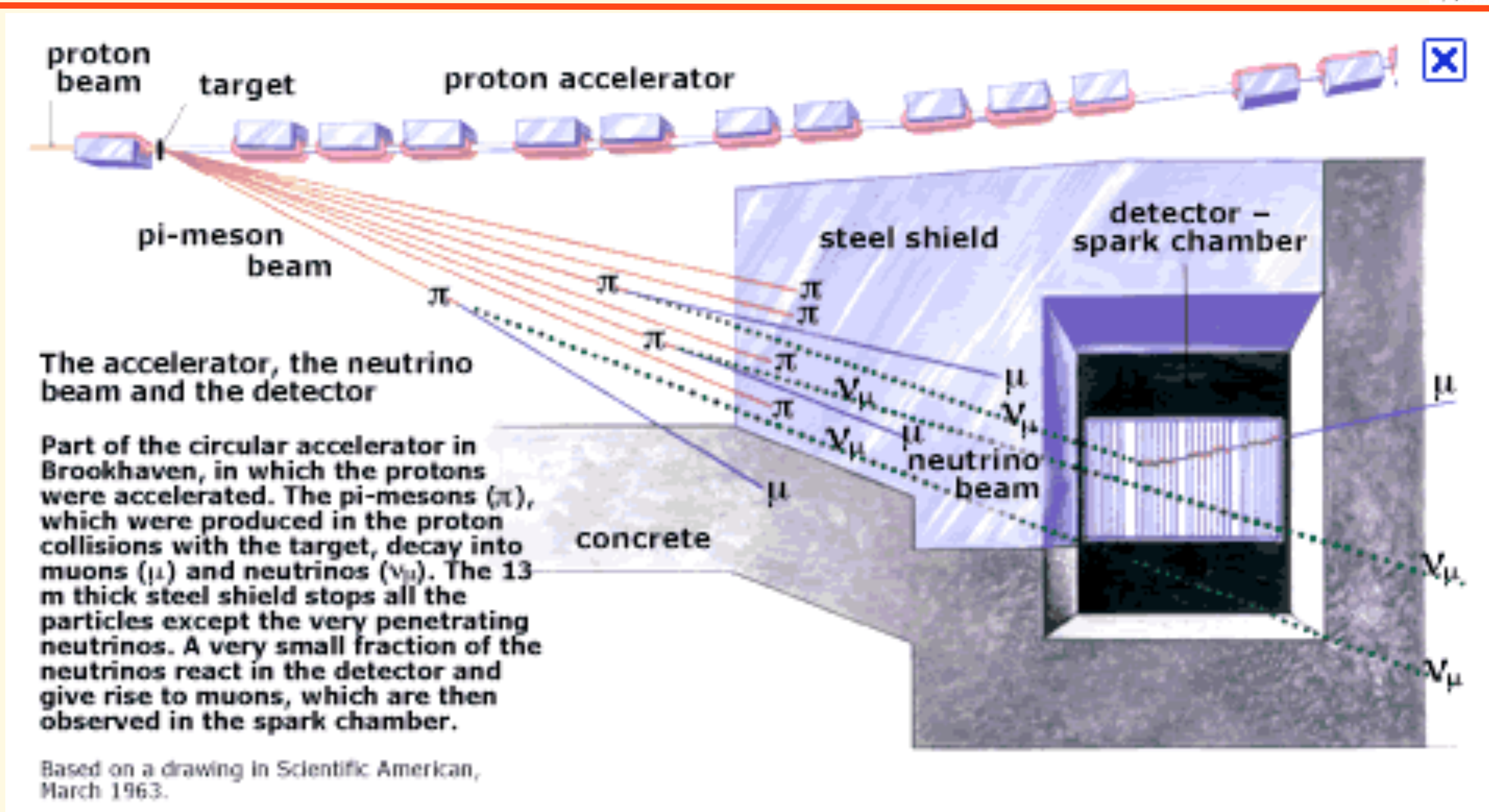

No electrons observed, only muons

Hence there must be at least 2 neutrinos, ν_μ and ν_e

More about BNL Expt

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The principal authors: Steinberger, Schwartz, Lederman

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- Extraction of accelerated proton beam
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  - Allowed greater flexibility in target and focusing
  - Allowed creation of 0^{o} neutrino beams
- Significant increase in the accelerated proton intensity and energy

Accelerator neutrinos

Technical details

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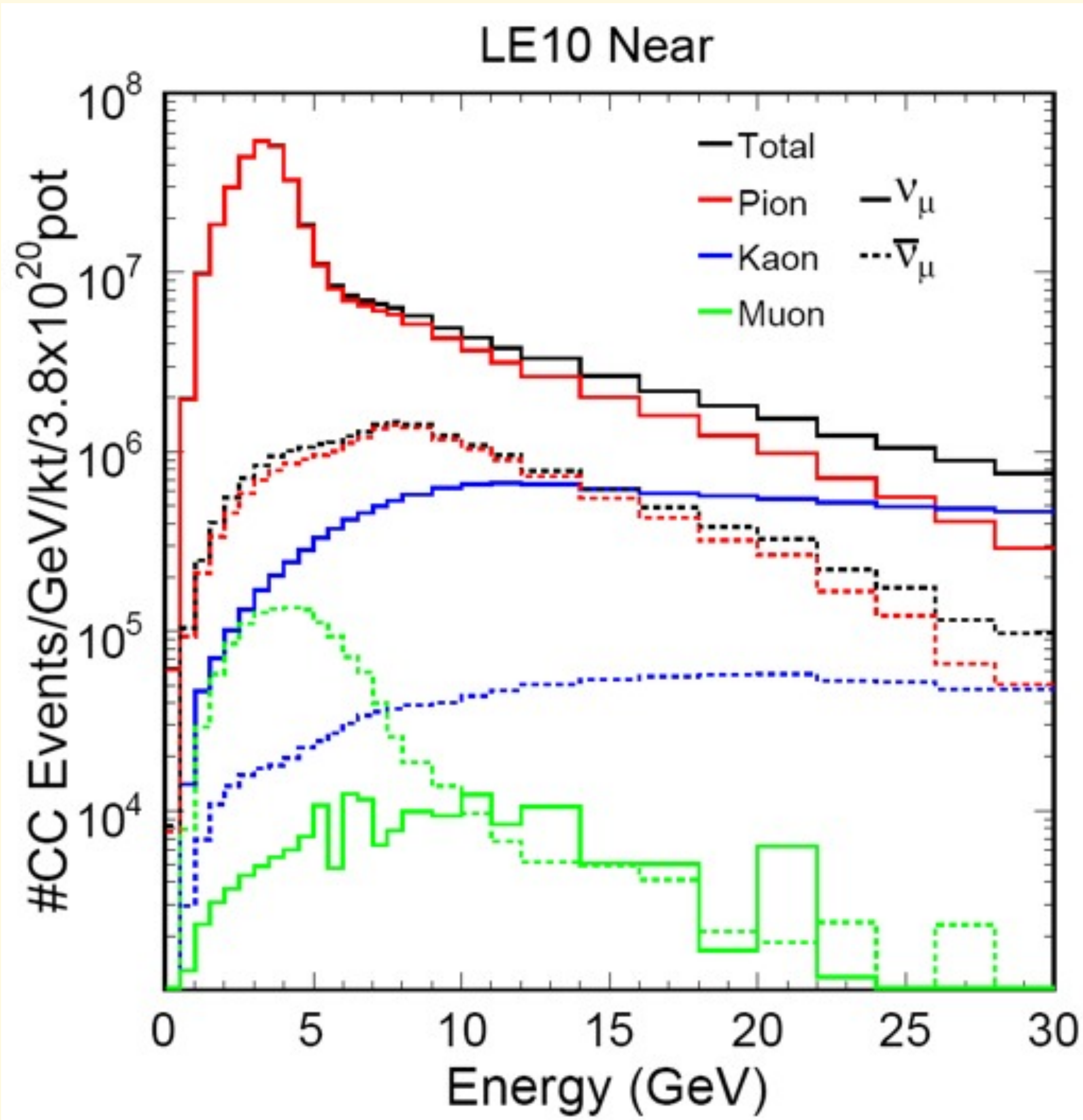
Secondary sources (last 2 important for ν_e's):

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

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

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

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

$E_\nu < E_K$

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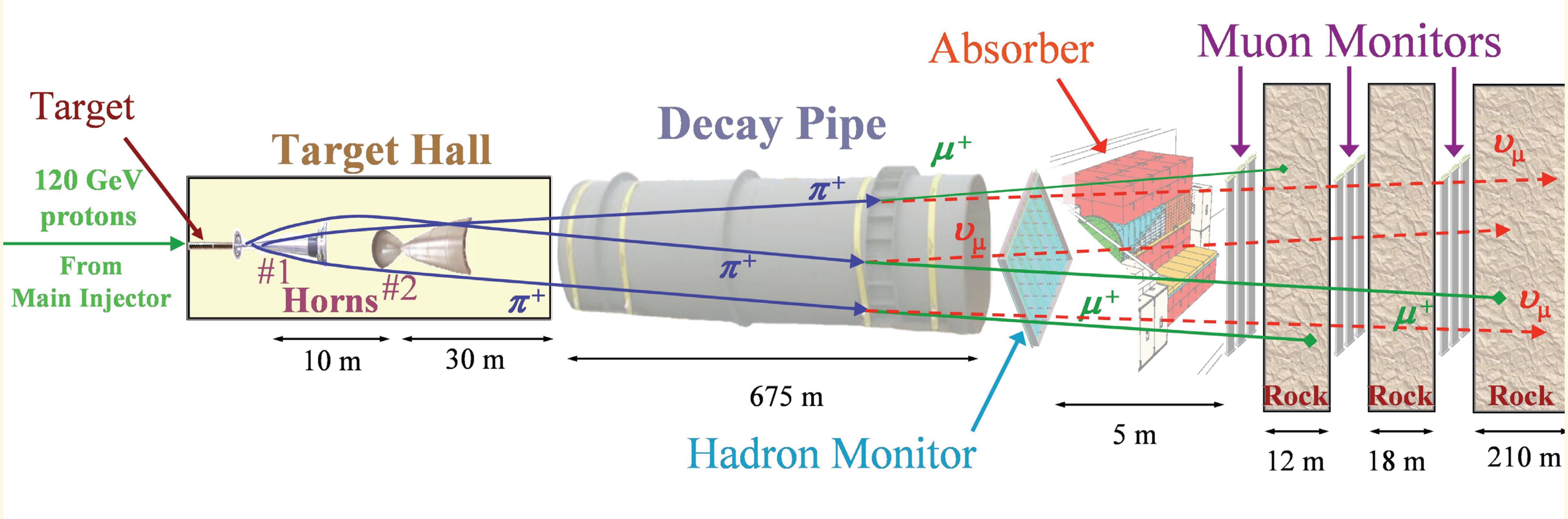

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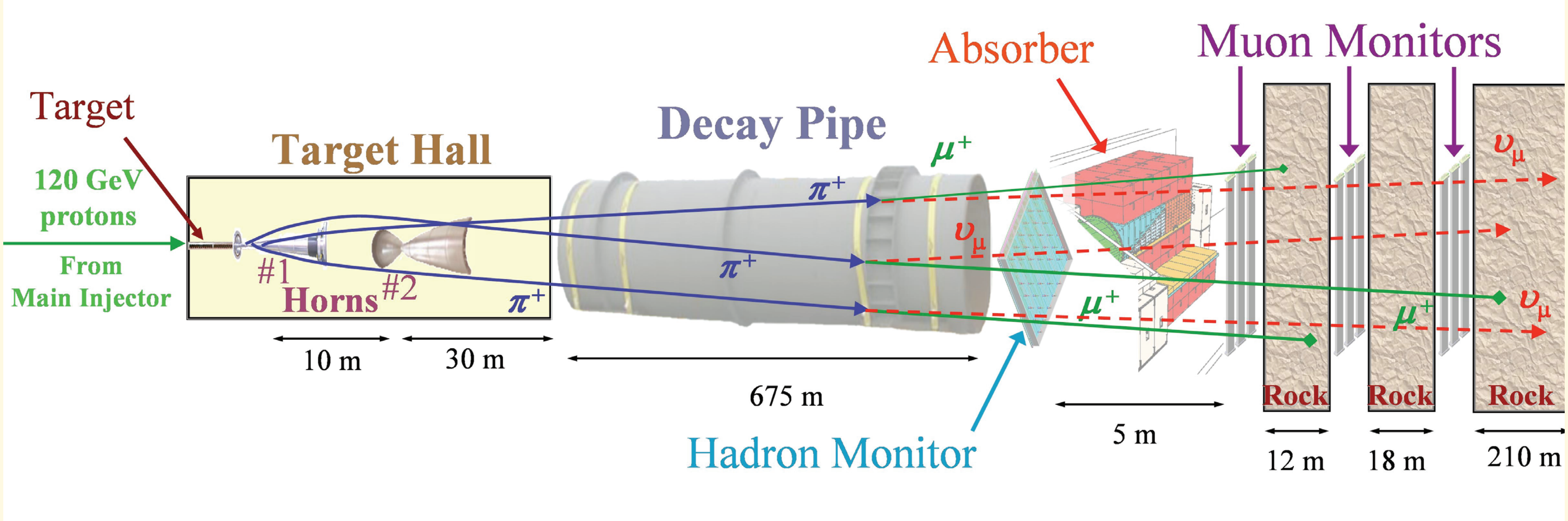

Target - interact protons, produce π and K mesons
Focusing horns - focus mesons with desired energies and charge
Decay pipe - allow mesons to decay into neutrinos; vacuum or He
Hadron monitor - used for tuning and monitoring total flux
Absorber - absorb residual protons and undecayed mesons
Muon monitors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

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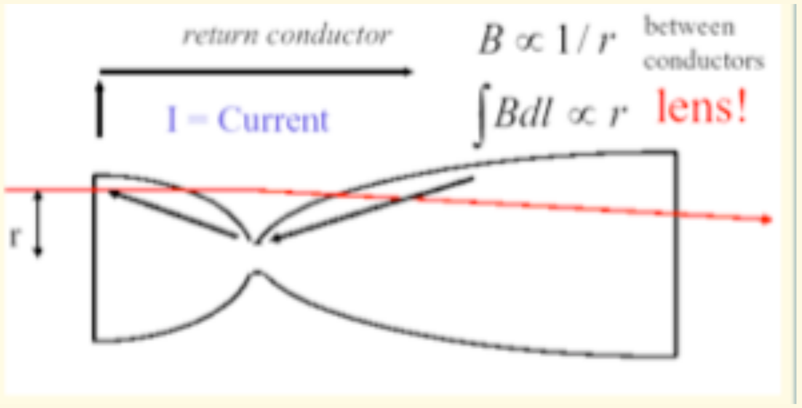

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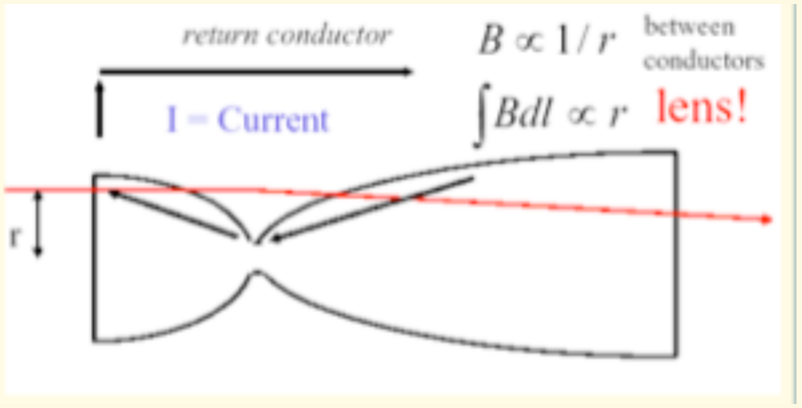

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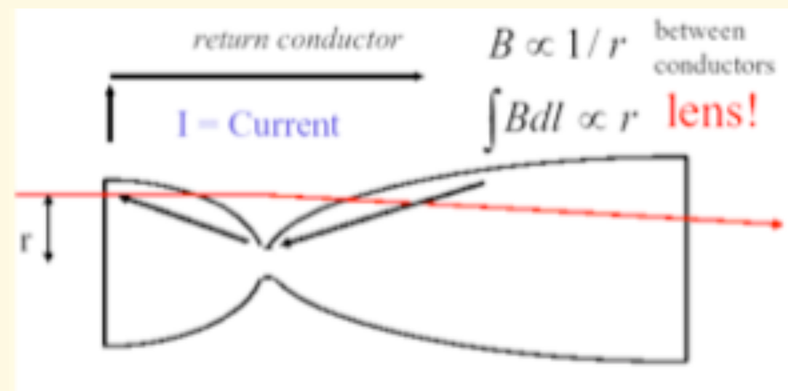

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$$\theta = p_T^{beam} / p = r / z \qquad p_T^{horn} \alpha \int B\,dl = k \frac{1}{r} r^2 = kr$$

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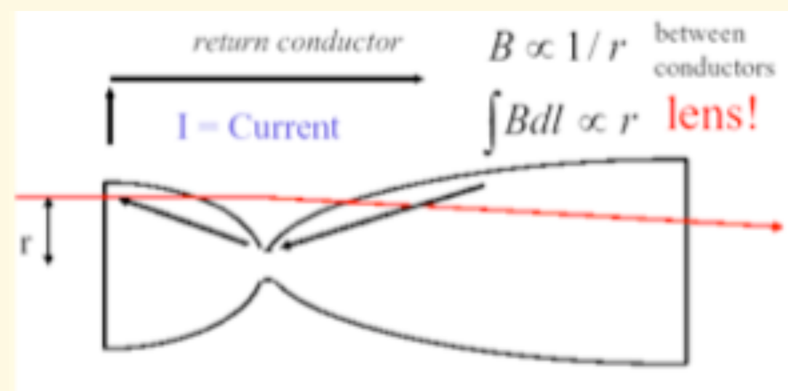

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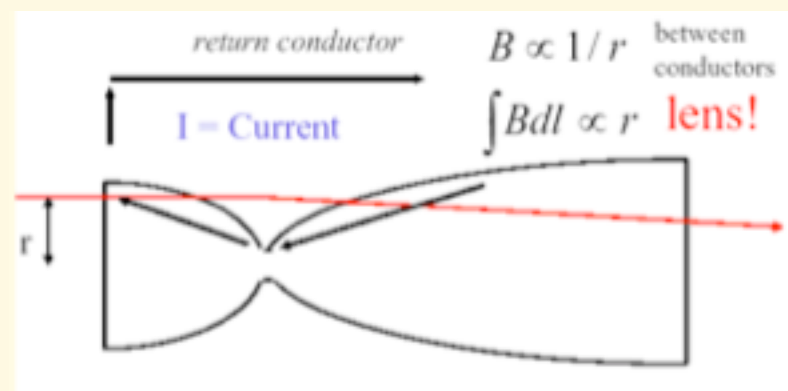

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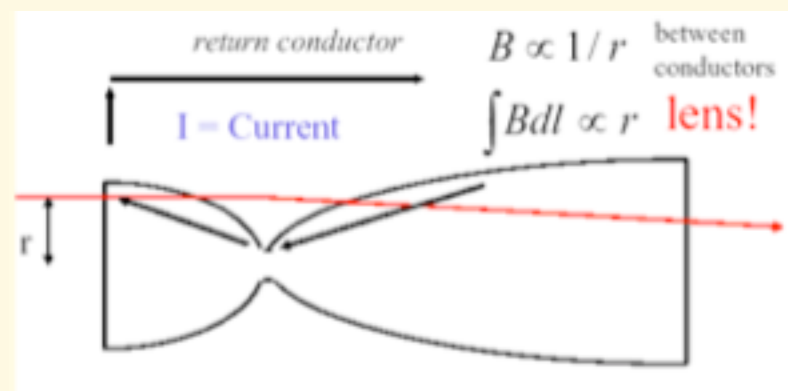

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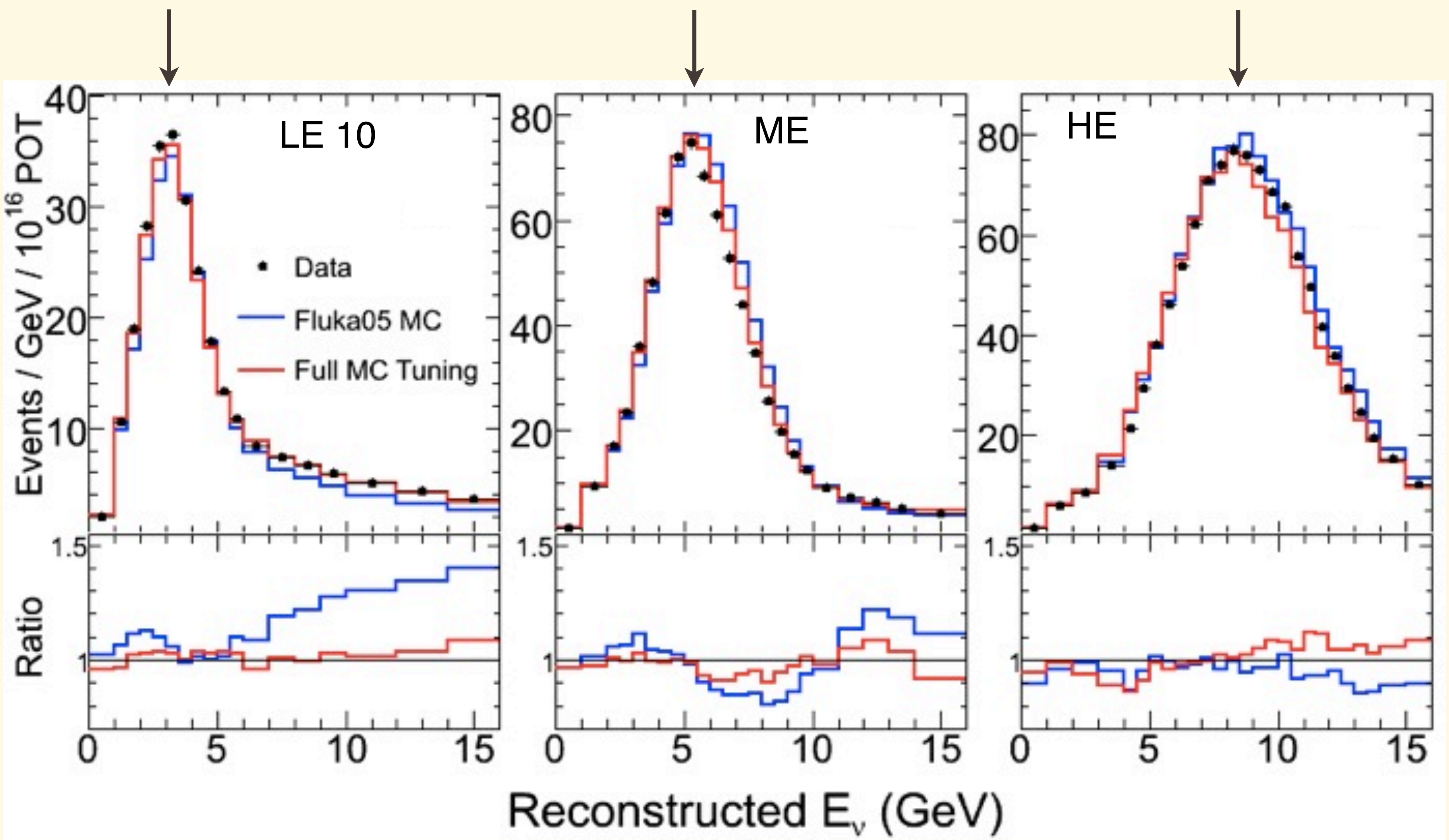
Example: NuMI Beam

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

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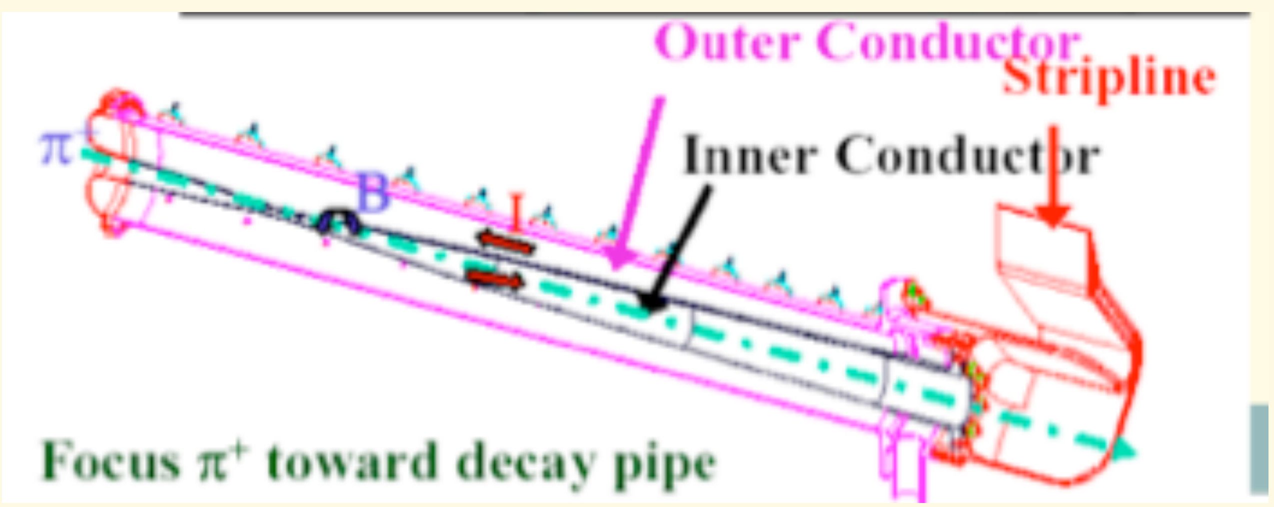

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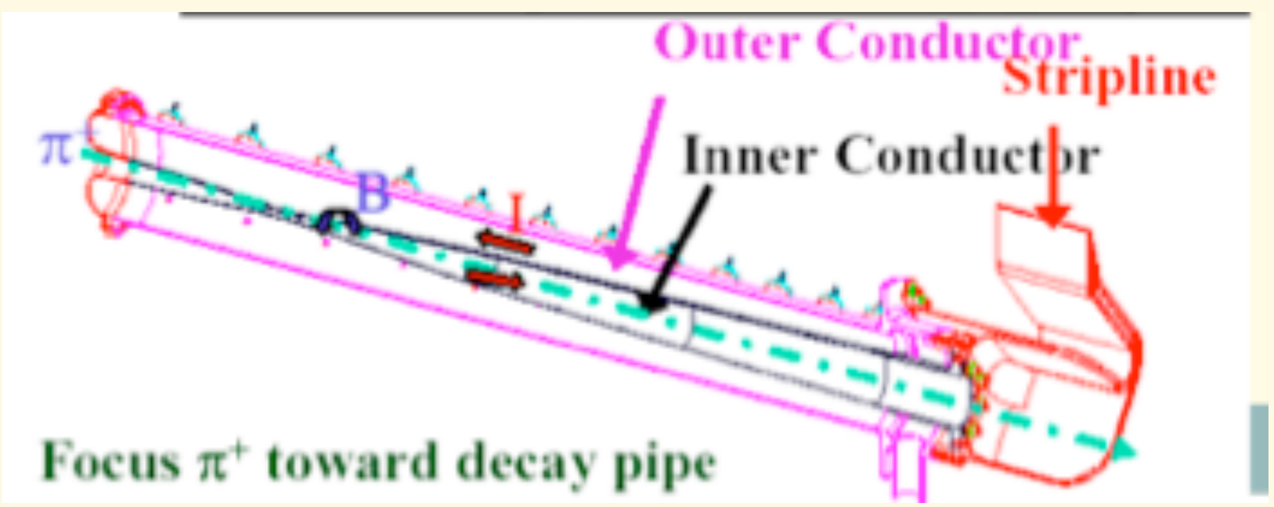
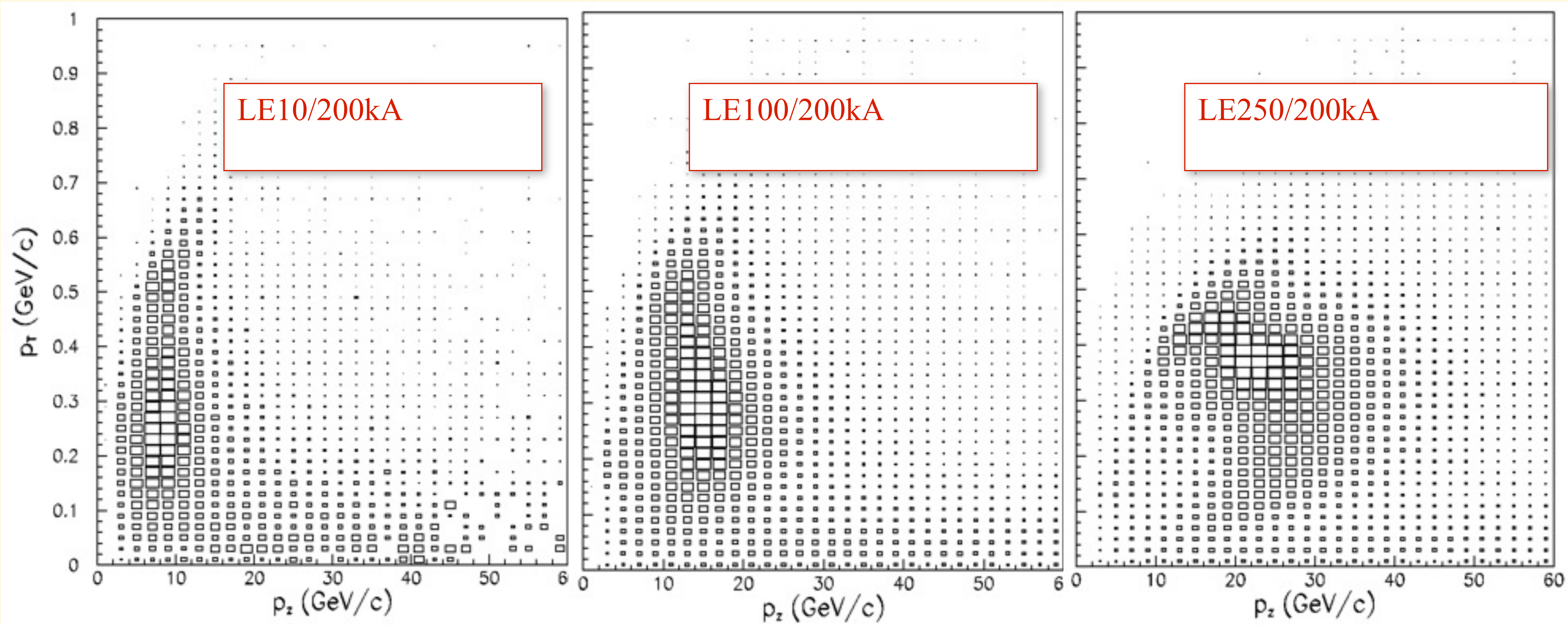
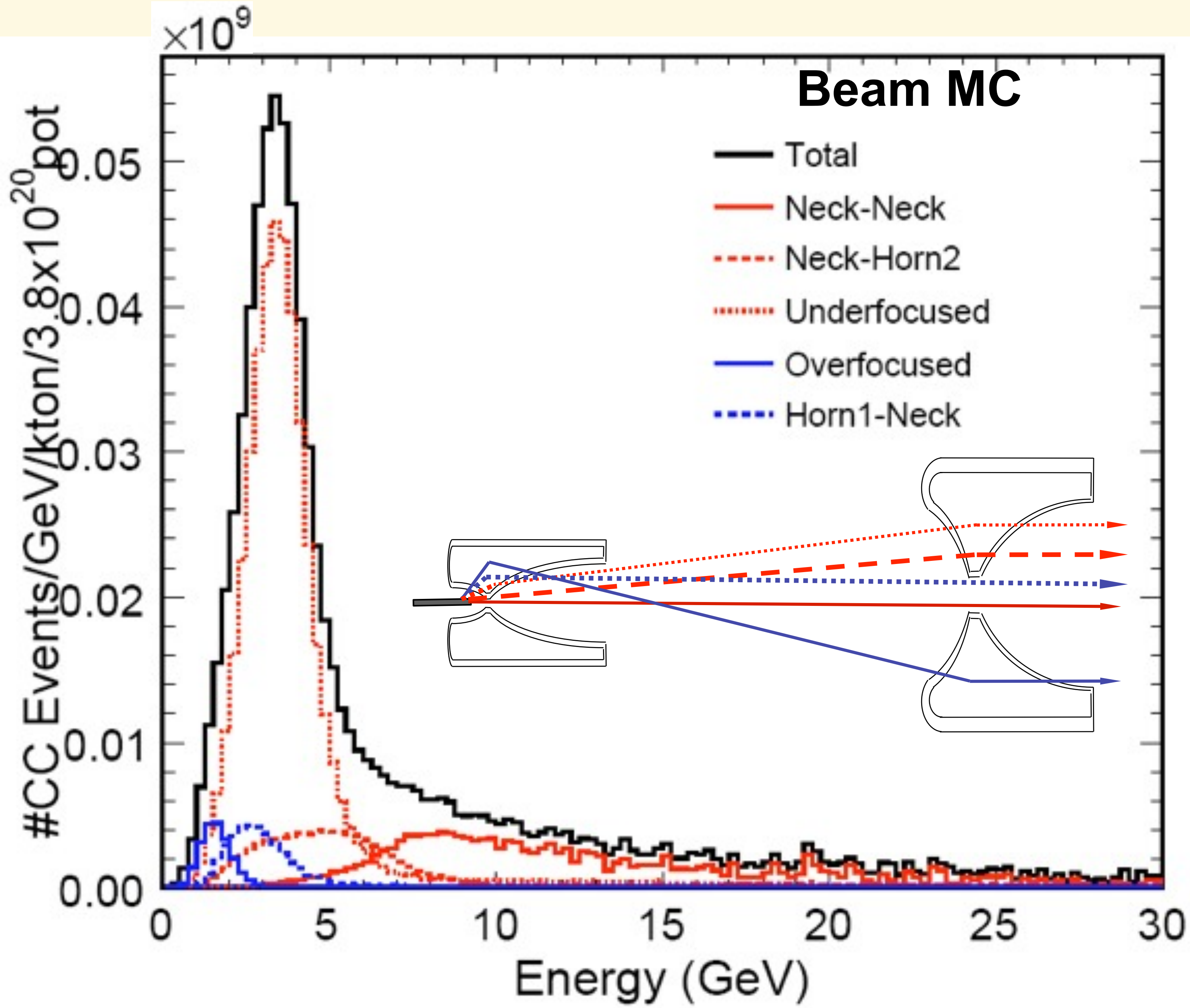


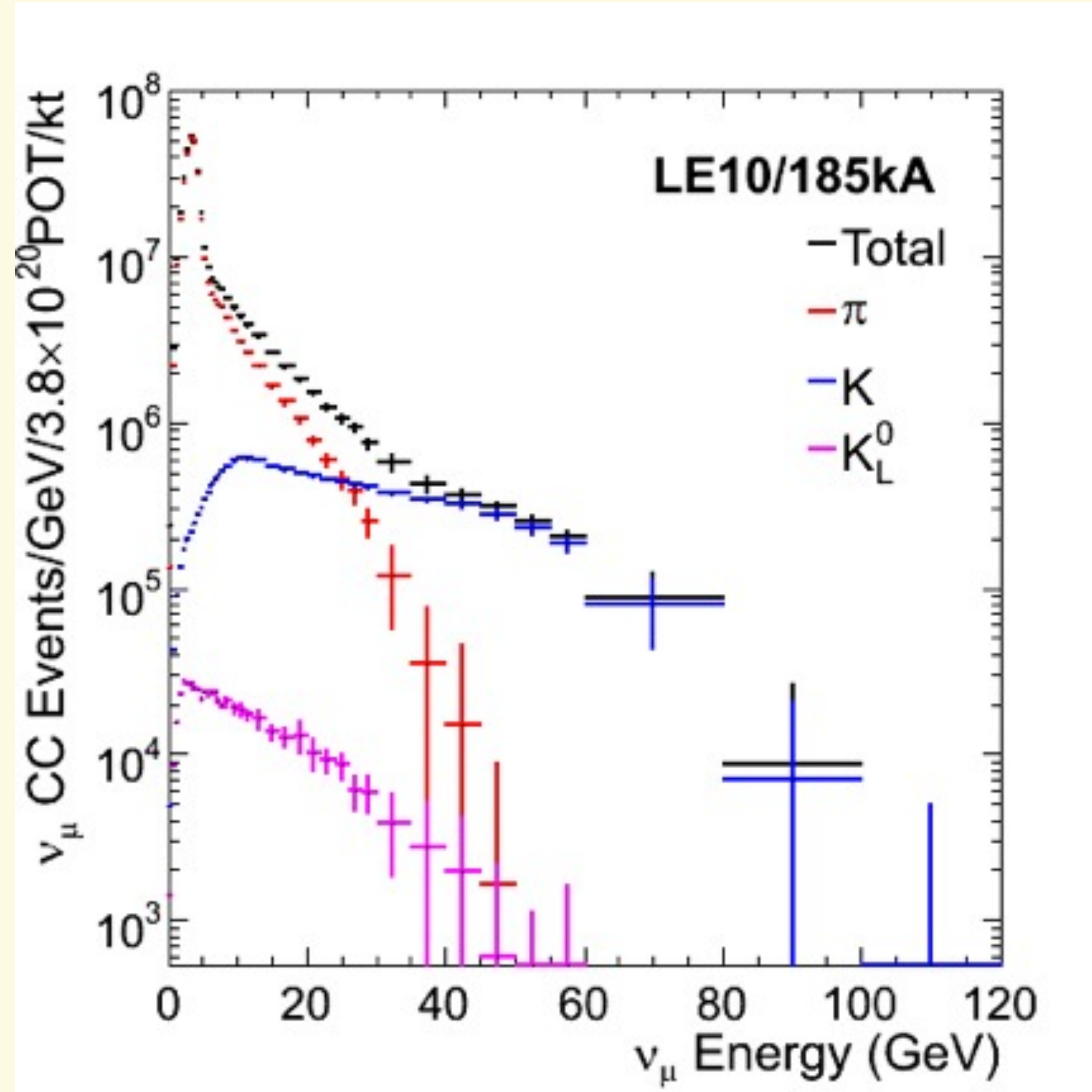
P_T - P_z Distributions



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





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  - Off-axis beam; the detector is positioned at a small angle away from the beam axis. This enhances a narrow band of neutrino energies

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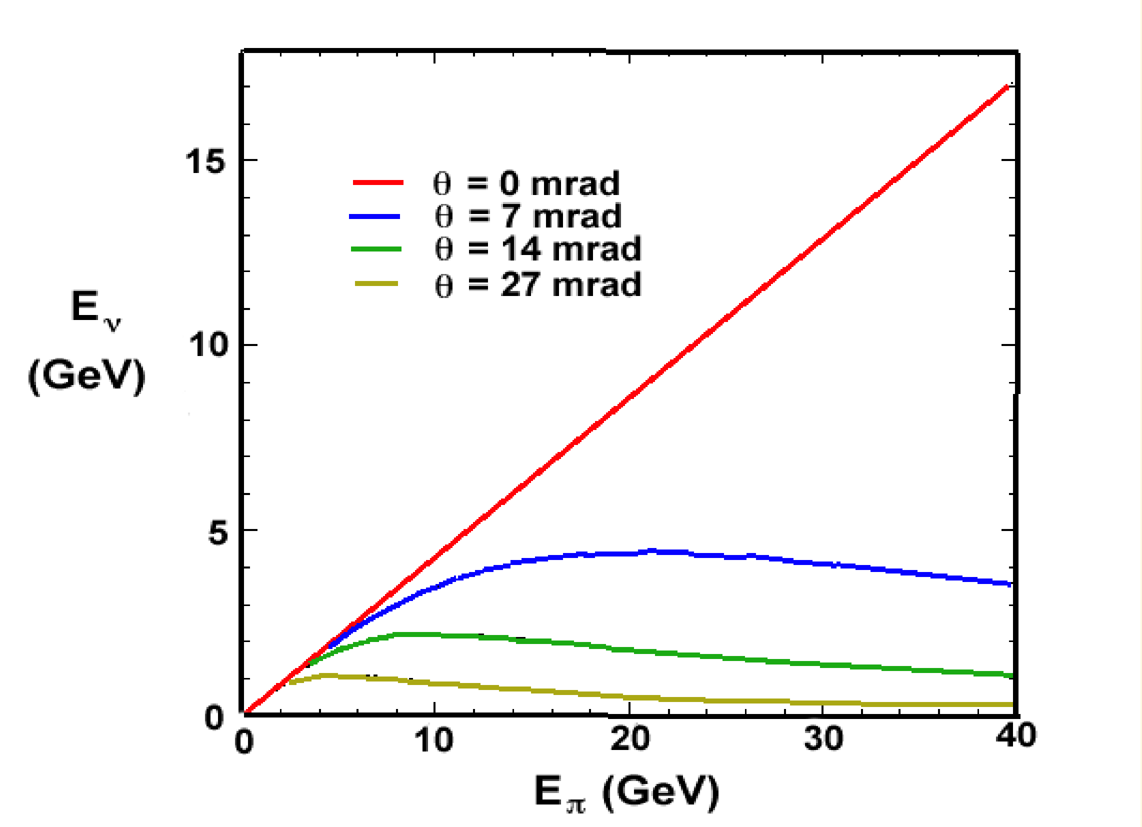

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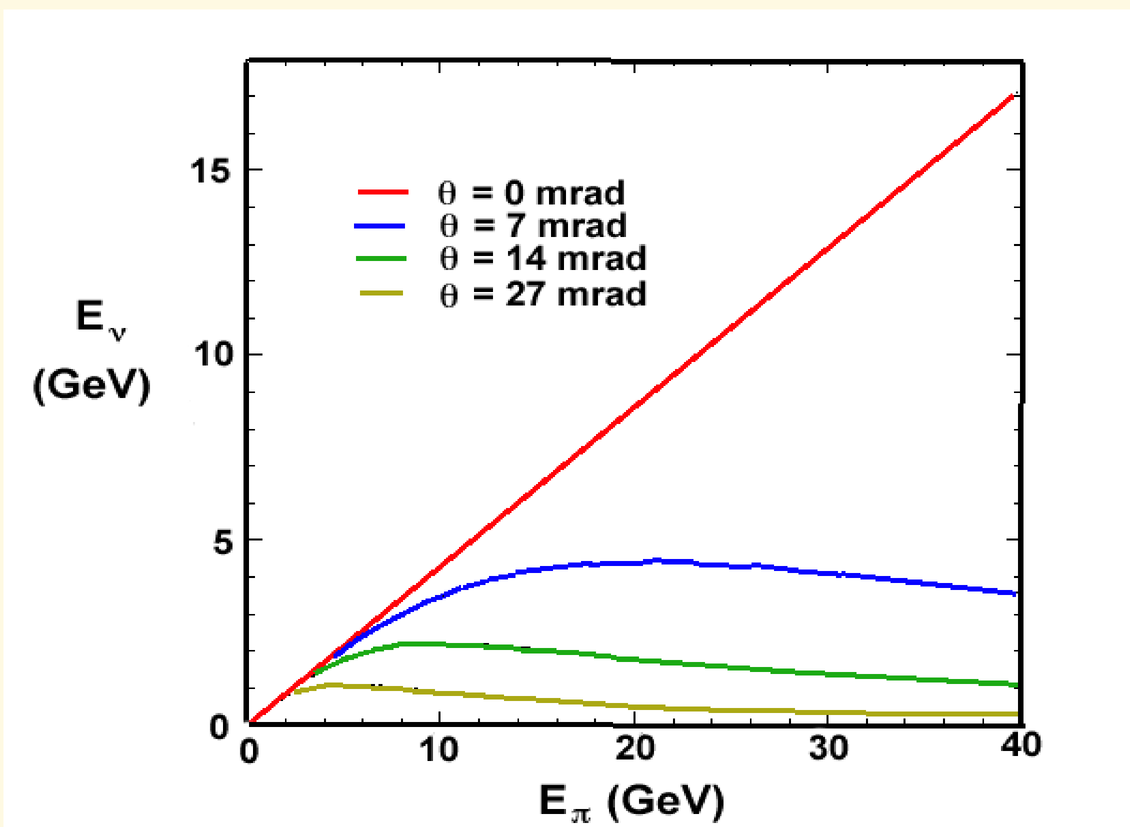

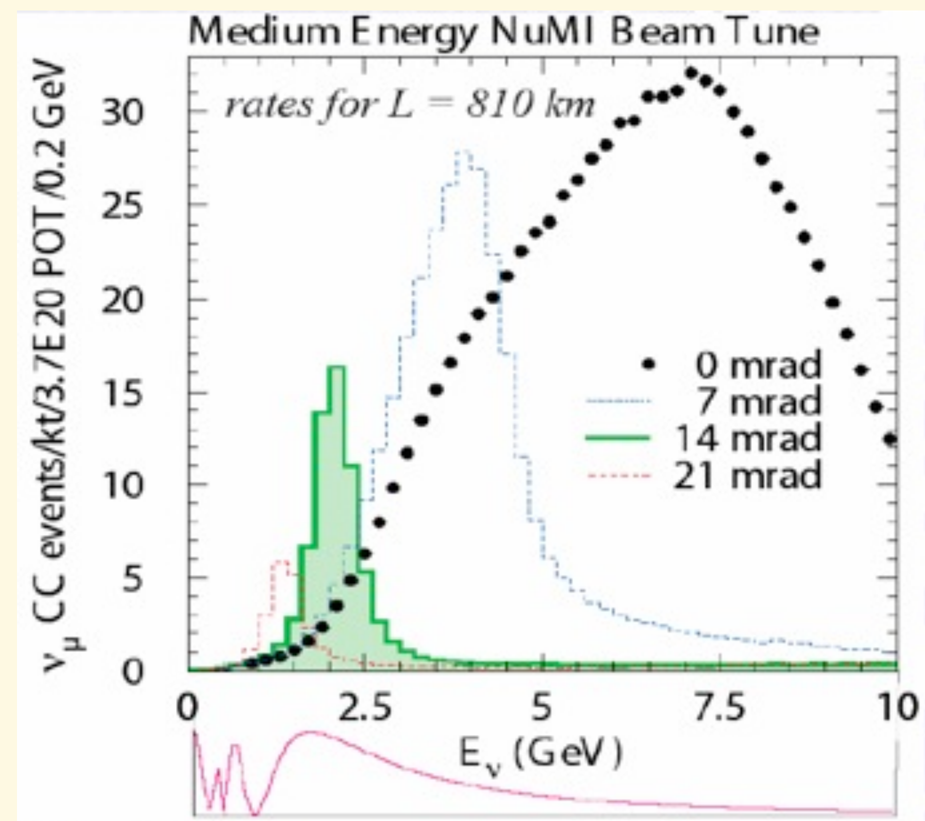

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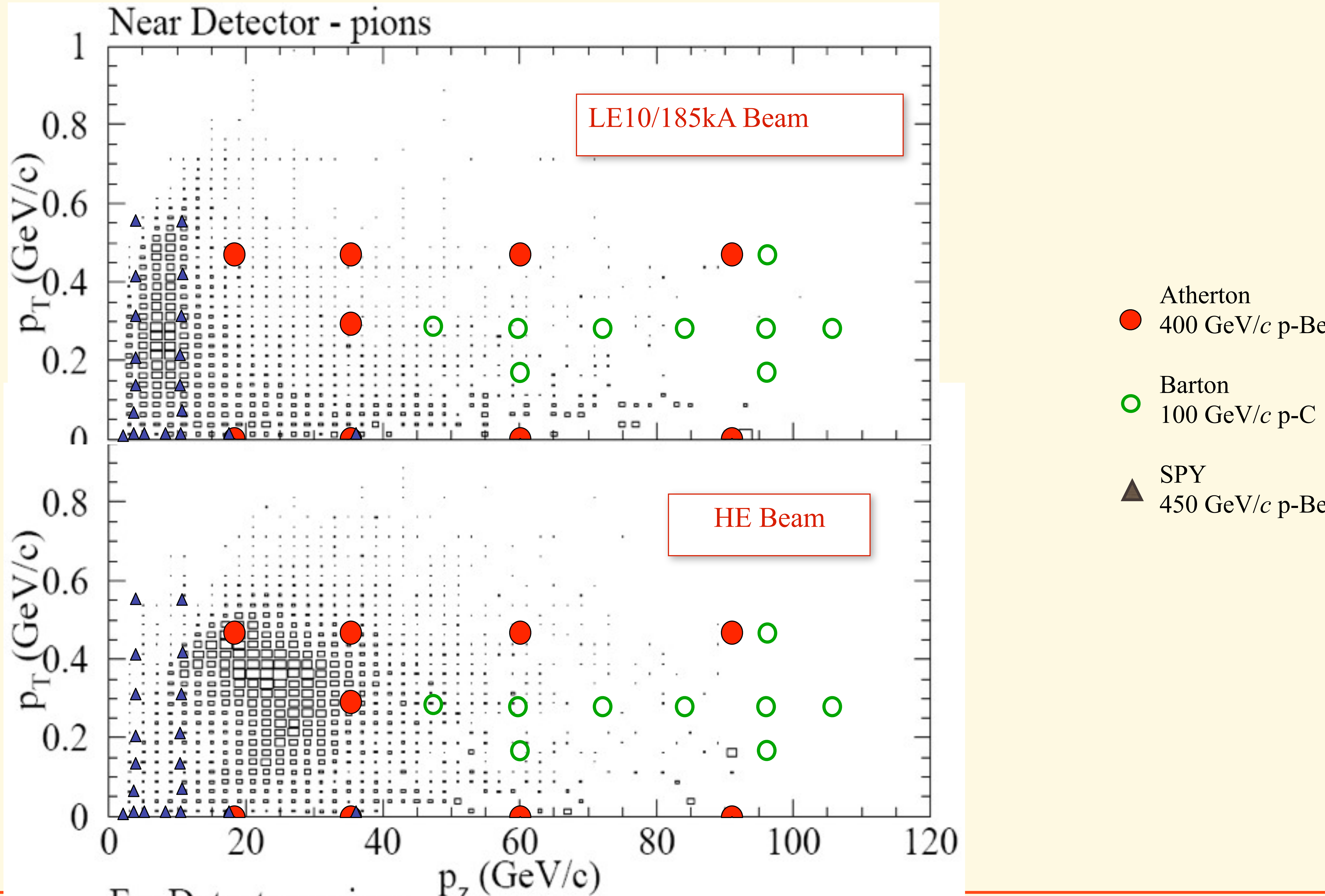
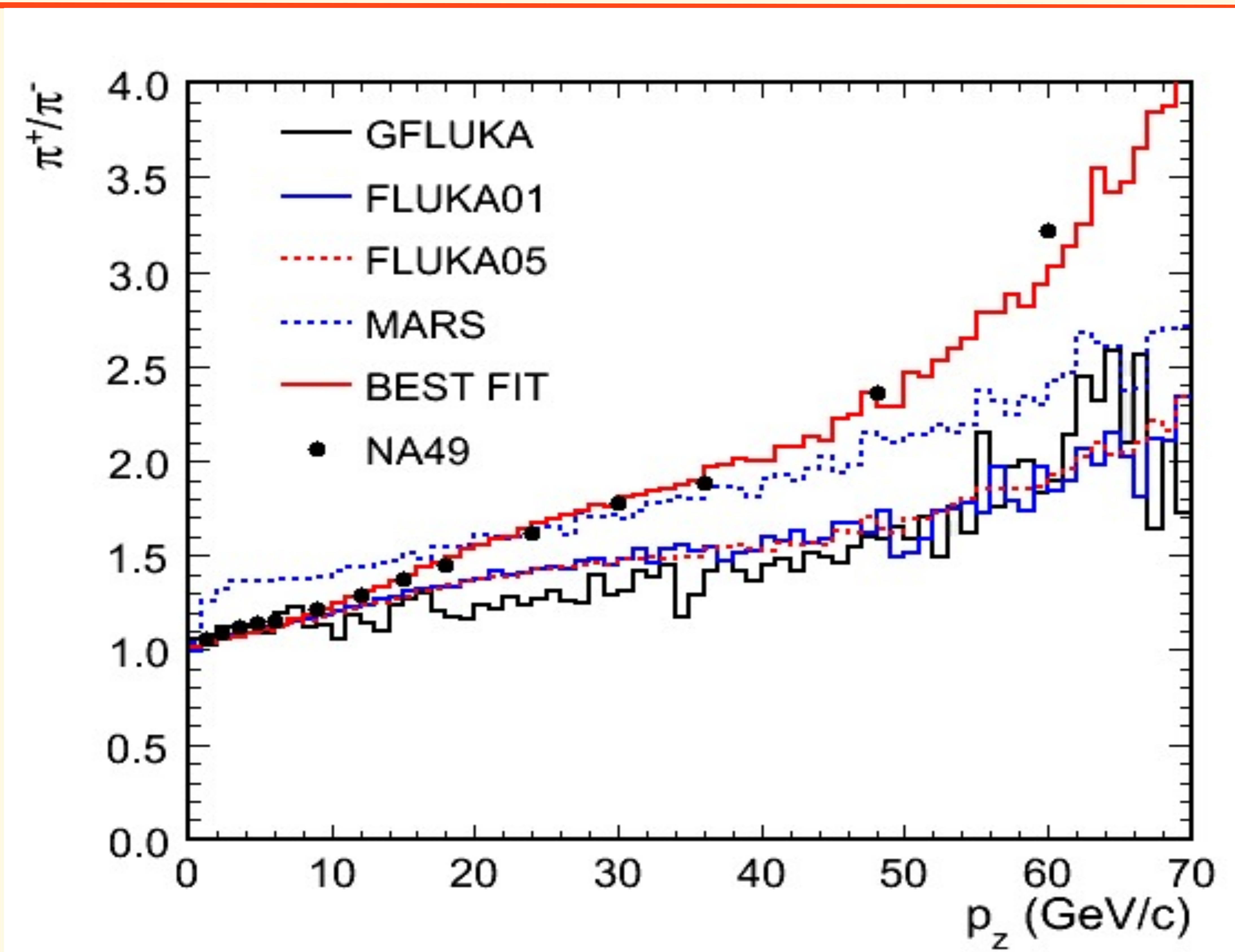
- 2 detector configuration, allowing extraction of Far Detector flux from Near Detector data appears to be the currently favored method to do this for long baseline oscillation experiments

Available Production Data



NuMI spectra



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  - 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

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

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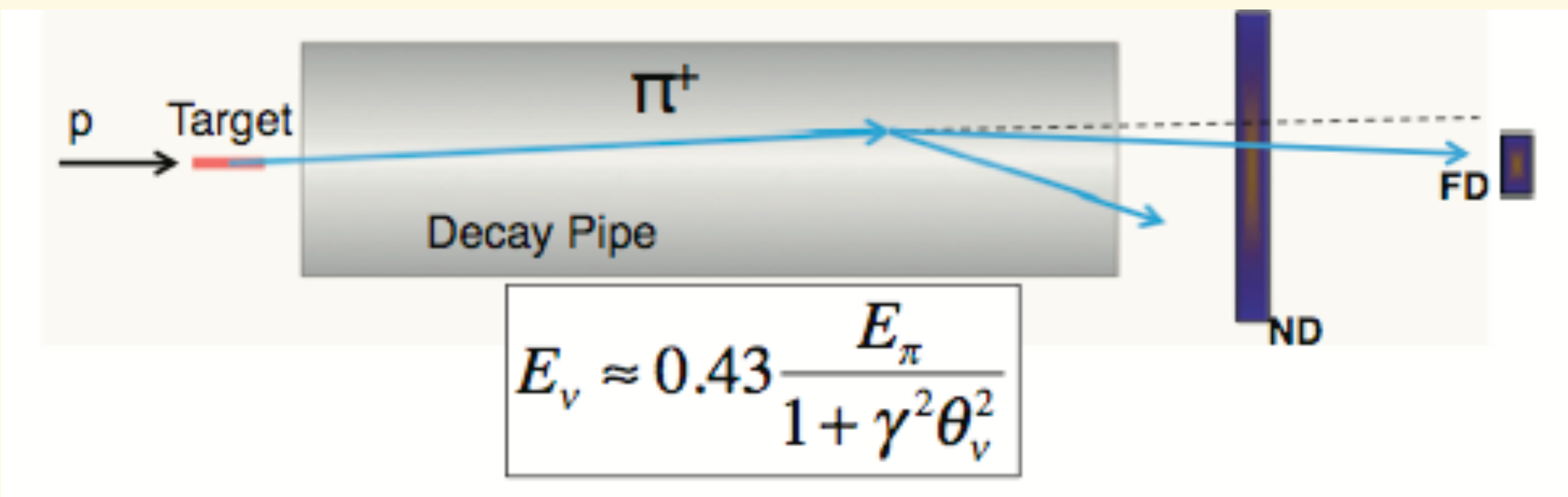
The spectra in the two detectors are similar but not identical in the two detectors

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

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The Far Detector flux can be obtained from:

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

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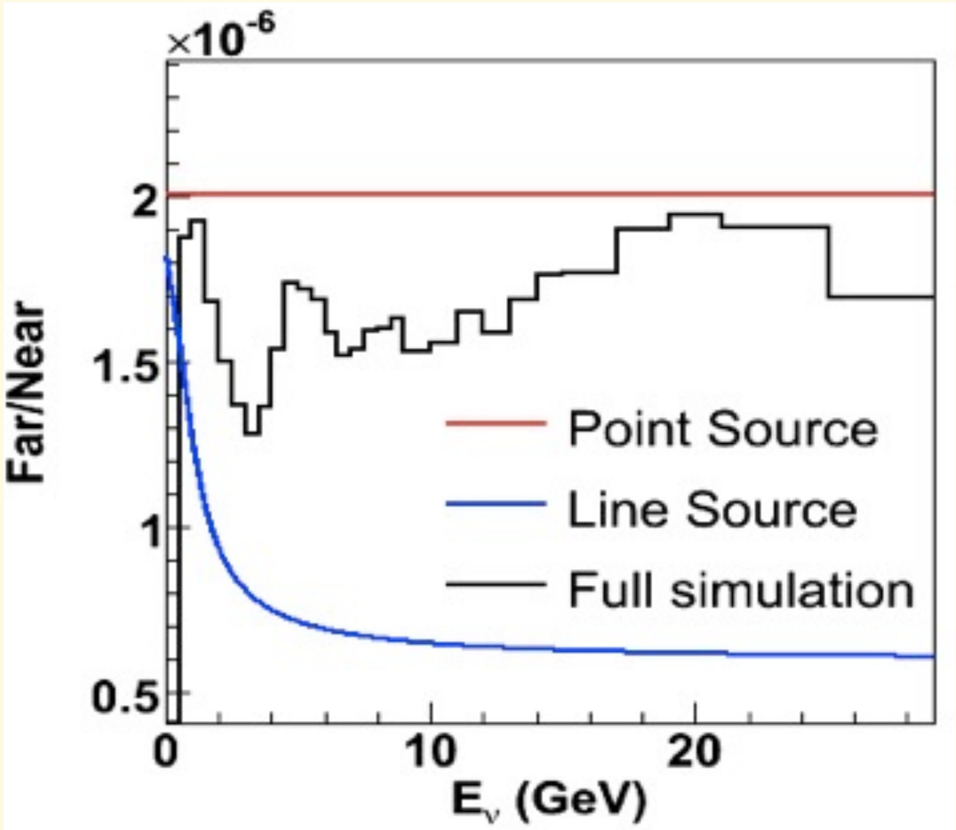

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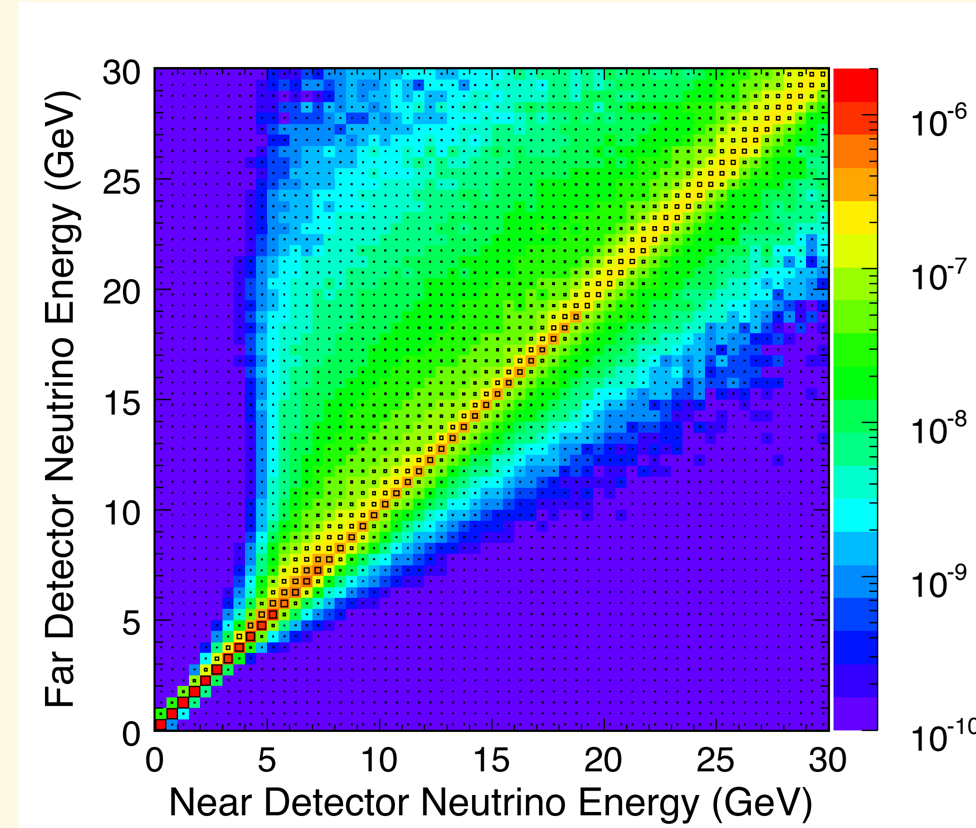

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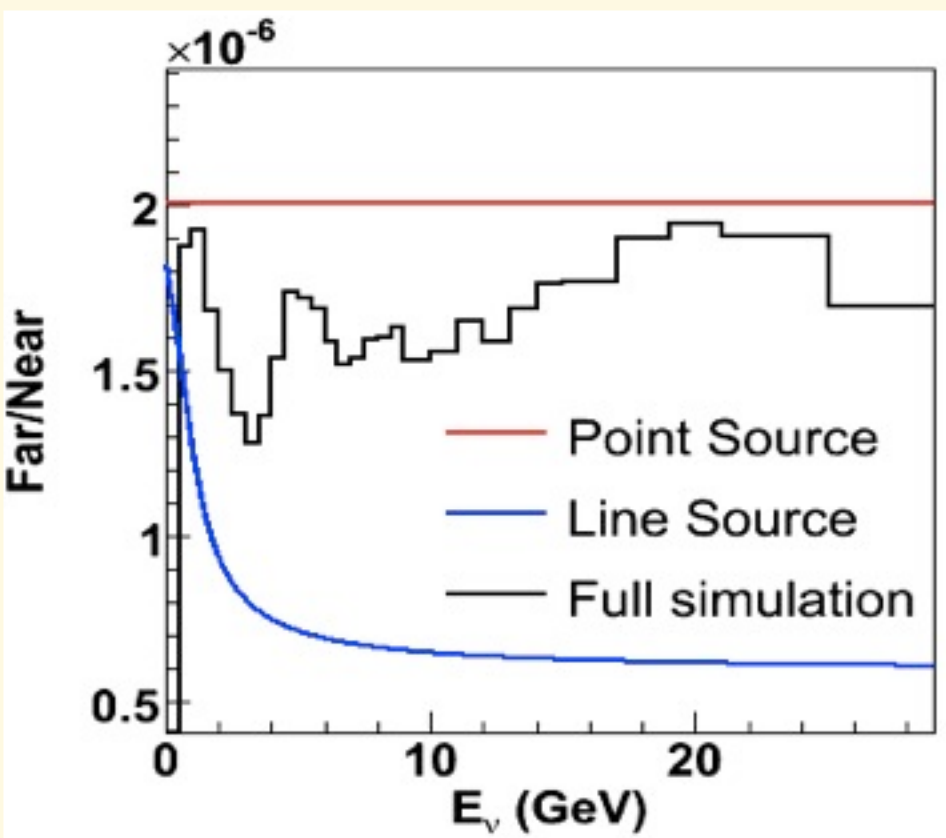

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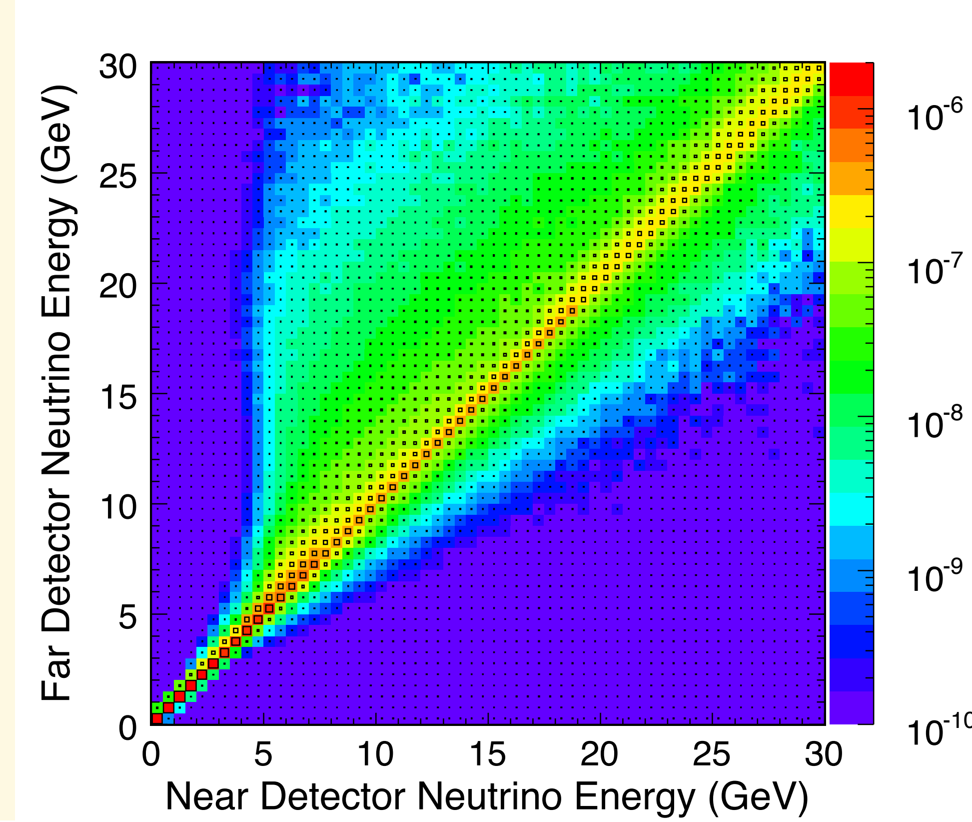

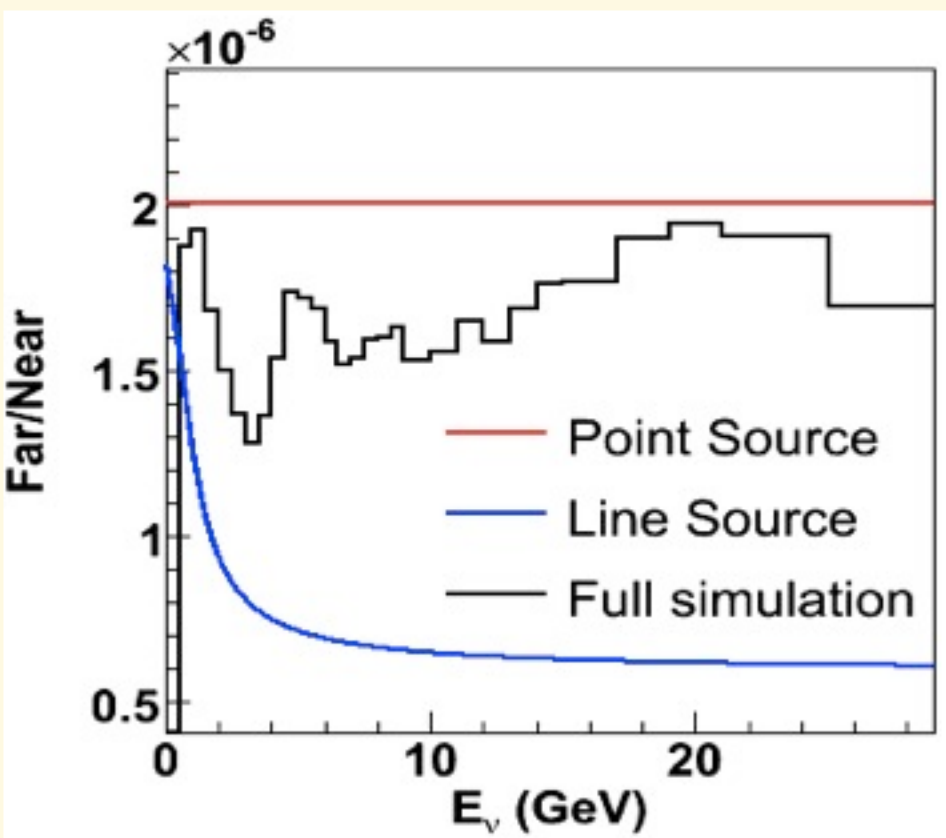

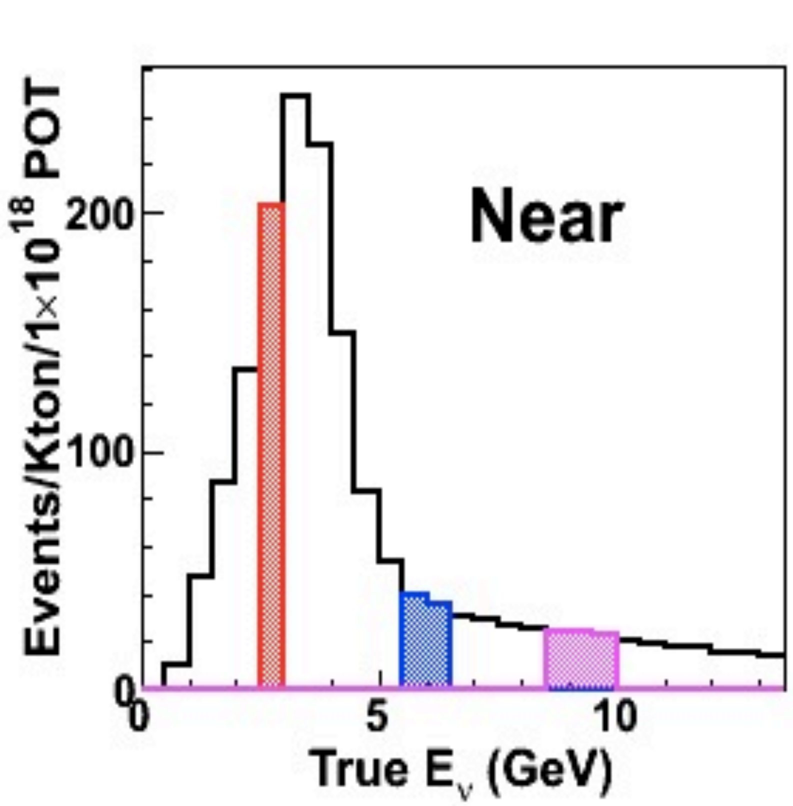

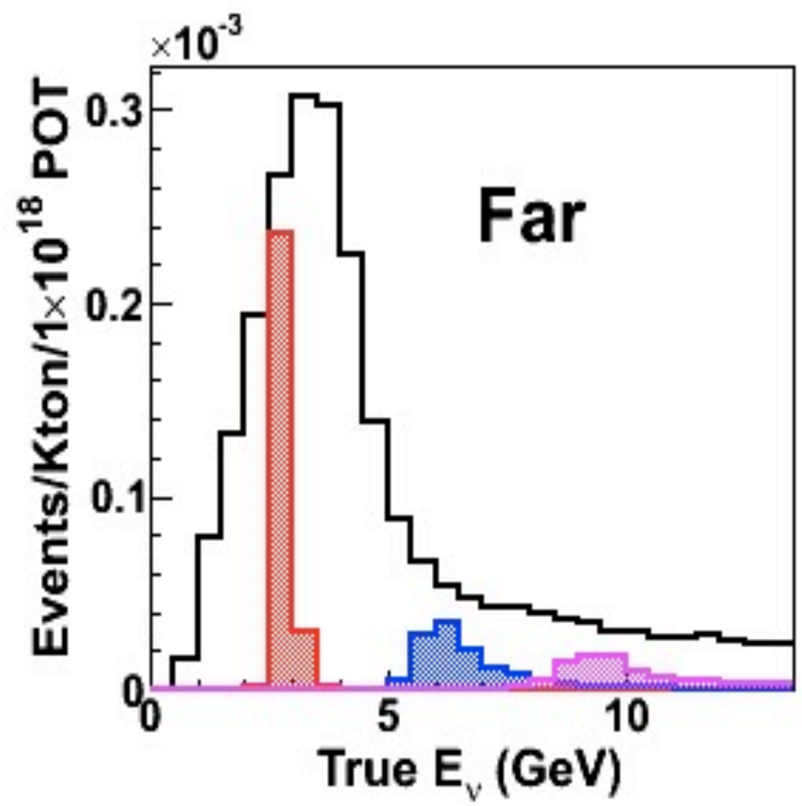

Studies of $\sin^2(2\theta_{23})$ and Δm^2_{31}

General Method

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

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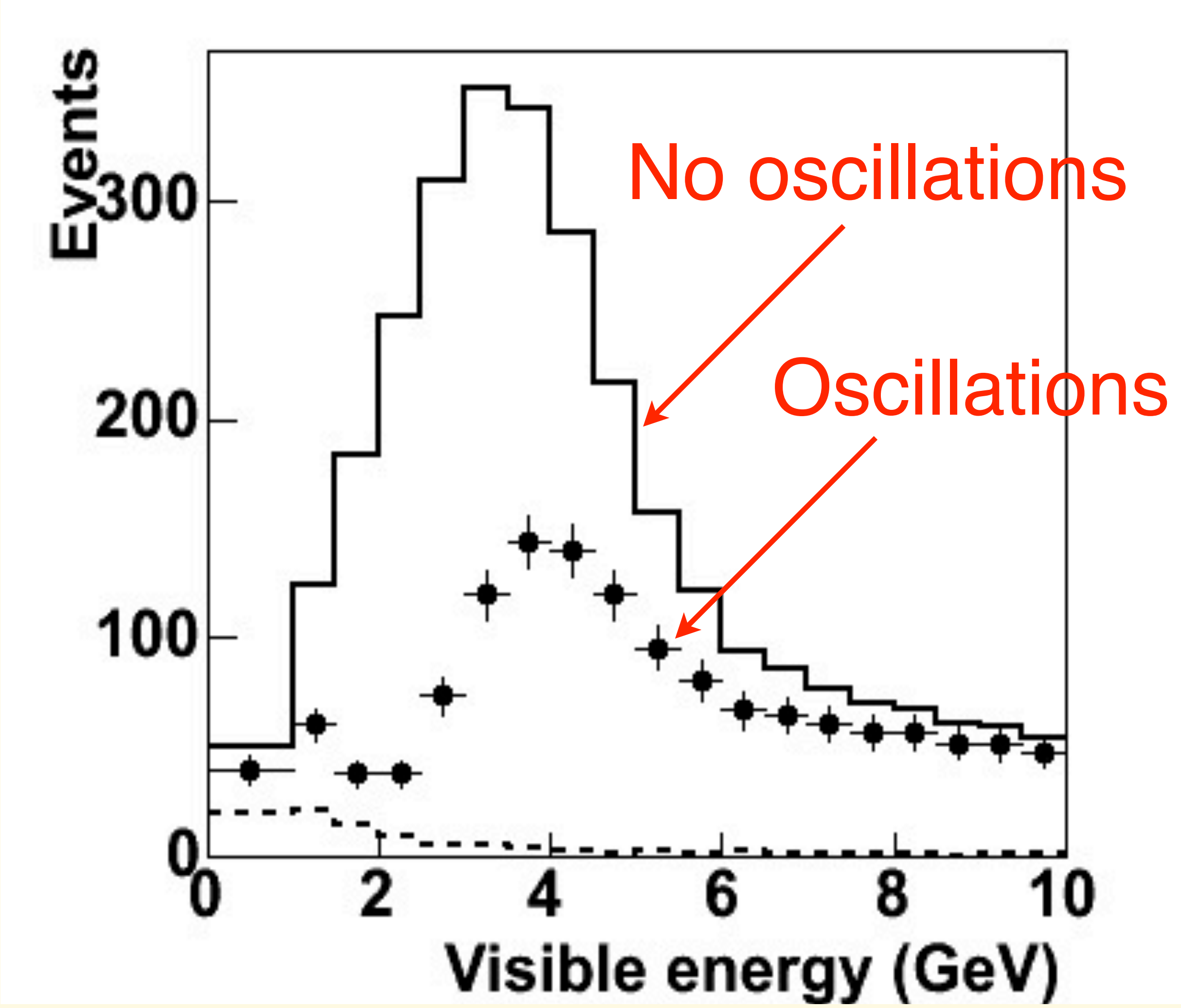

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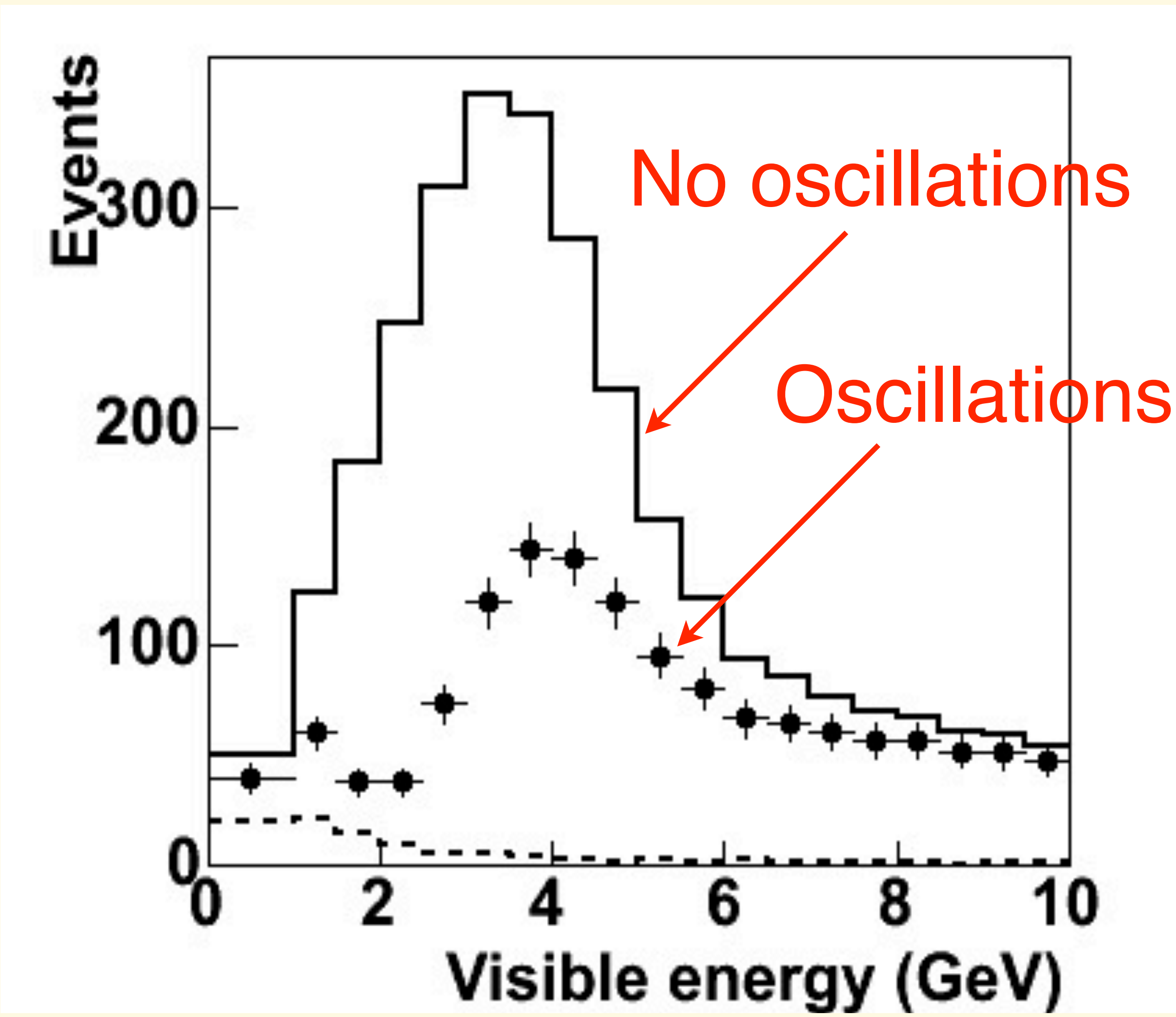

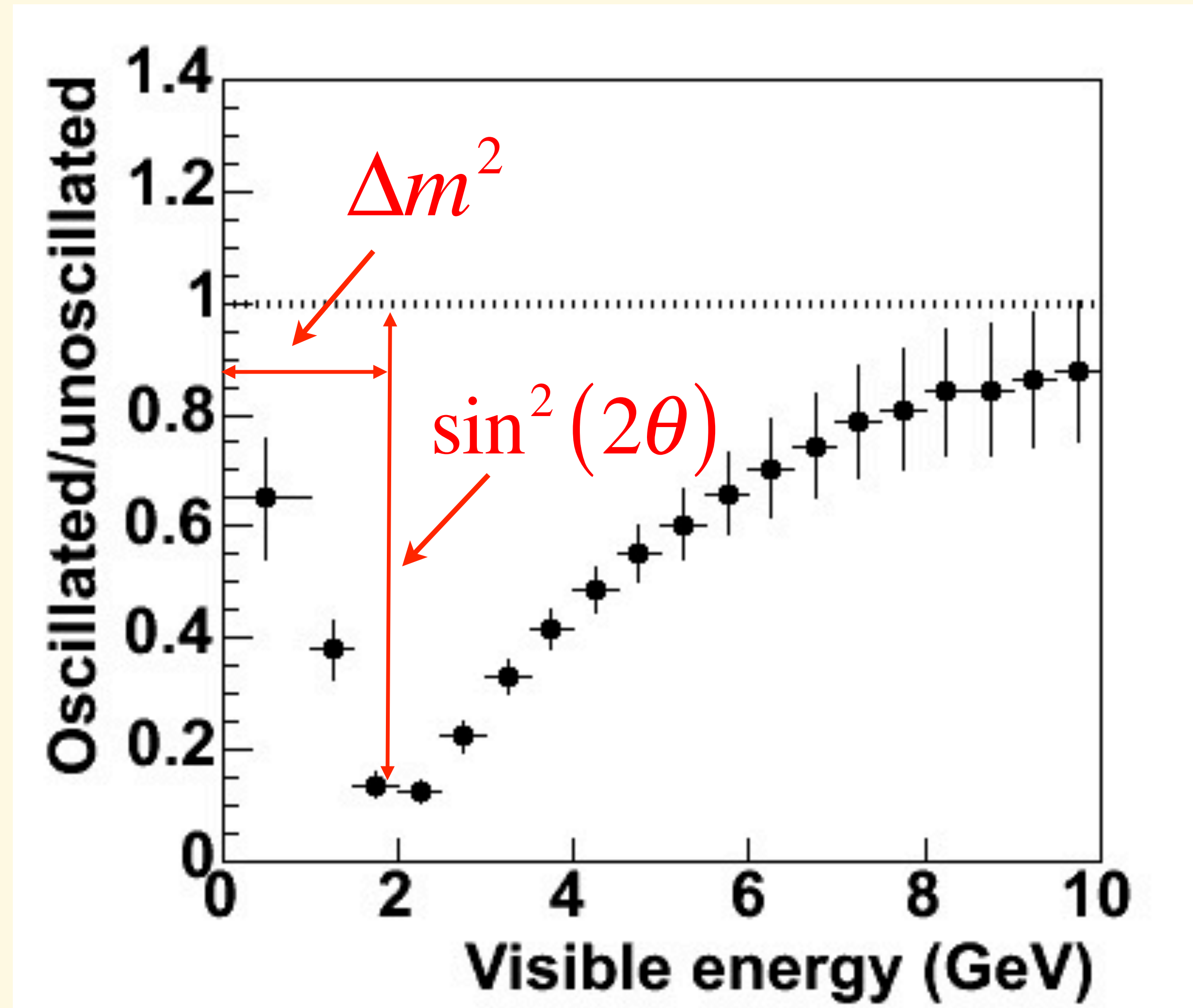

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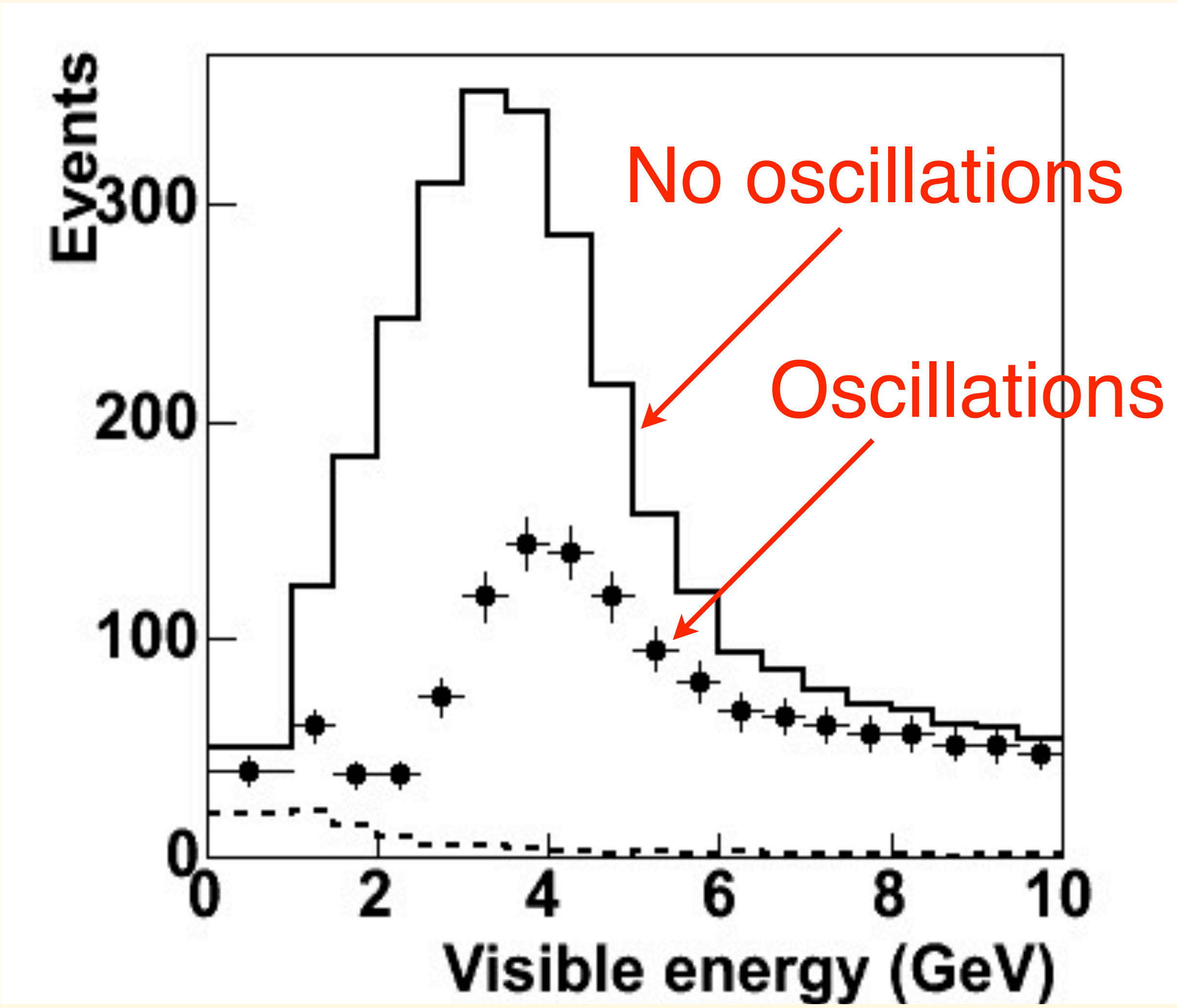

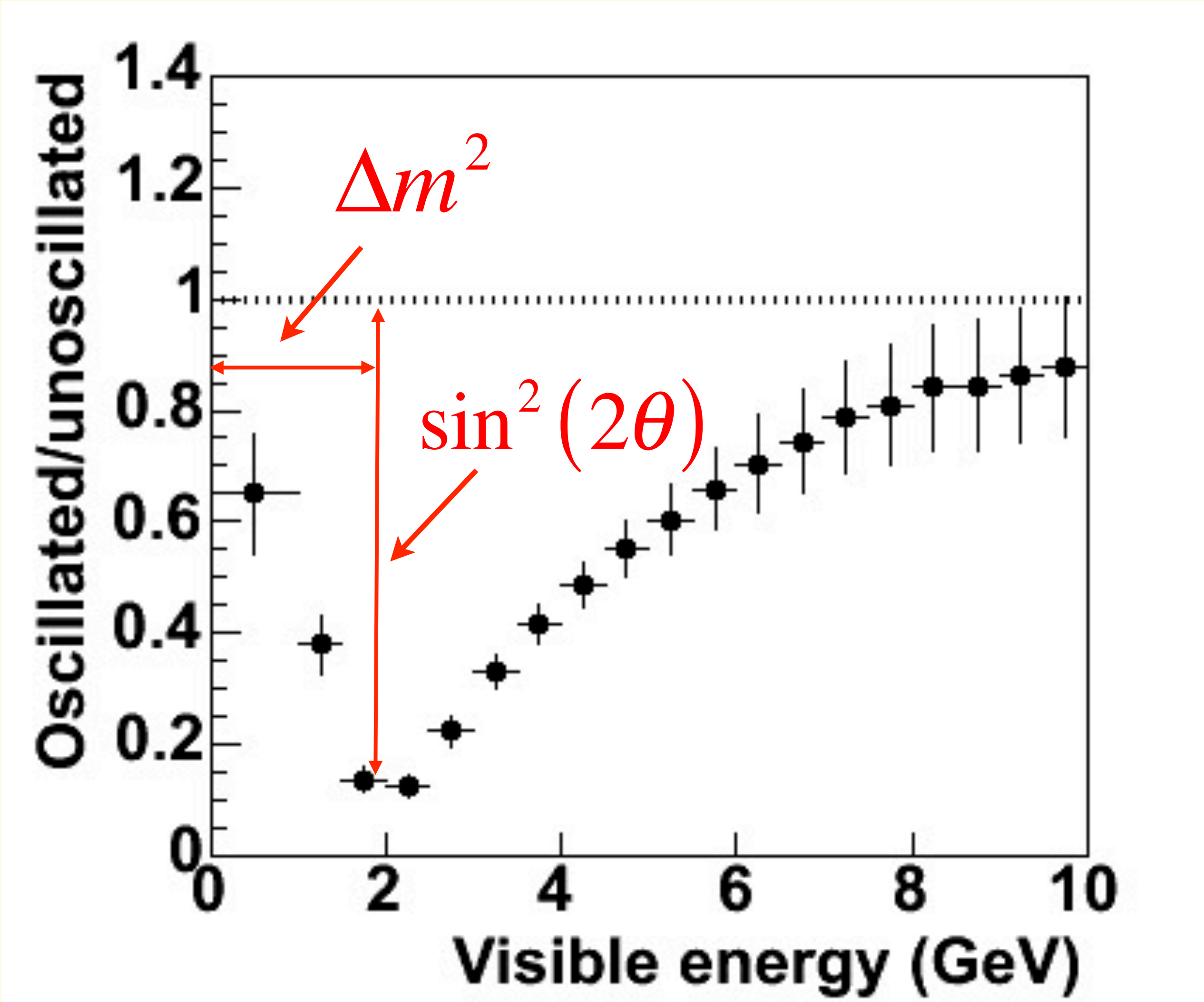

Size of dip gives the mixing angle; location of dip Δm^2

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

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K2K Results

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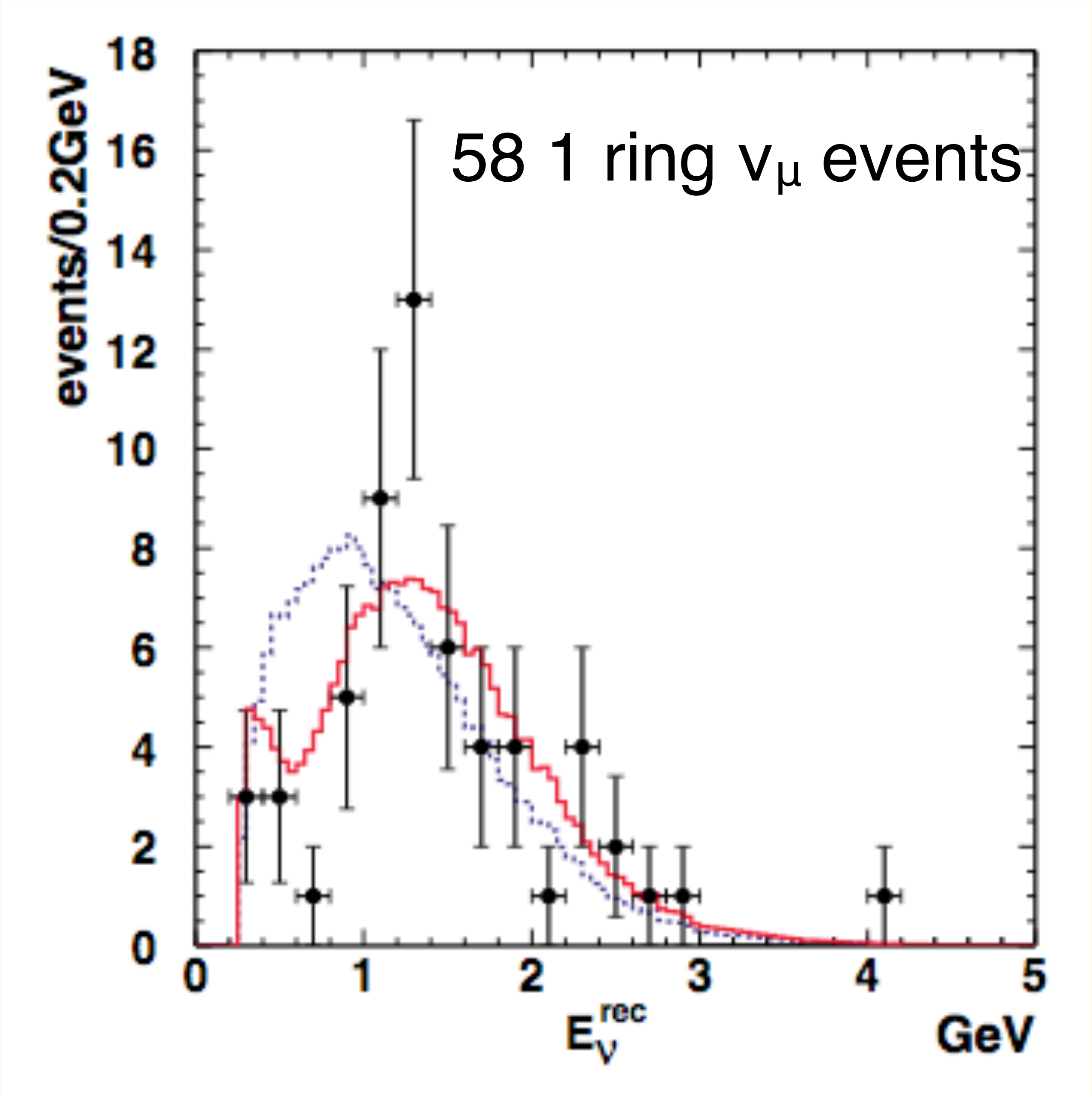
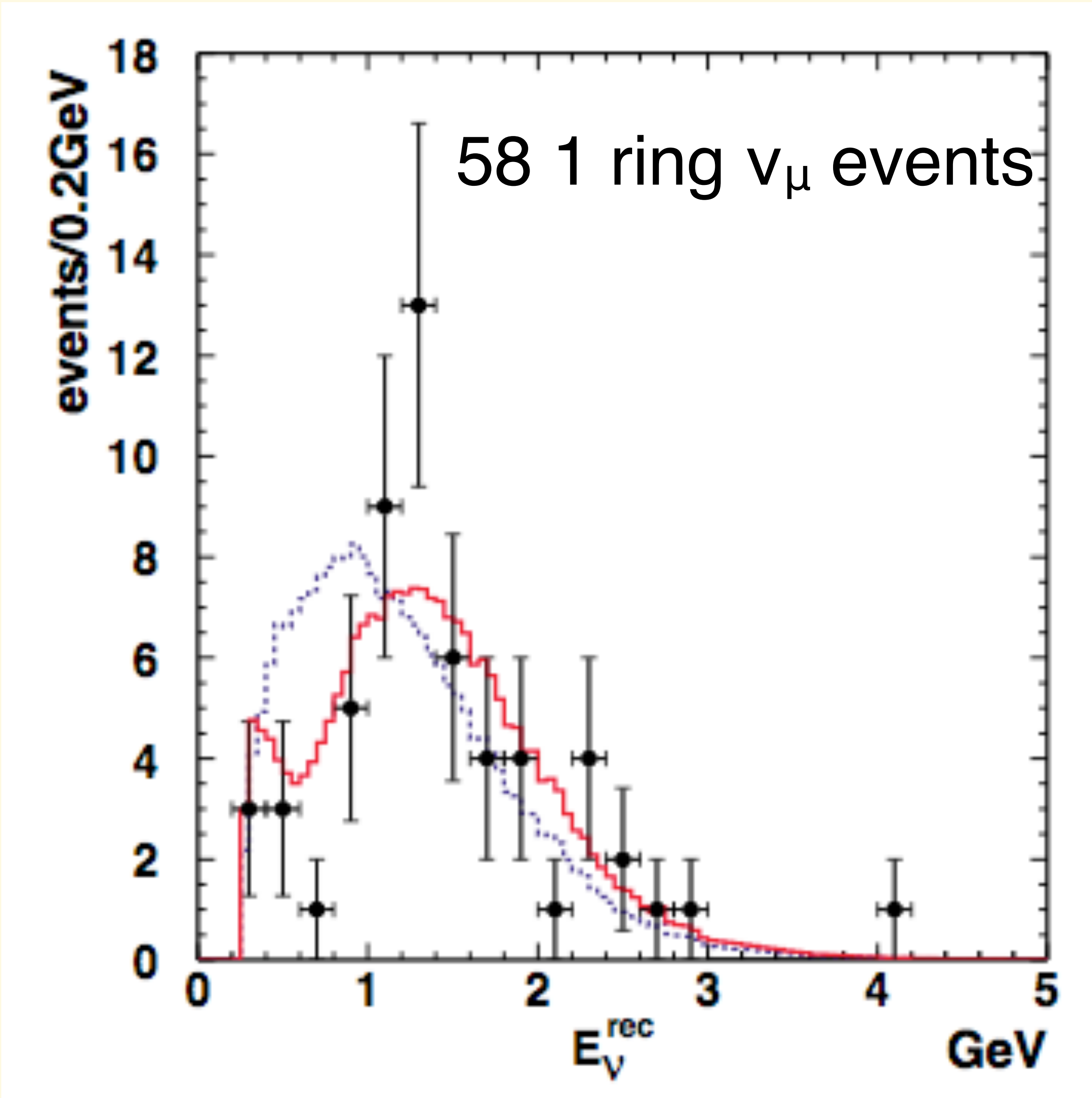


58 1 ring ν_μ events
events/0.2GeV
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
E_ν^rec
GeV

K2K Results



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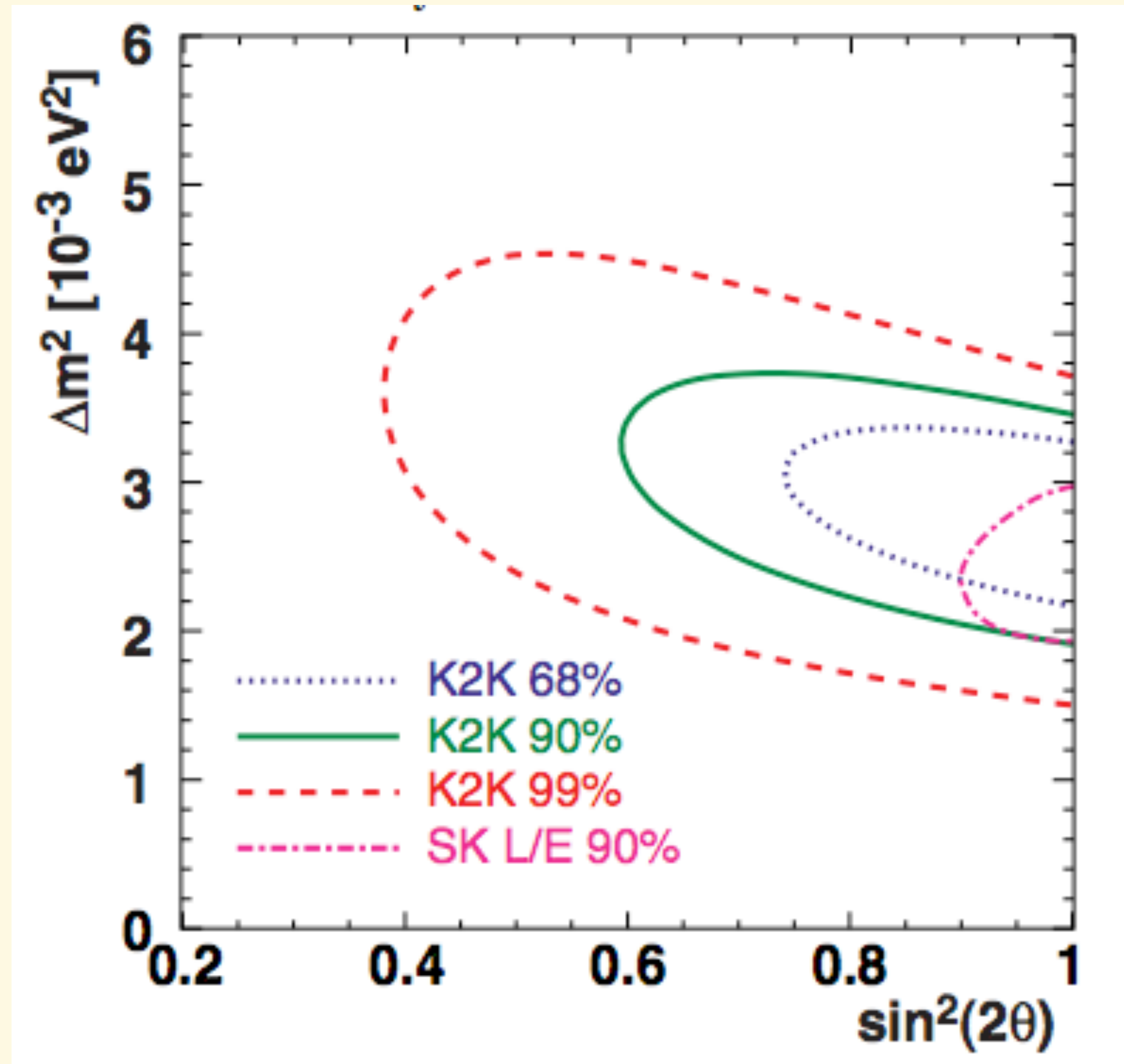
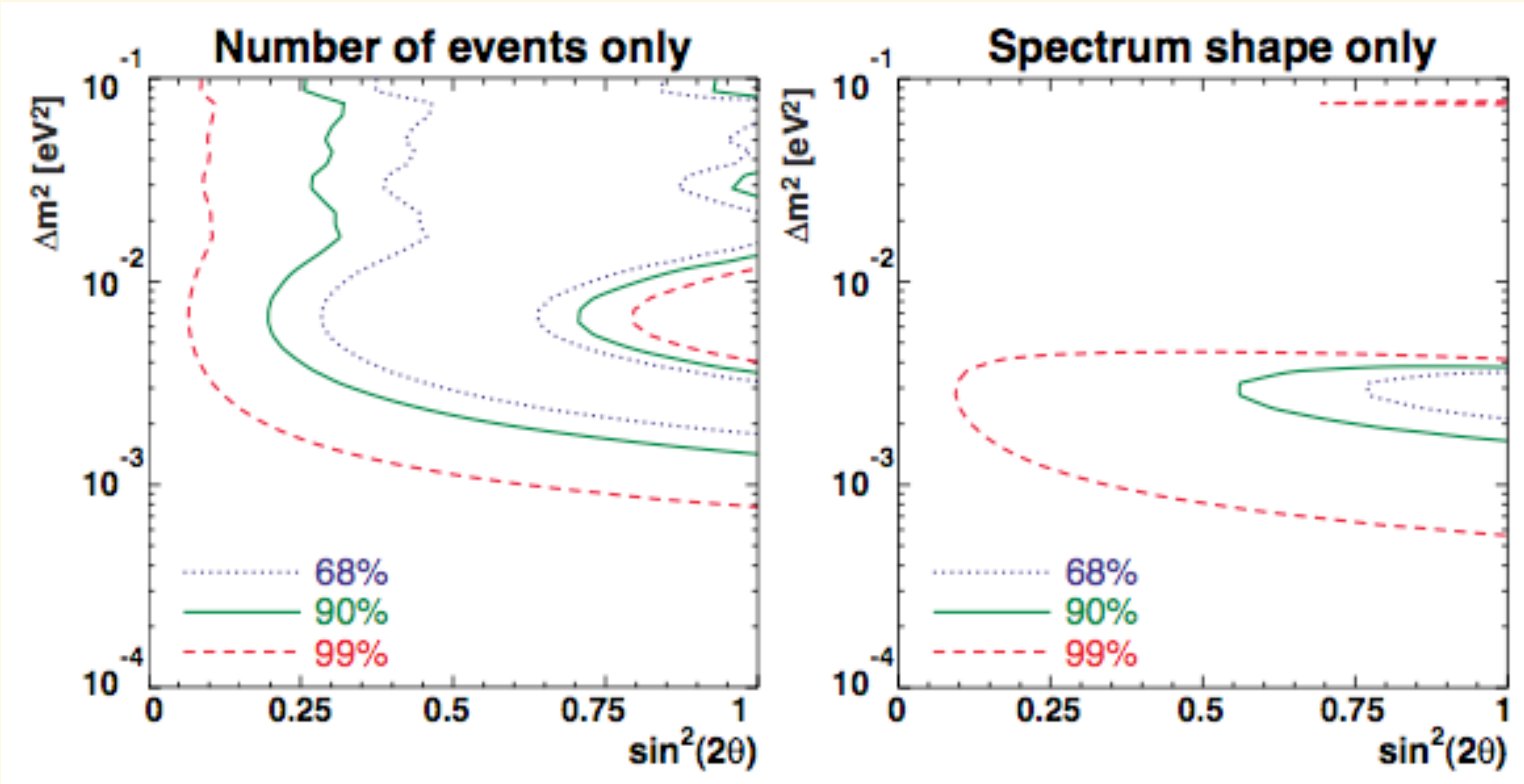


Δm^2 [10^{-3} eV^2]
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1
$\sin^2(2\theta)$
K2K 68%
K2K 90%
K2K 99%
SK L/E 90%

Rate or Shape

Rate or Shape



MINOS Experiment

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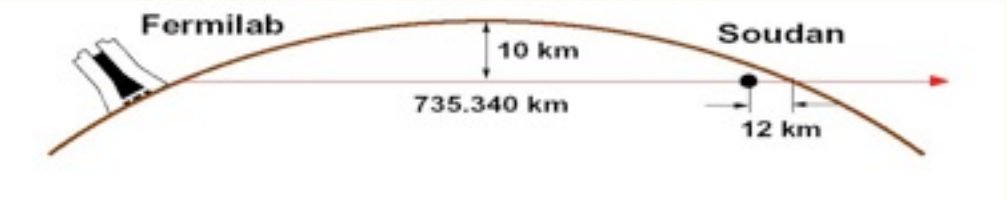

Neutrino beam produced at Fermilab
Near Detector - 1 km from the target
Far Detector - 735 km away and
710 m underground

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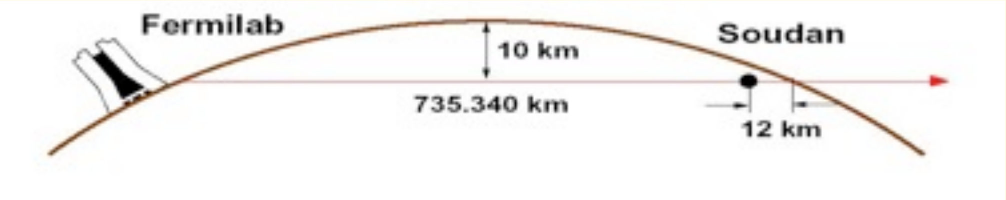

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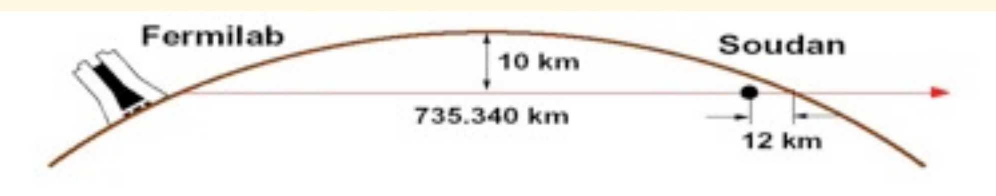

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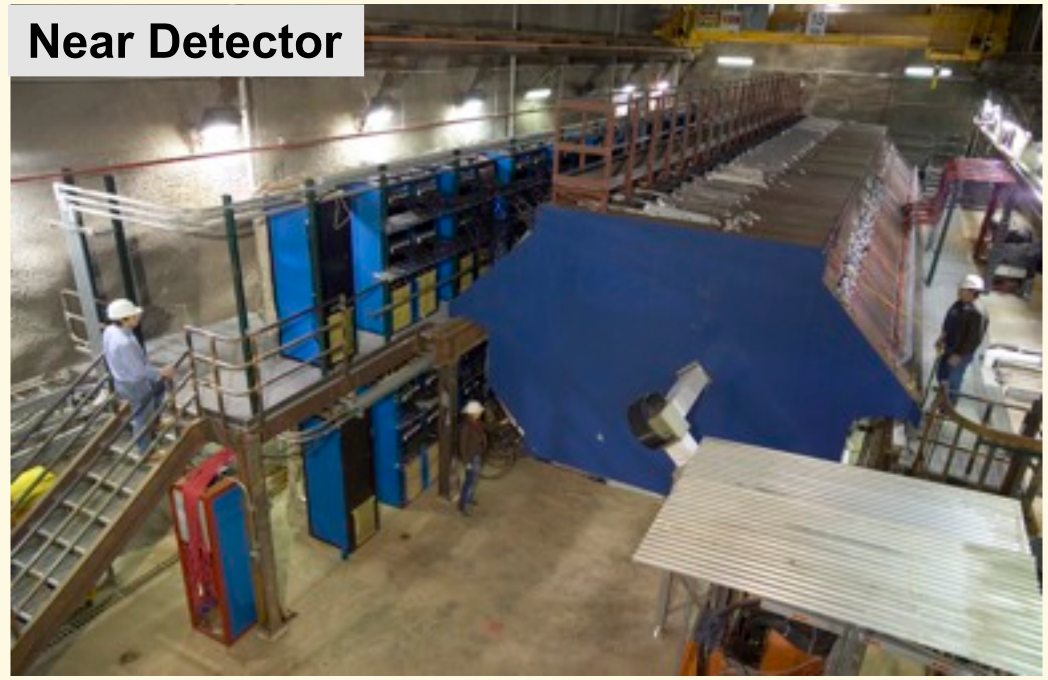
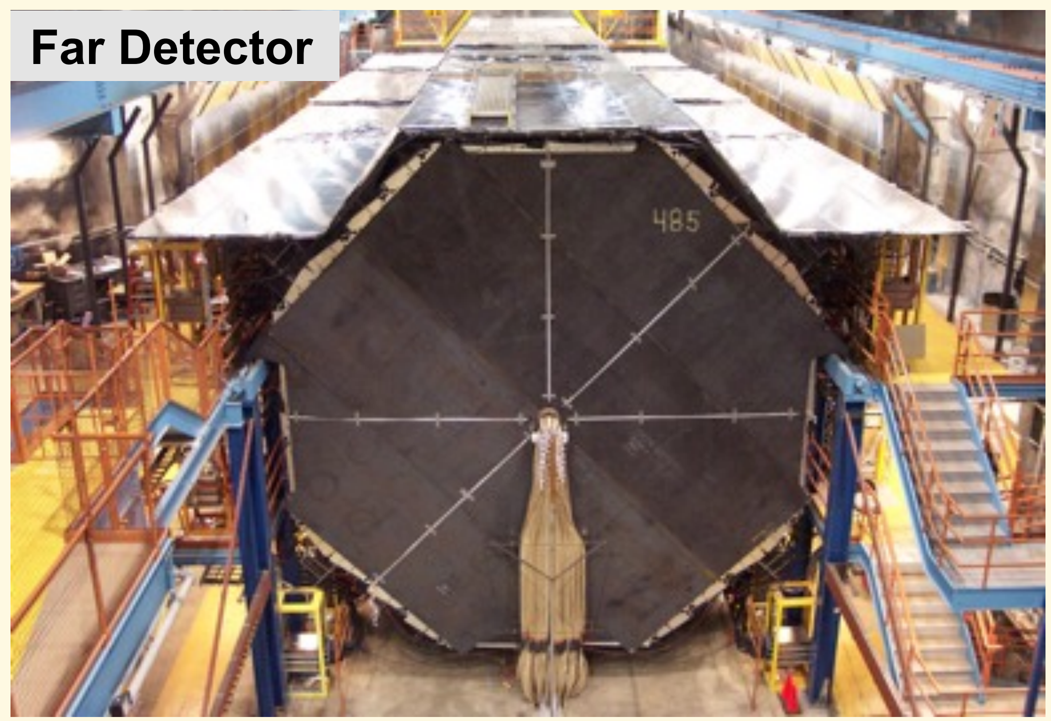
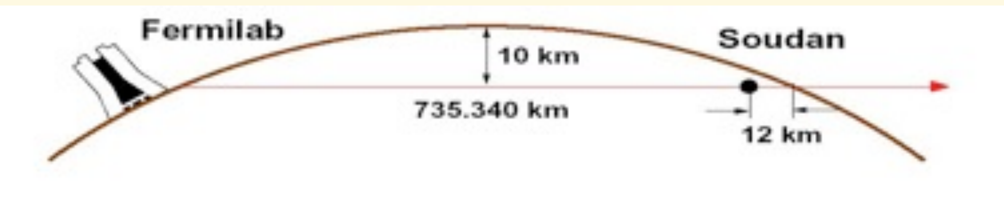
Near Detector



Far Detector



MINOS Experiment



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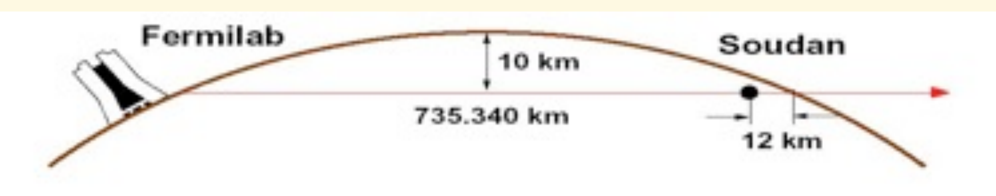
MINOS Detectors

- 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°
    - 1 cm thick
    - 4.1 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

MINOS Experiment



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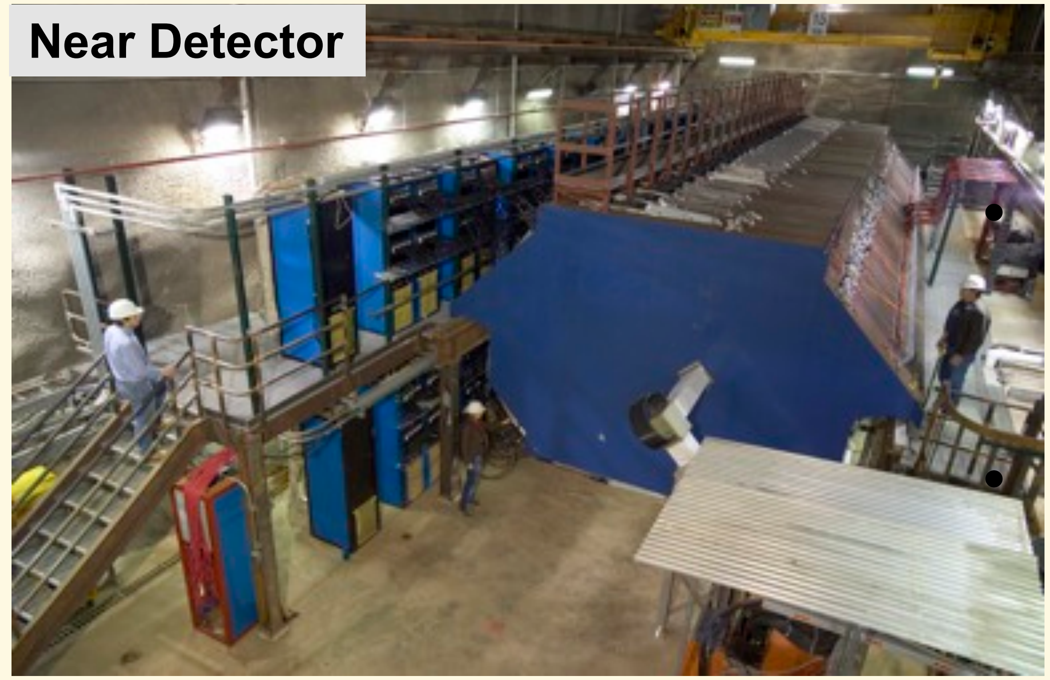

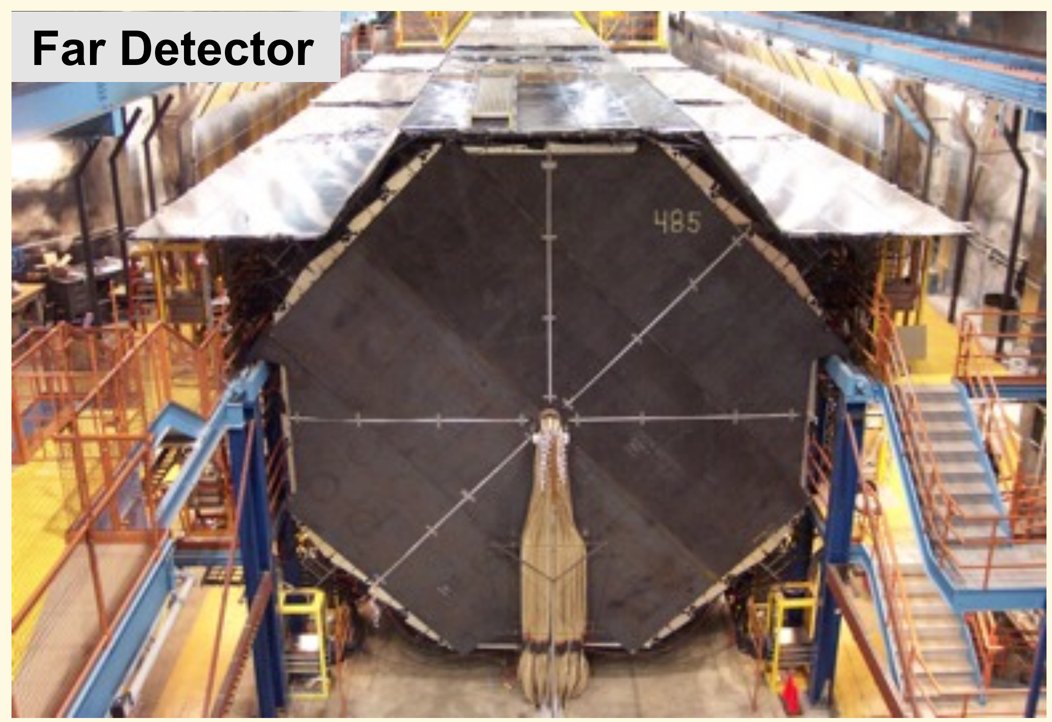

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The flux is measured in the Near Detector and then extrapolated to obtain prediction in the Far Detector

MINOS Events (MC)

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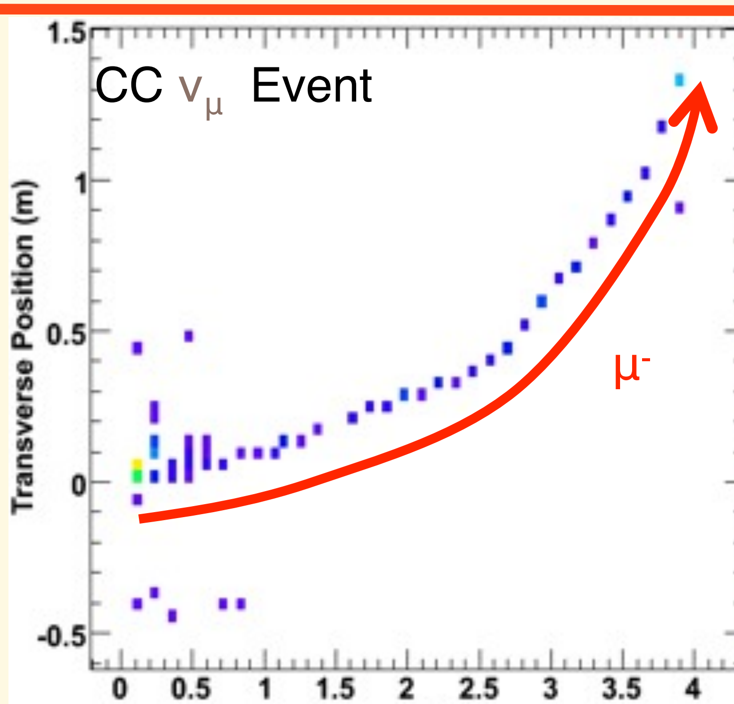

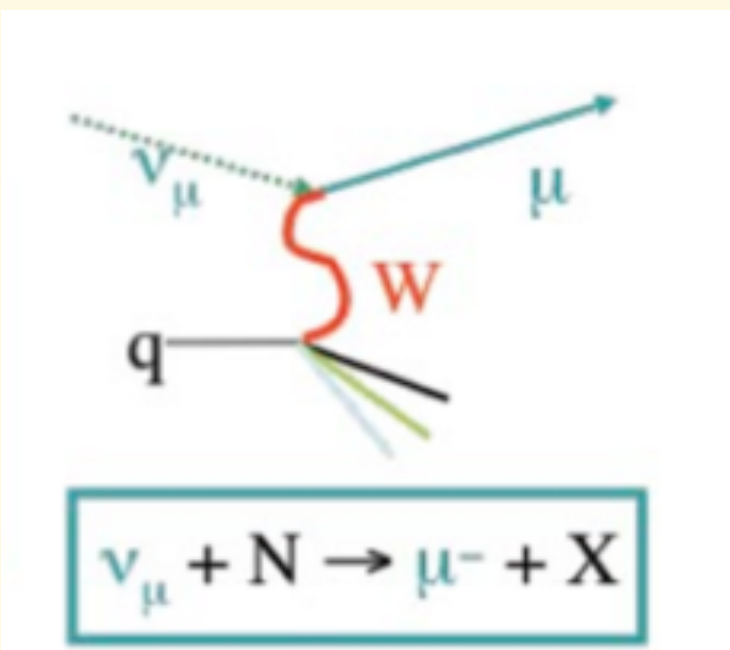

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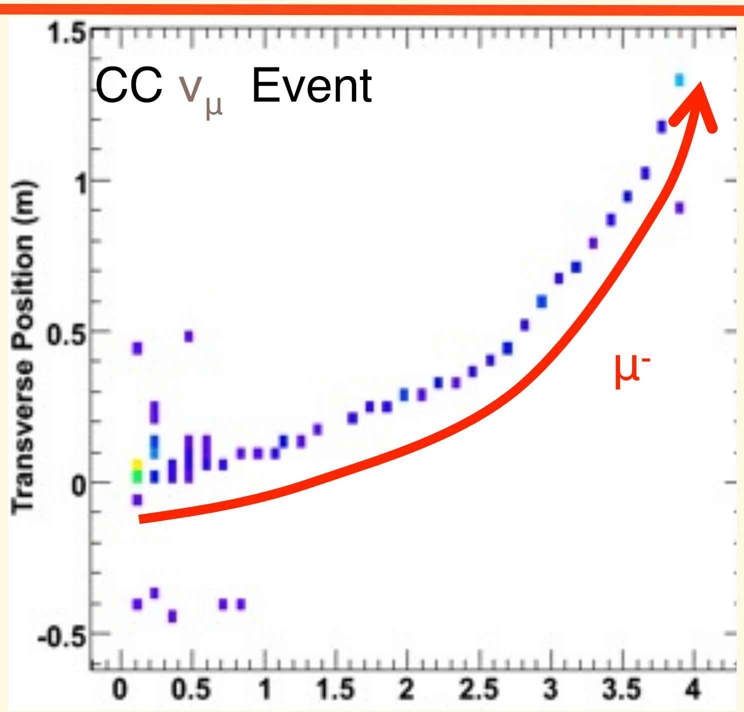

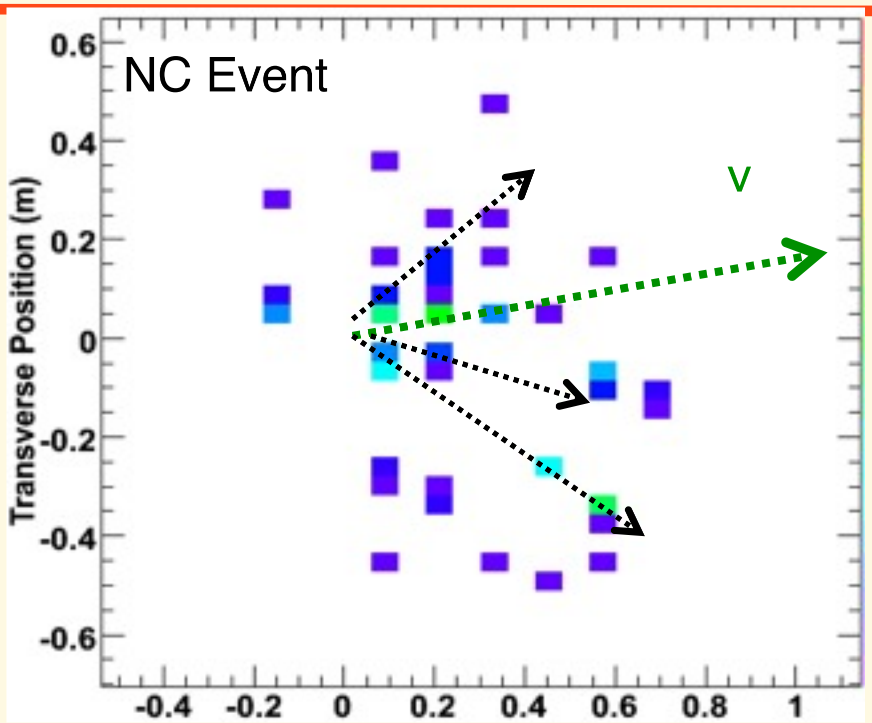

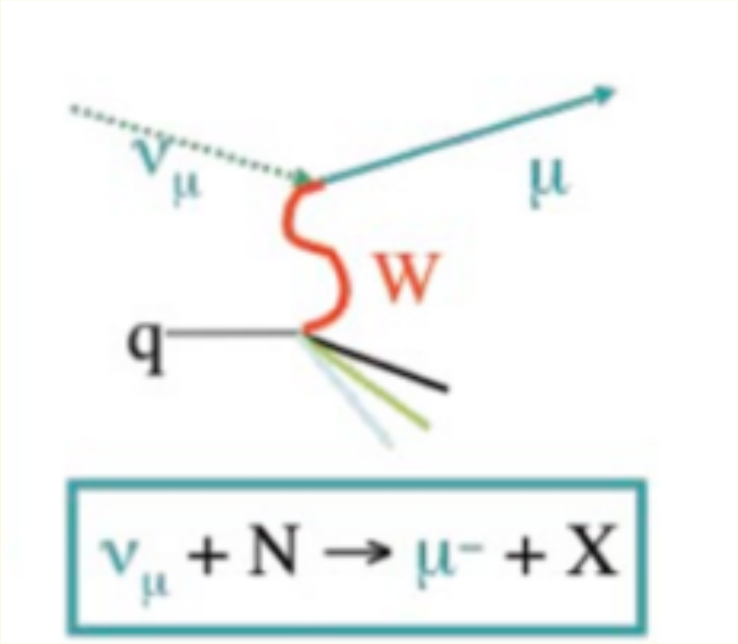

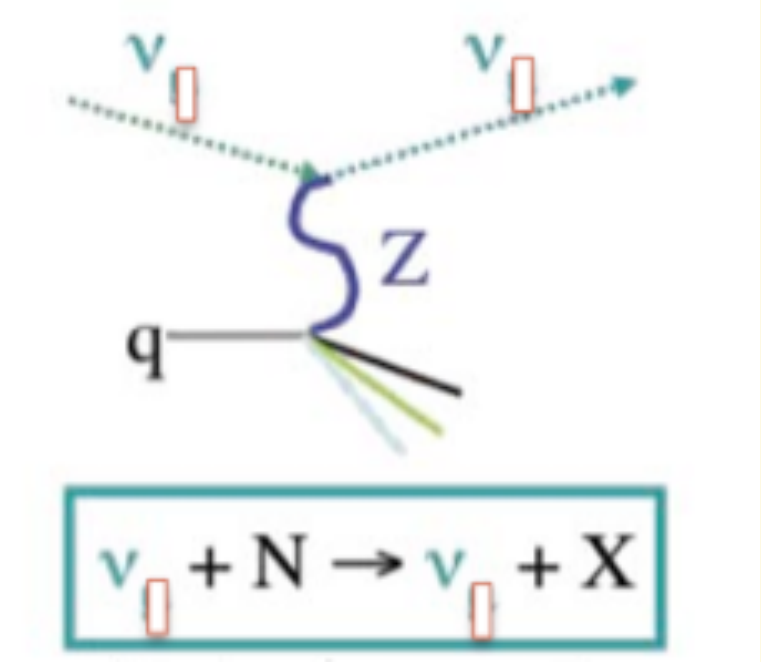

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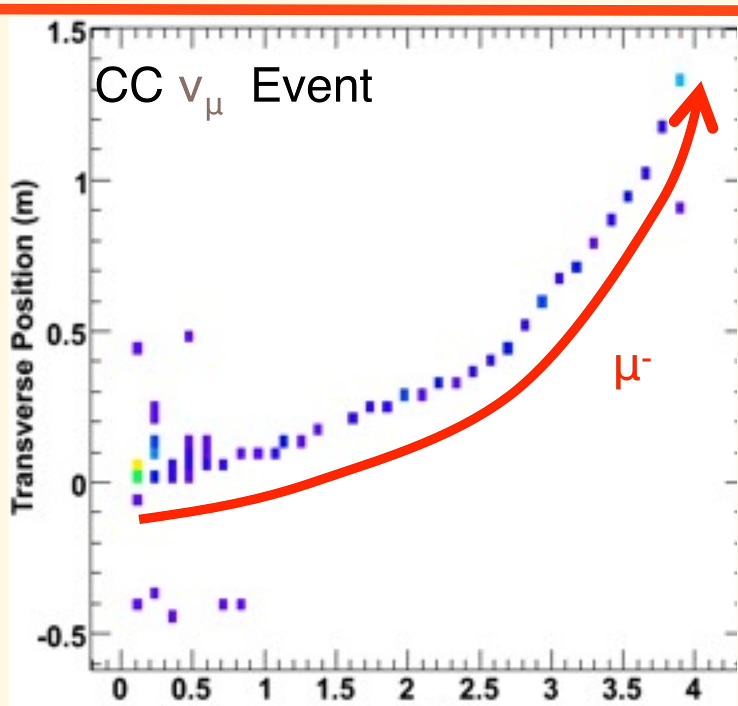
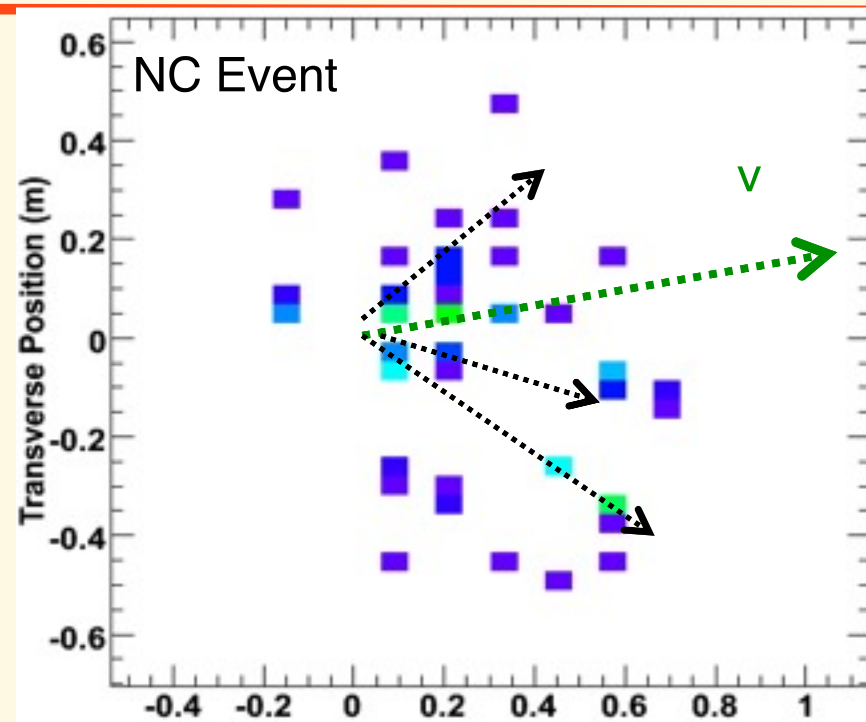
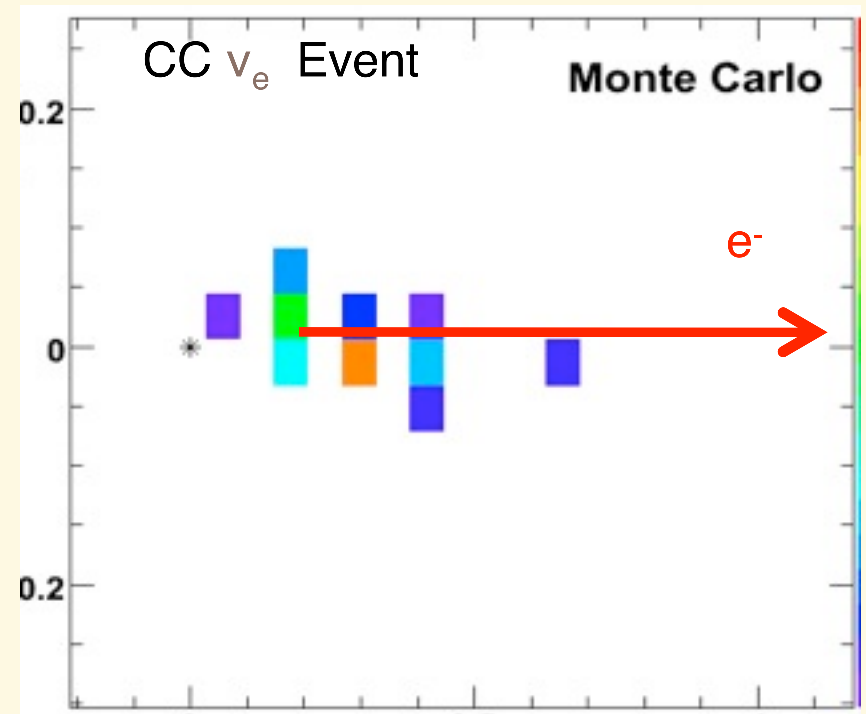
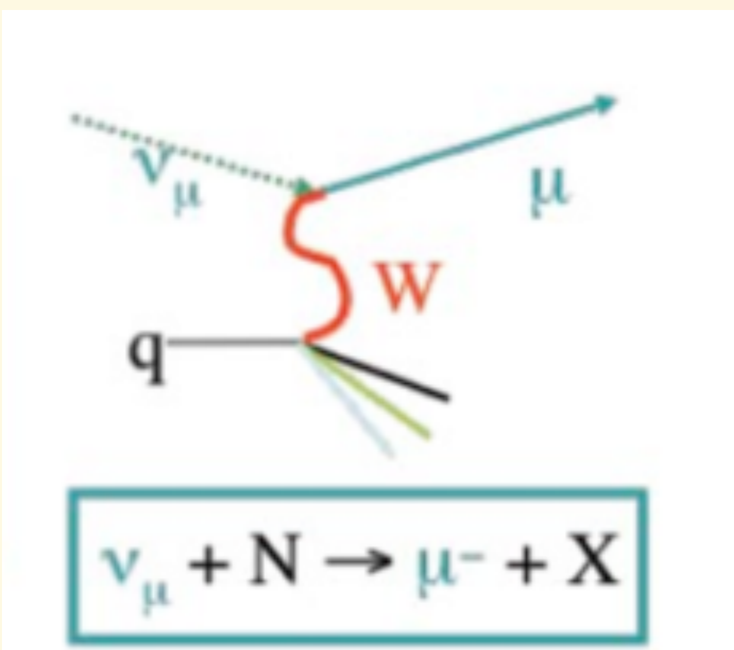
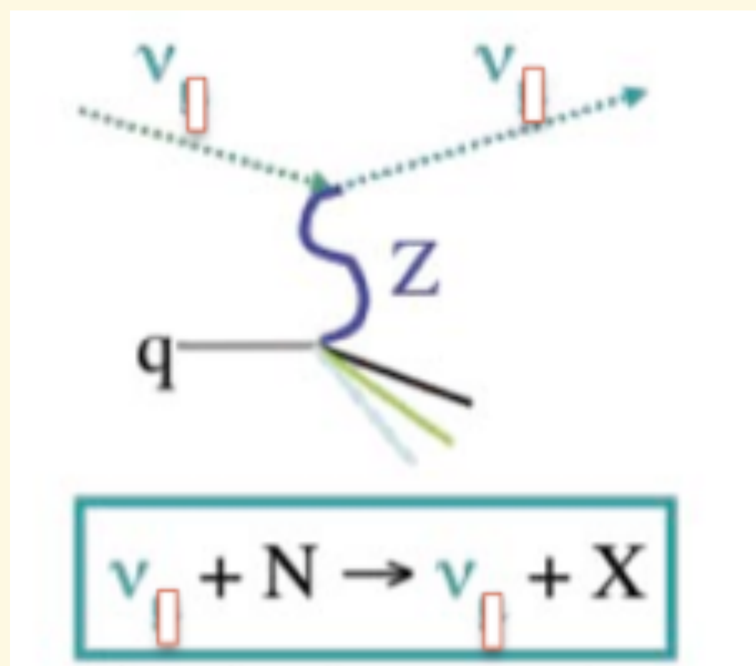
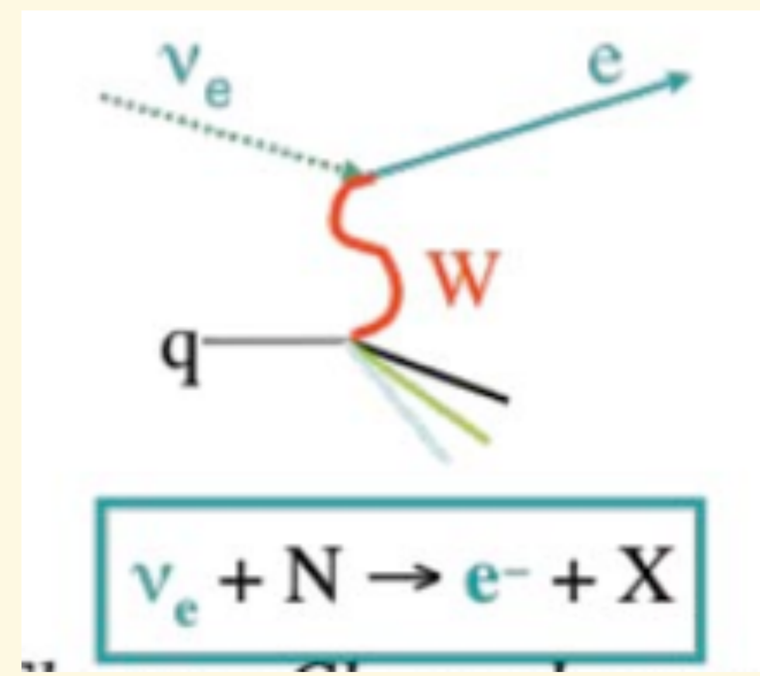




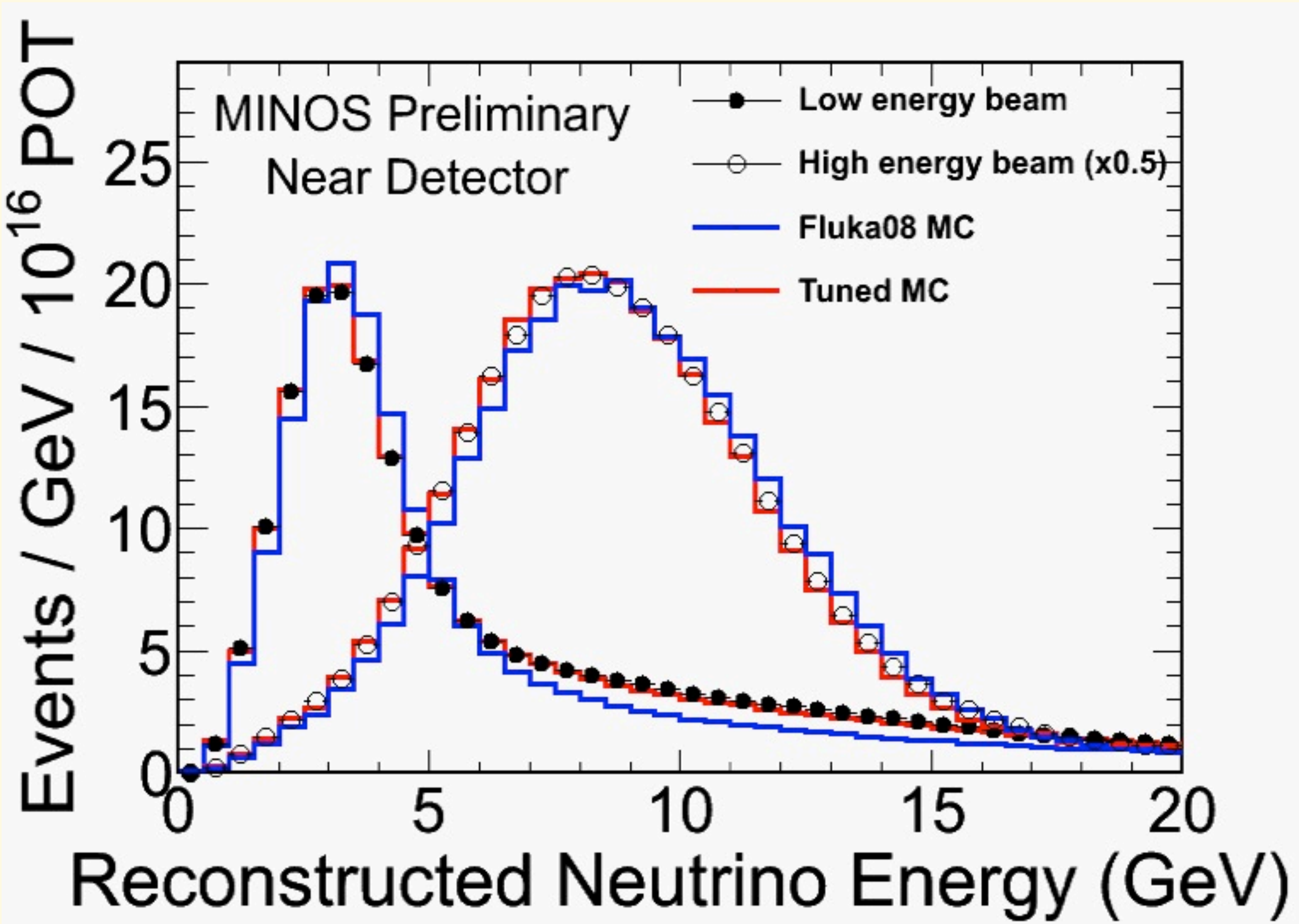








Near Detector Data



MINOS E_ν Spectrum

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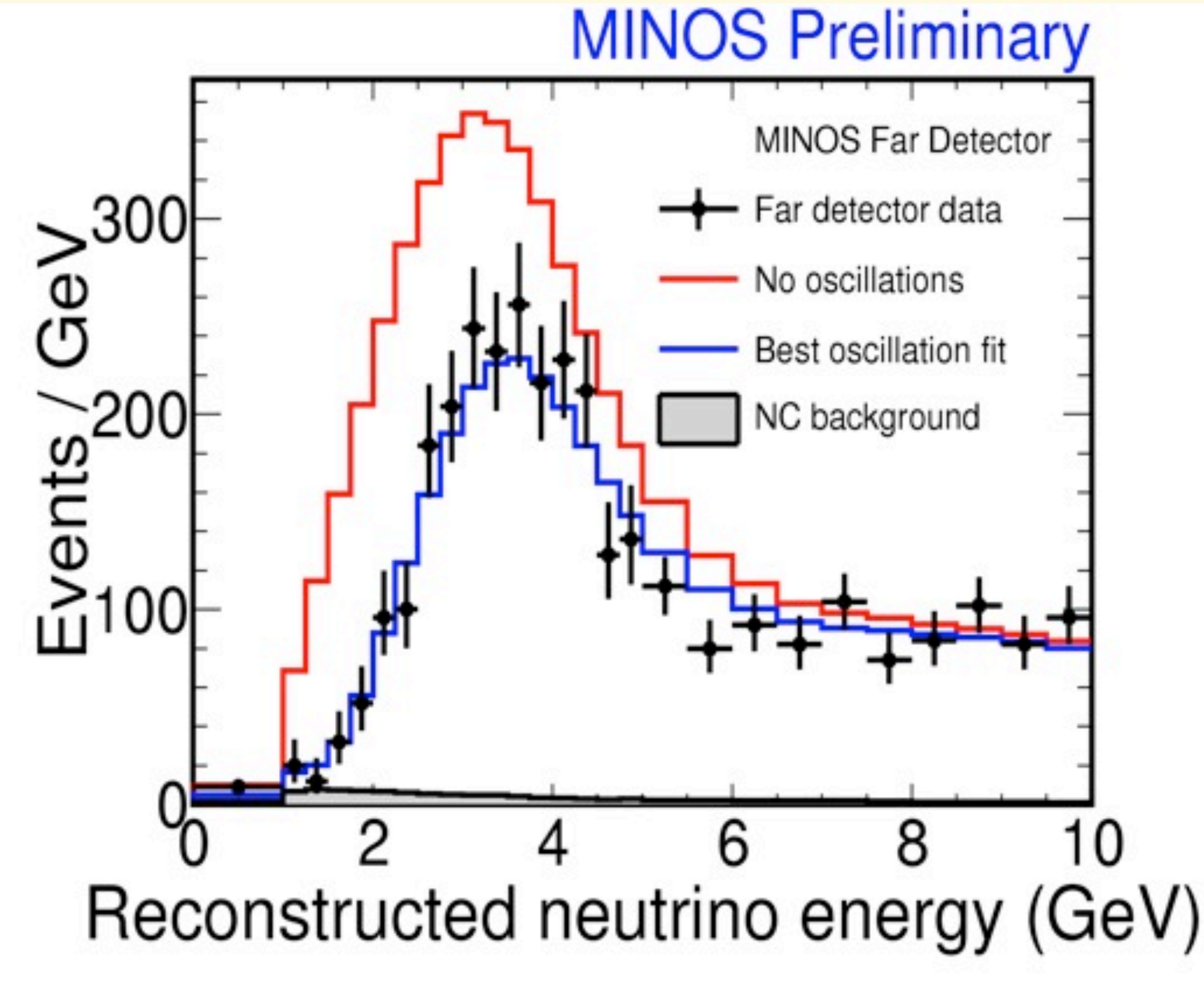

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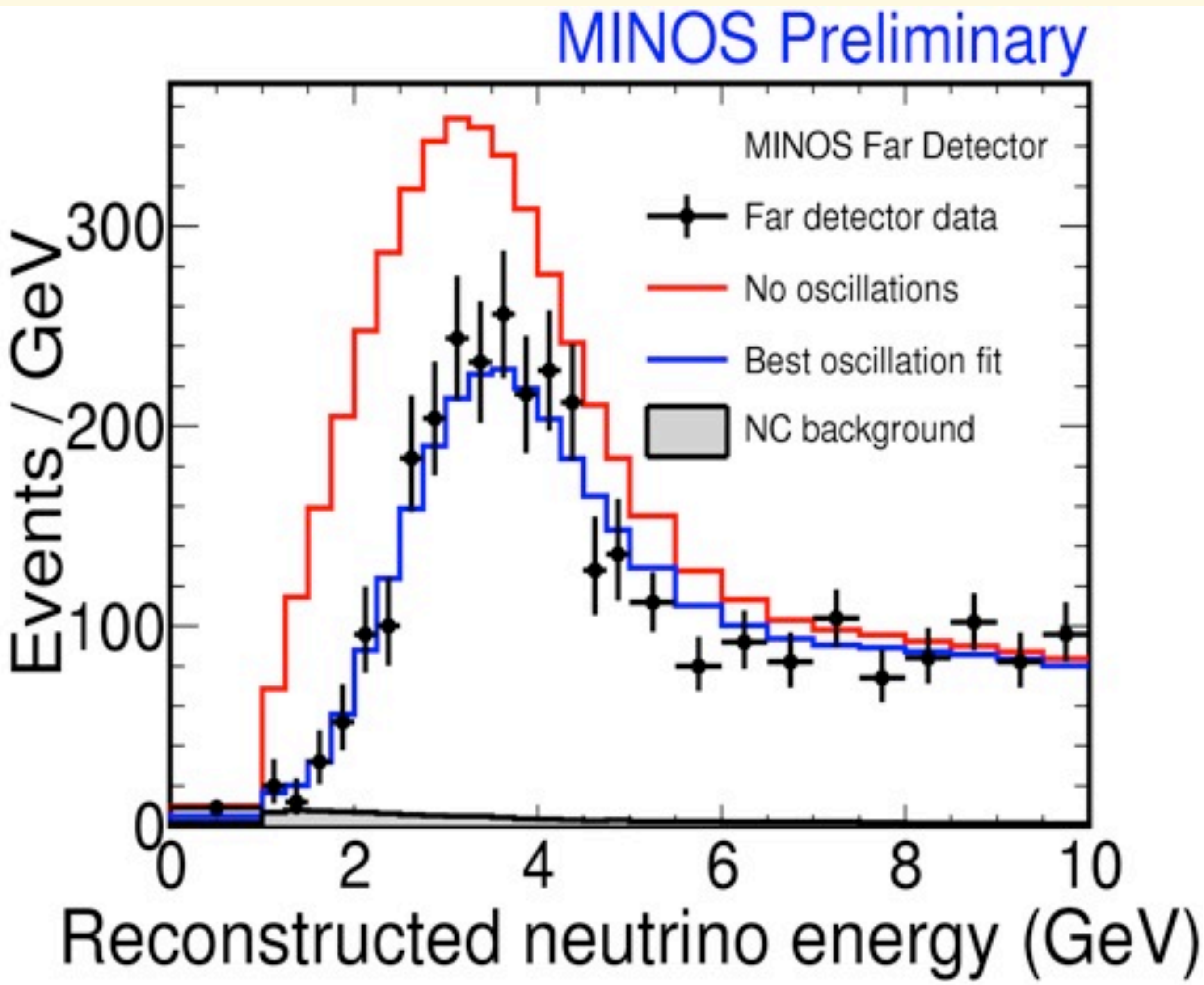

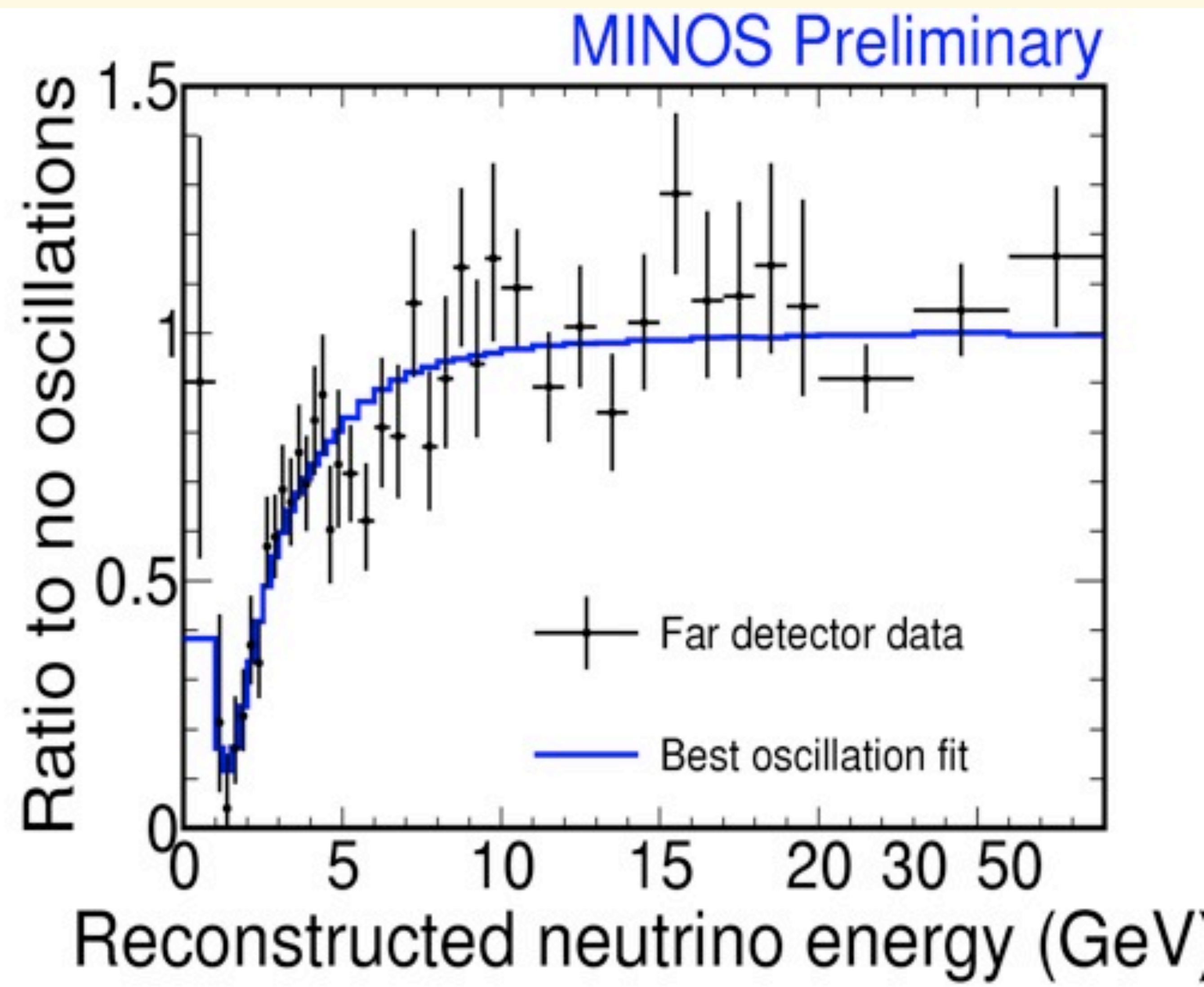

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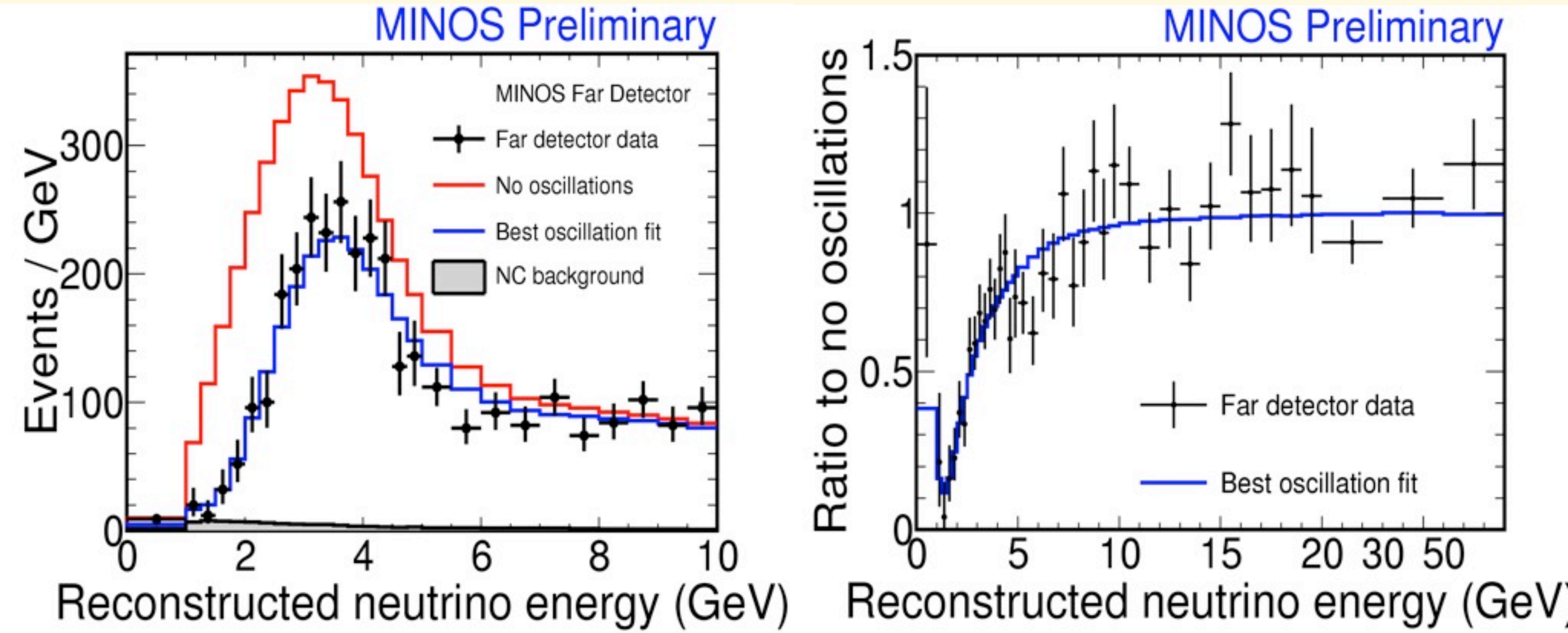
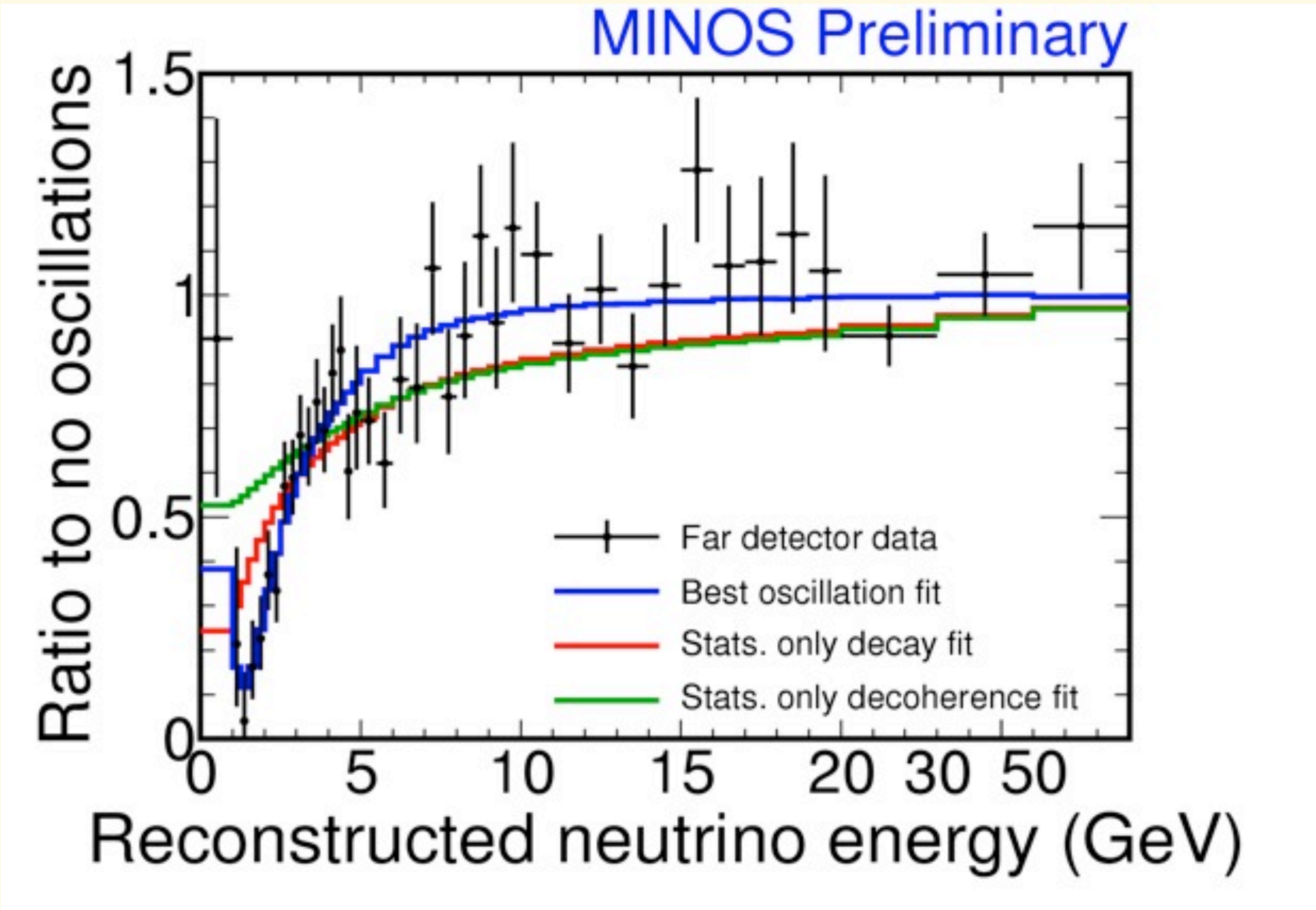


Good agreement with oscillation hypothesis
Alternative hypotheses (decay, decoherence) excluded at a significant level >6σ

Alternative Models

Alternative Models



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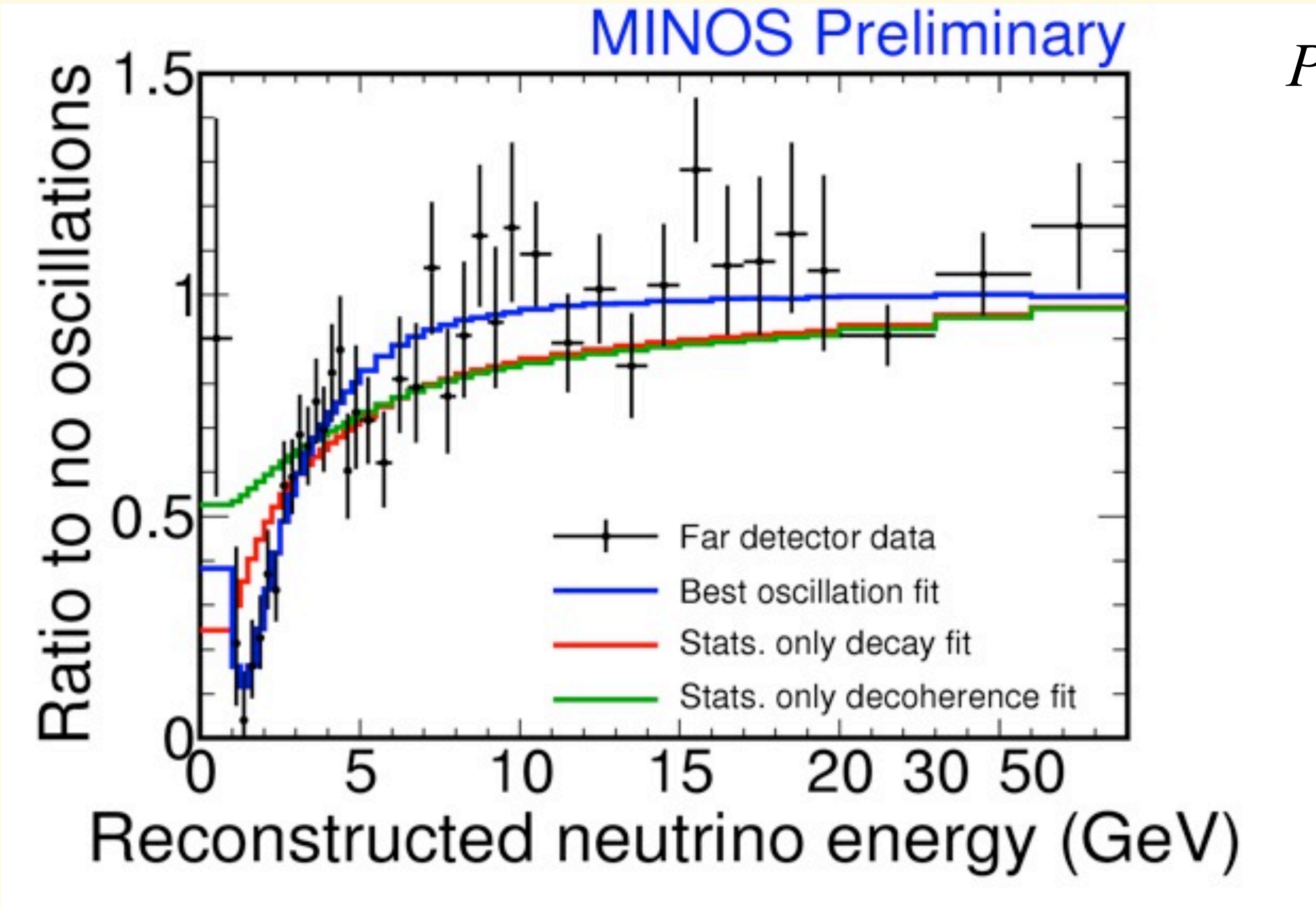

Decay:

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

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

$\Delta\chi^2 = 46.3$

disfavored at 6.8σ

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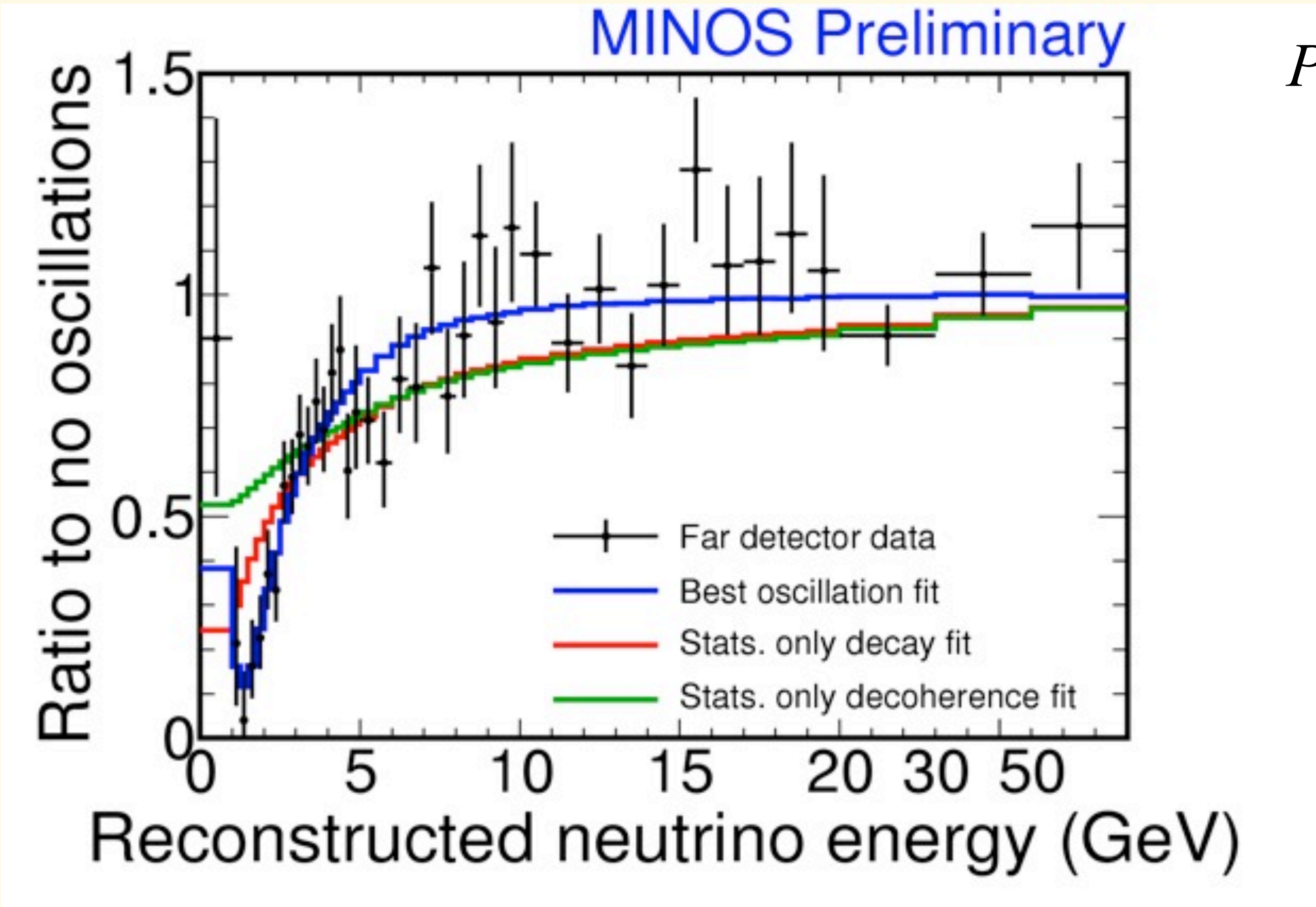

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Decoherence:

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

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

$\Delta\chi^2 = 78.1$

disfavored at 8.8σ

MINOS Contour

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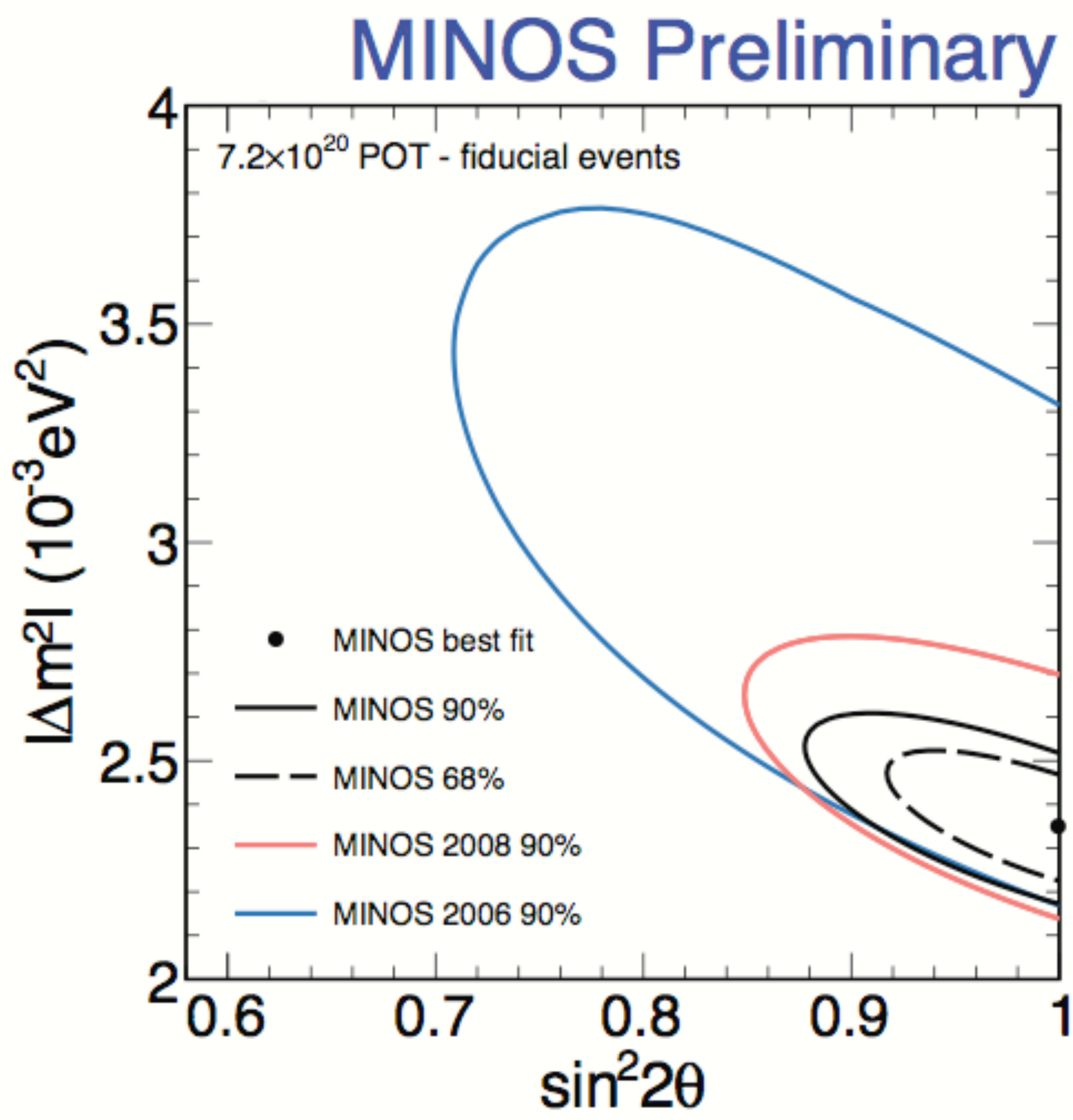

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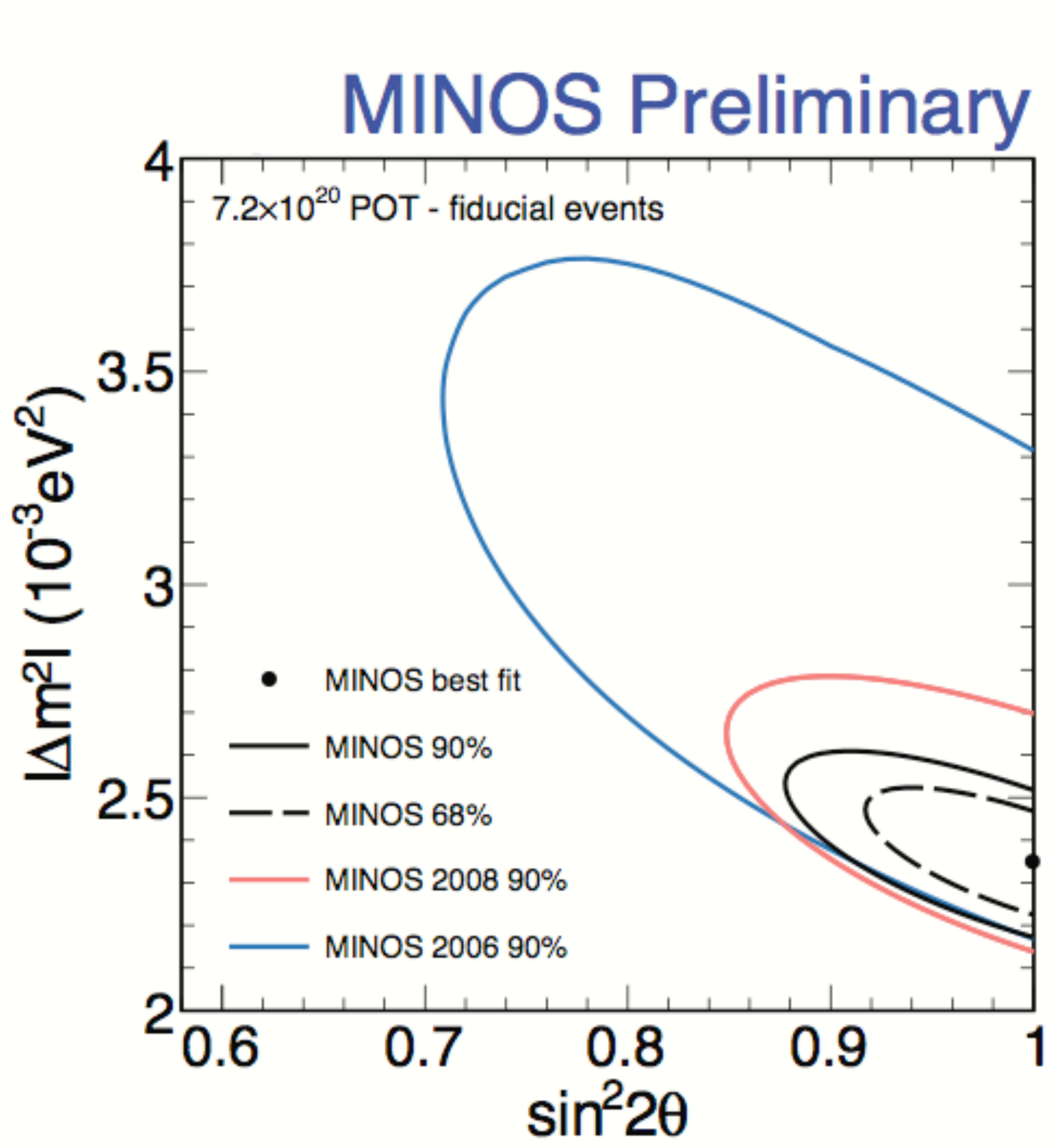


Fit results

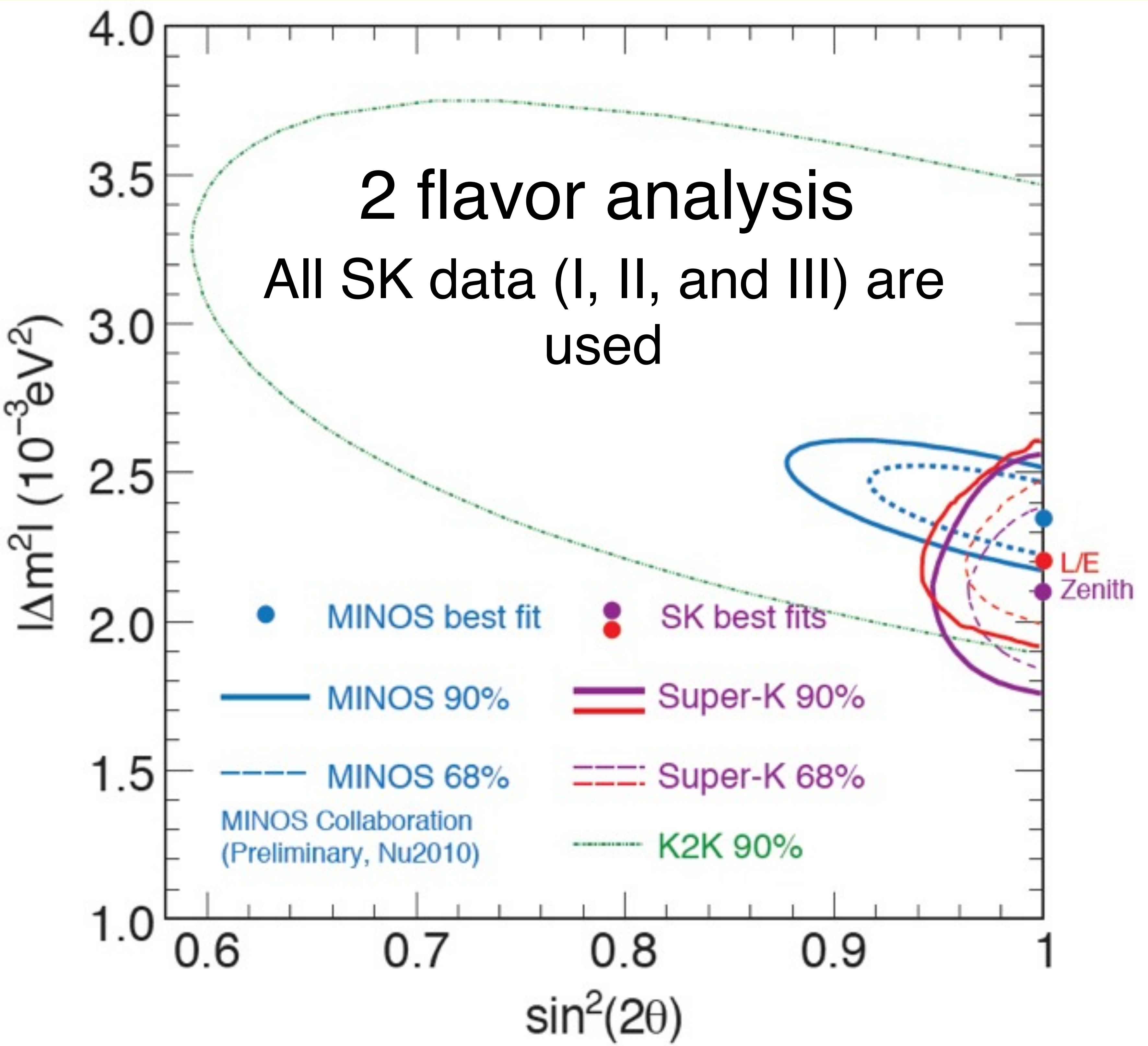
$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

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

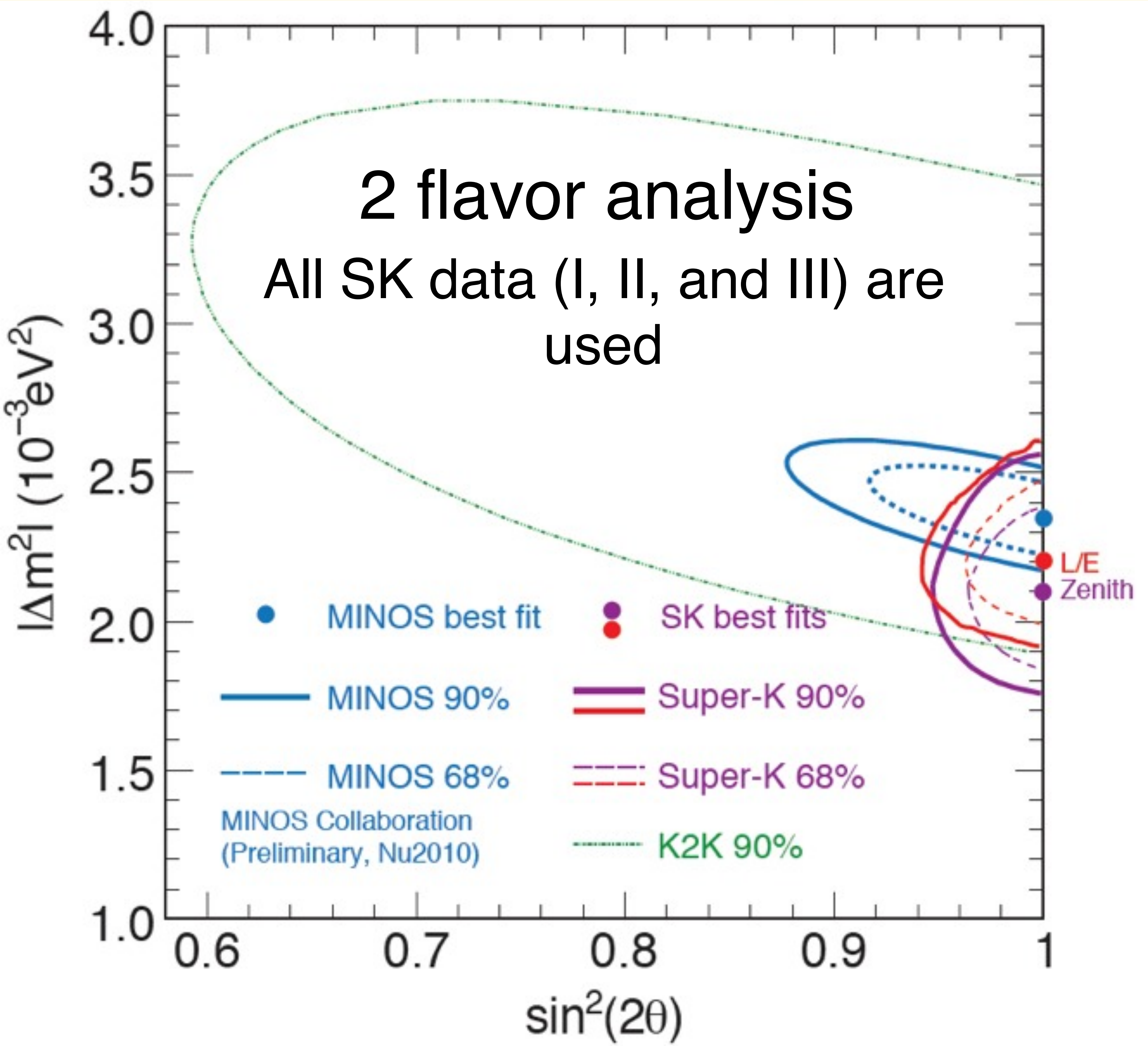
The fit accounts for the principal systematic effects

SuperK/MINOS

SuperK/MINOS

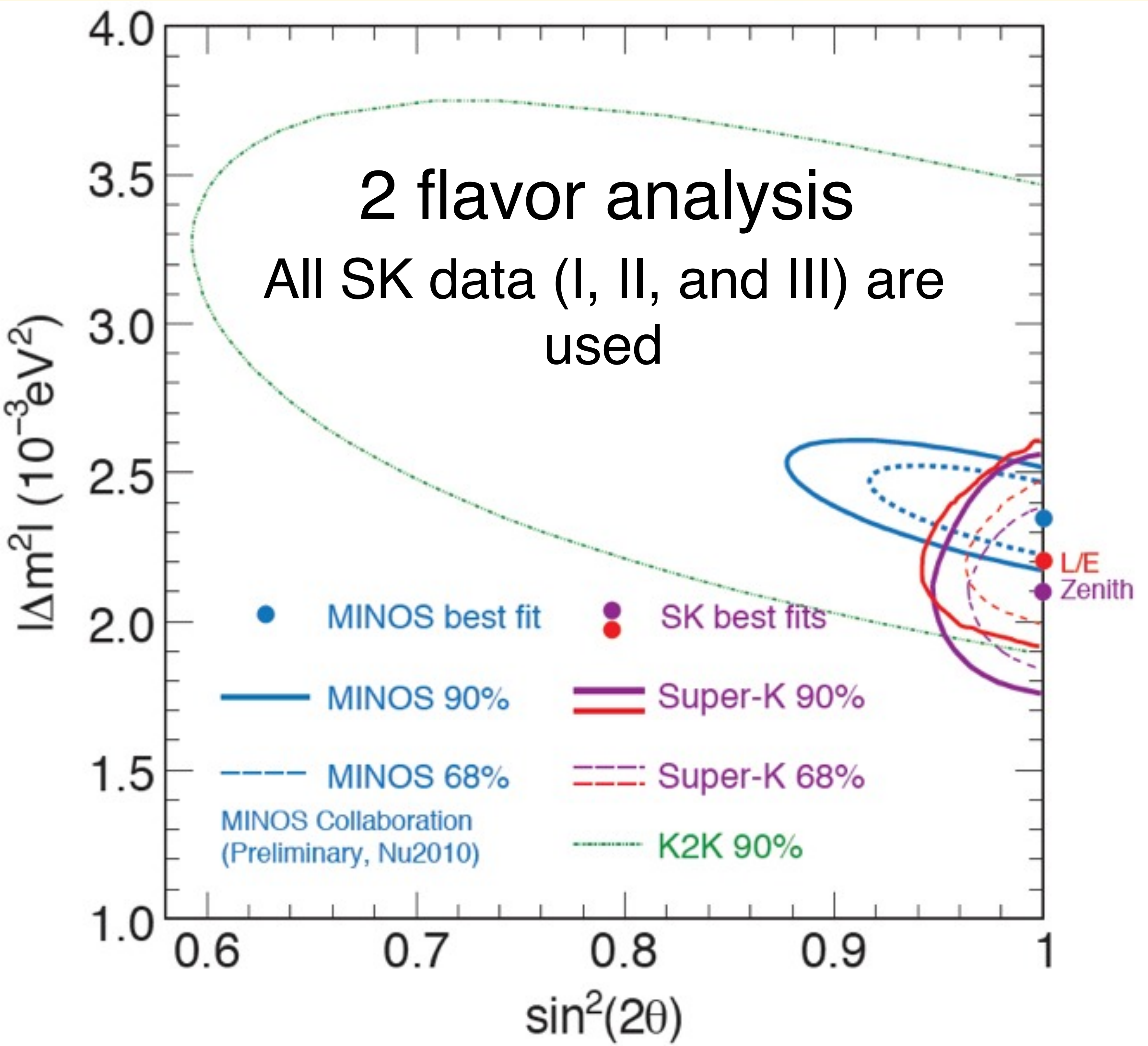


SuperK/MINOS



MINOS does better on Δm^2 determination

SuperK/MINOS



MINOS does better on Δm^2 determination

SuperK does better on the mixing angle

Summary - Atmospheric sector

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

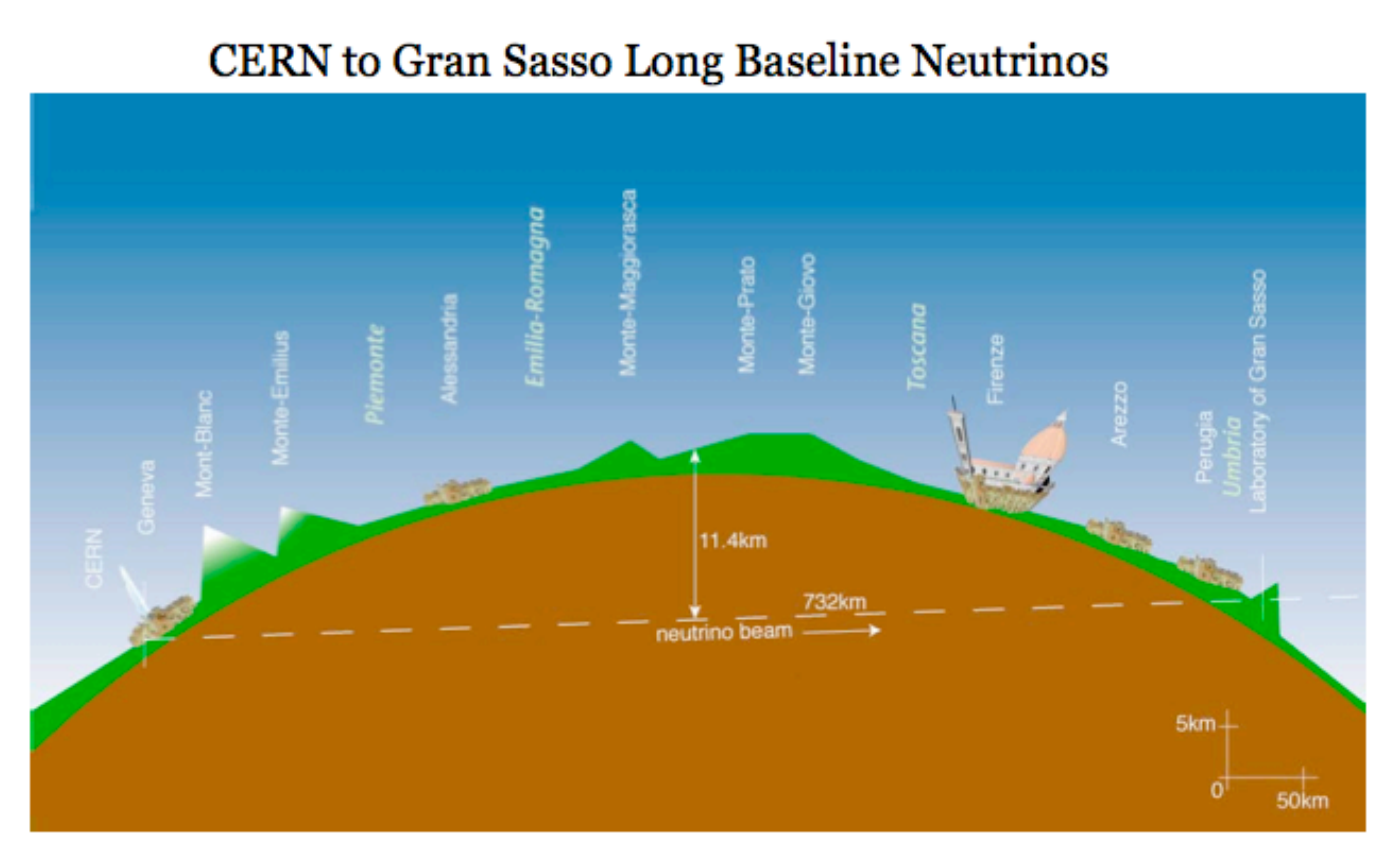
Oscillation to what?

- 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

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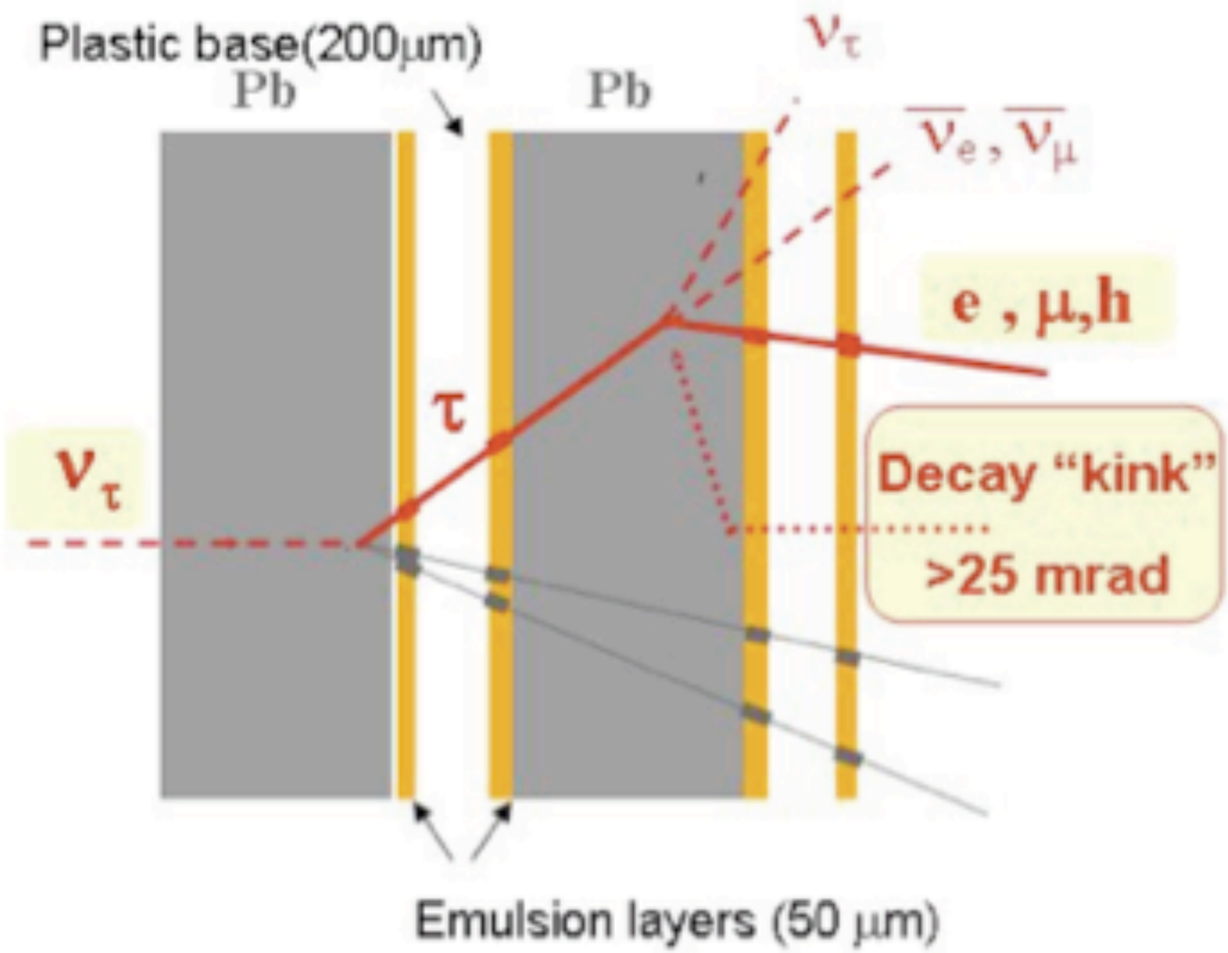
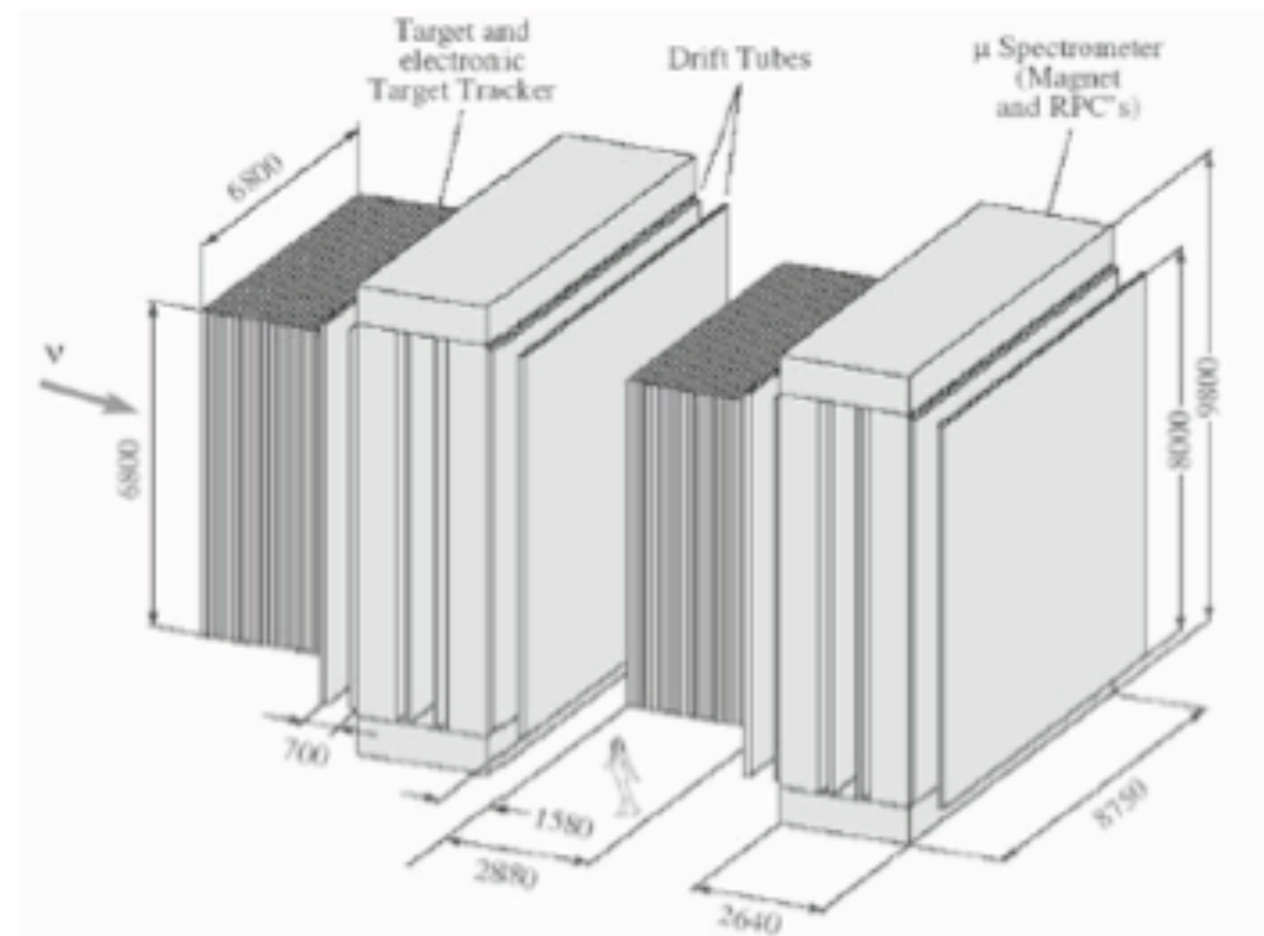
10th Int. Conf. on Topics in Astroparticle and Underground Physics (TAUP2007) IOP Publishing
Journal of Physics: Conference Series 120 (2008) 052042 doi:10.1088/1742-6596/120/5/052042





How to Choose the Energy

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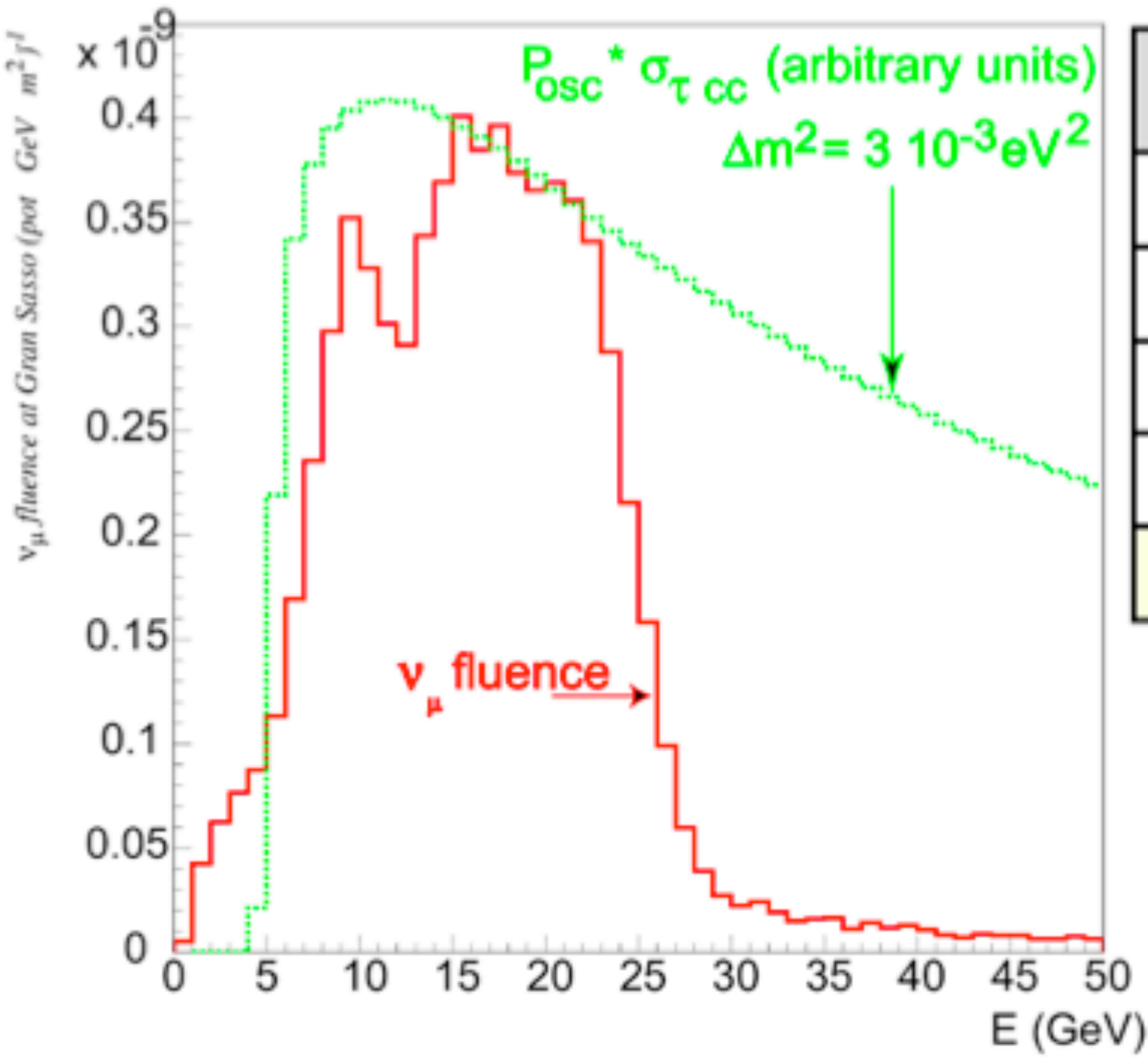

Decay channel	Detection efficiency(%)	Branching ratio(%)	Signal ($\Delta m^2=2.5\times10^{-3}$)	Background
$\tau\to\mu$	17.5	17.7	2.9	0.17
$\tau\to e$	20.8	17.8	3.5	0.17
$\tau\to h$	5.8	49.5	3.1	0.24
$\tau\to 3h$	6.3	15	0.9	0.17
ALL	effxBR=10.6%		**10.4**	**0.75**

5 year exposure @4.5×10^{19} POT/year

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

OPERA - 1st Candidate

→

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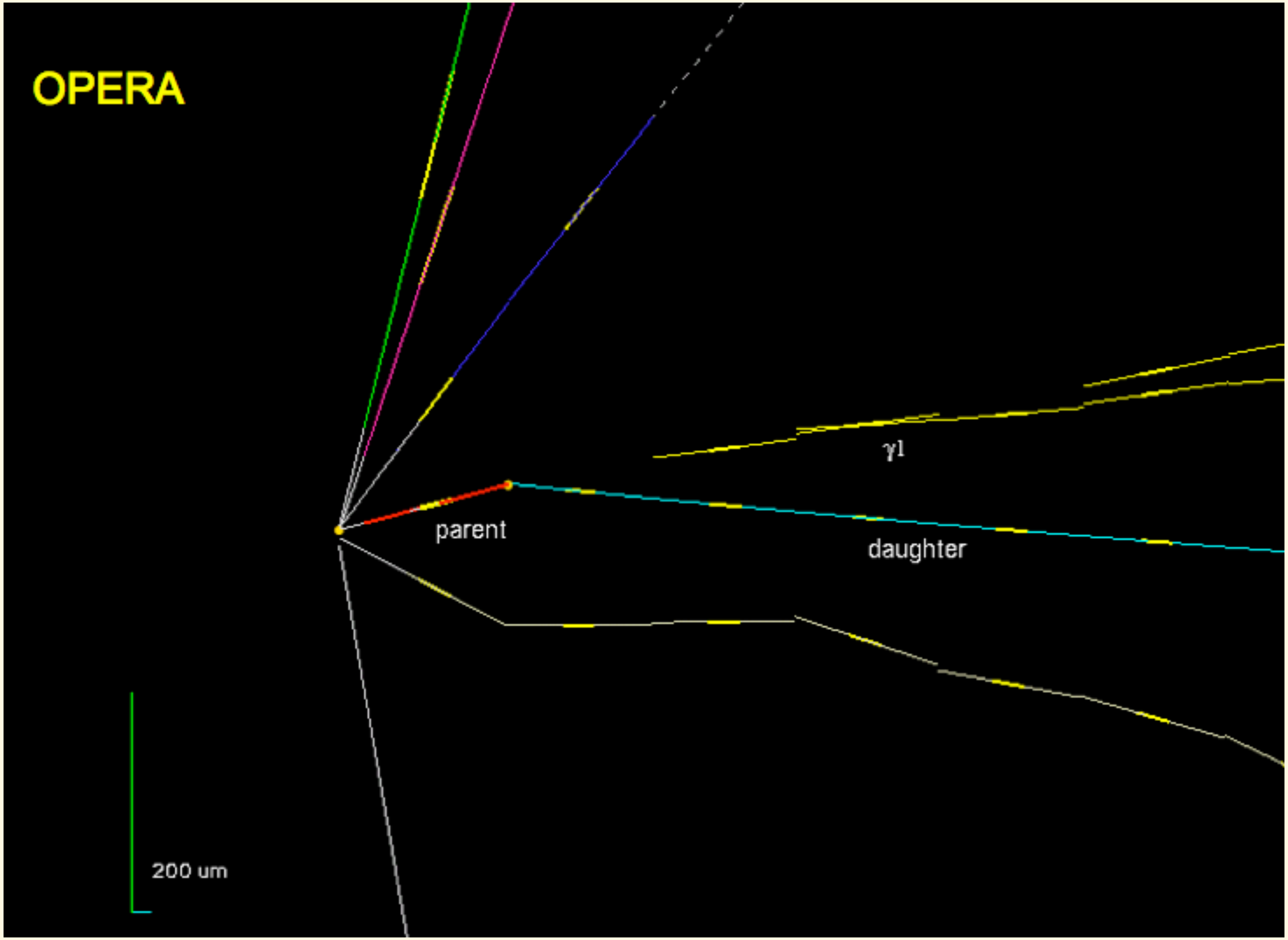

First candidate $\nu_\mu \to \nu_\tau \quad \tau^- \to \pi^- + \pi^0$

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

Mixed (Subdominant) Sector

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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

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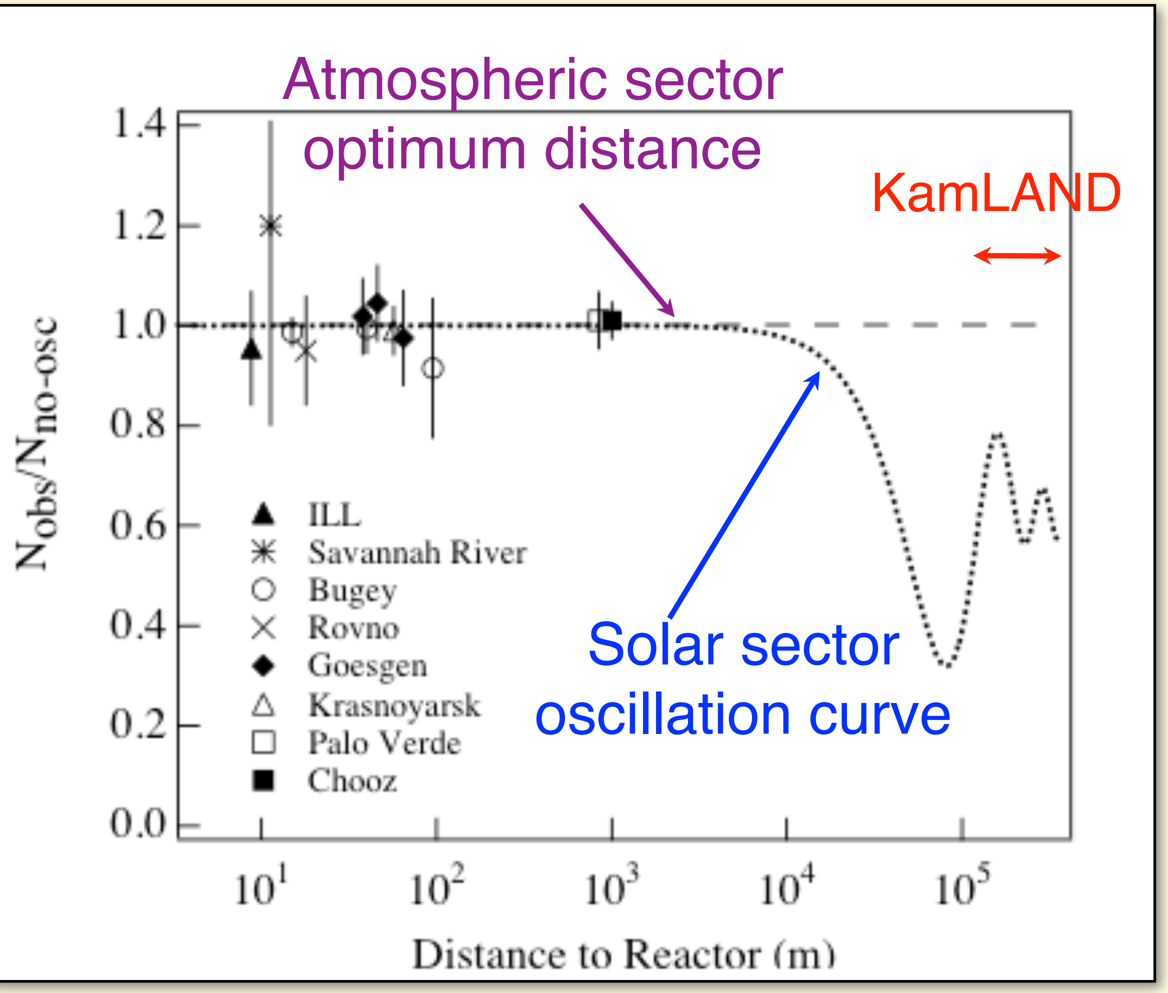

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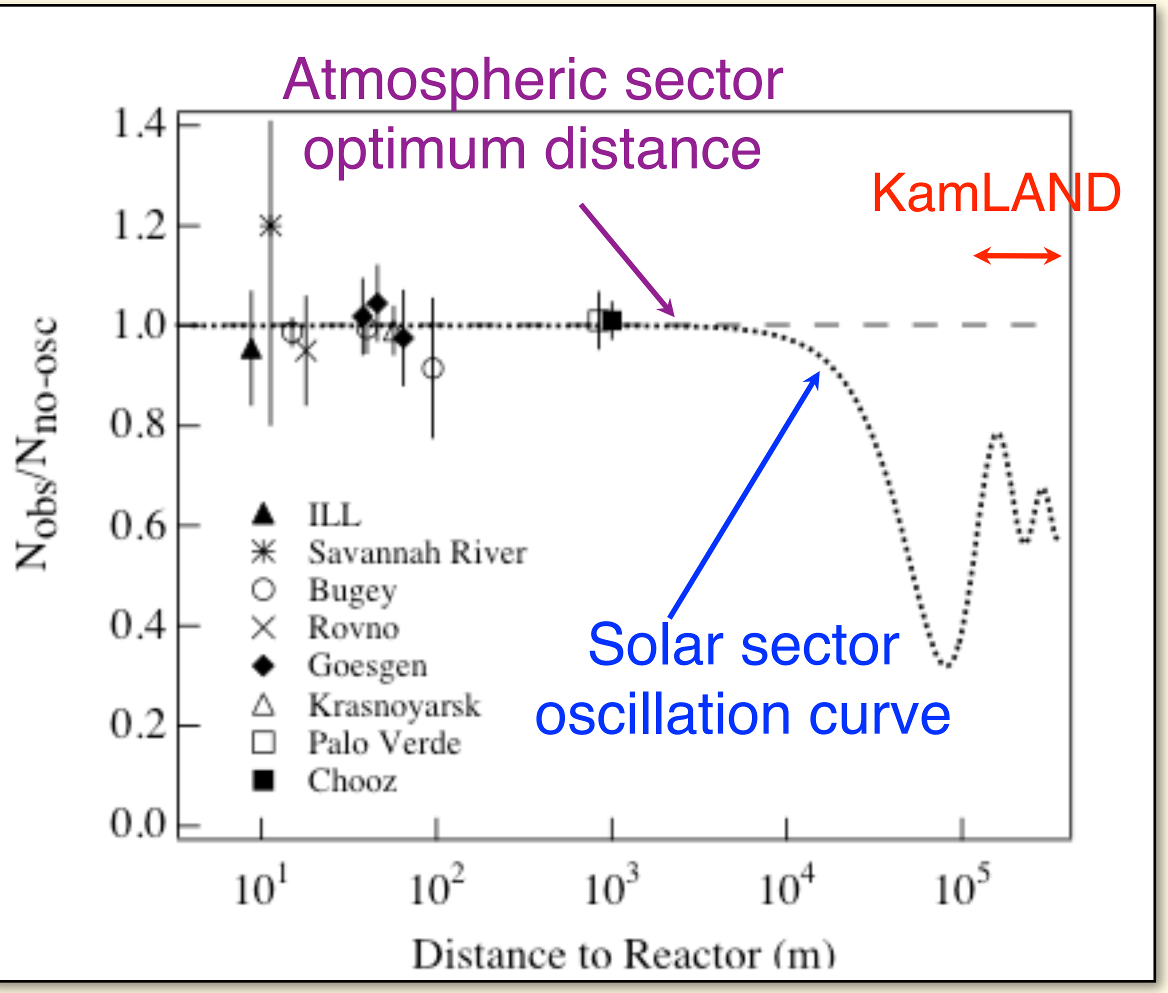
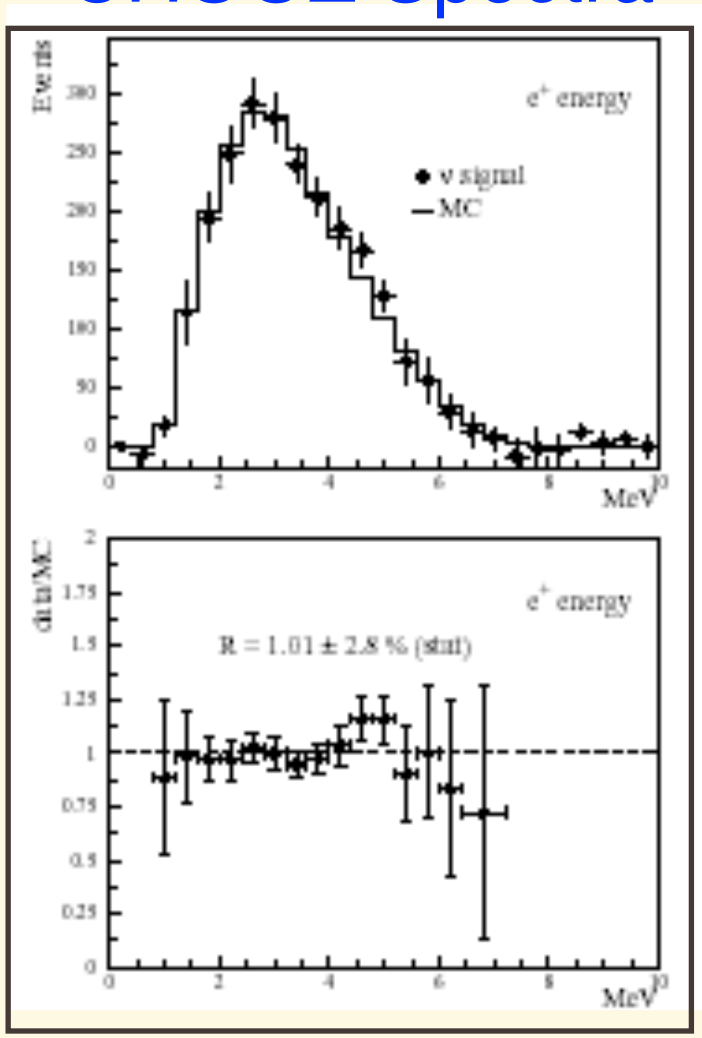


CHOOZ Spectra



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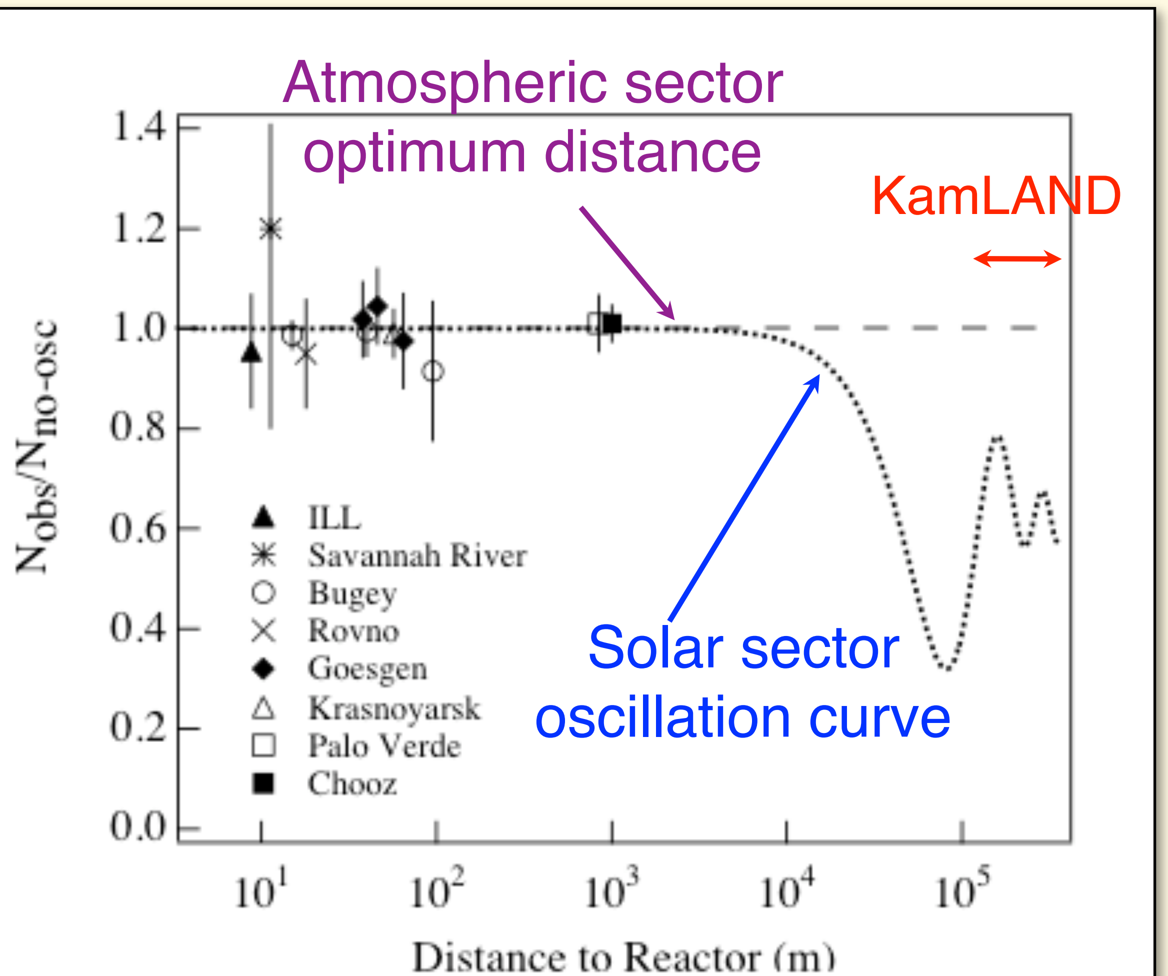

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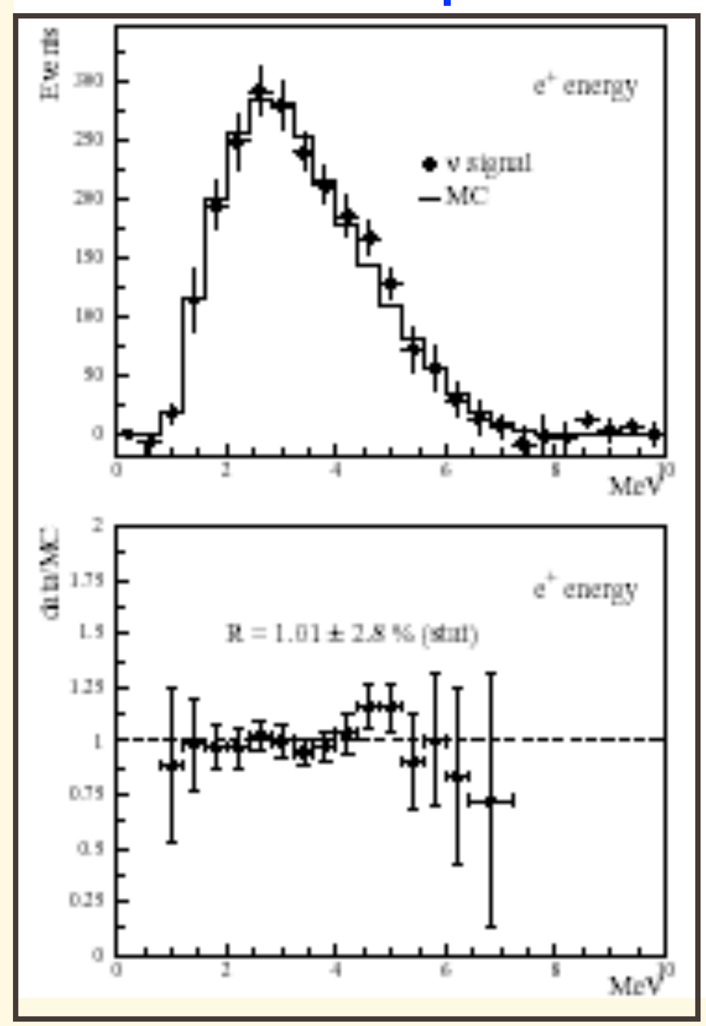
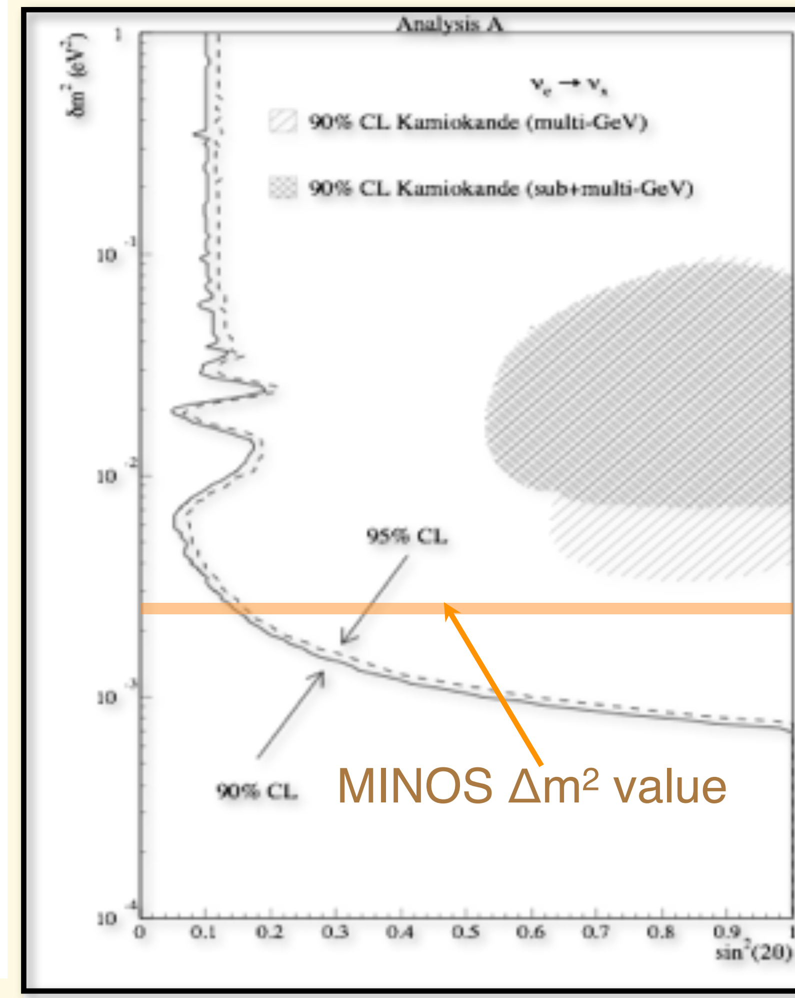


CHOOZ Limits



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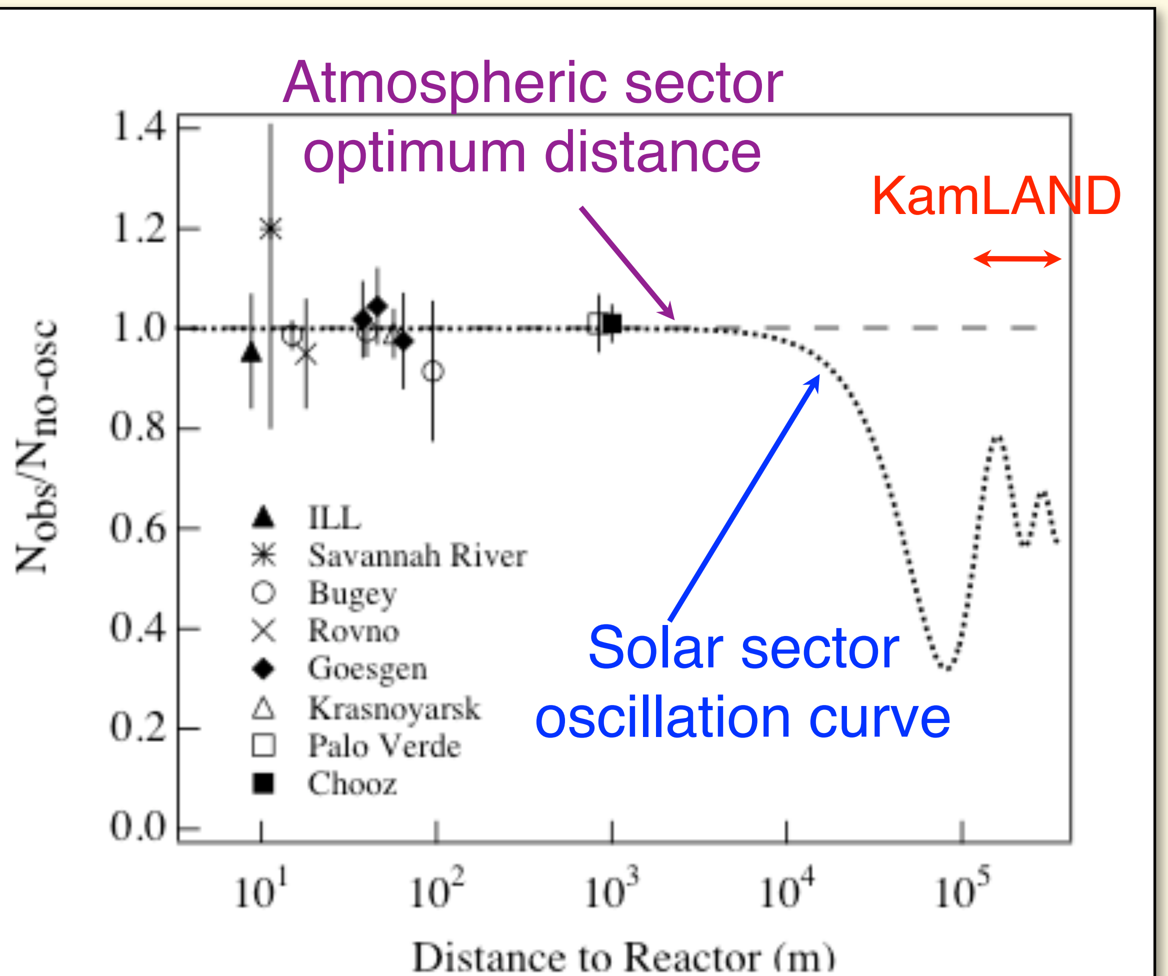

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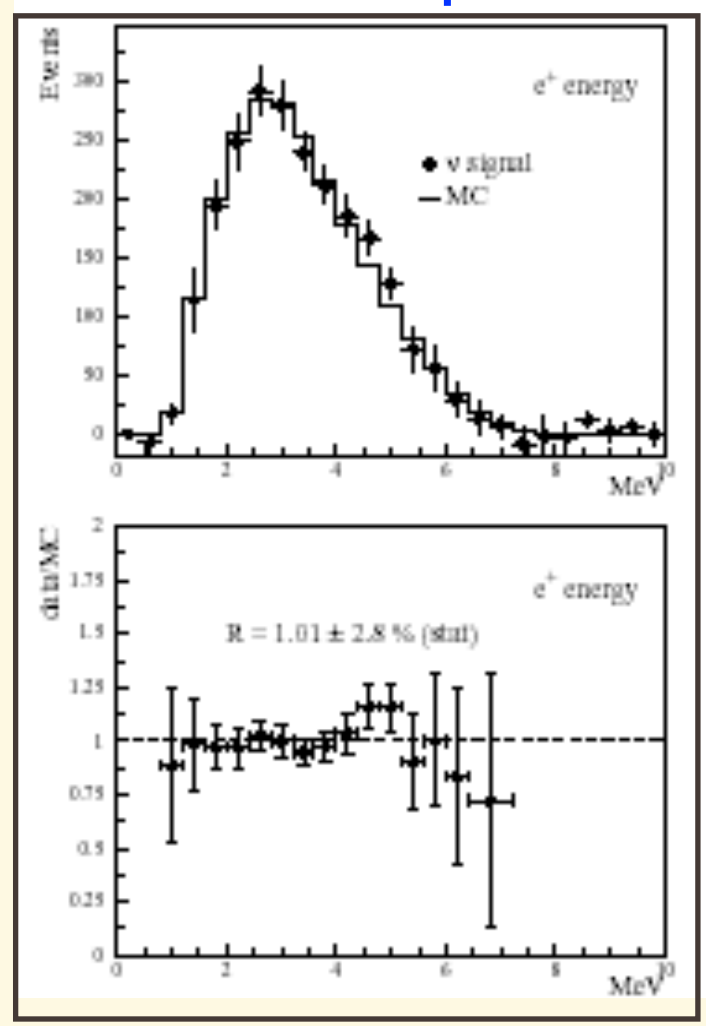

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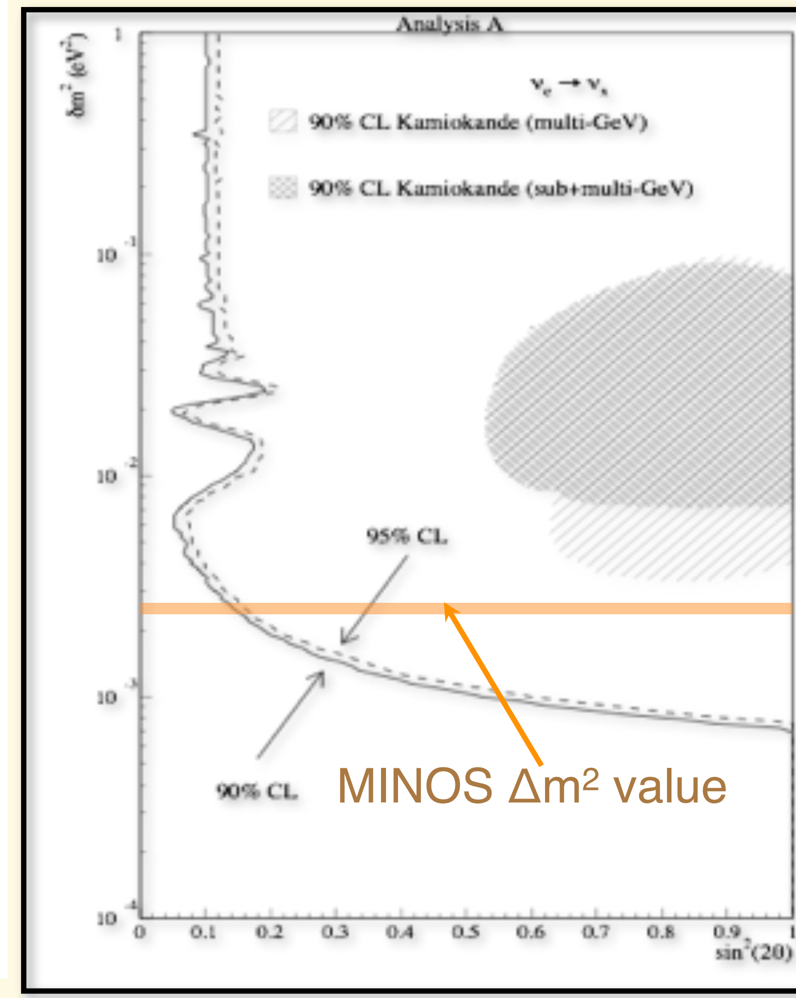

CHOOZ limit: $\sin^2(2\theta_{13})<0.15$ (90% C.L.)

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

ν_e Appearance

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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

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

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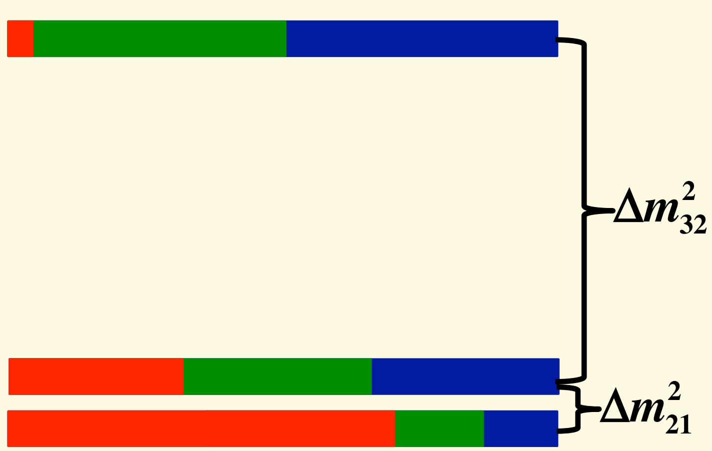
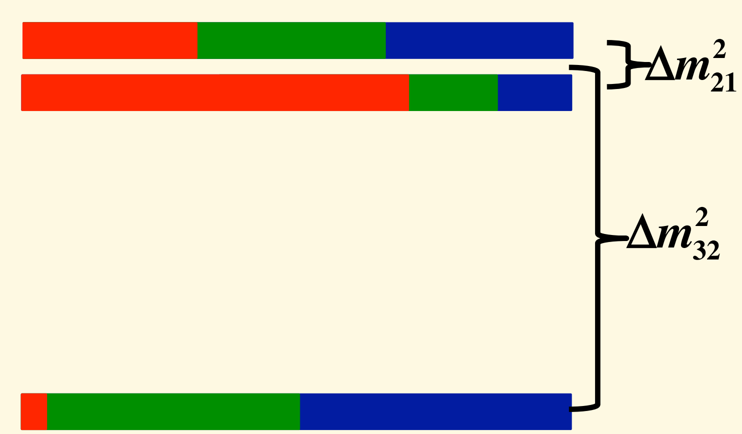


Normal hierarchy



Inverted hierarchy

Matter Effects

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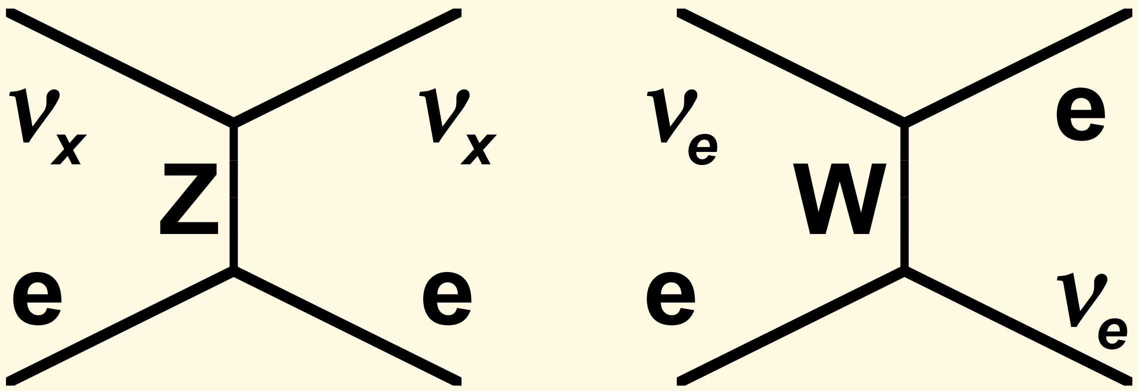
In matter, ν_e's interact differently than other flavor neutrinos because of additional interaction with electrons



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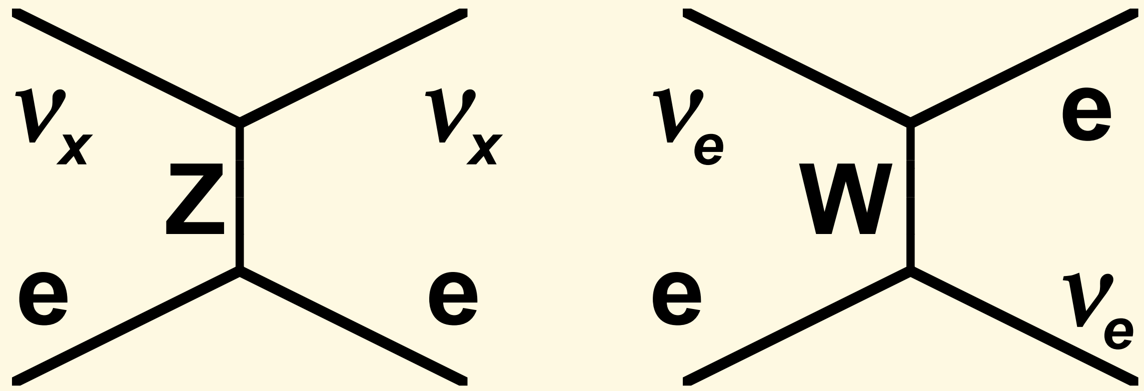

As a result, the transition $\nu_\mu \to \nu_e$ will be enhanced for normal hierarchy and suppressed for inverse hierarchy. Opposite will be true for antineutrinos.

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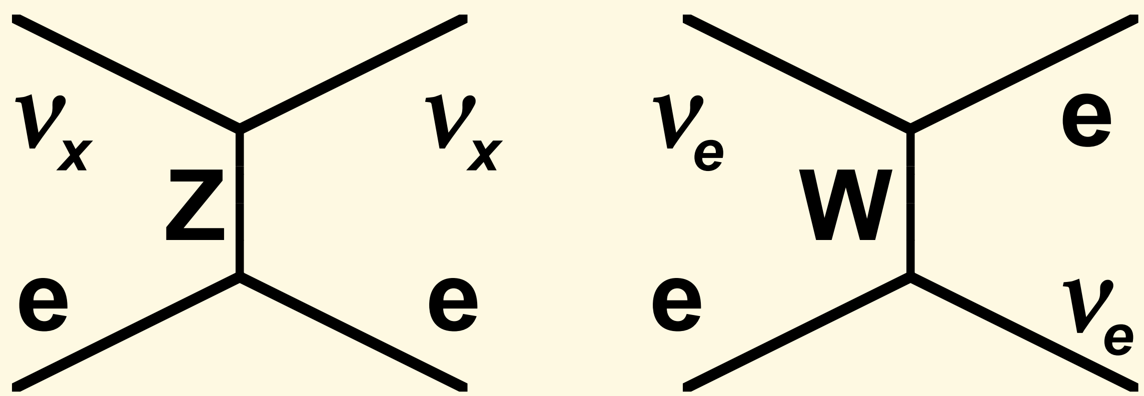

As a result, the transition ν_μ->ν_e will be enhanced for normal hierarchy and suppressed for inverse hierarchy. Opposite will be true for antineutrinos.

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

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- 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

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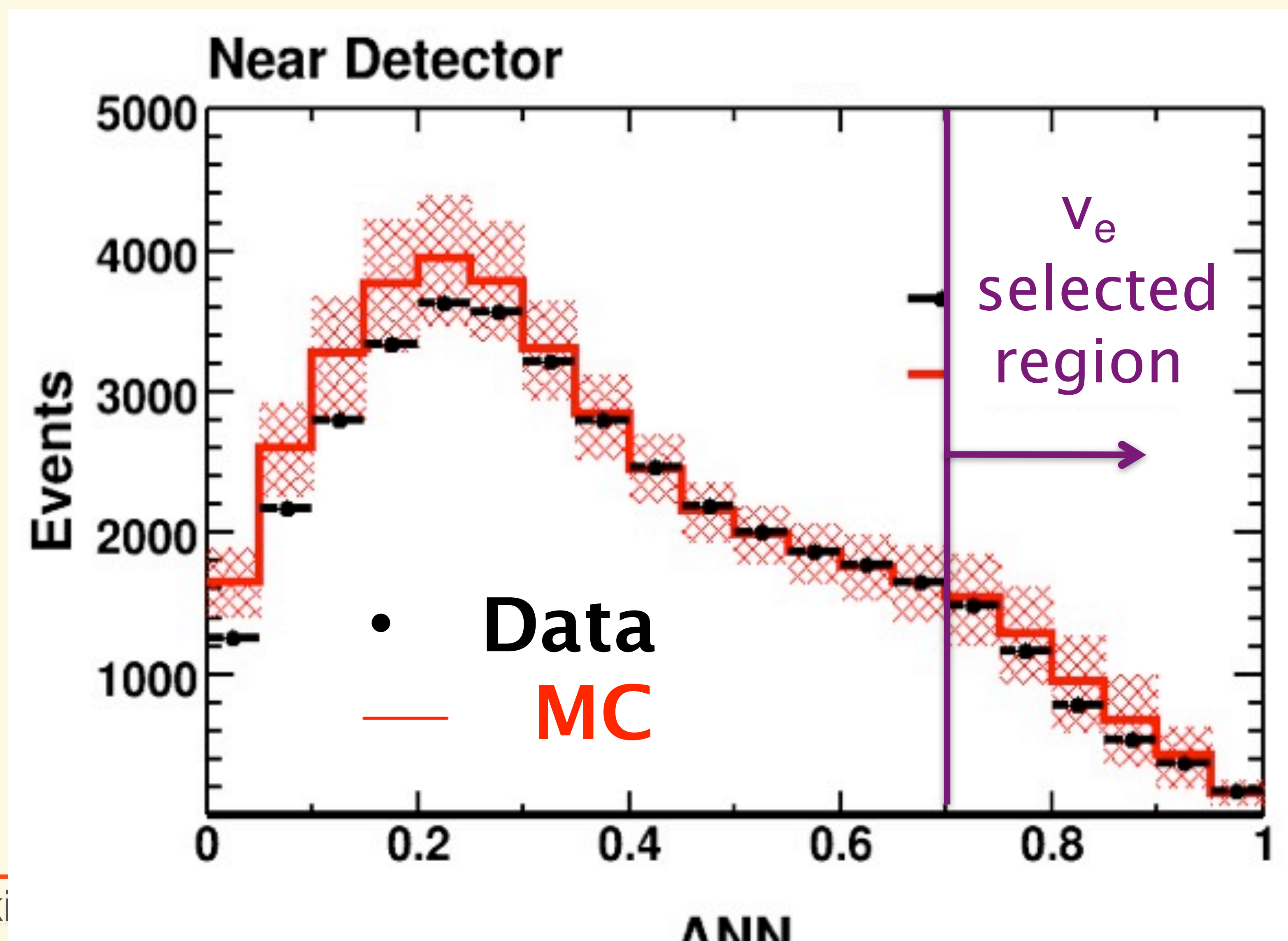
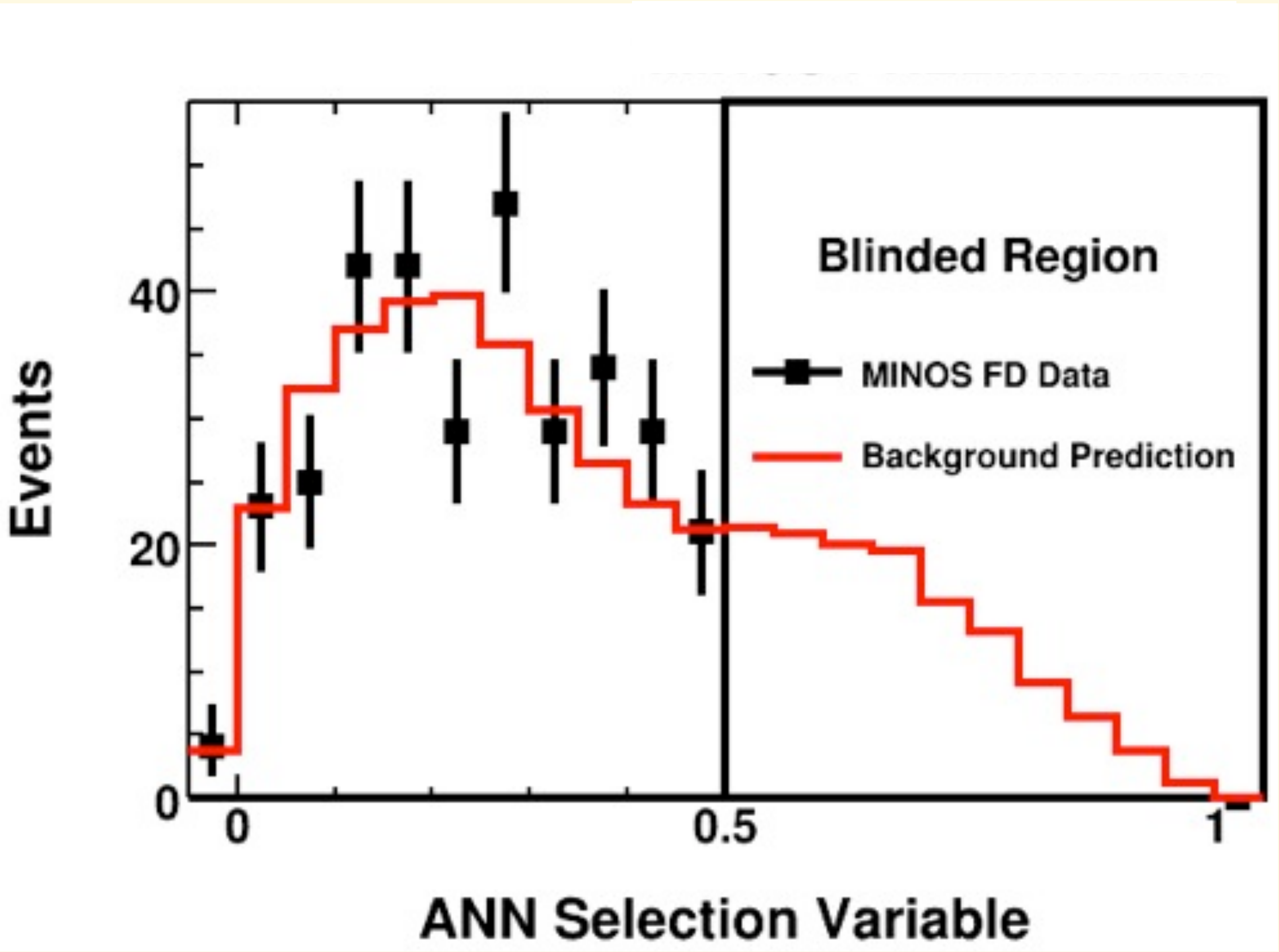
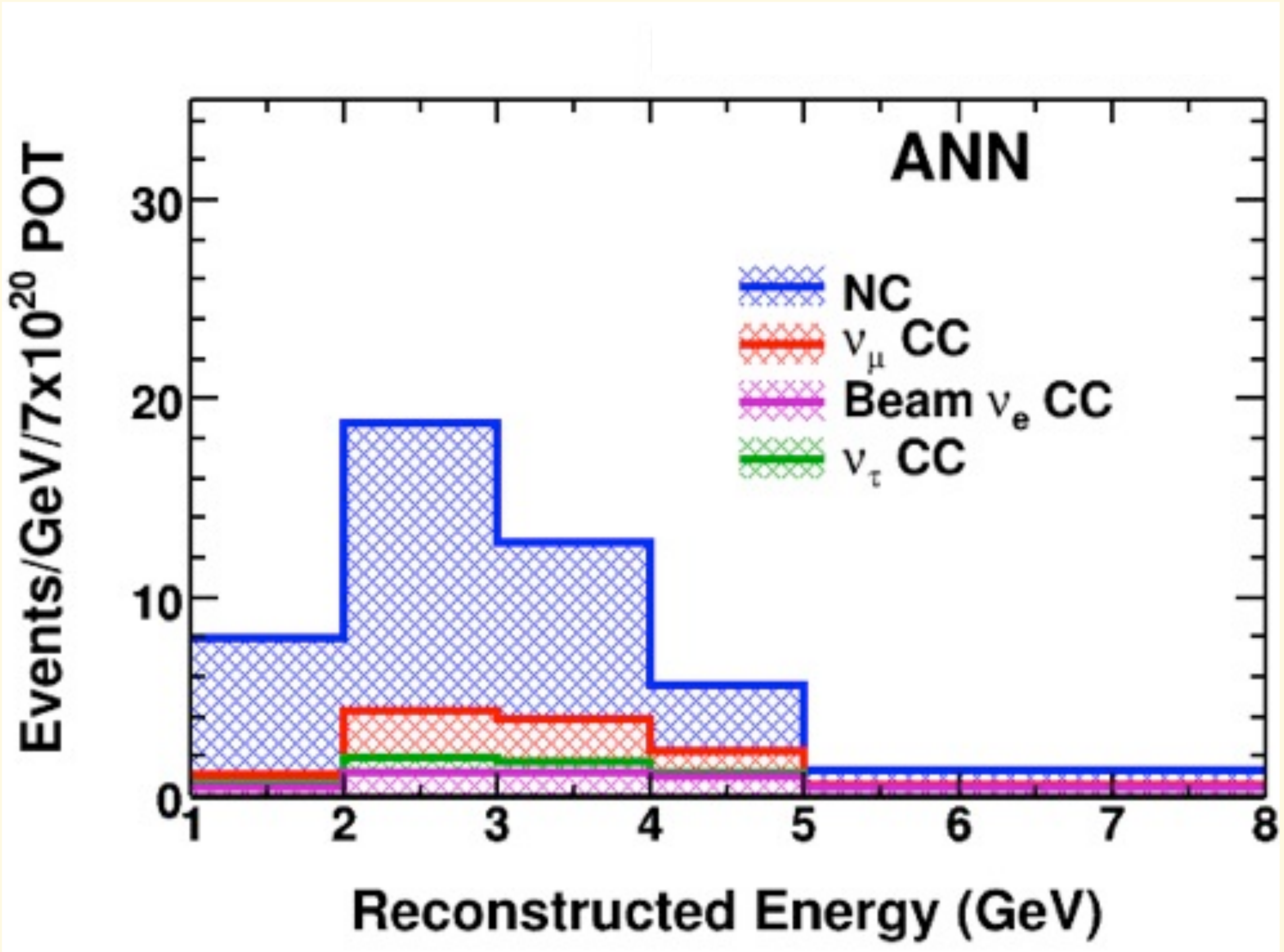


ν_e Appearance Results

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





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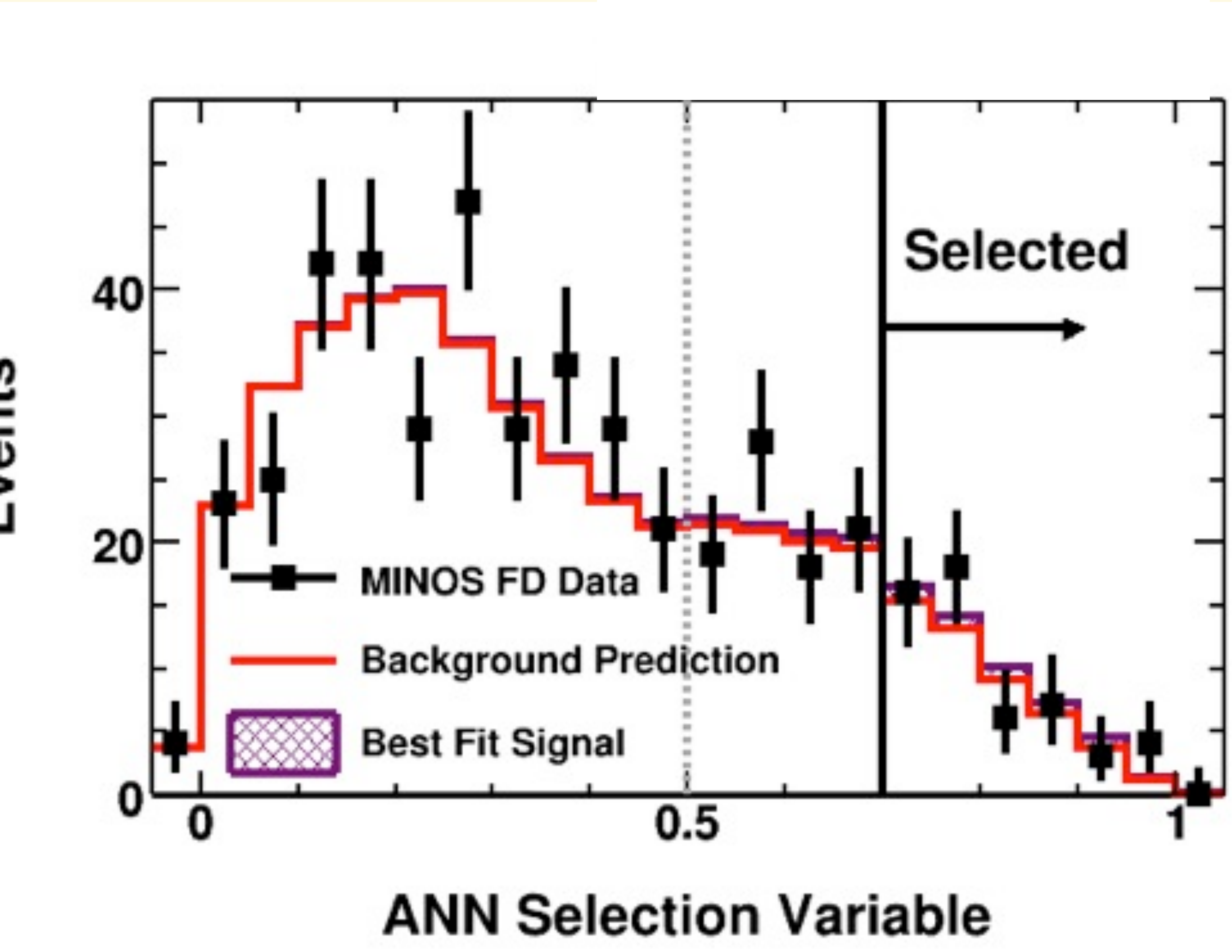

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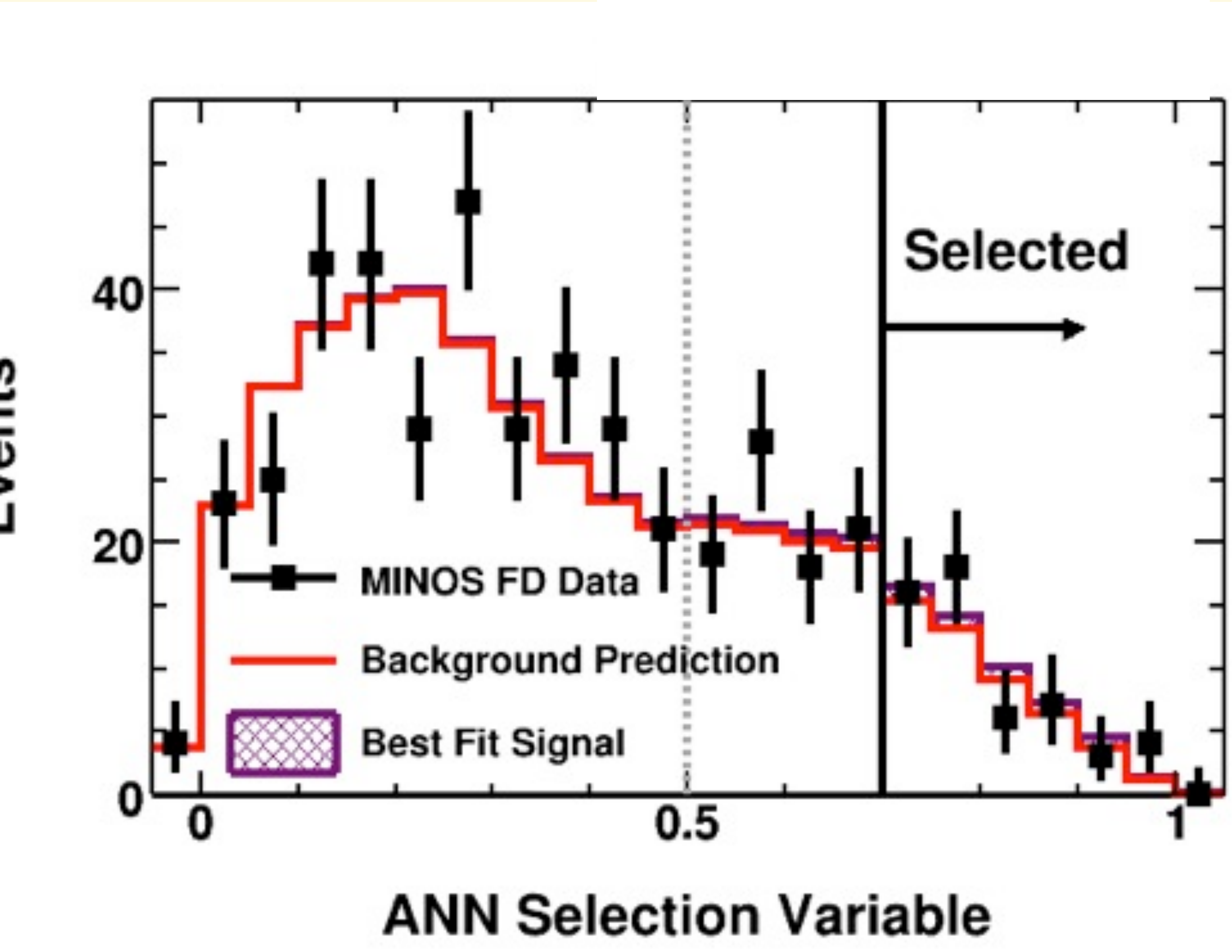

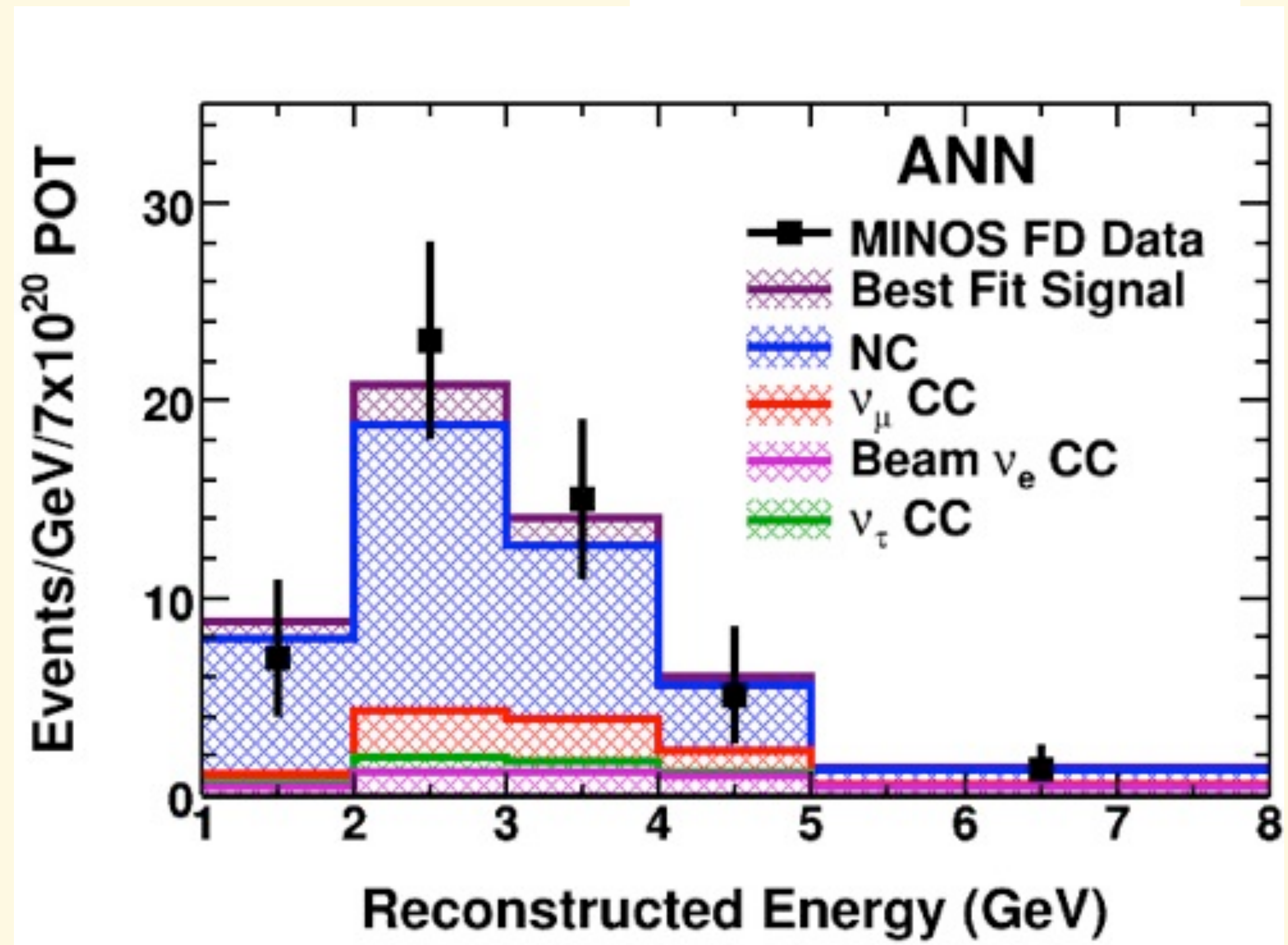

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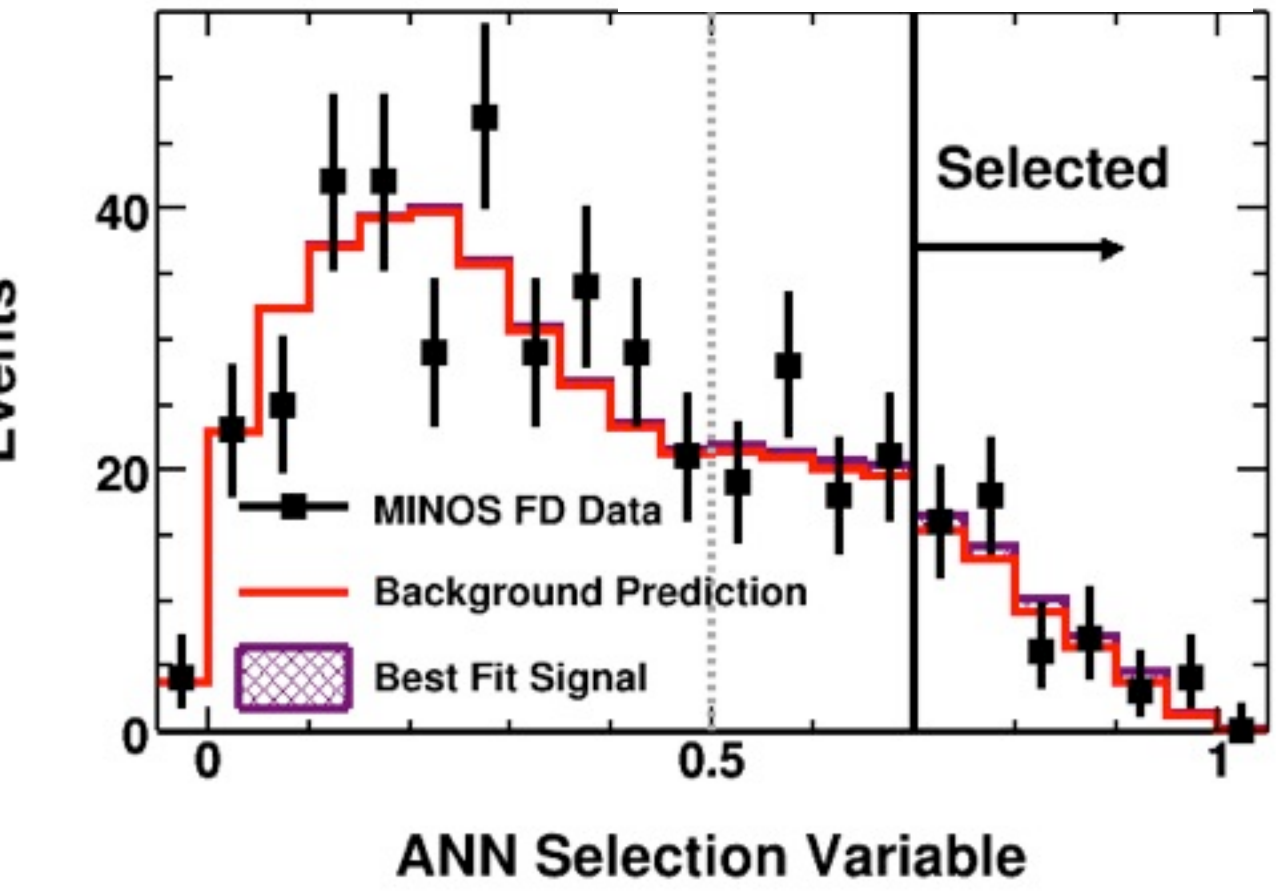

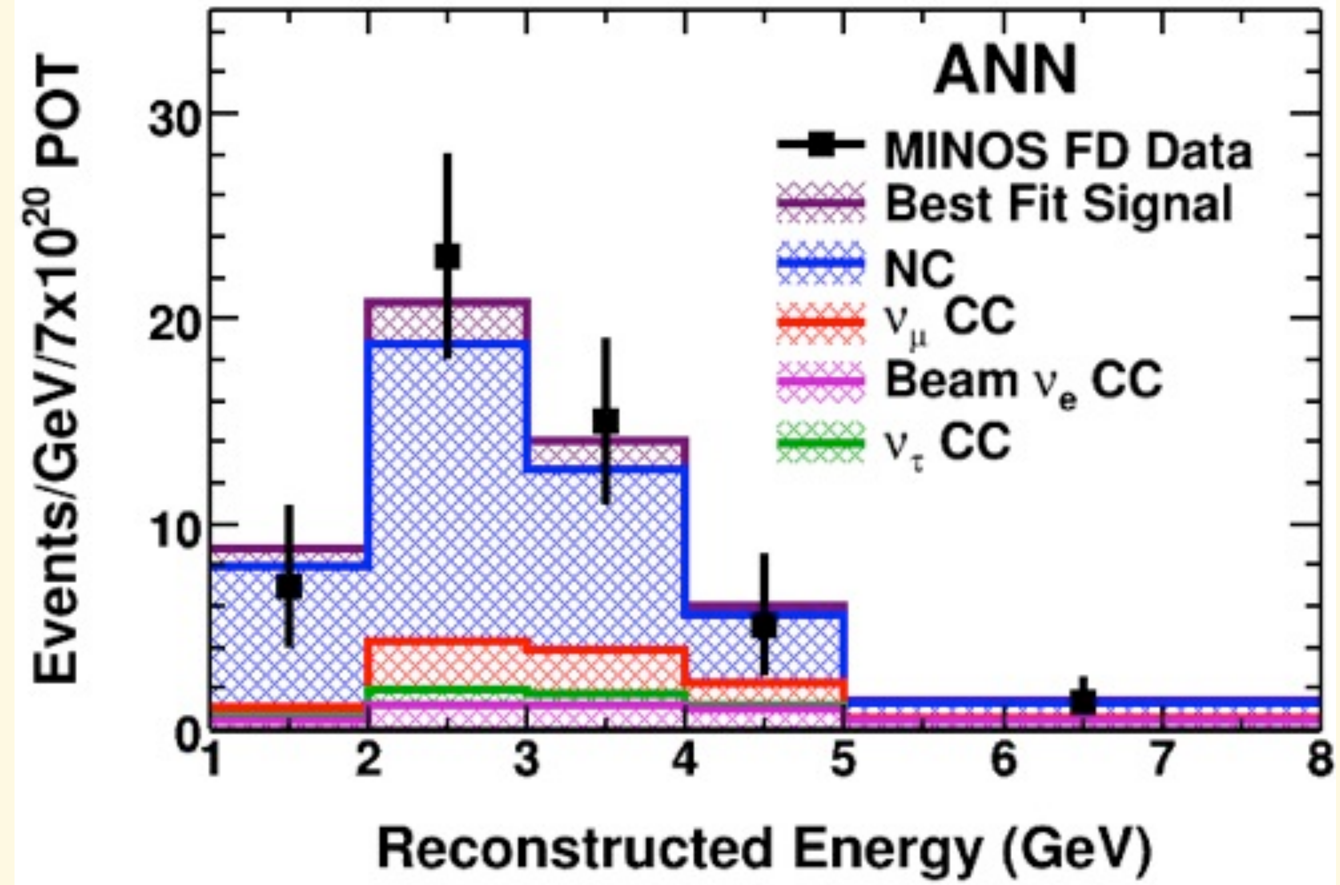

The ND analysis predicts:

49.1±7.0(stat.)±2.7(syst.)

events in the Far Detector

54 observed, **0.7σ** excess

MINOS Result

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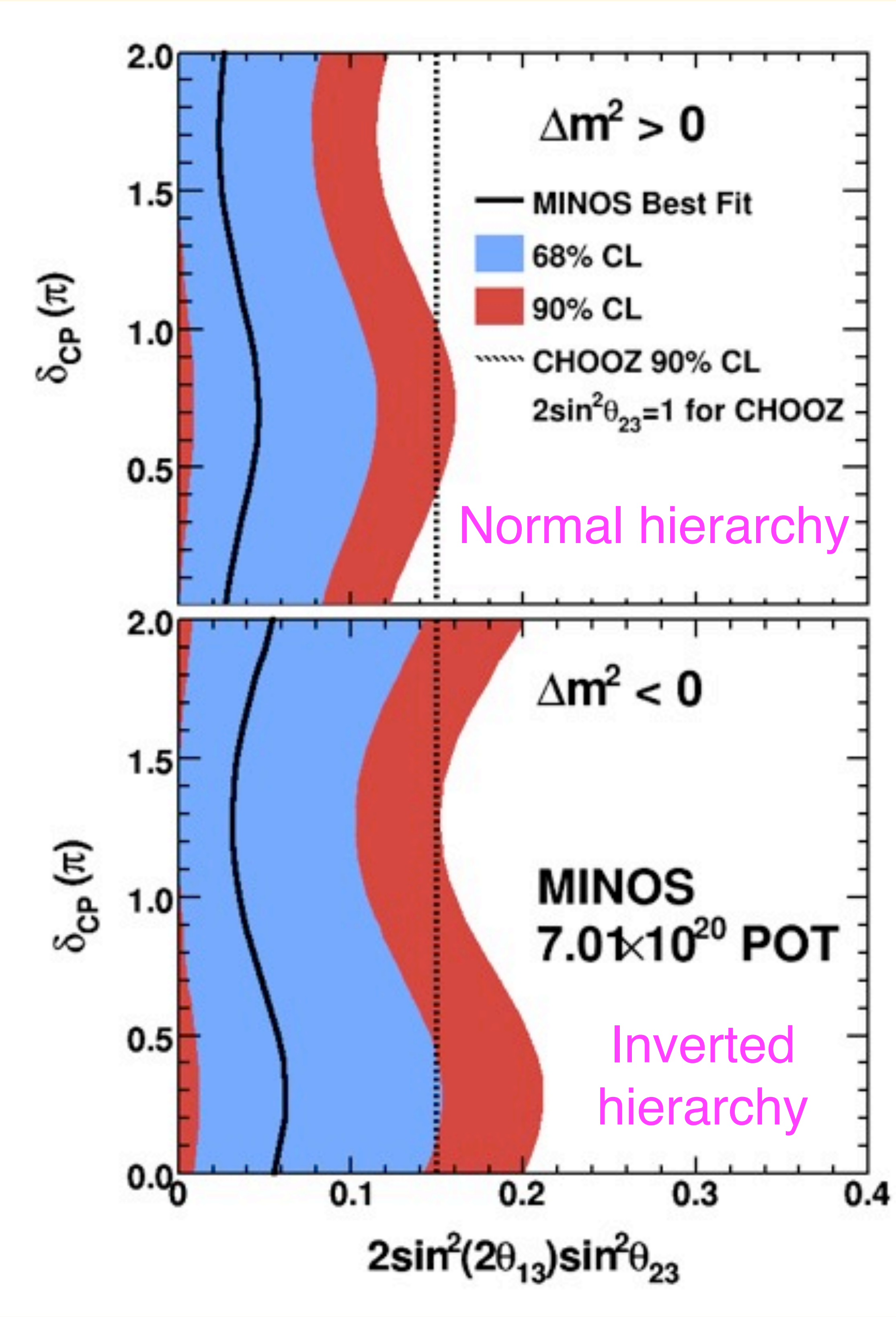

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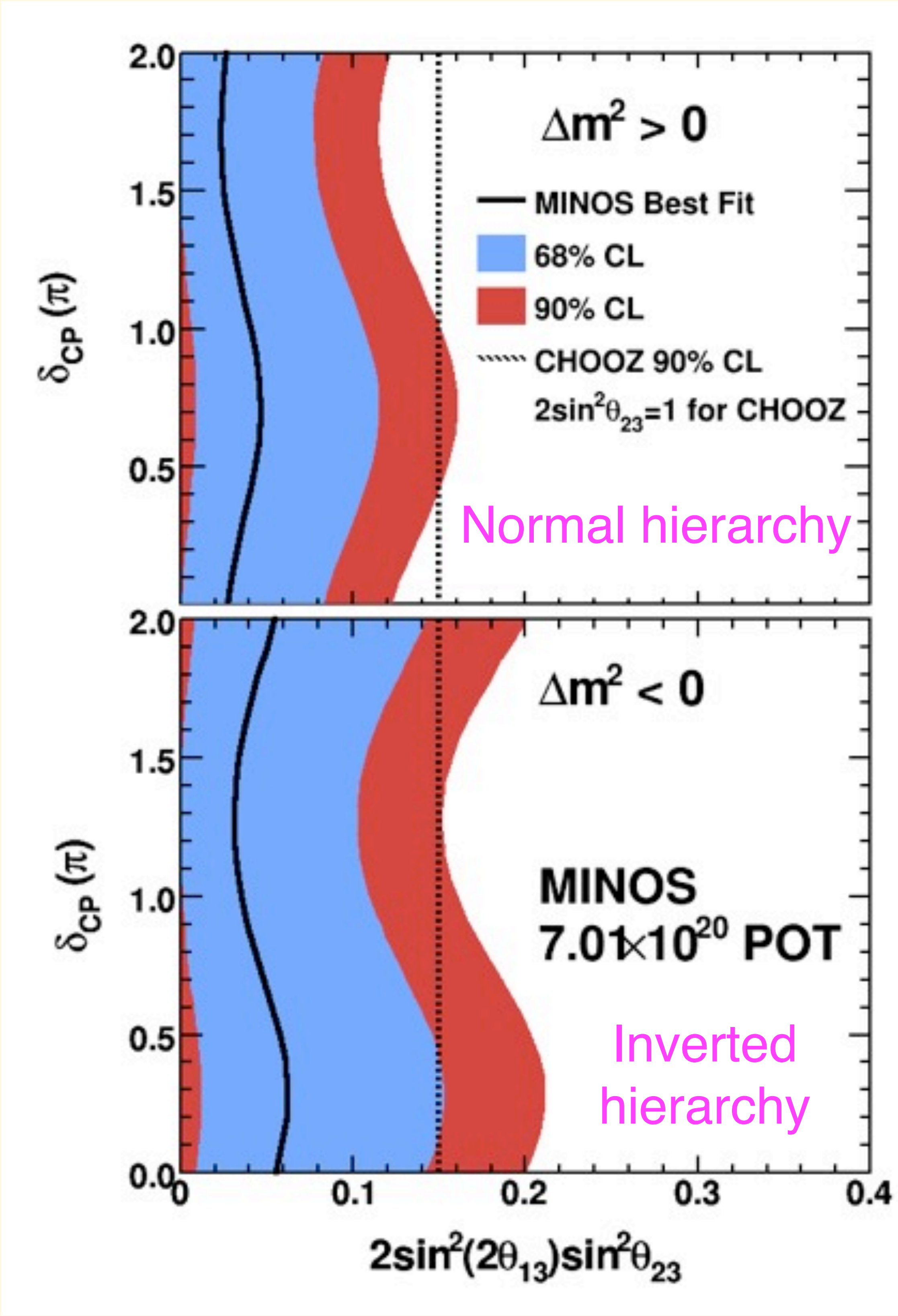
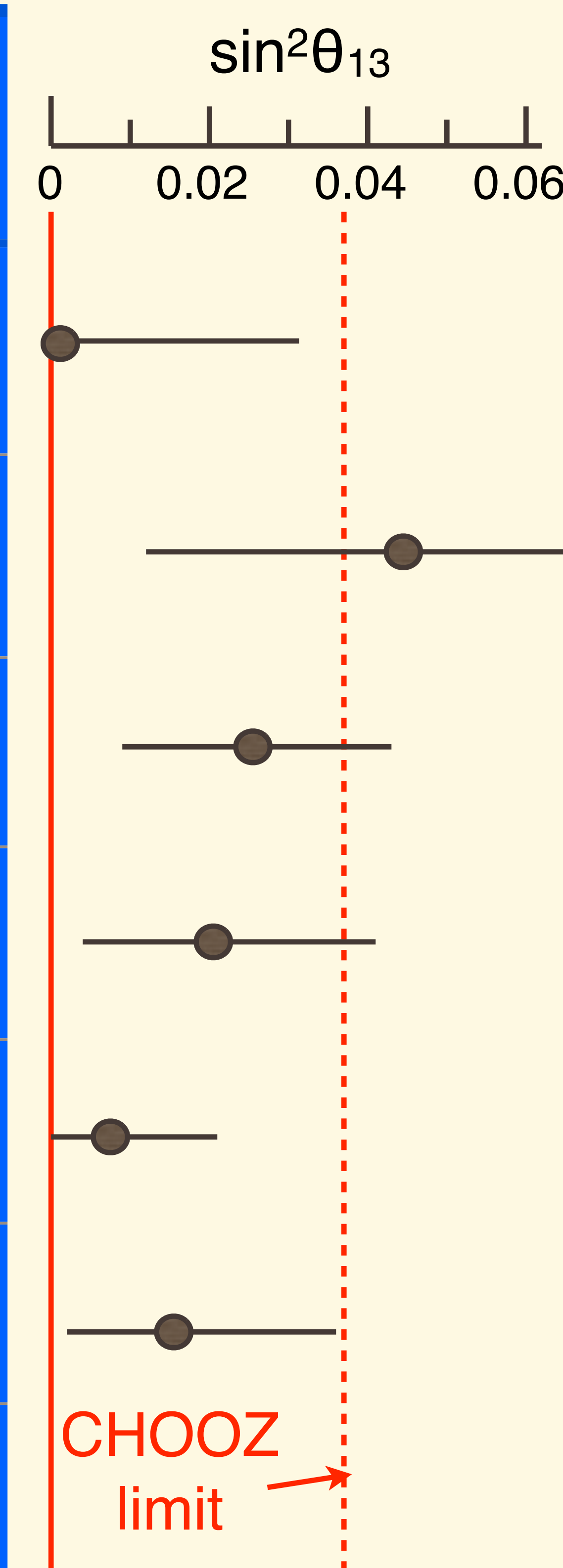


The 90% C.L. limits are:
$\sin^2(2\theta_{13}) < 0.12$ (normal)
$\sin^2(2\theta_{13}) < 0.20$ (inverse)
for
$\sin^2(2\theta_{23}) = 1$, $\delta_{CP} = 0$,
$|\Delta m^2_{31}| = 2.43 \times 10^{-3}$ eV^2

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

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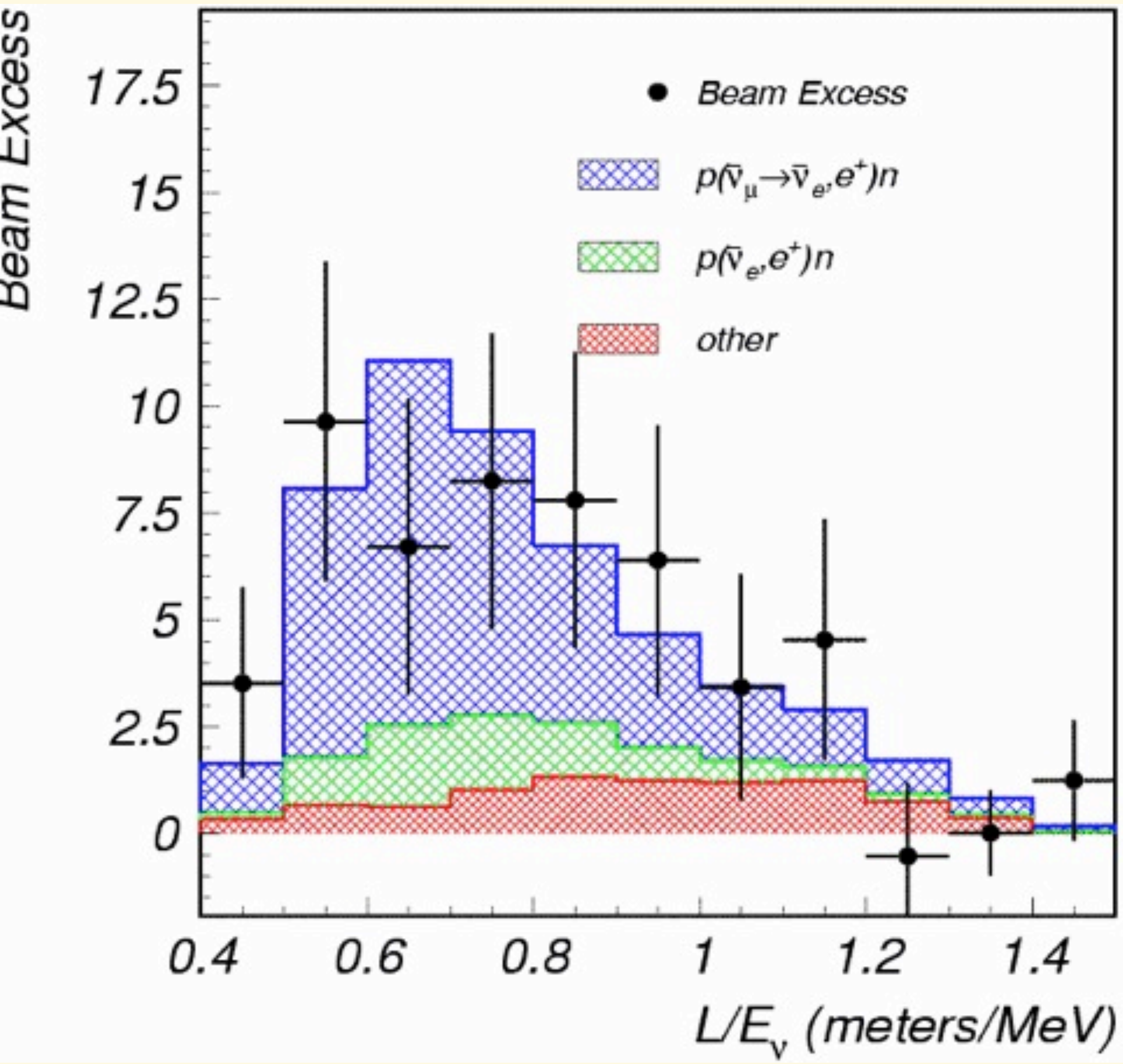
Note that no $\overline{\nu}_e$ are produced in these processes

LSND Effect

R. Van de Water Nu2010

LSND Effect

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



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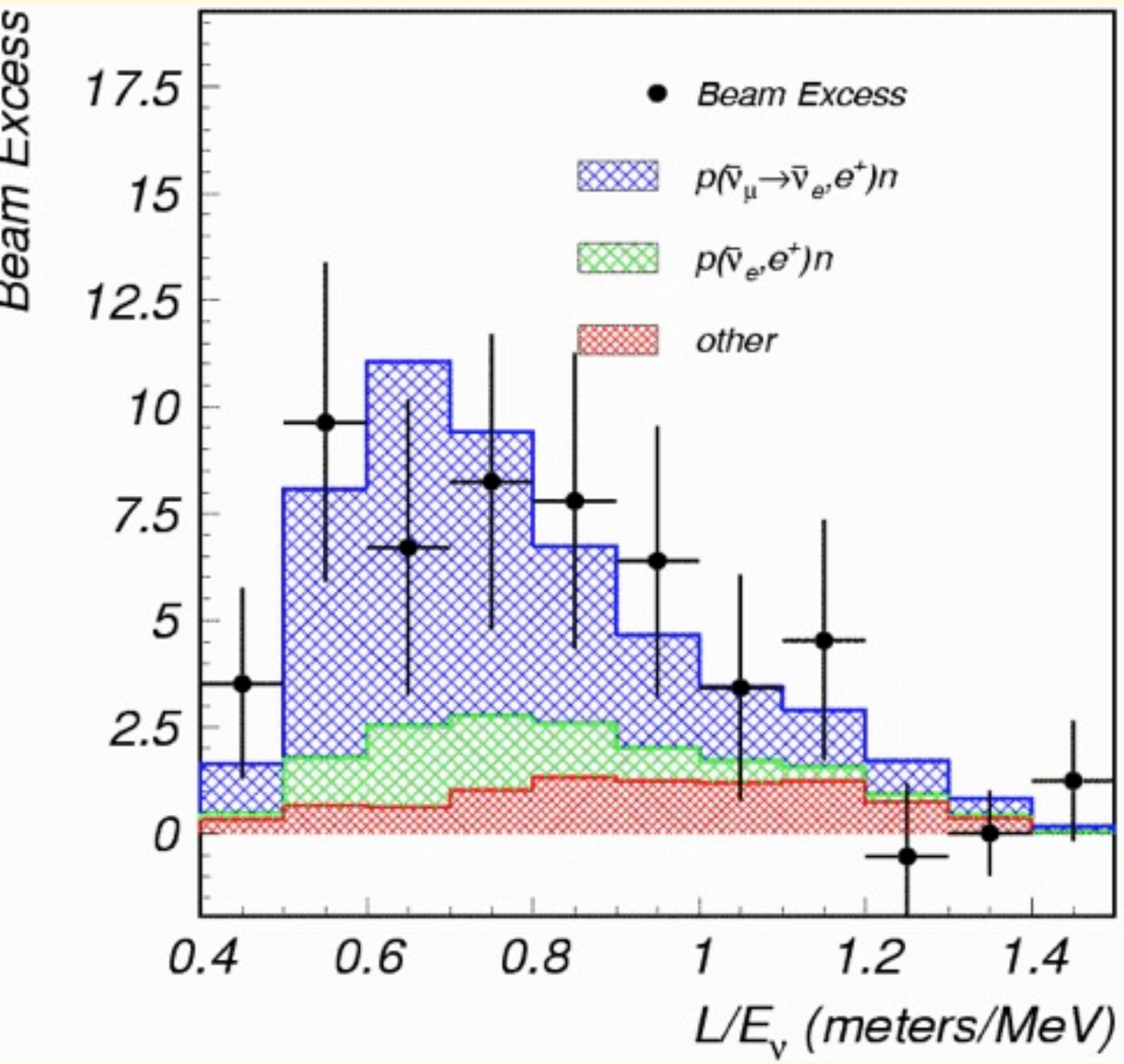
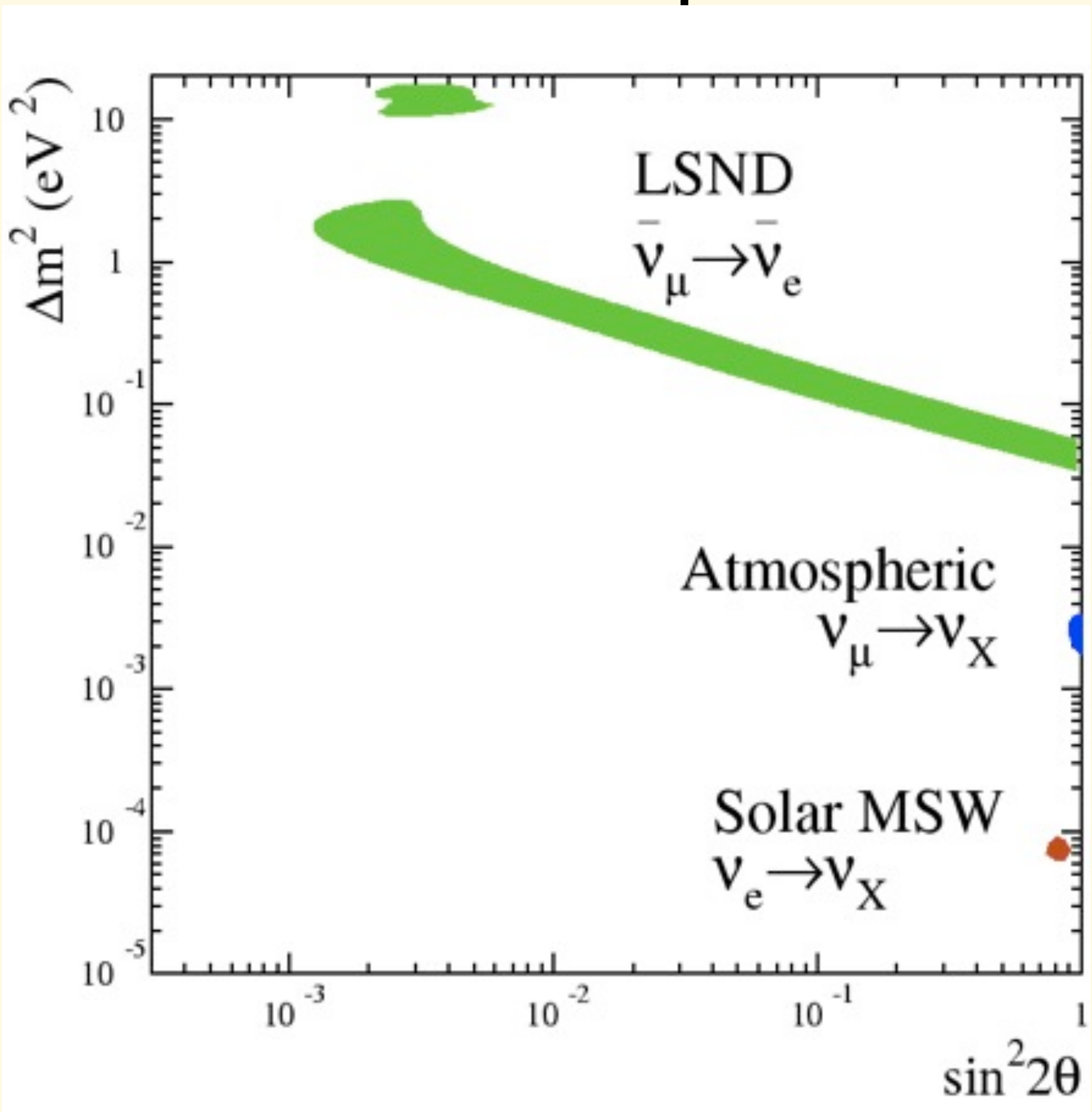


Oscillation interpretation



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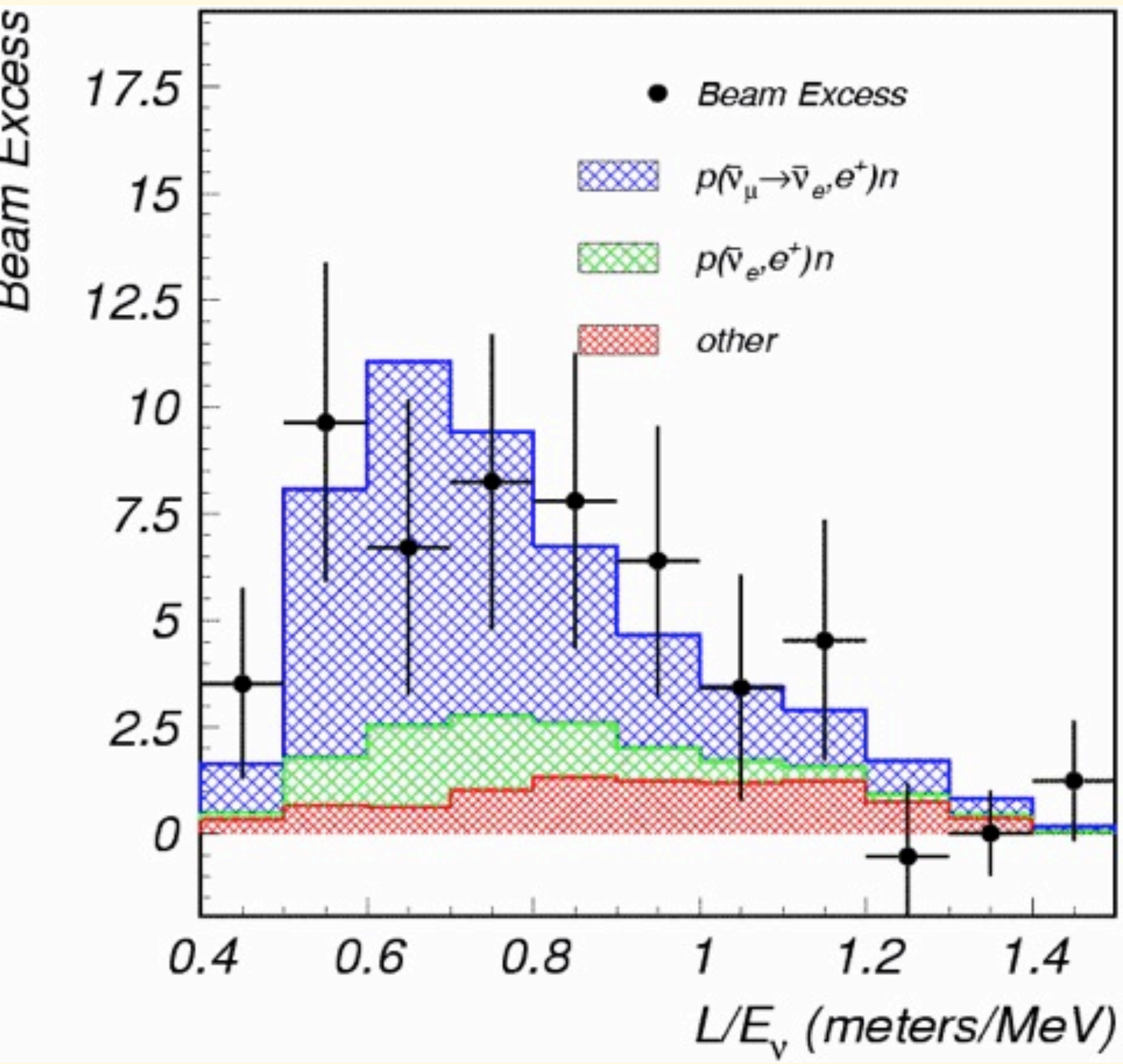

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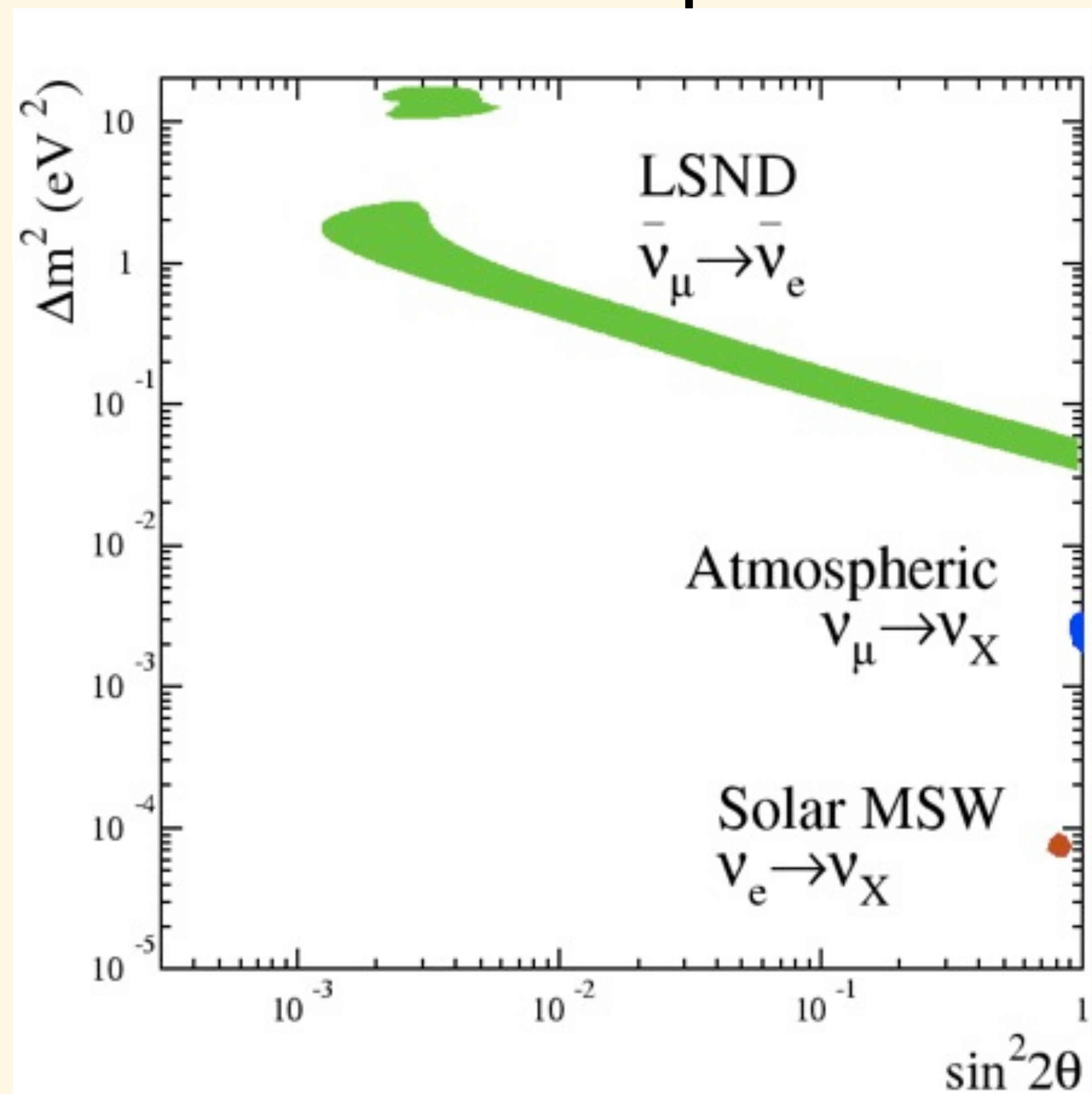

If effect is due to oscillations, there must be a 4th, sterile, neutrino

Backgrounds

- Signal to background ratio is low so understanding backgrounds well is crucial
- Sources of backgrounds:
  - Non-beam (cosmic) - measured during off-beam time (duty cycle is ~7%)
  - Accidentals from cosmic and beam - can be calculated from off-beam measurements - small
  - Beam related - main source $\bar{\nu}_e$ from π^-,μ^- decay chain
    - π^- decays in flight (produced upstream?)
    - underestimate of π^- production (Anastasia's poster)

MiniBooNE

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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

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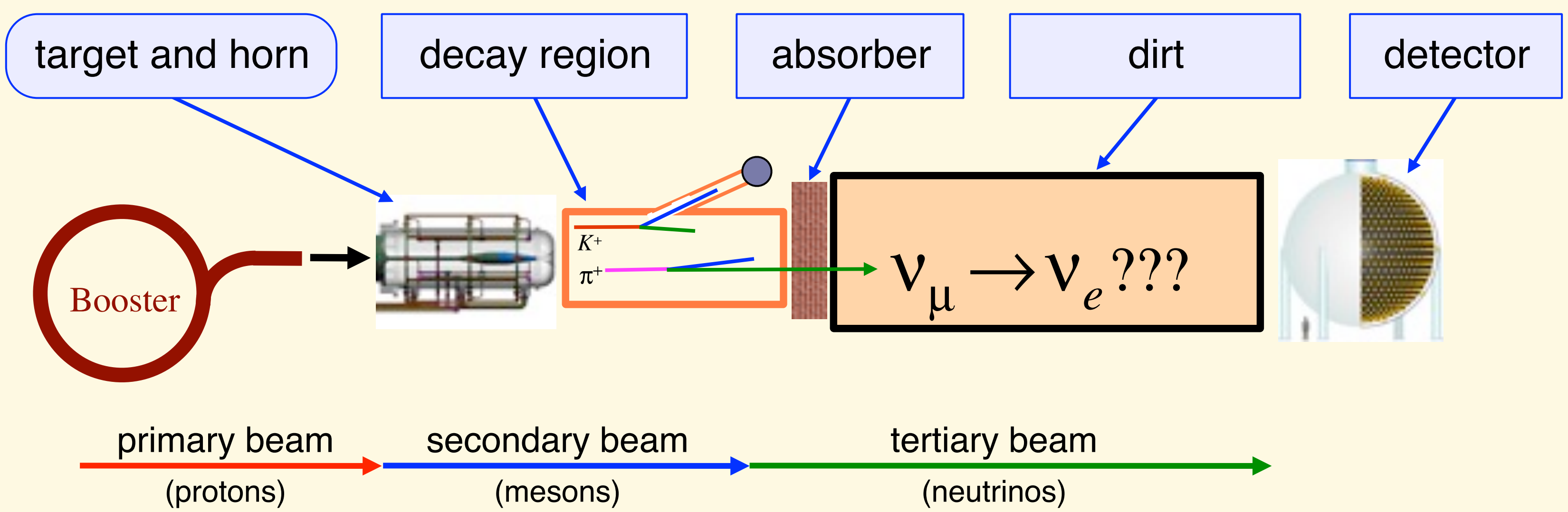

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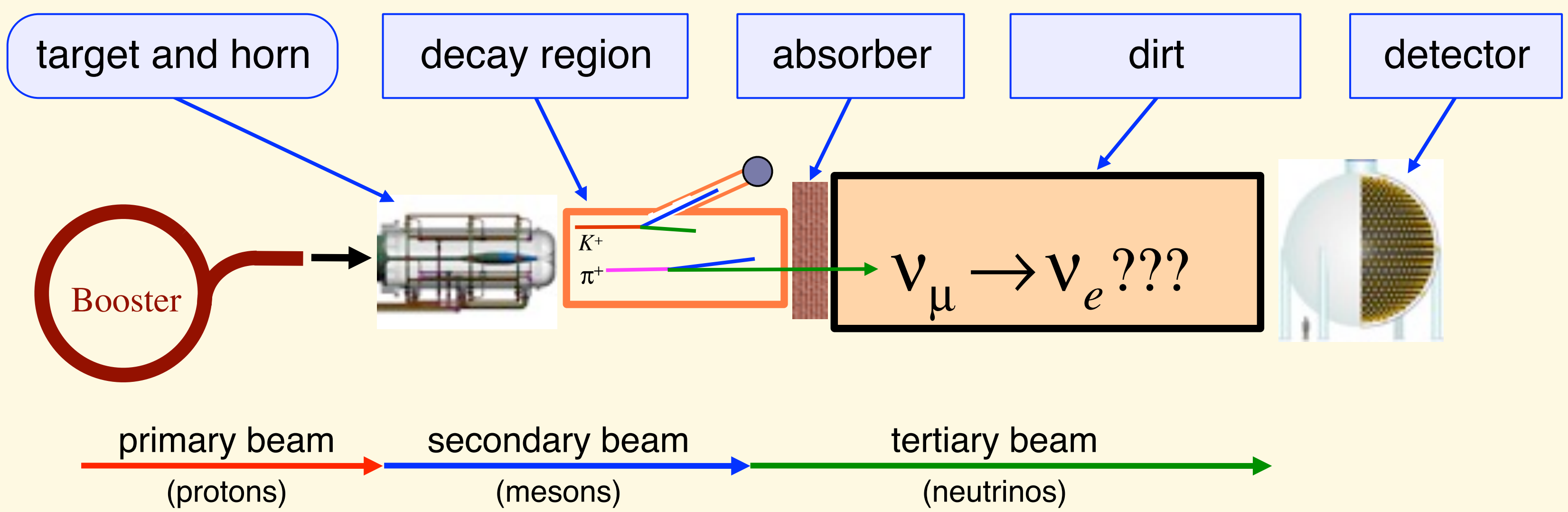


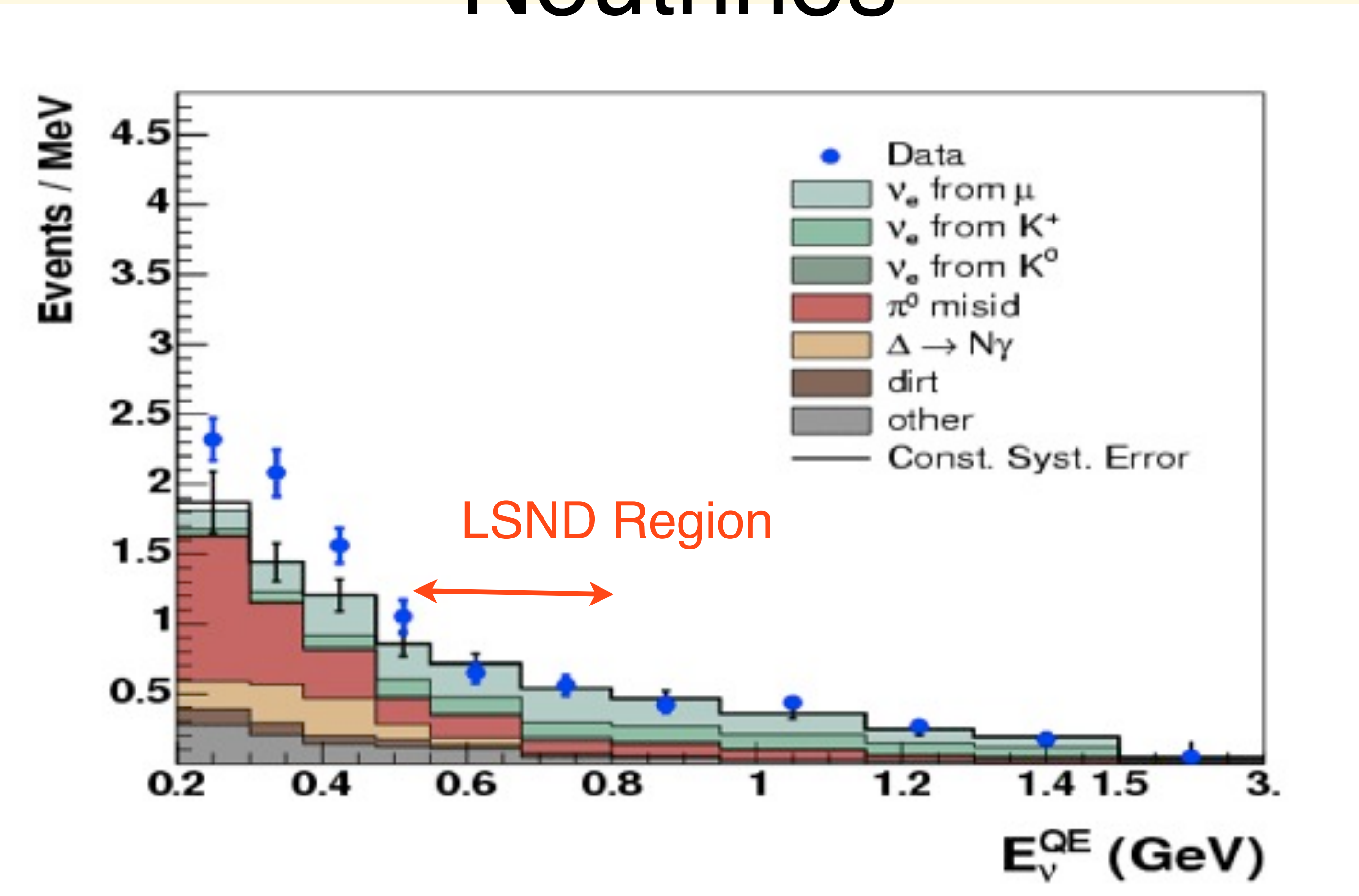
Both neutrino and antineutrino exposures were obtained

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

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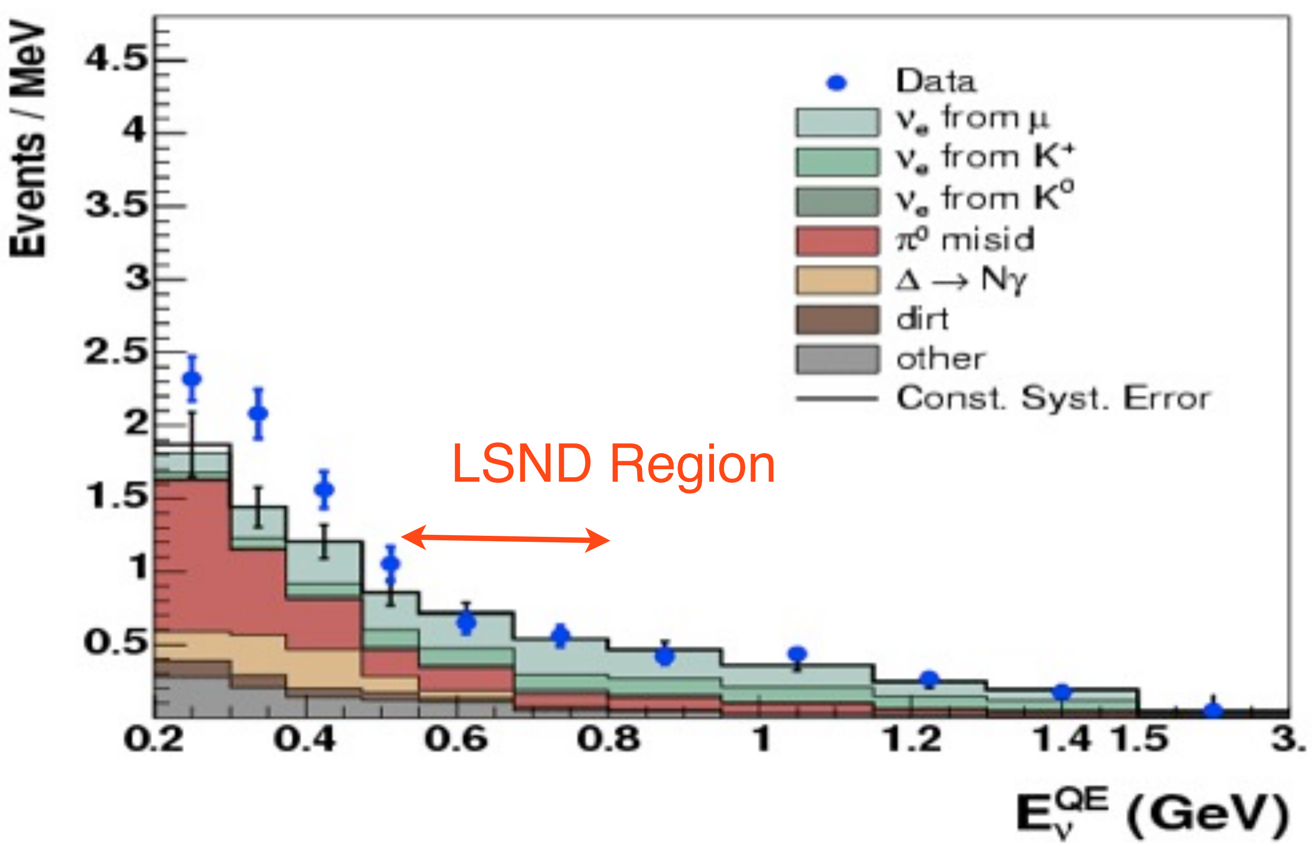
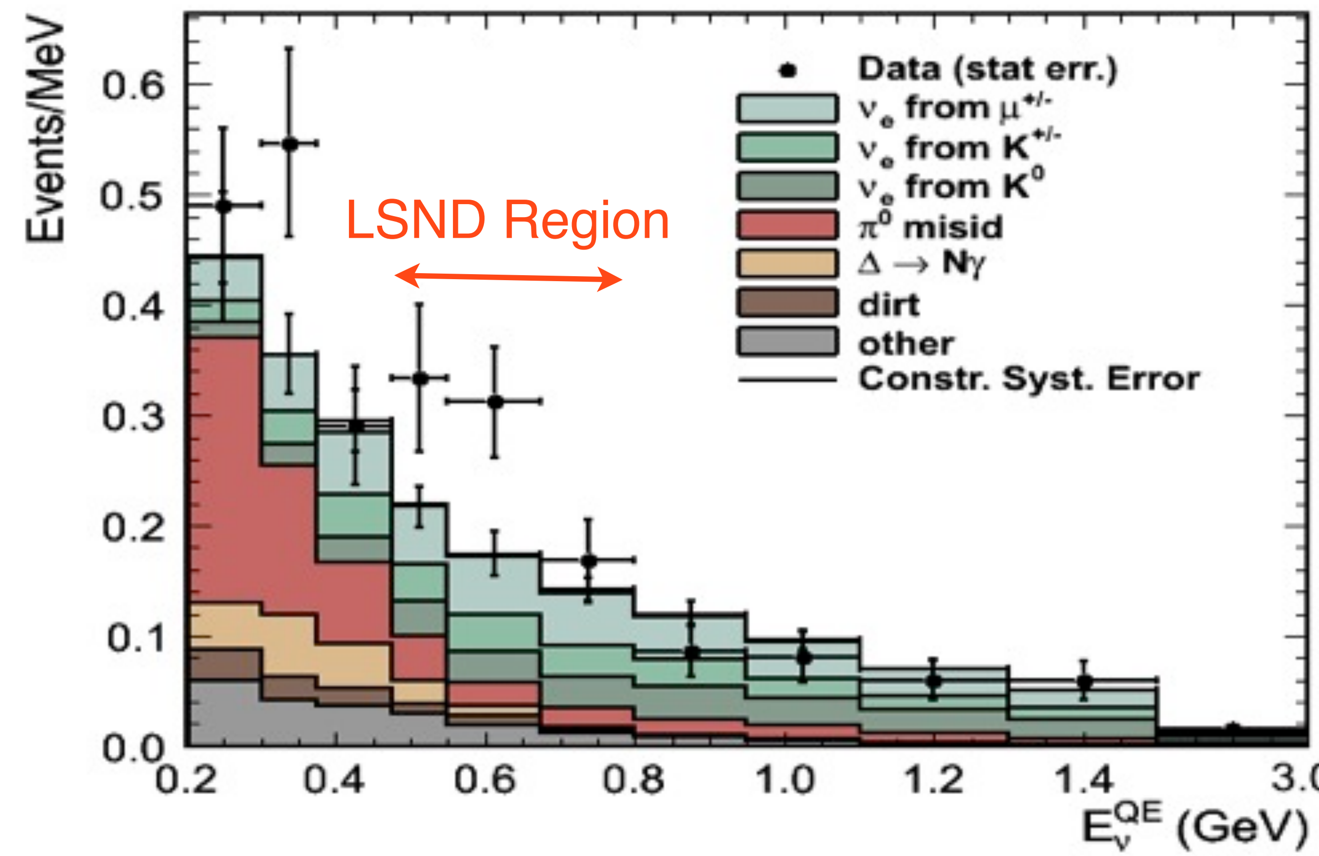


Antineutrinos



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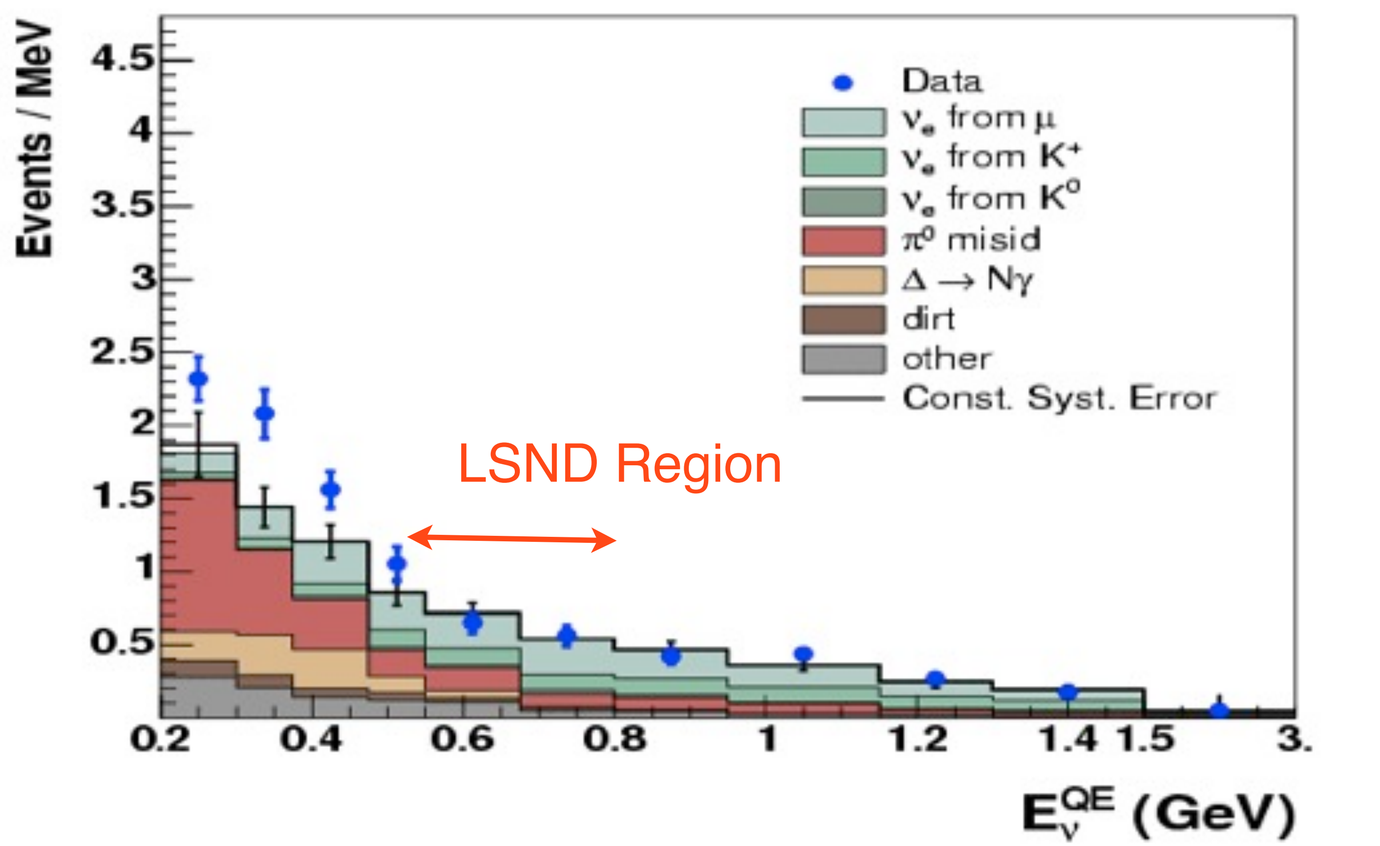
Excess of events in LSND region

MiniBooNE Results

Neutrinos



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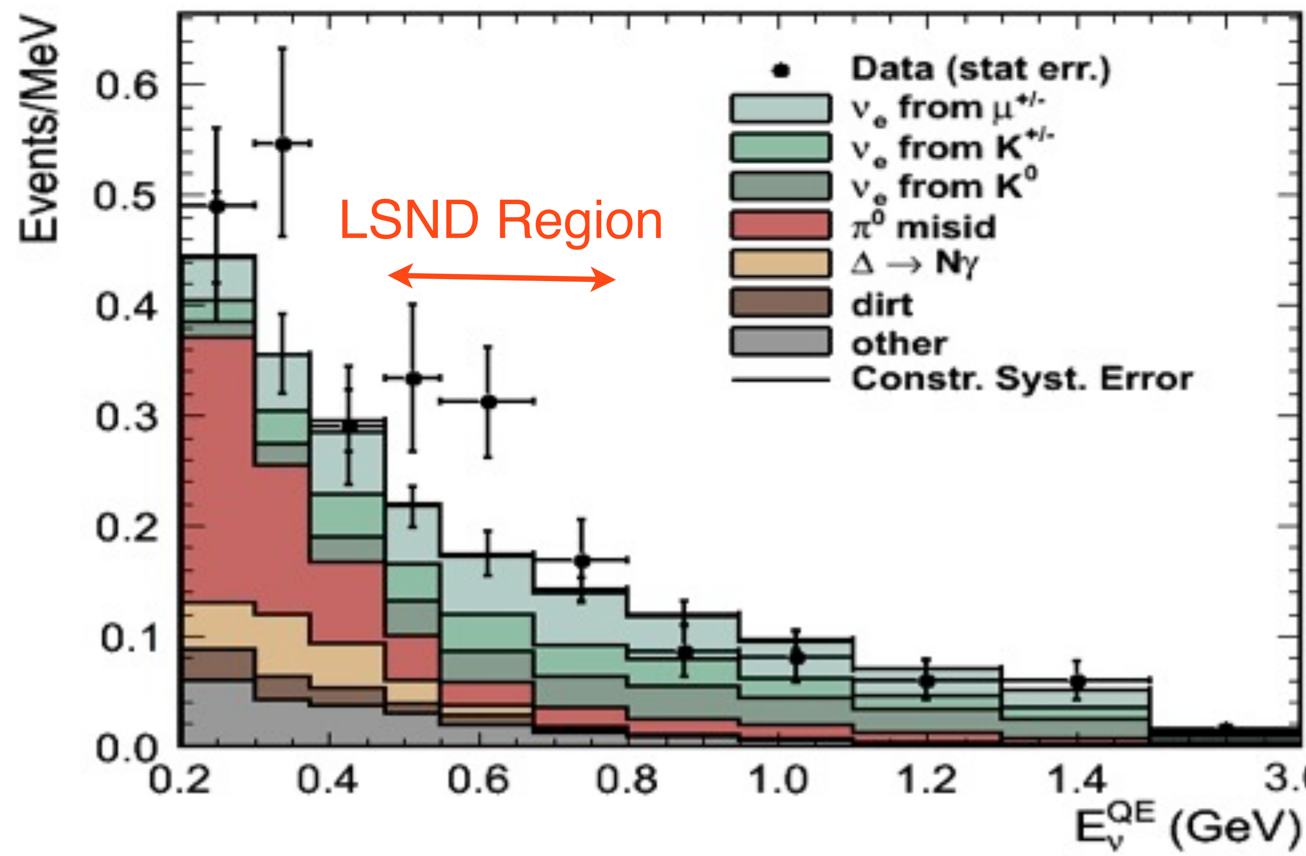

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Antineutrinos: Small excess below 475 MeV

Excess of events in LSND region

More data are needed to resolve these issues

MINOS Search

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

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

MINOS Search

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

Neutral Current Data

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The NC spectrum is measured in ND, extrapolated to FD

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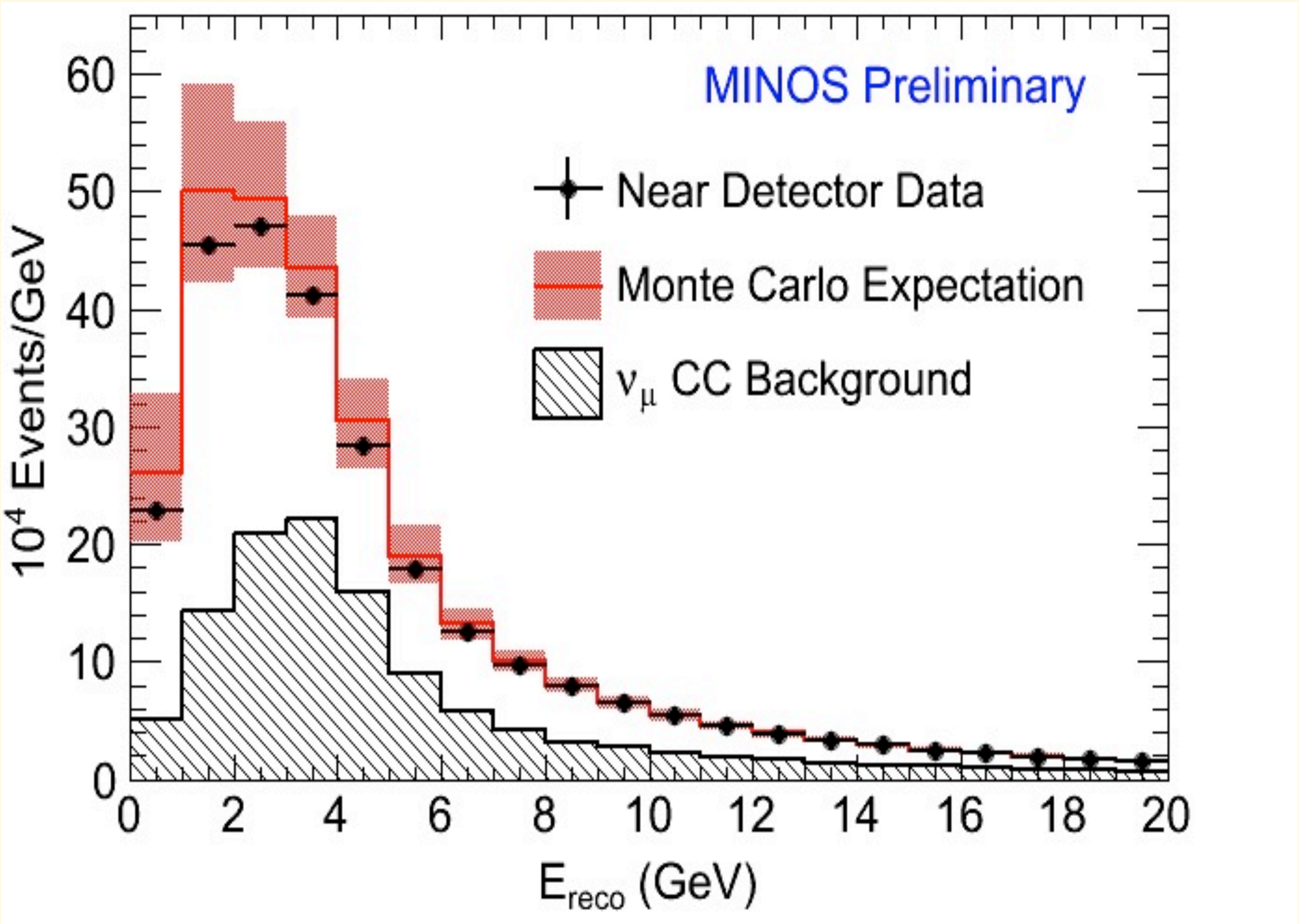

MINOS Result

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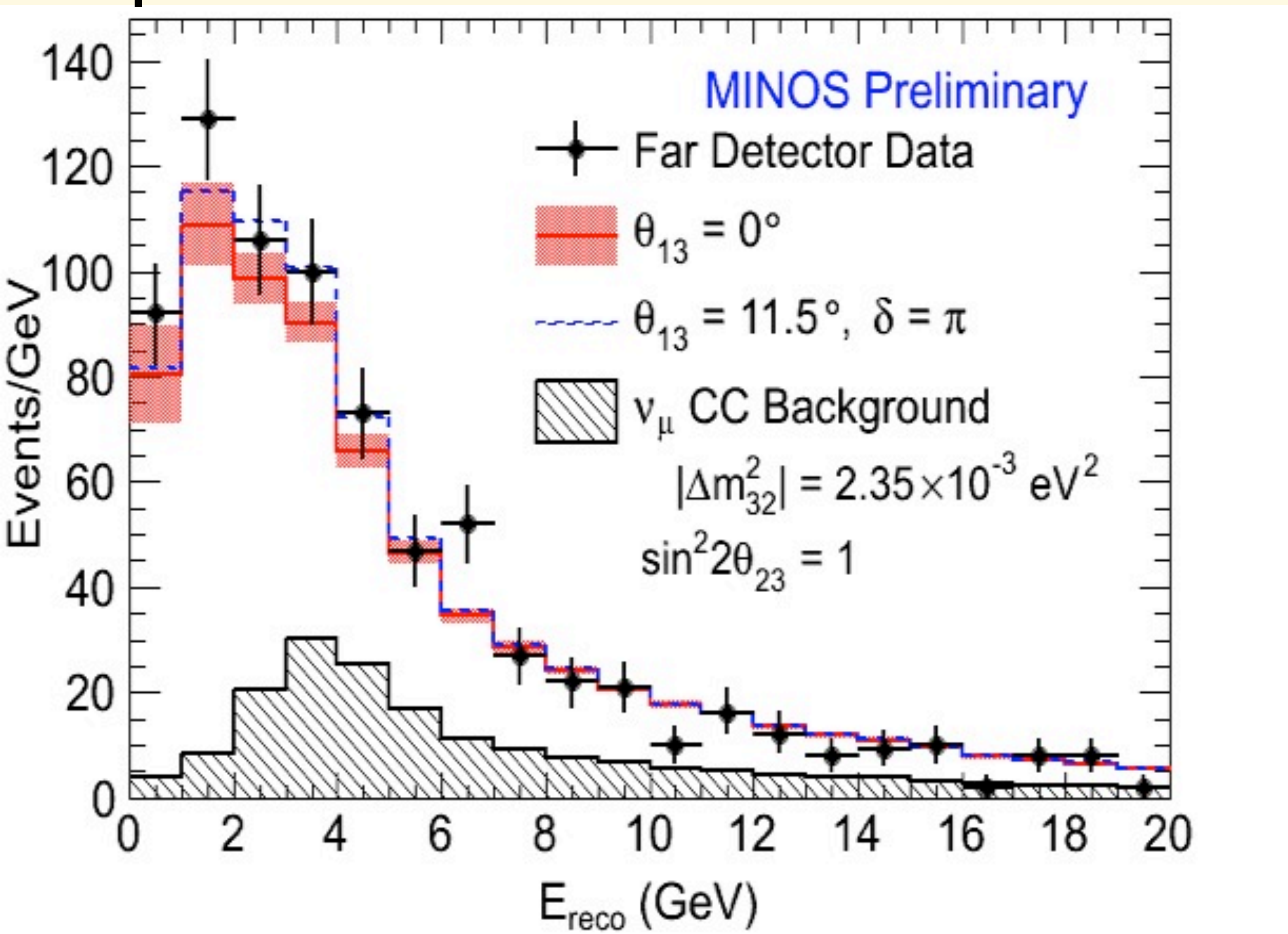
Spectrum of NC events in FD



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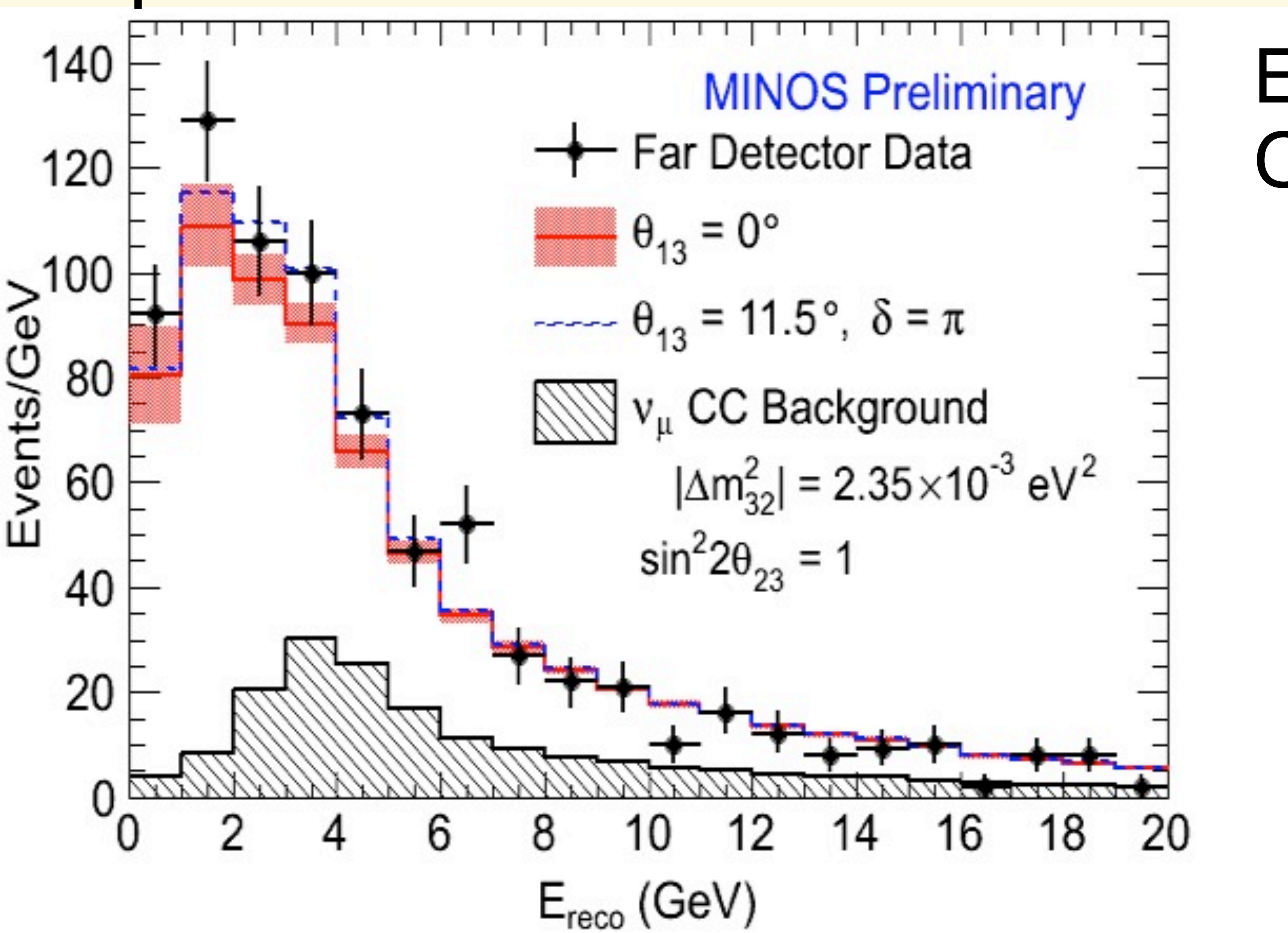

Expect (no ν_e): 757 events
Observe: 802 events

No depletion seen

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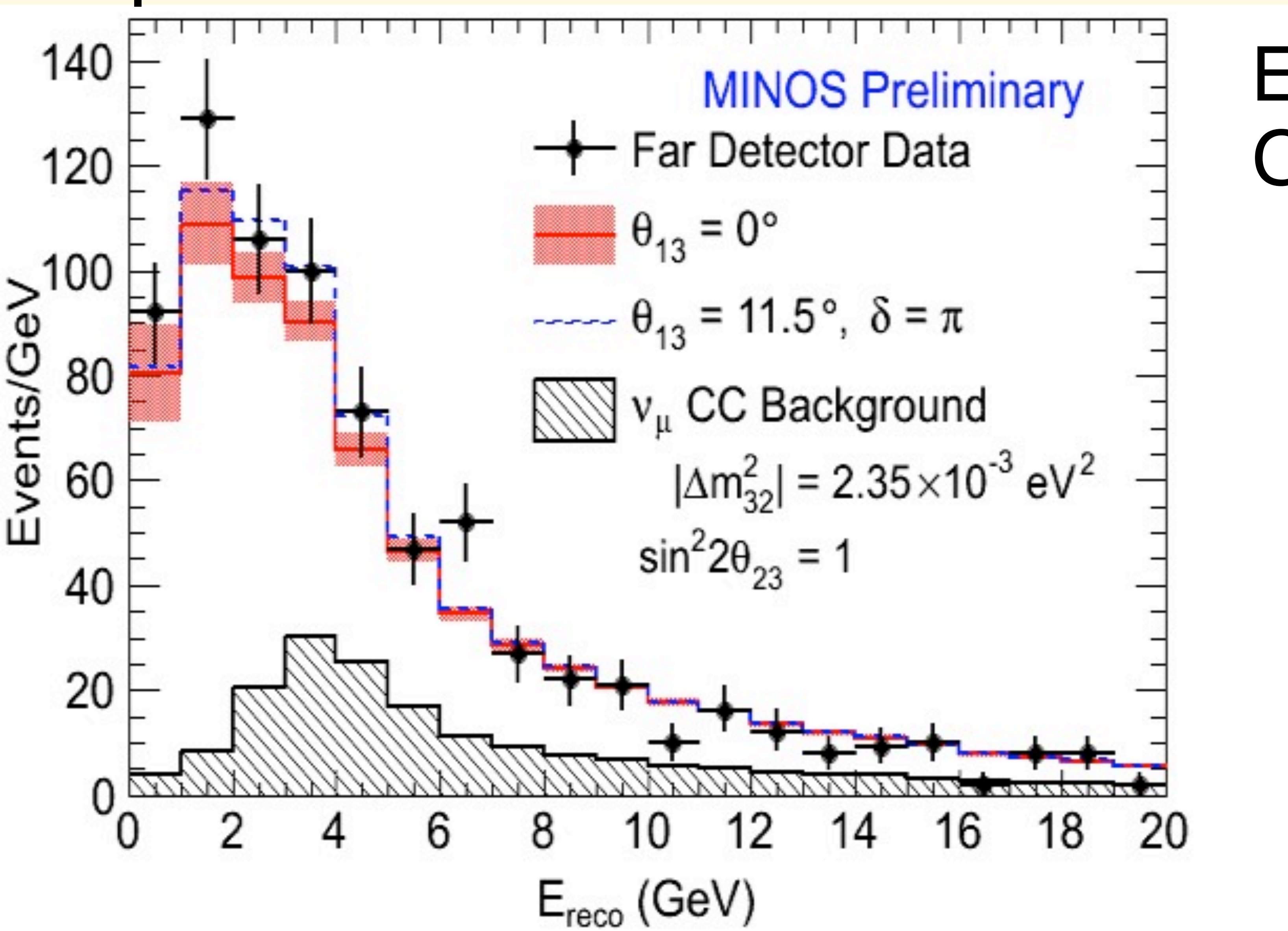

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Define: $R = \dfrac{N_{data} - BG}{S_{NC}}$

$1.09 \pm 0.06\ (\text{stat.}) \pm 0.05\ (\text{syst.})$
(no ν_e appearance)

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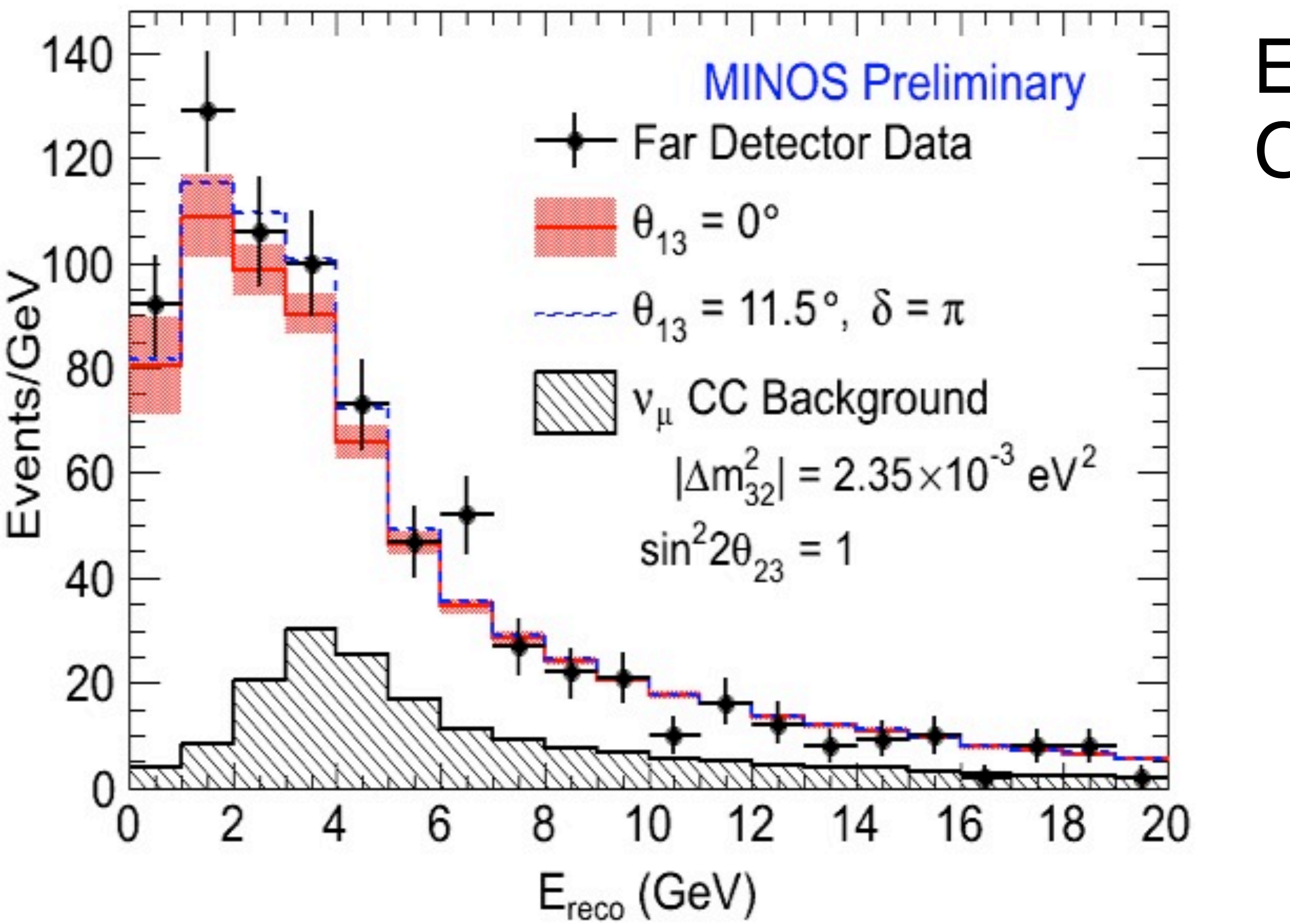

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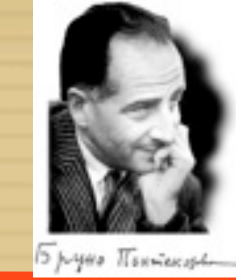
Limit on fraction, f_s, of oscillated ν_μ converting to ν_s:

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



Neutrino/Antineutrino Comparison

Antineutrino Beam

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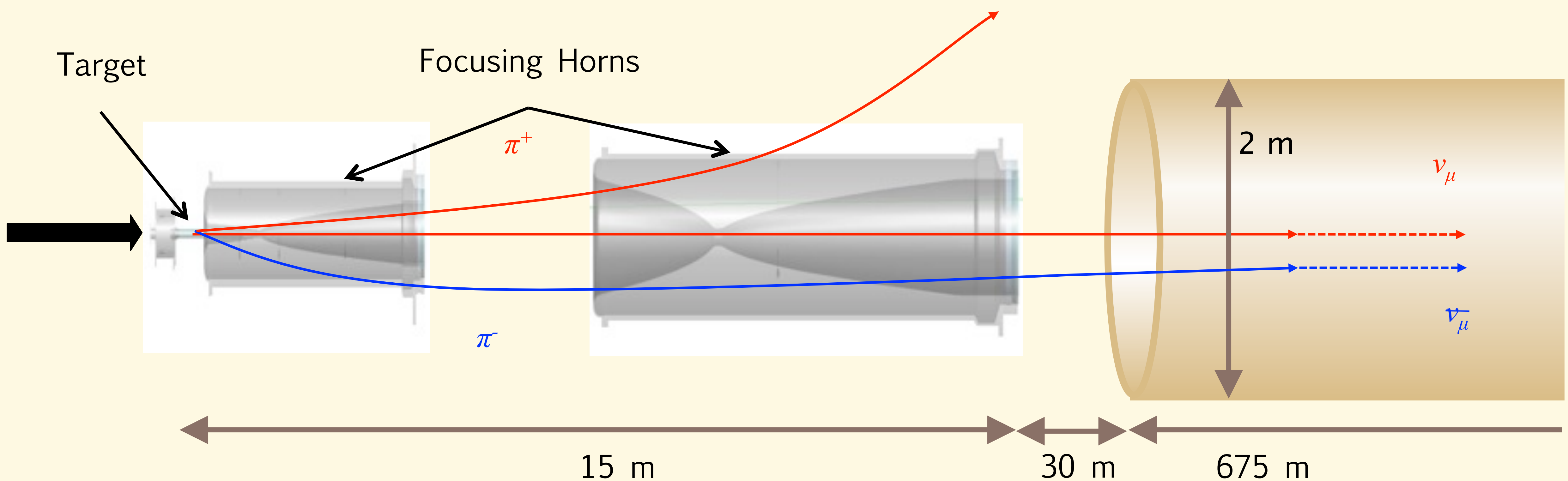

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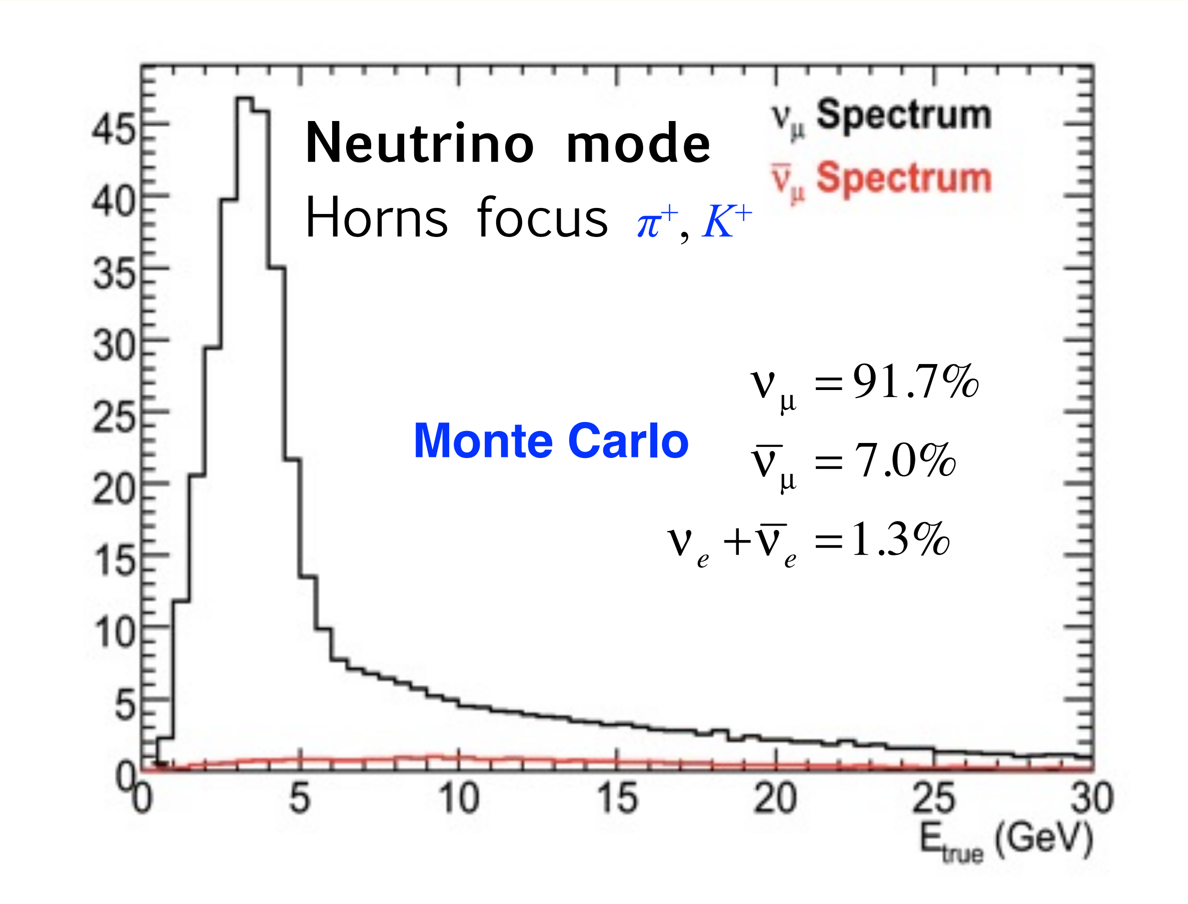

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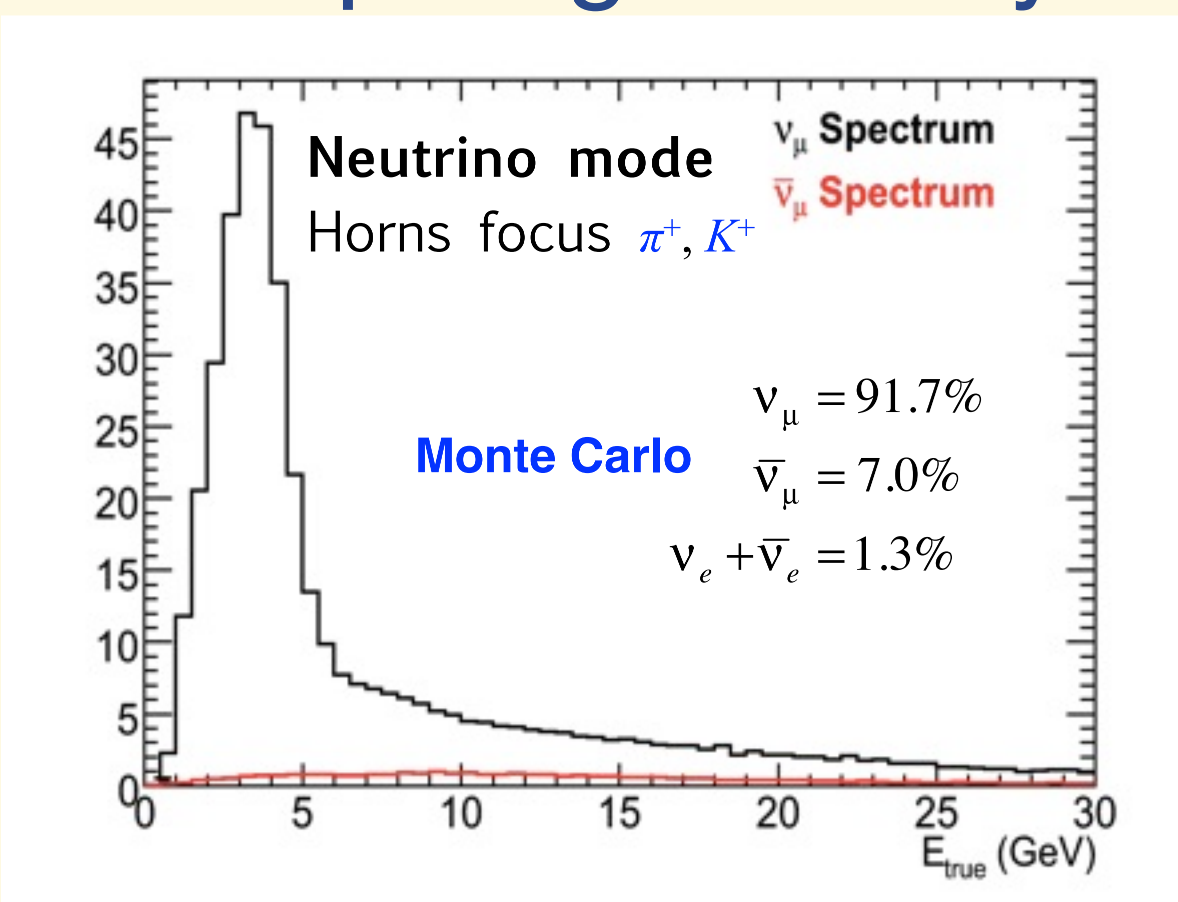

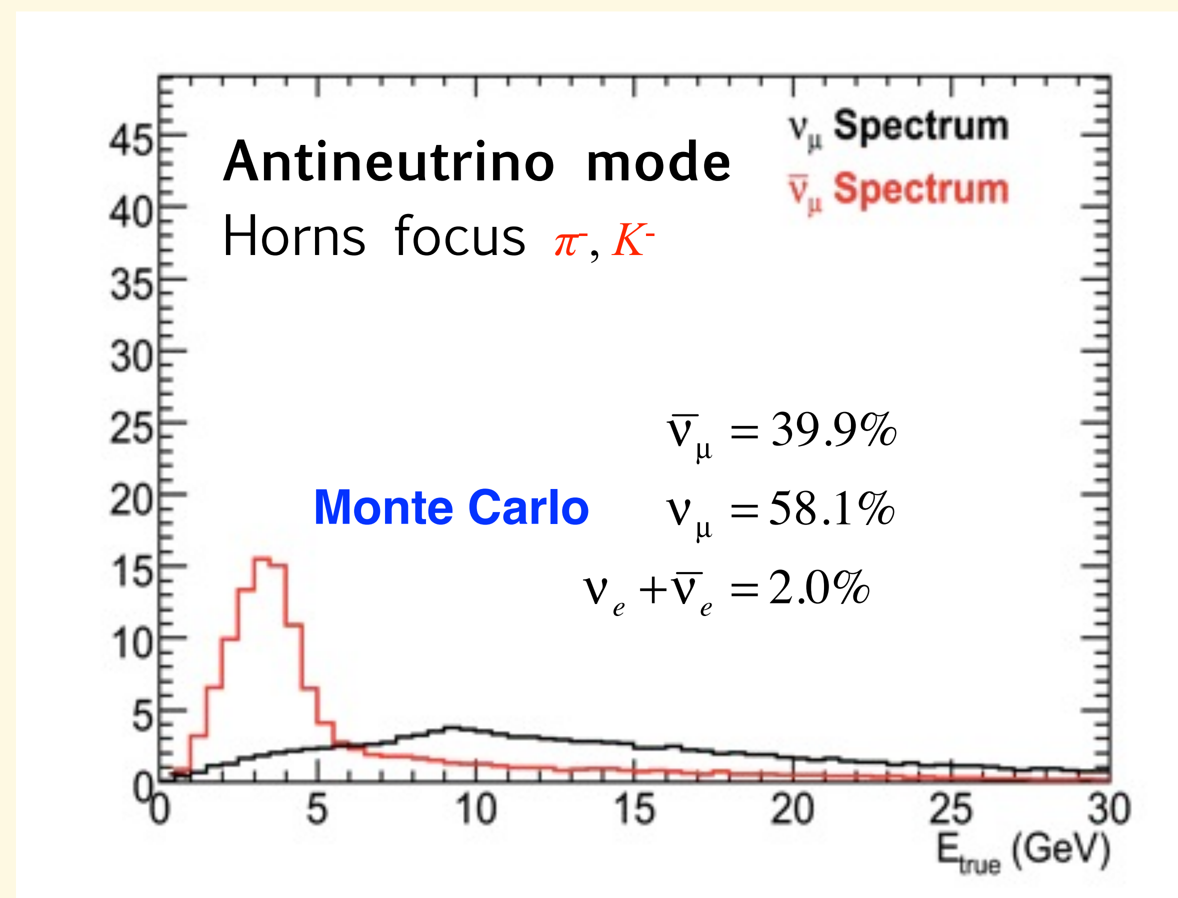

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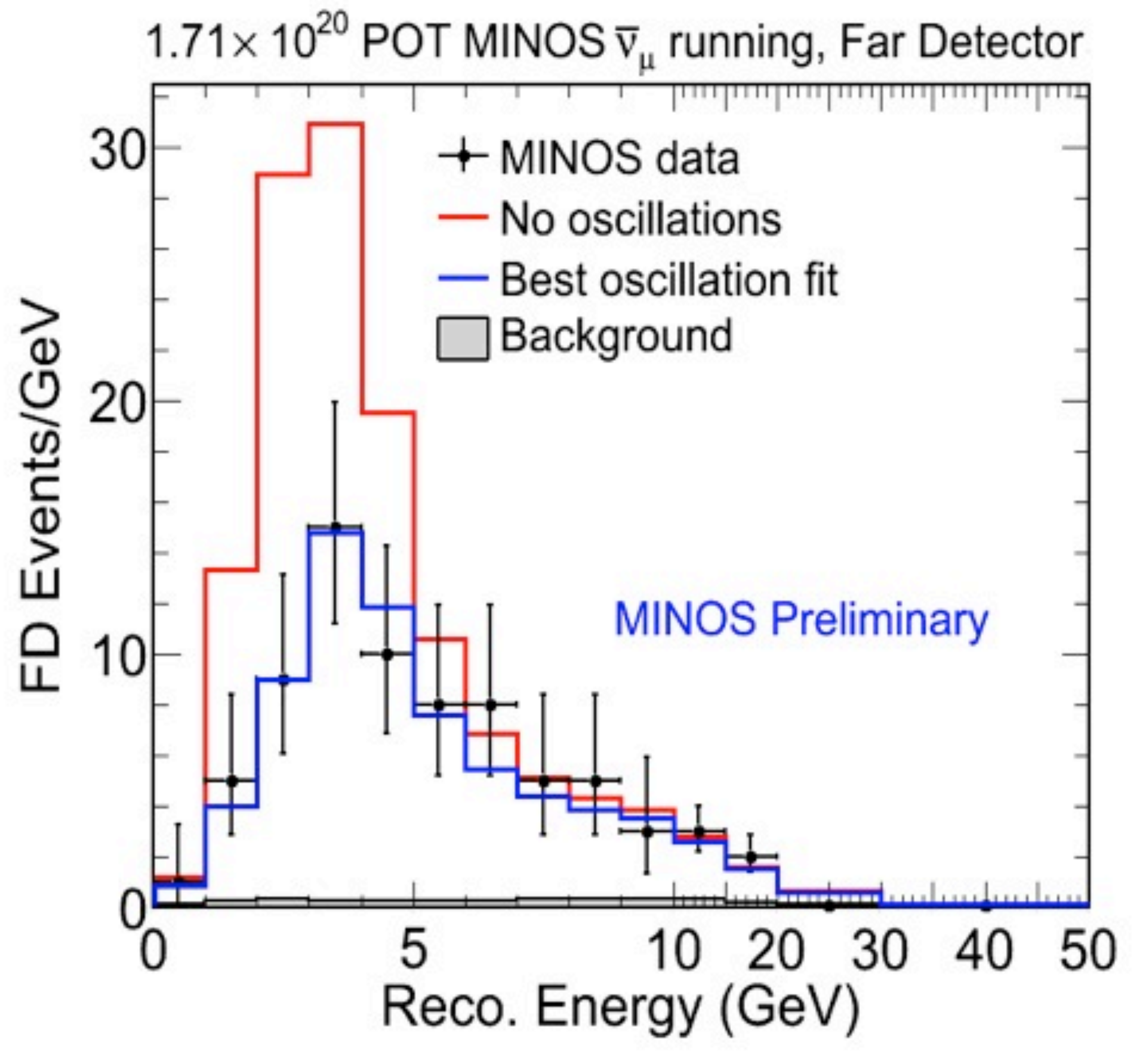
MINOS took 1.7E20 protons on target in $\overline{\nu}_\mu$ mode



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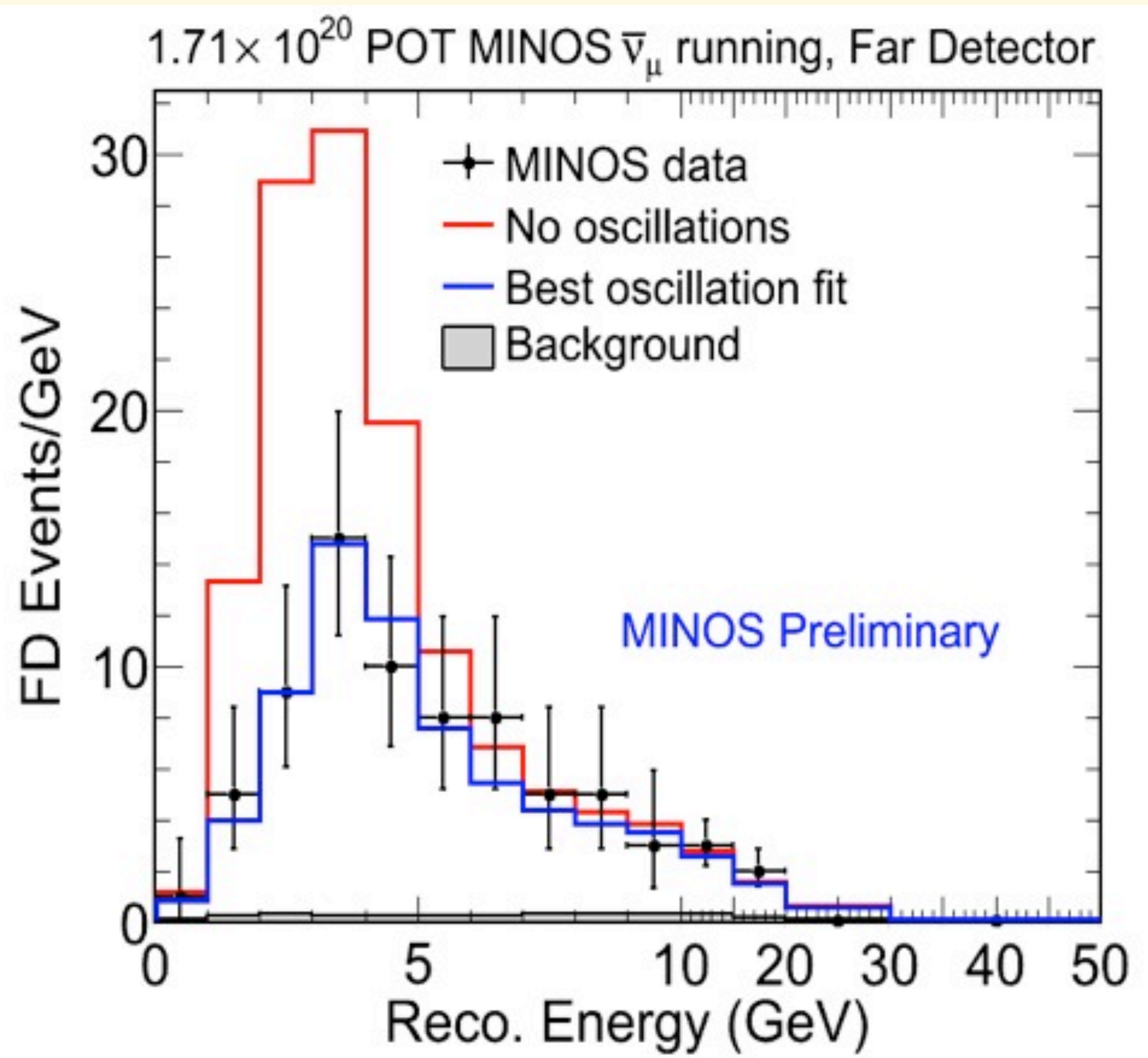

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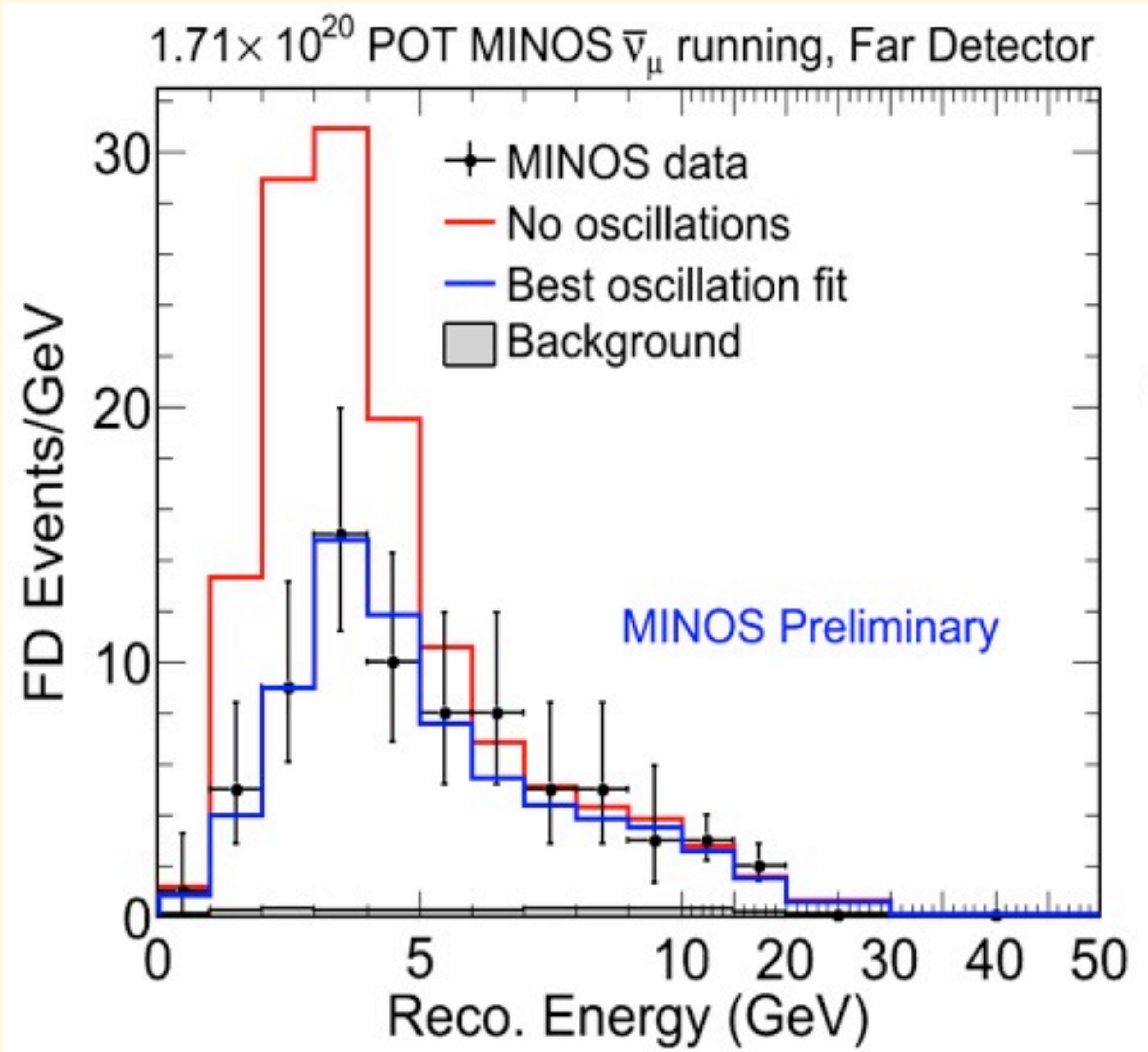

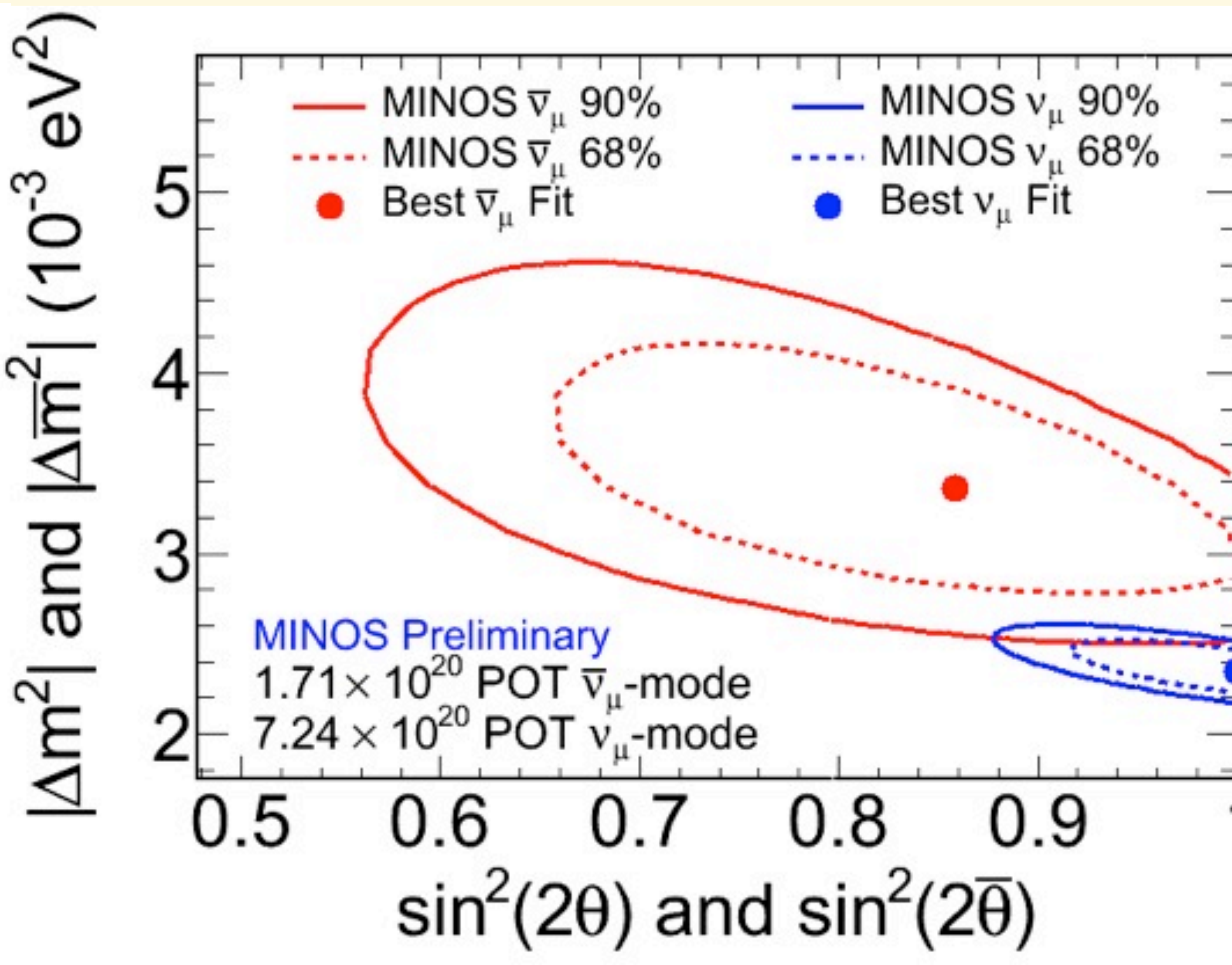

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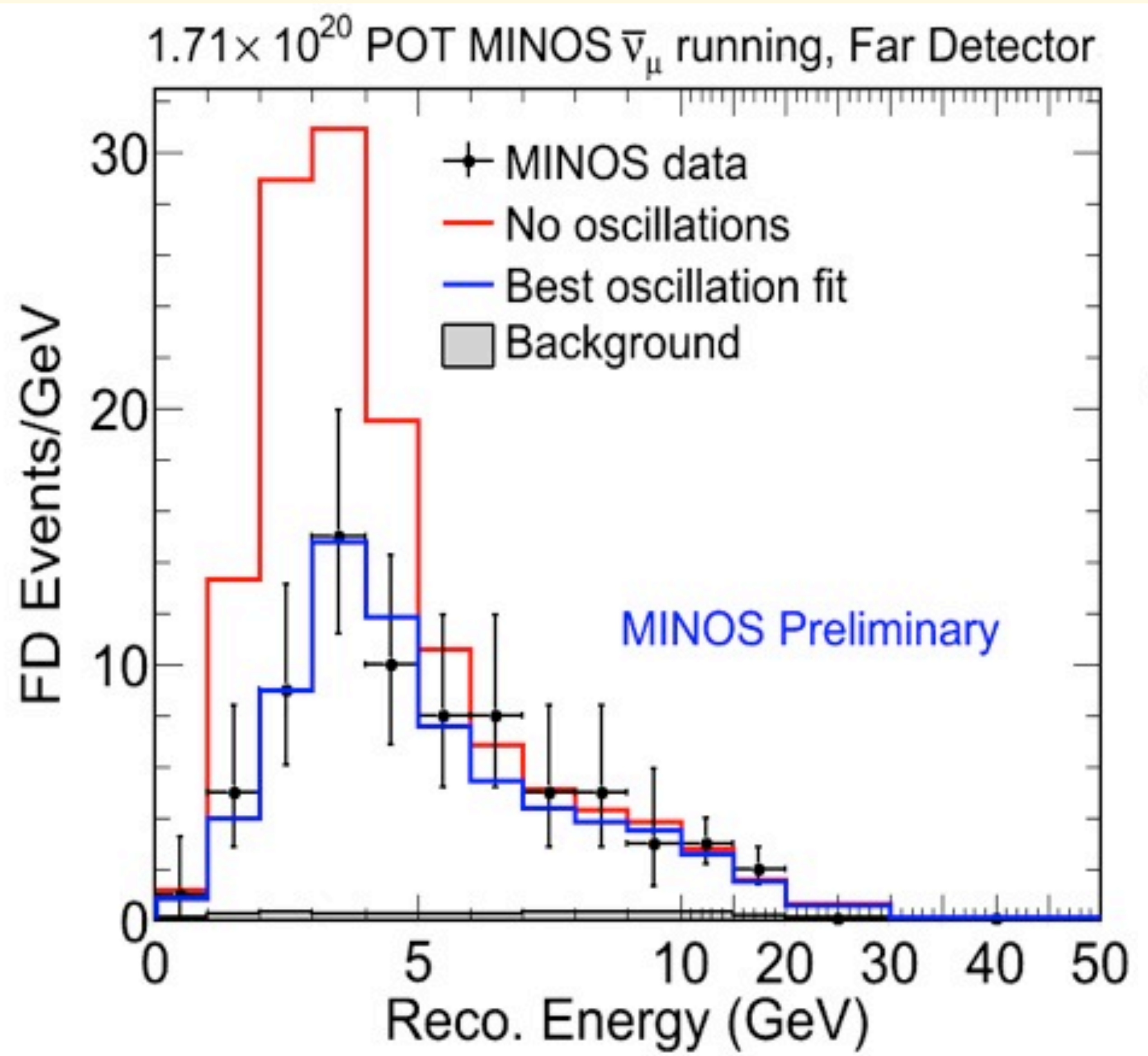

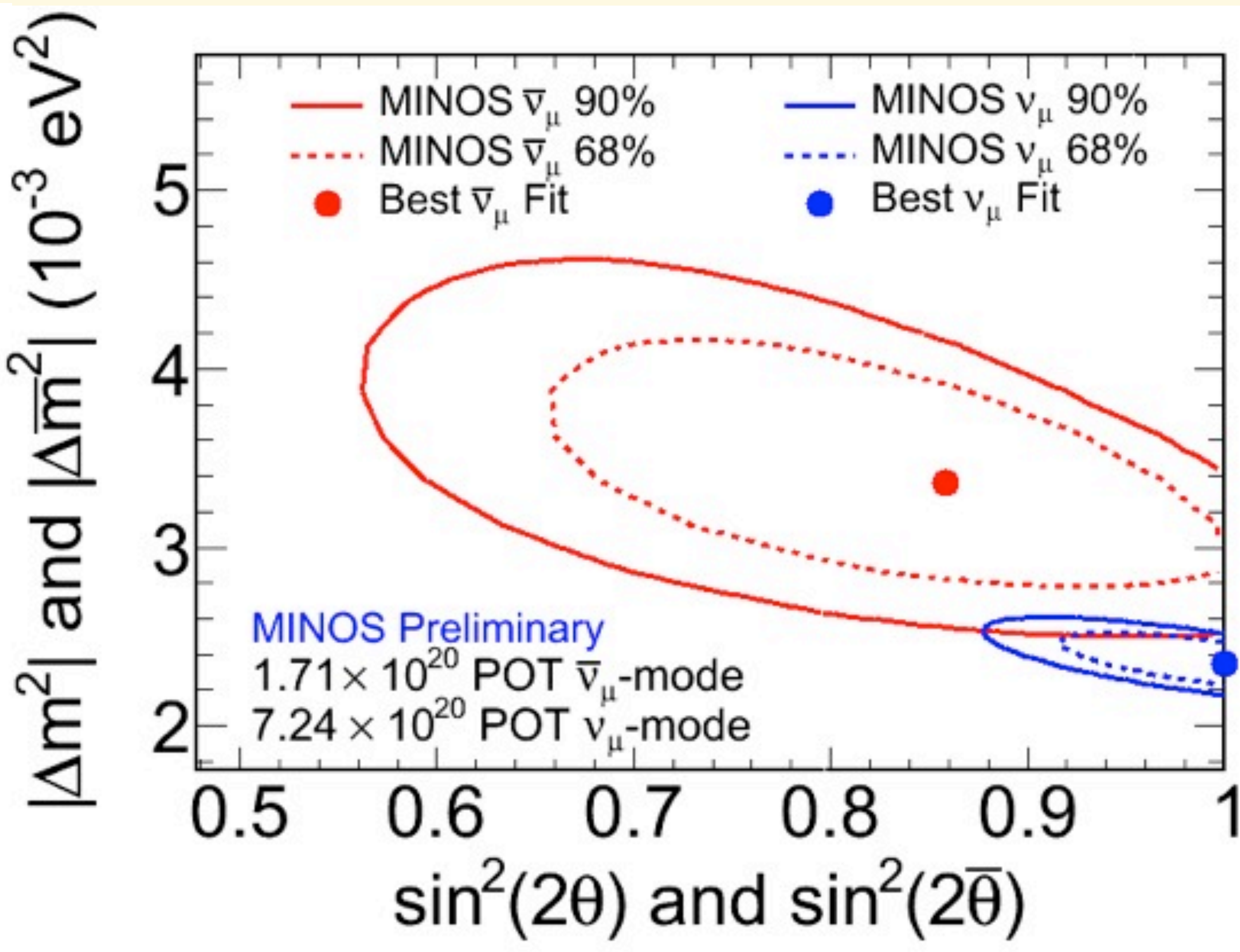

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There is a plan to increase the data set to 4E20 POT

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- Neutrinos and antineutrinos could have different <u>anomalous</u> interactions in the earth

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

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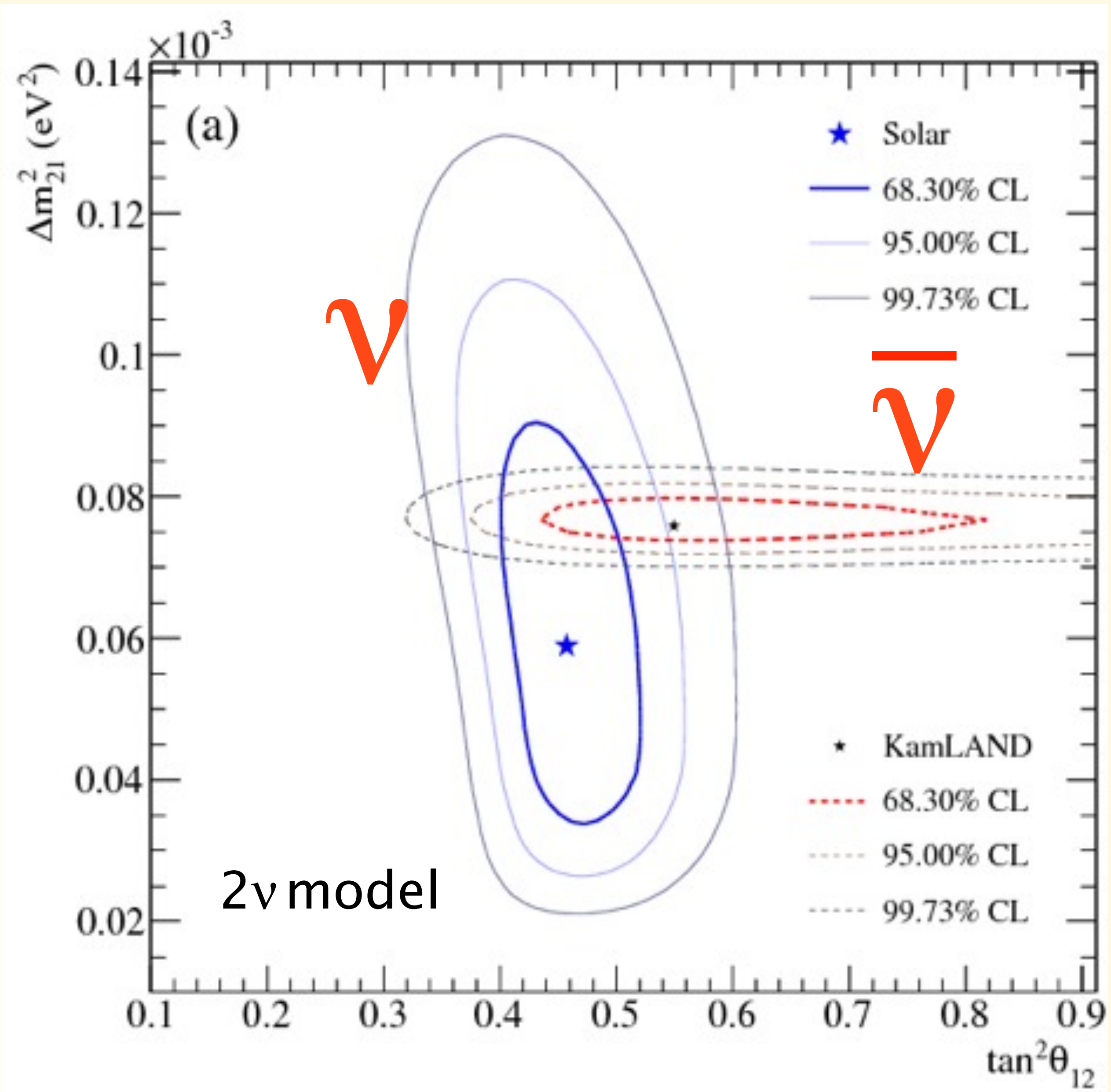

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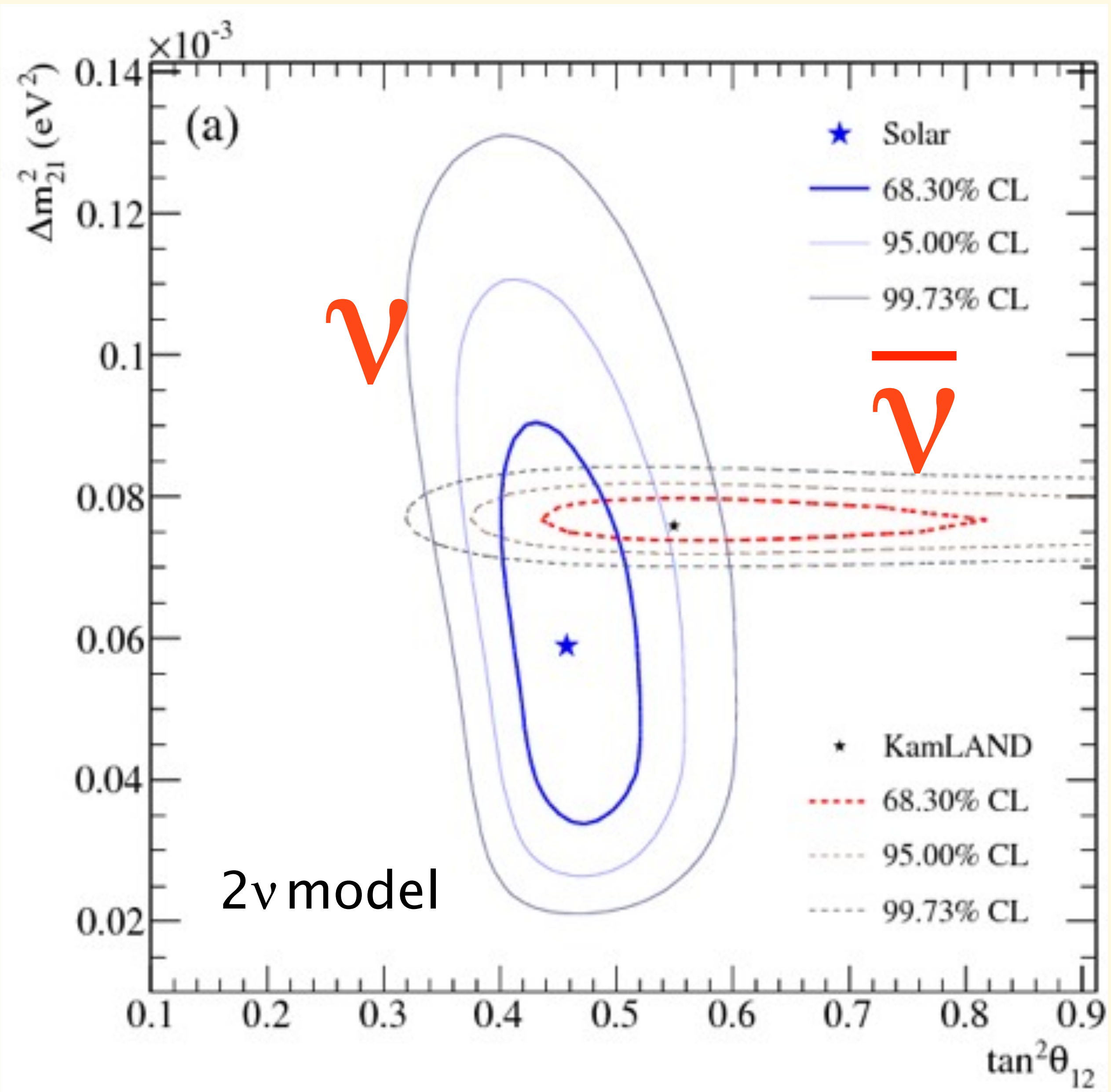

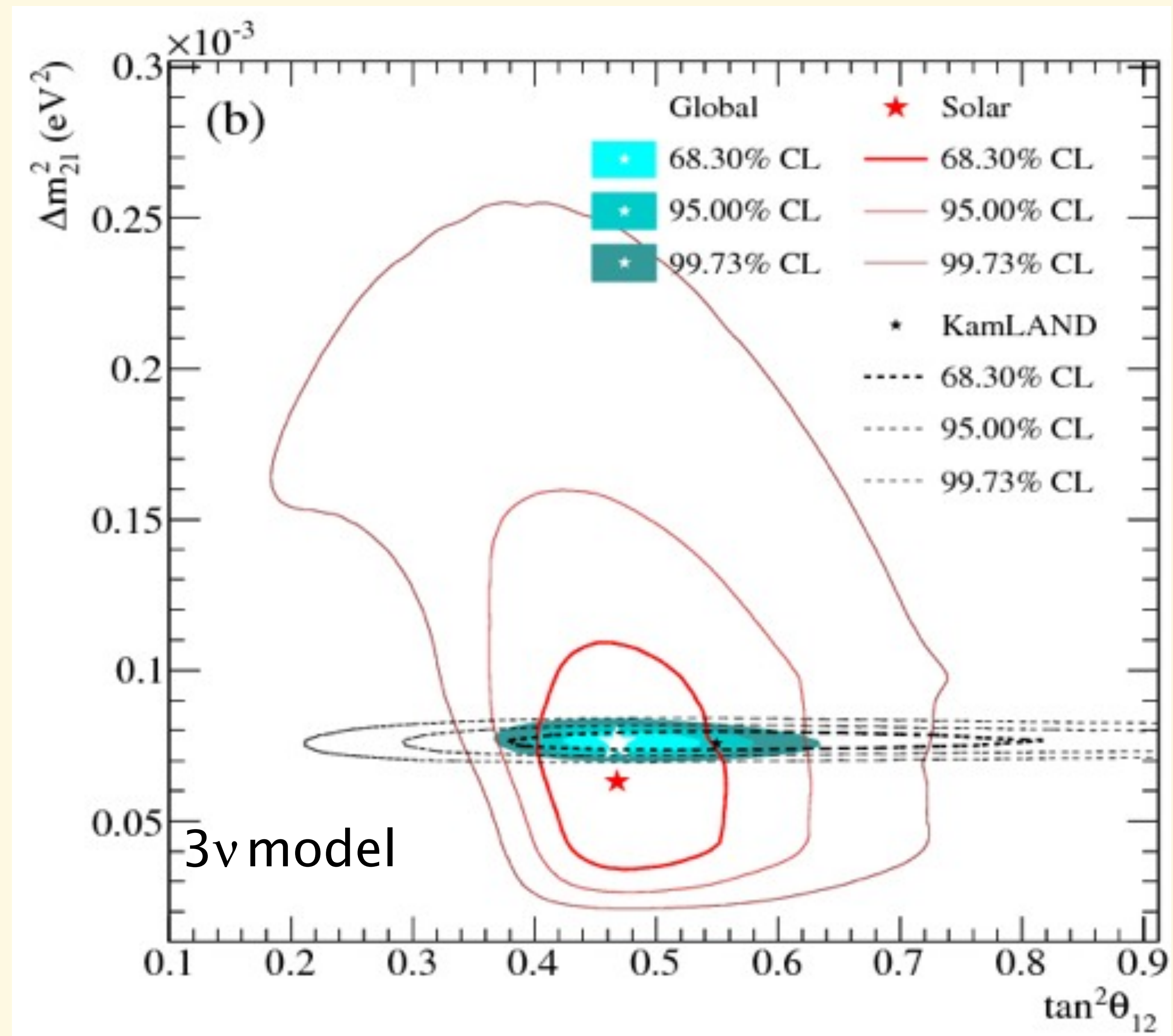

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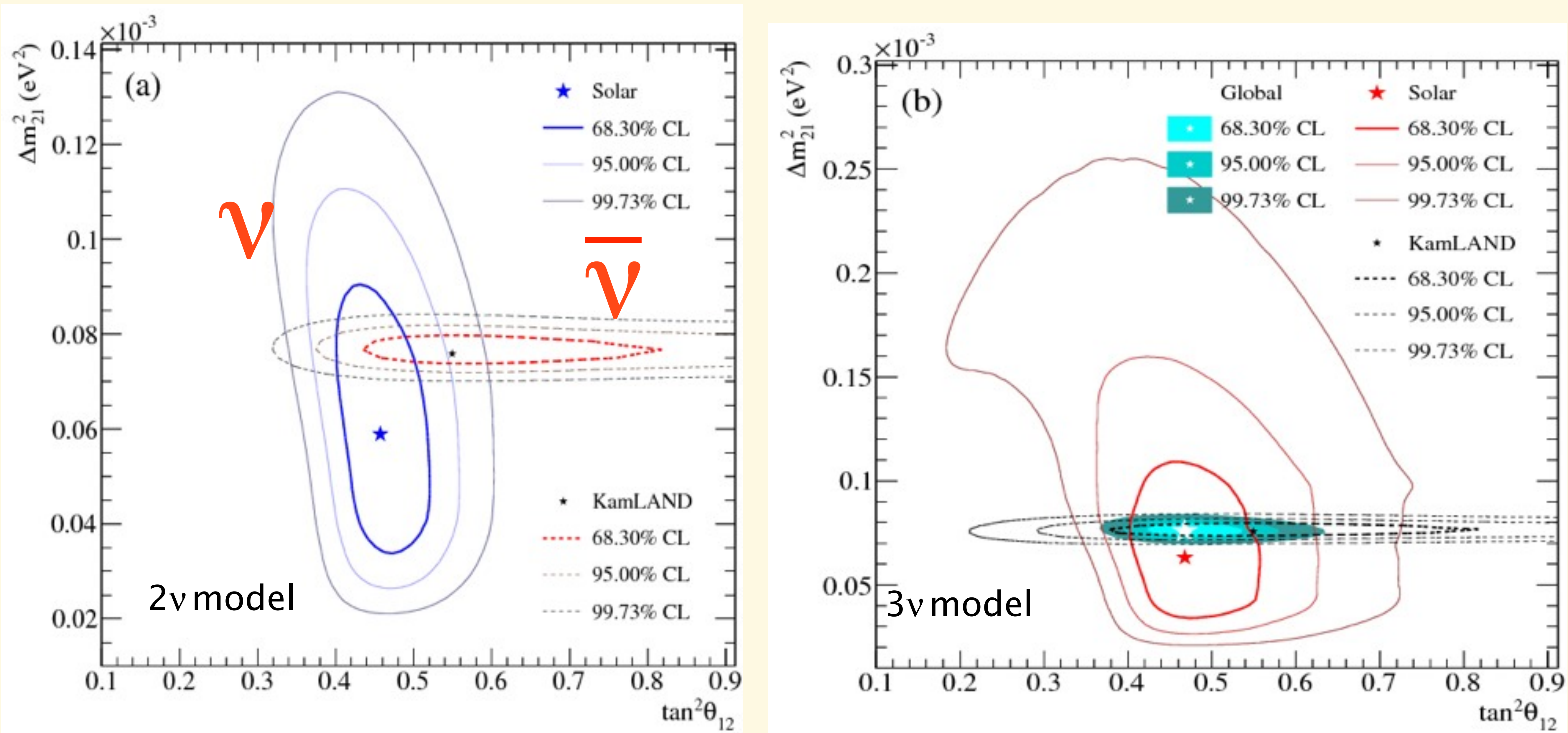

Thus identity is only verified to a factor of 2 (at 1σ level)

Future Accelerator Efforts (Near Term)

Current Status

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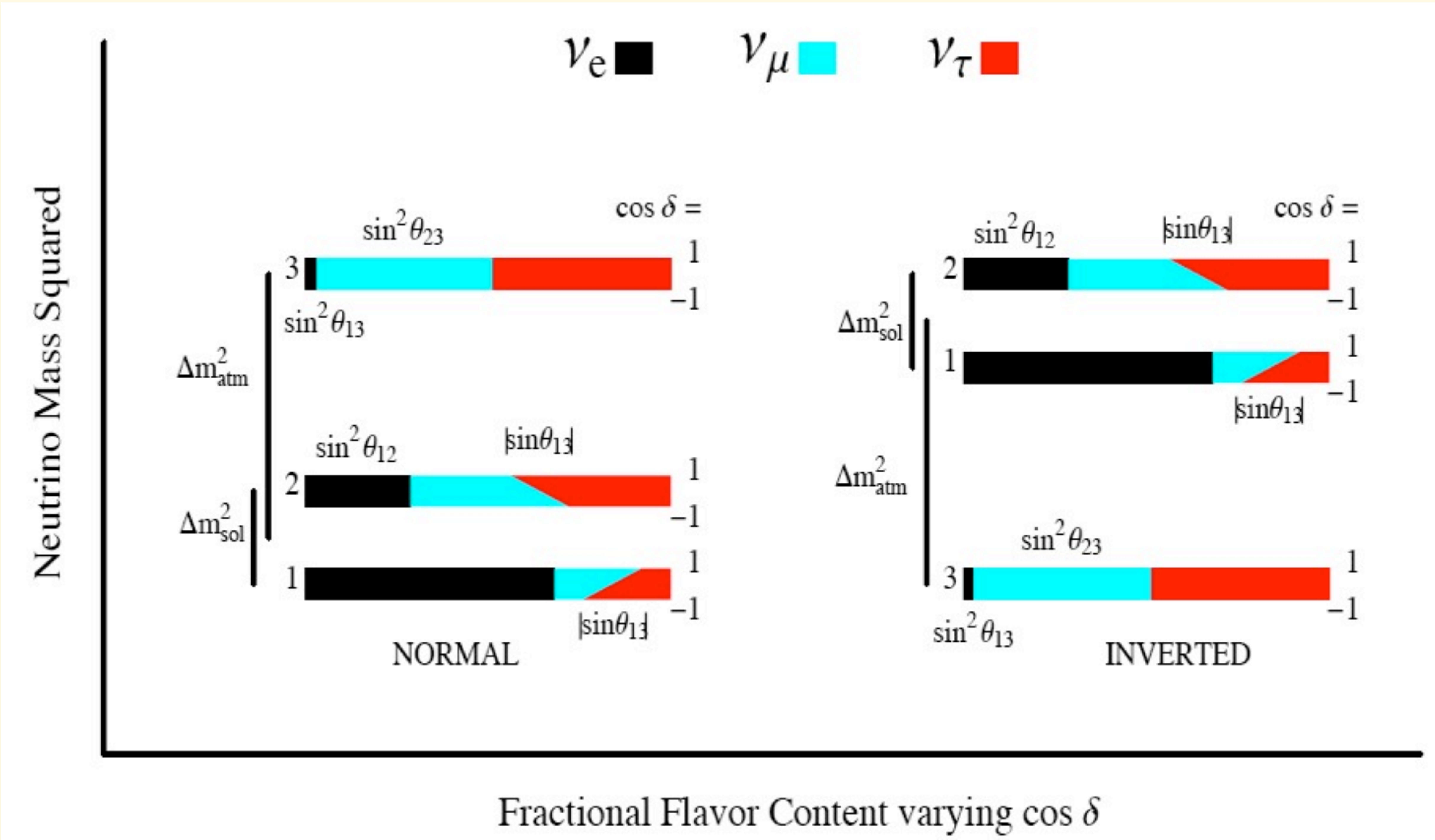

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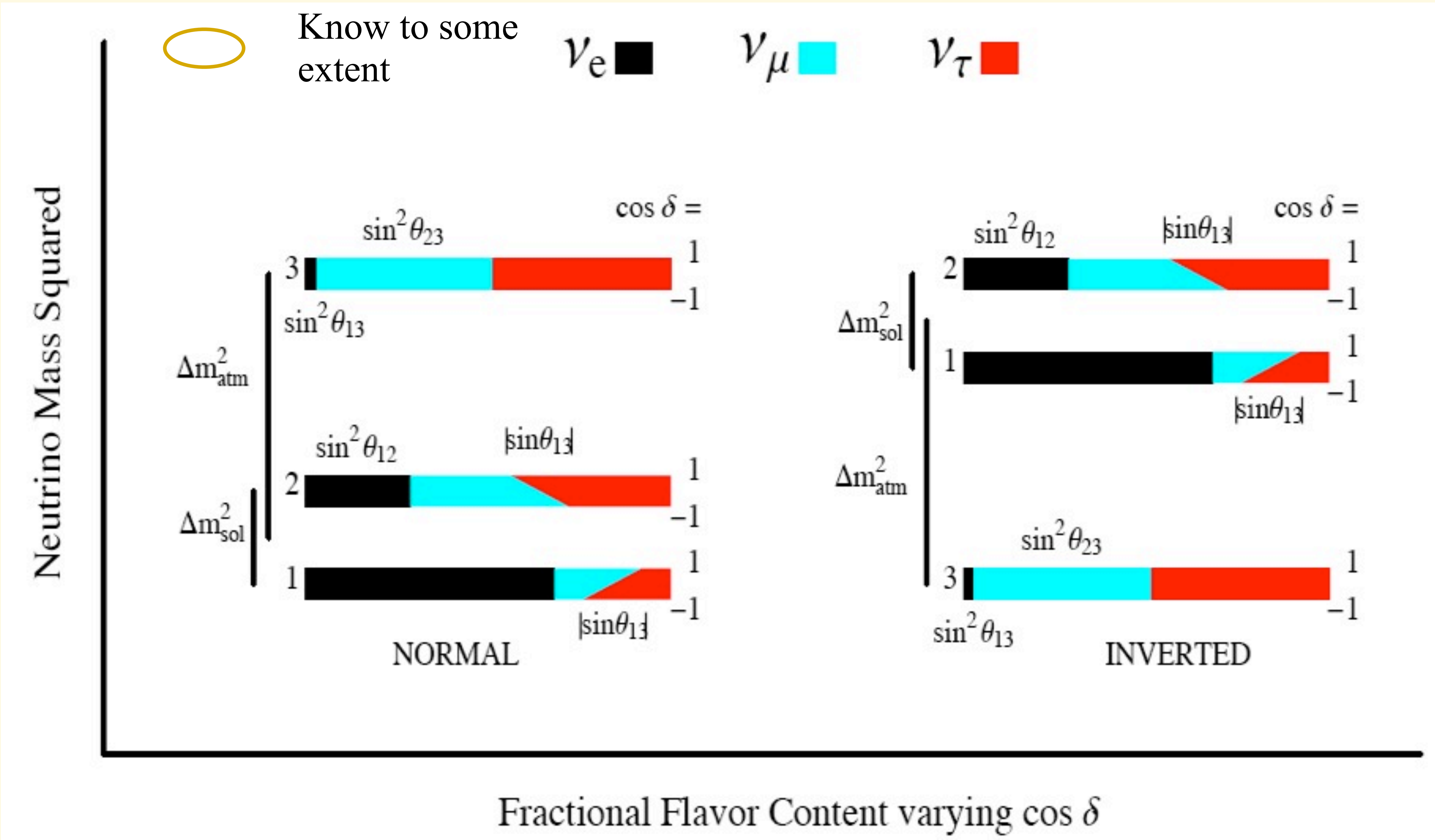

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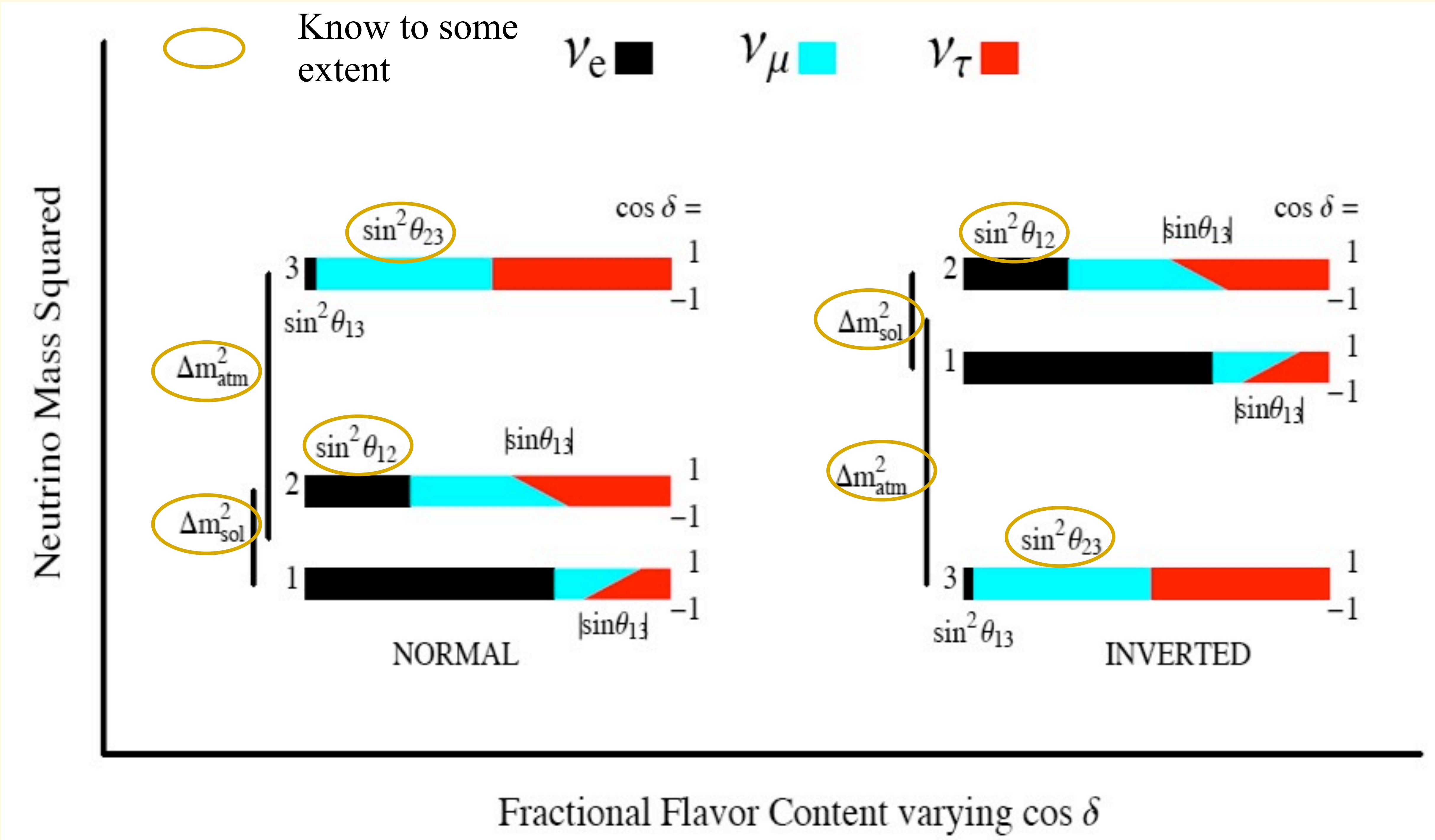

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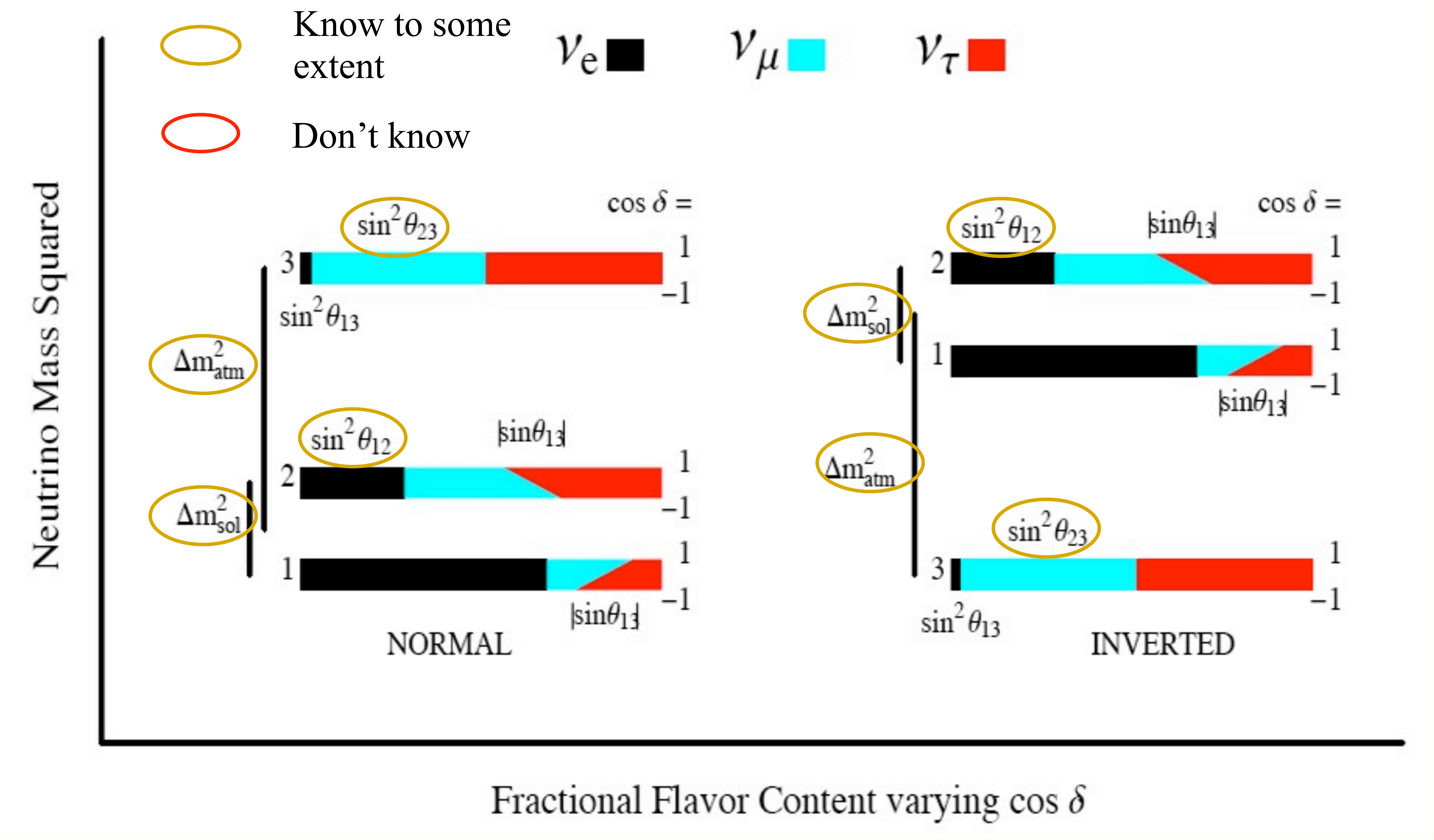

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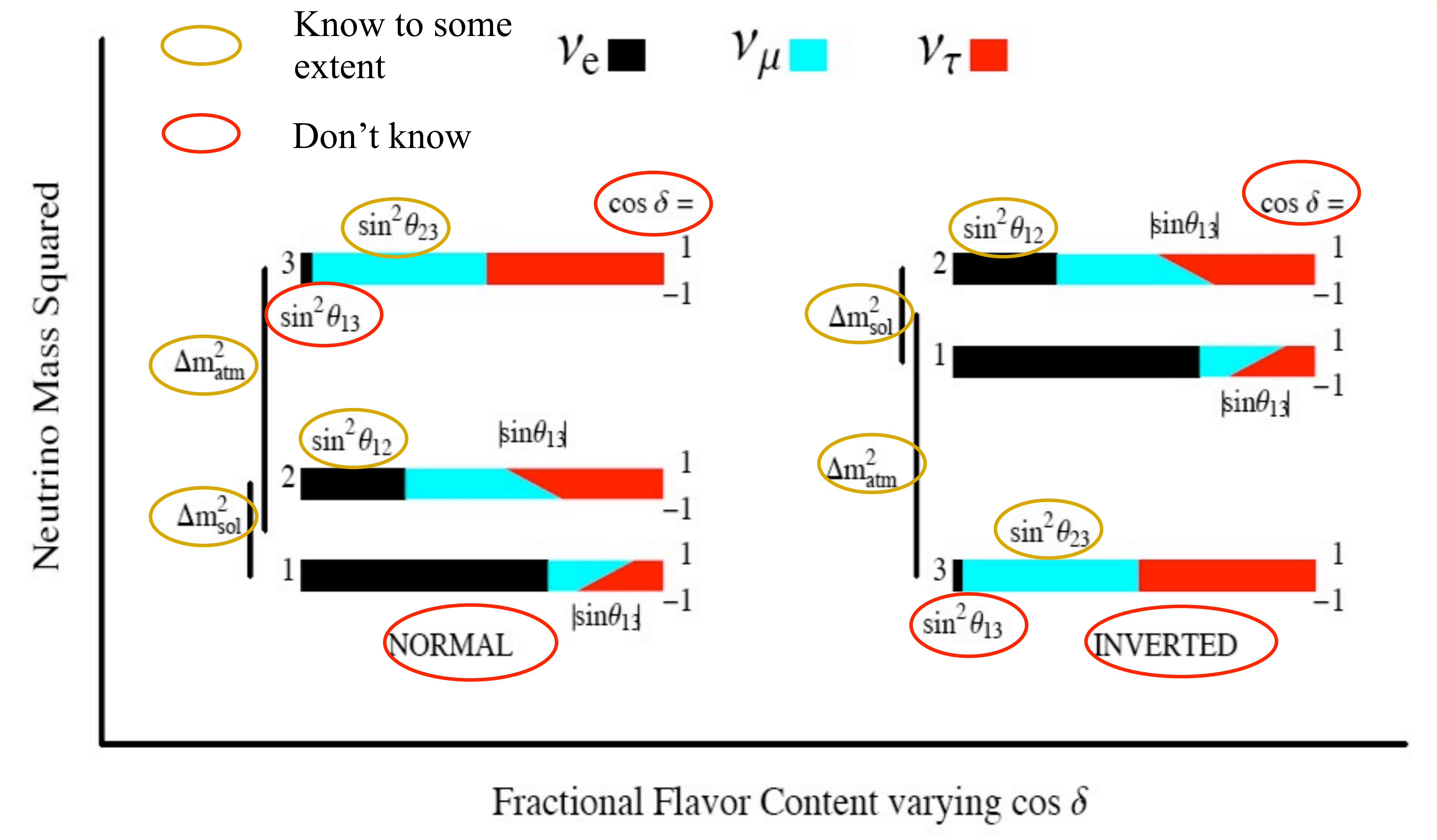

Accelerator Efforts

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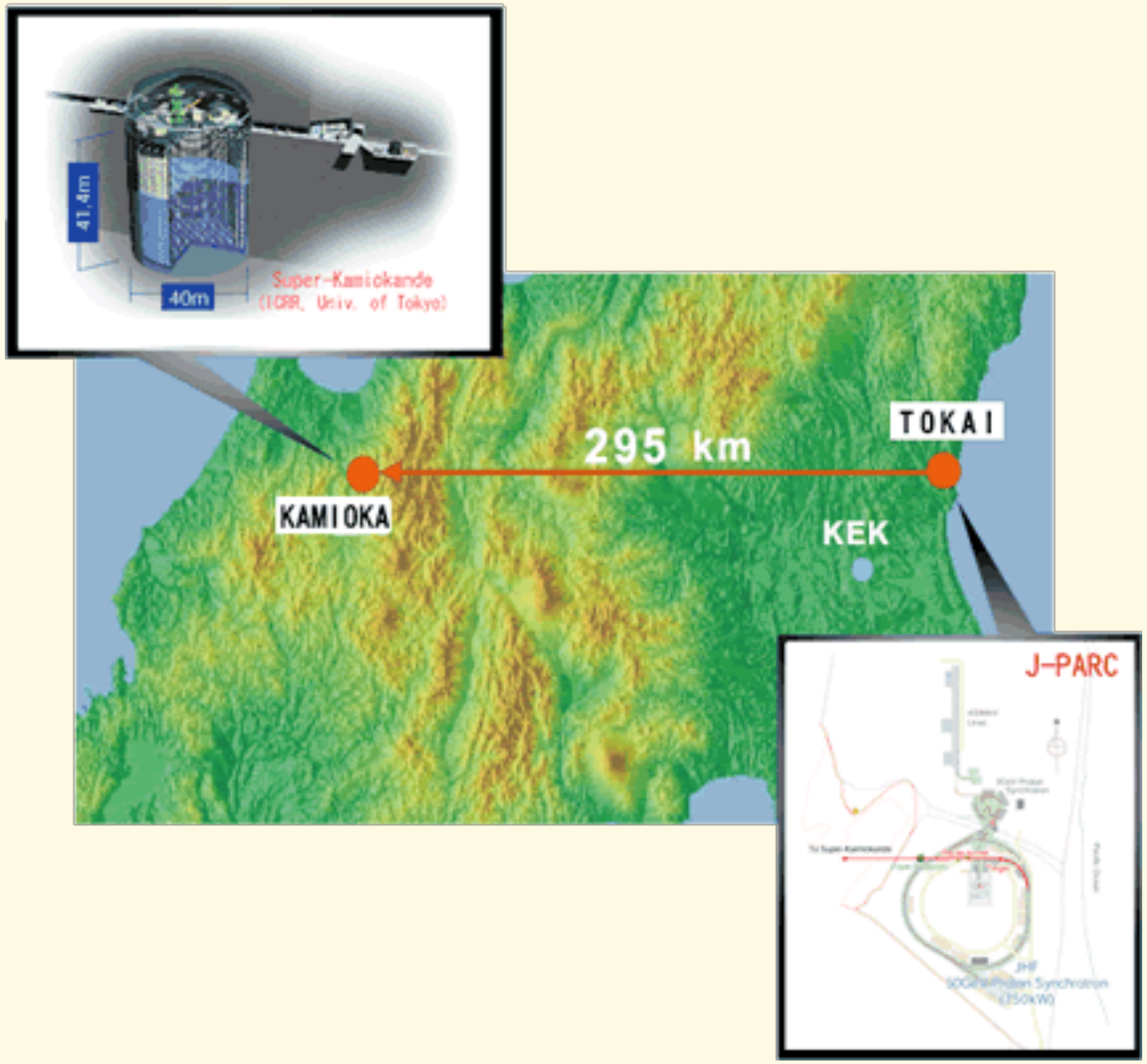

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Existing detector (SuperKamiokande)

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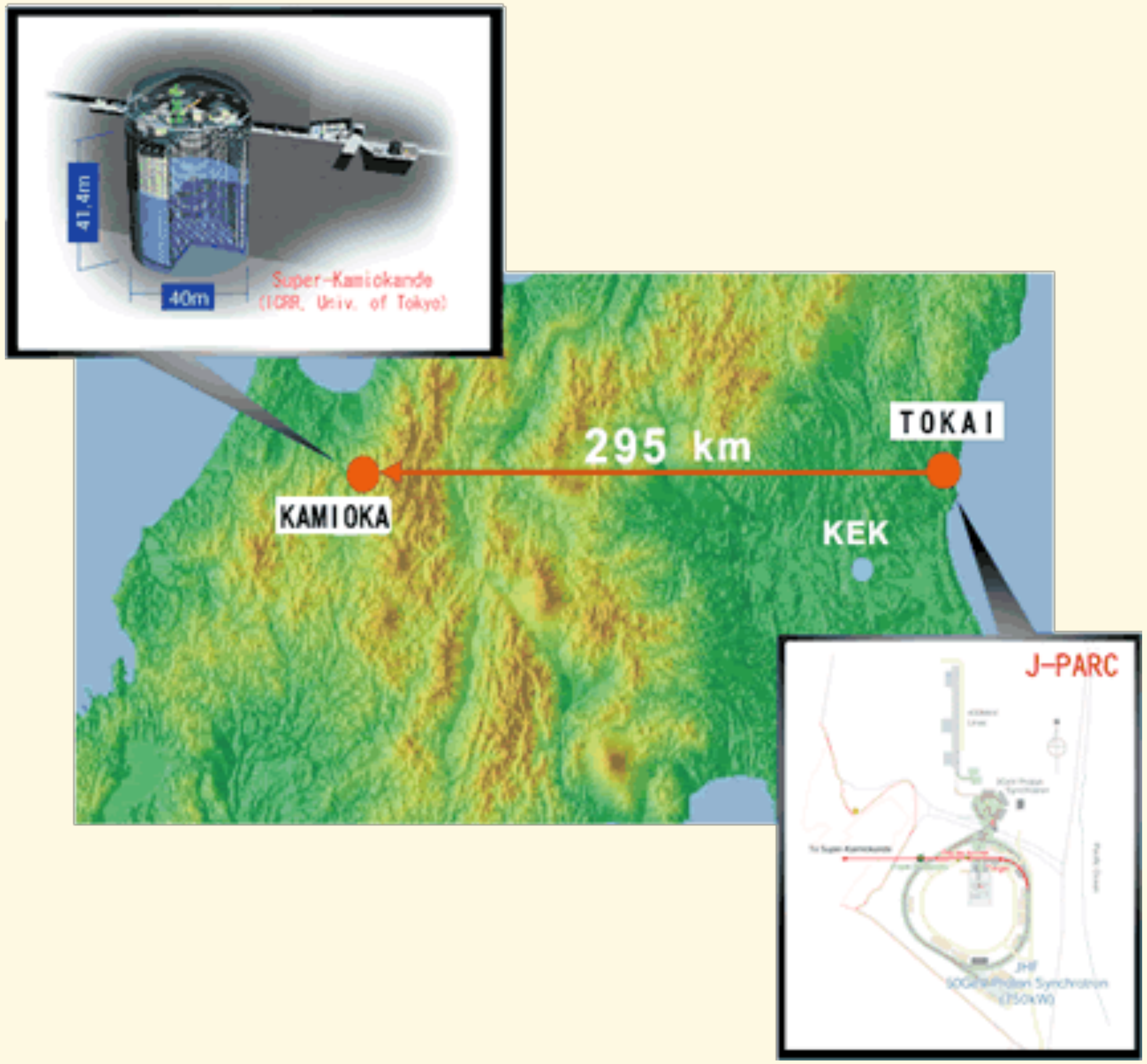

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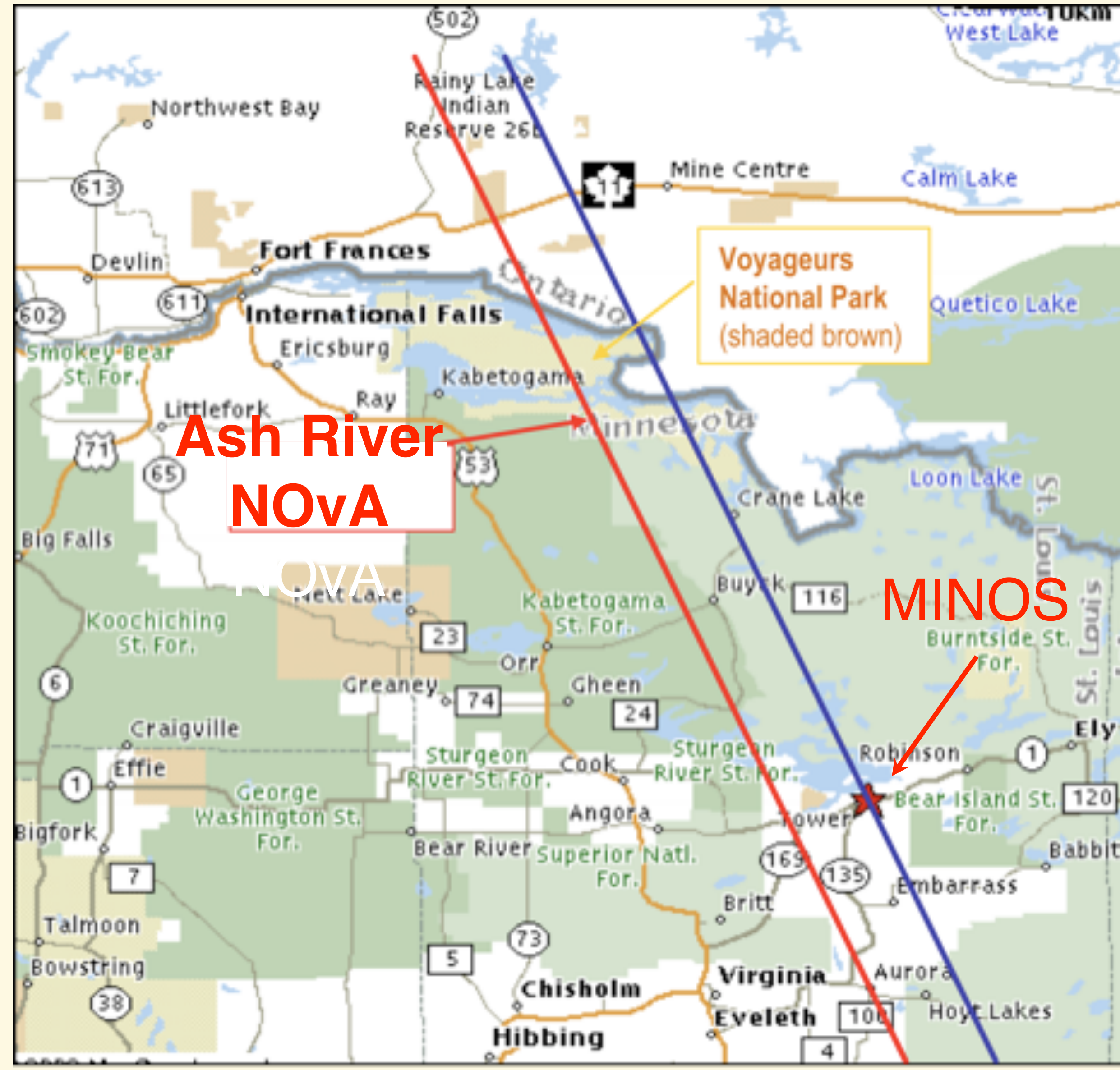
NOvA Beamline and Location



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

Data taking might start in early 2013 with partial detector

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- If $\sin^2(2\theta_{13})$ is large enough, NOvA can also determine the mass hierarchy

T2K Layout & Spectrum

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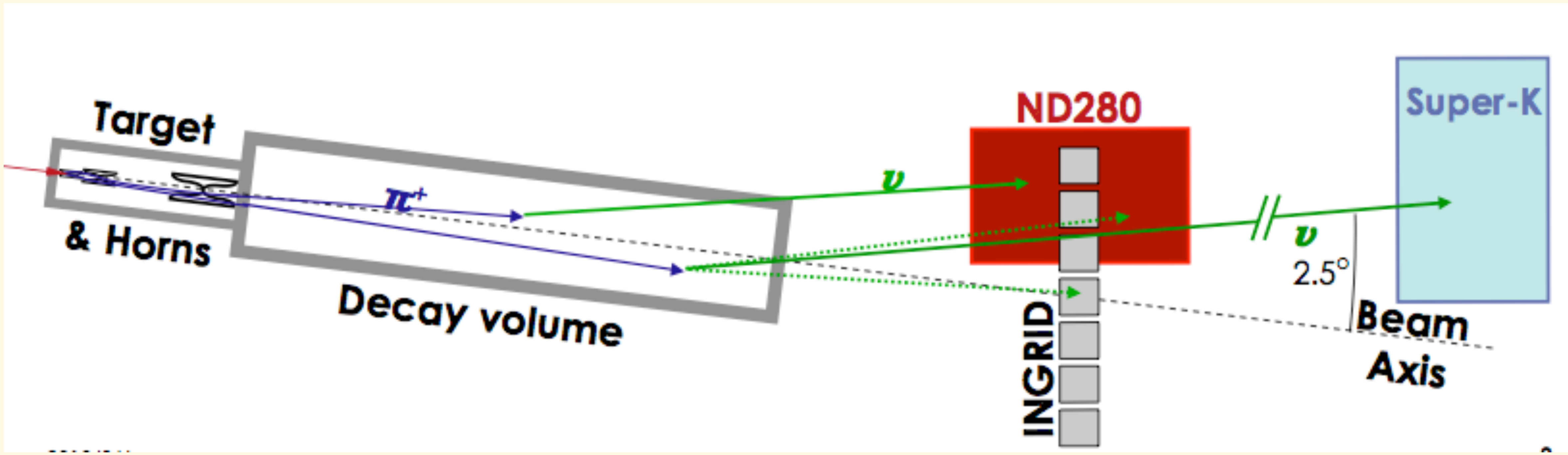

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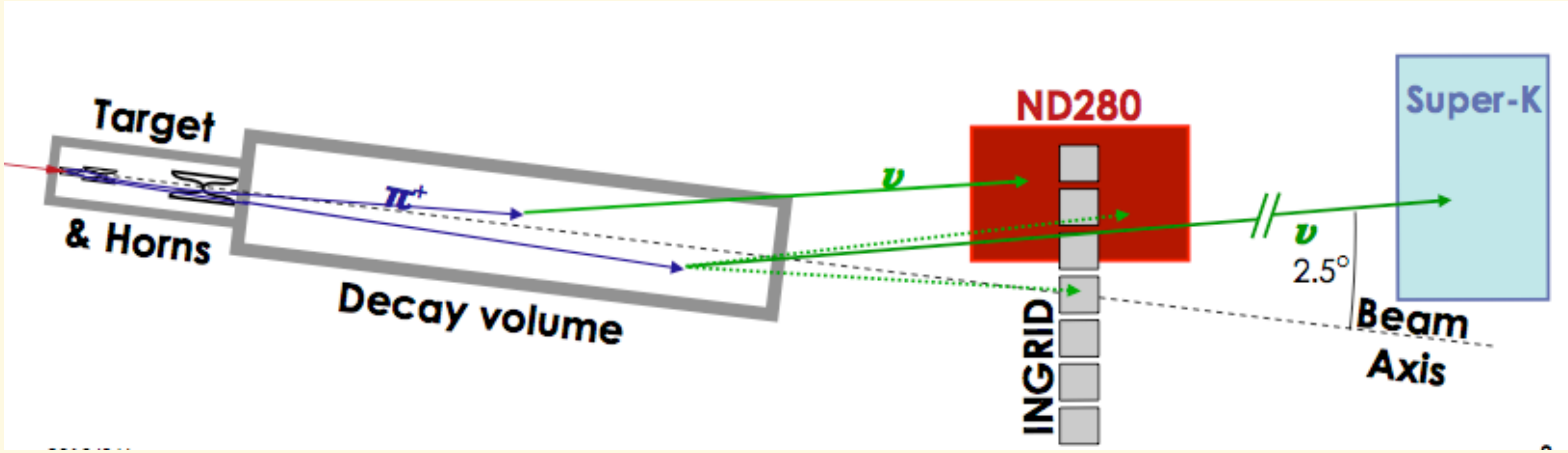

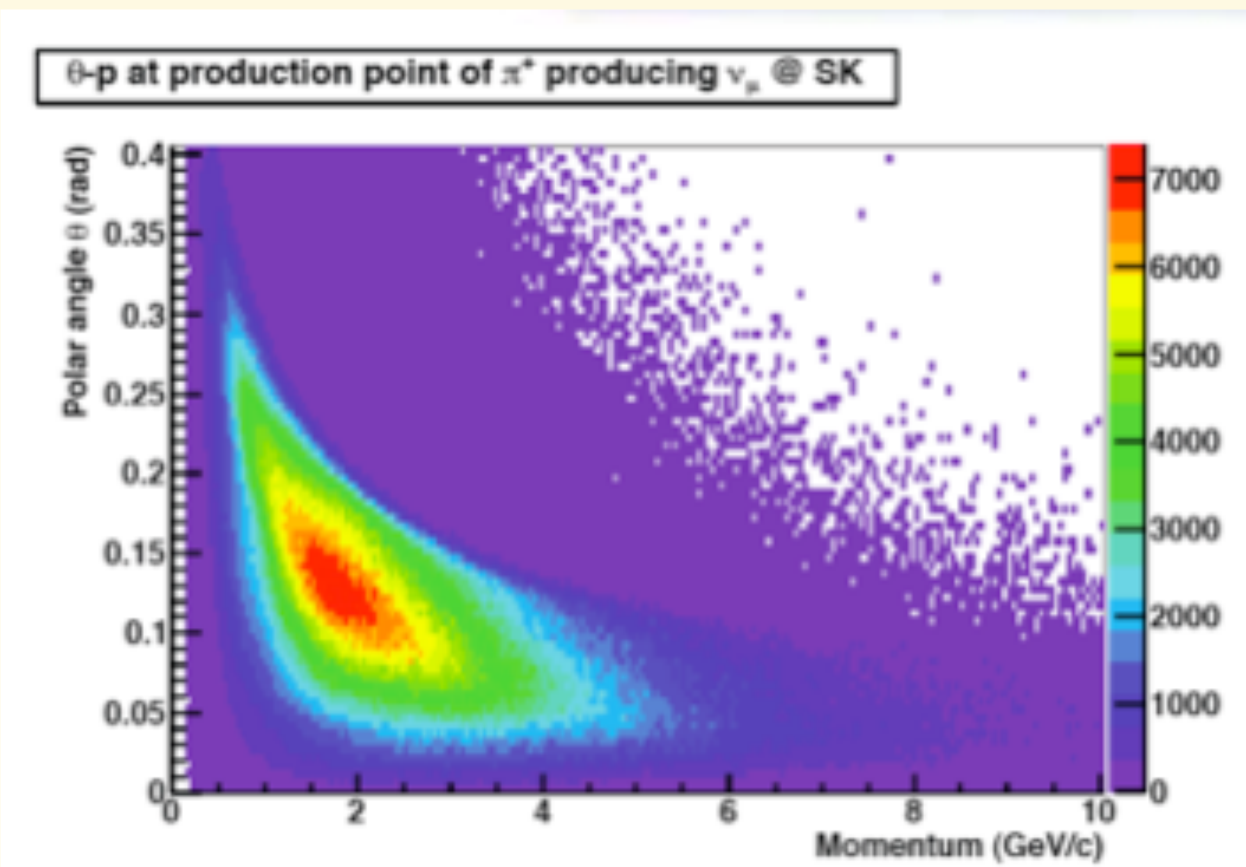

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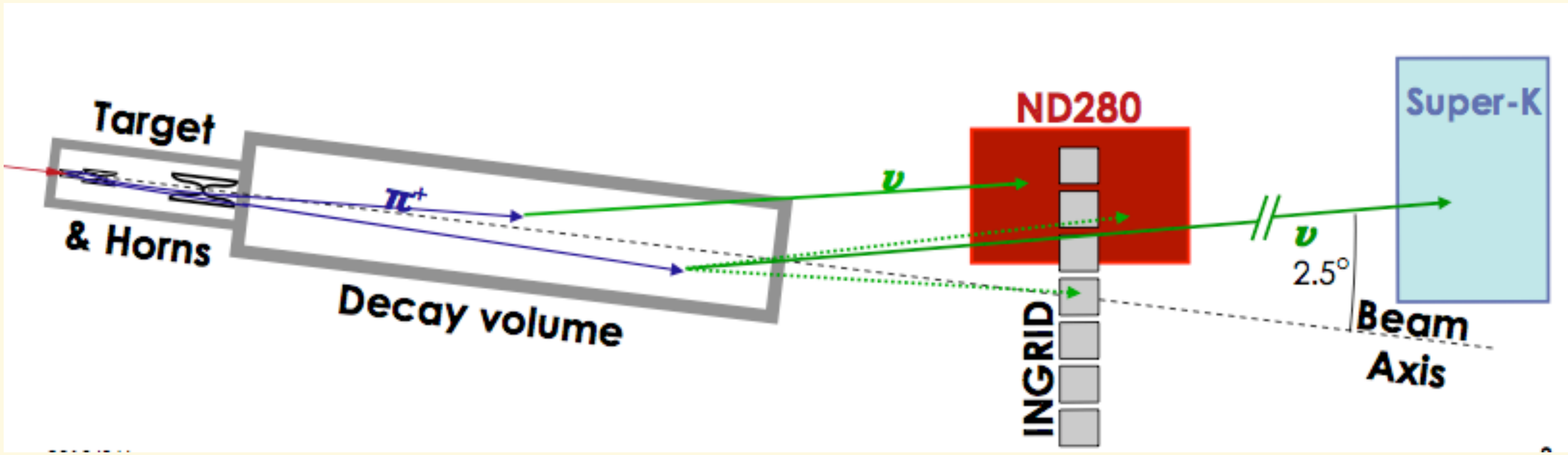

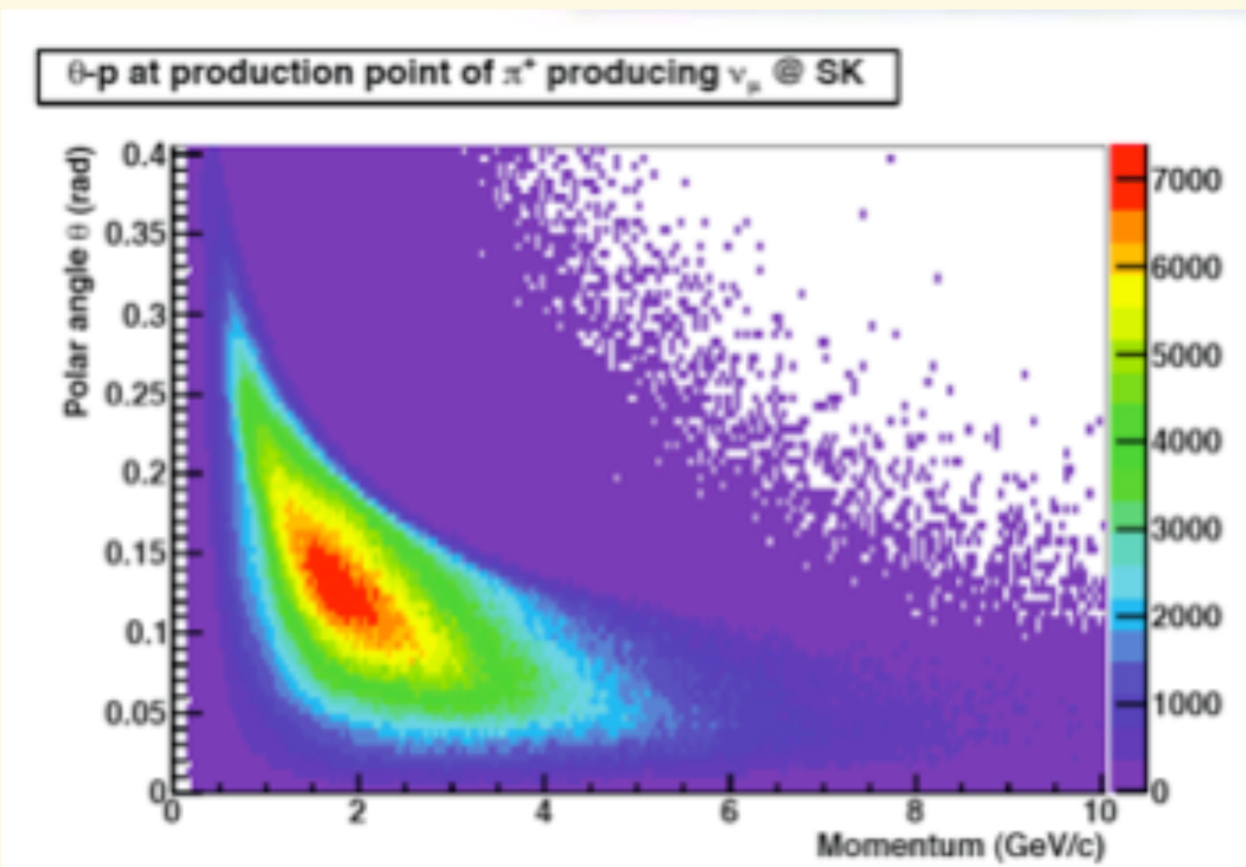

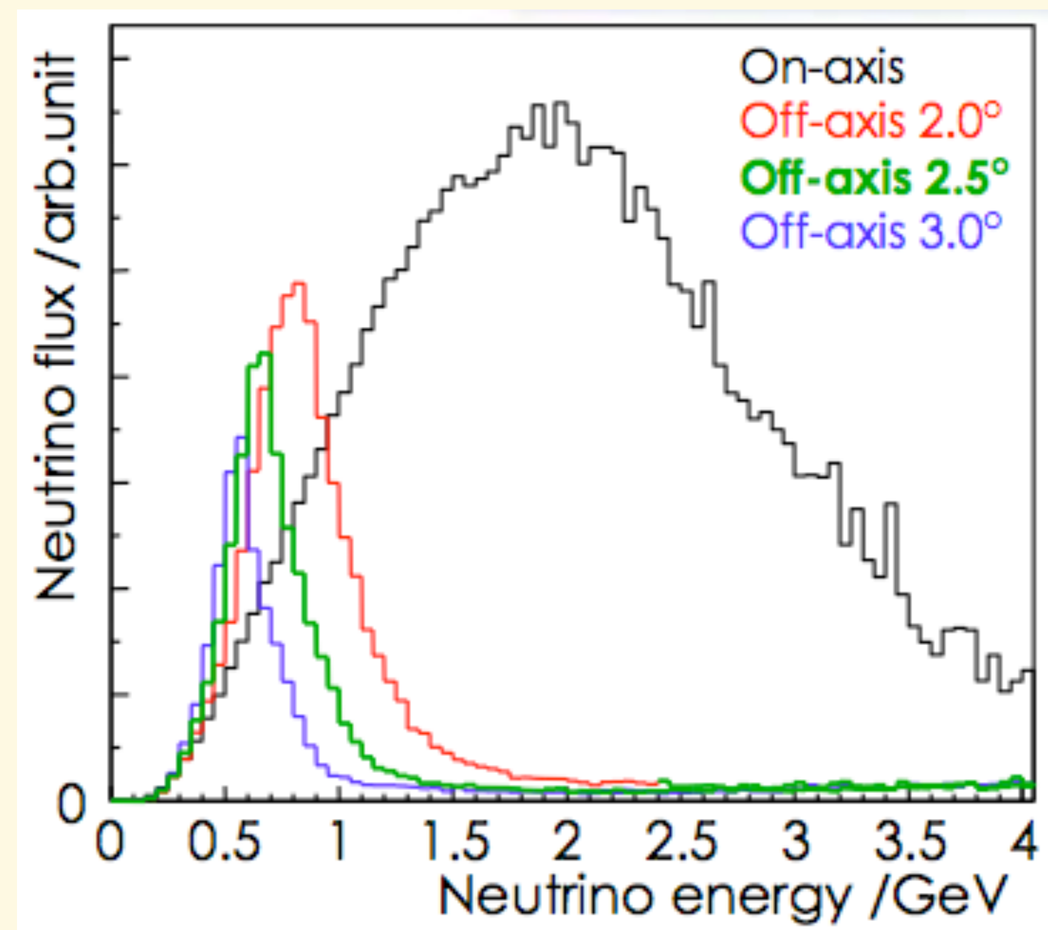

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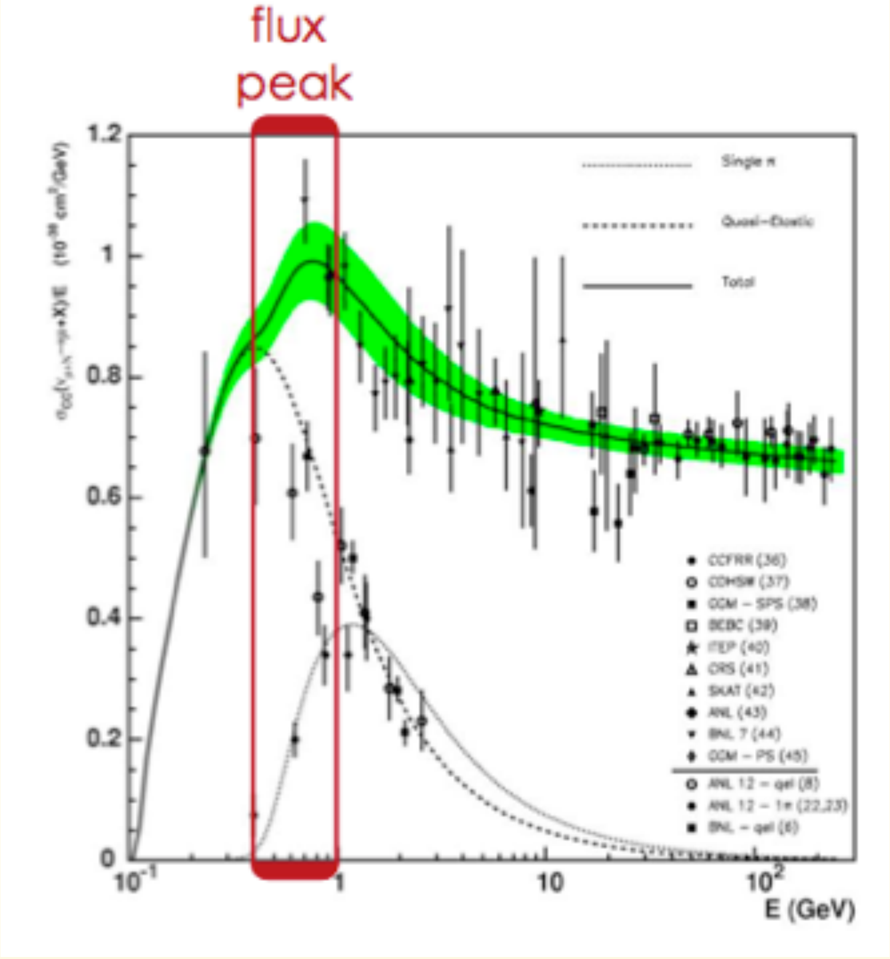

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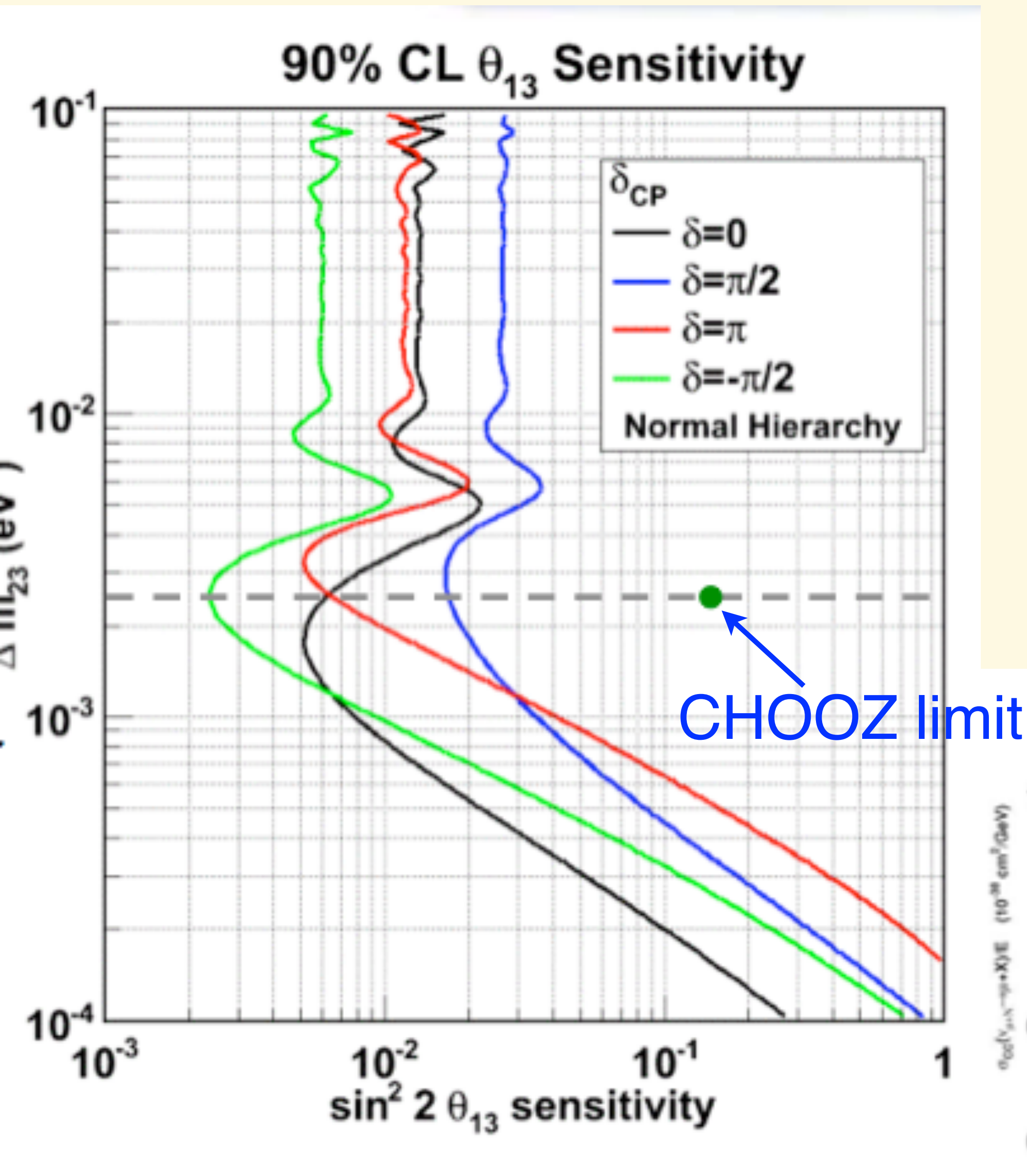

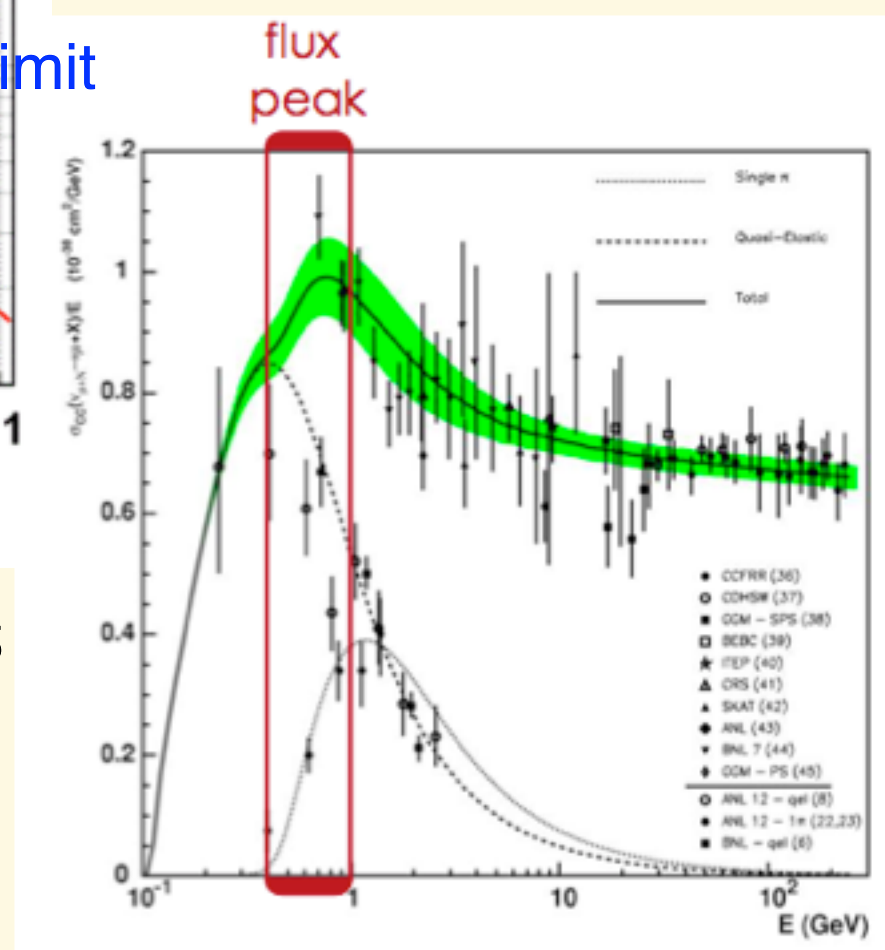

T2K: Assumes 5 years at 750 kW, 22.5 kton fiducial volume

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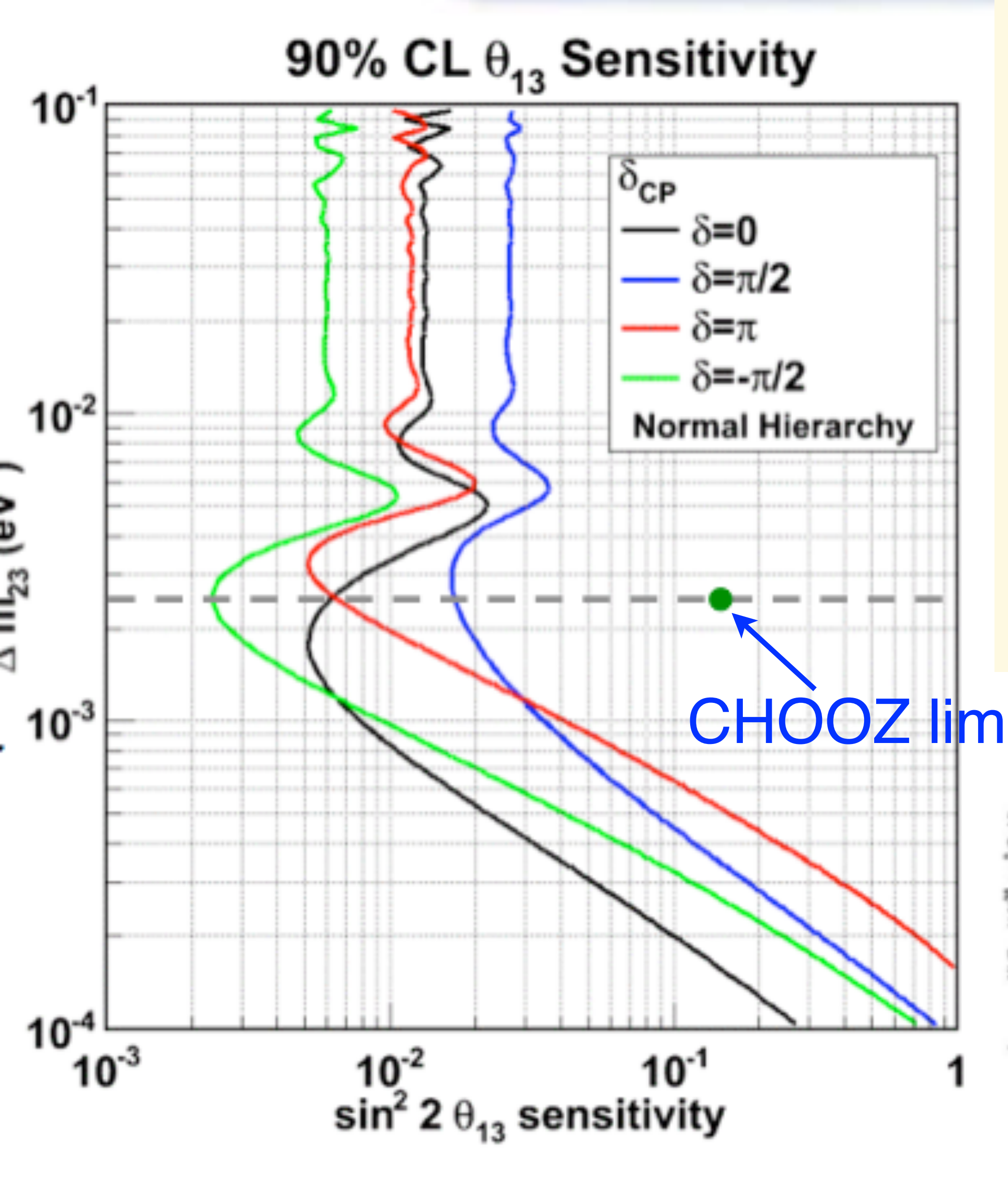

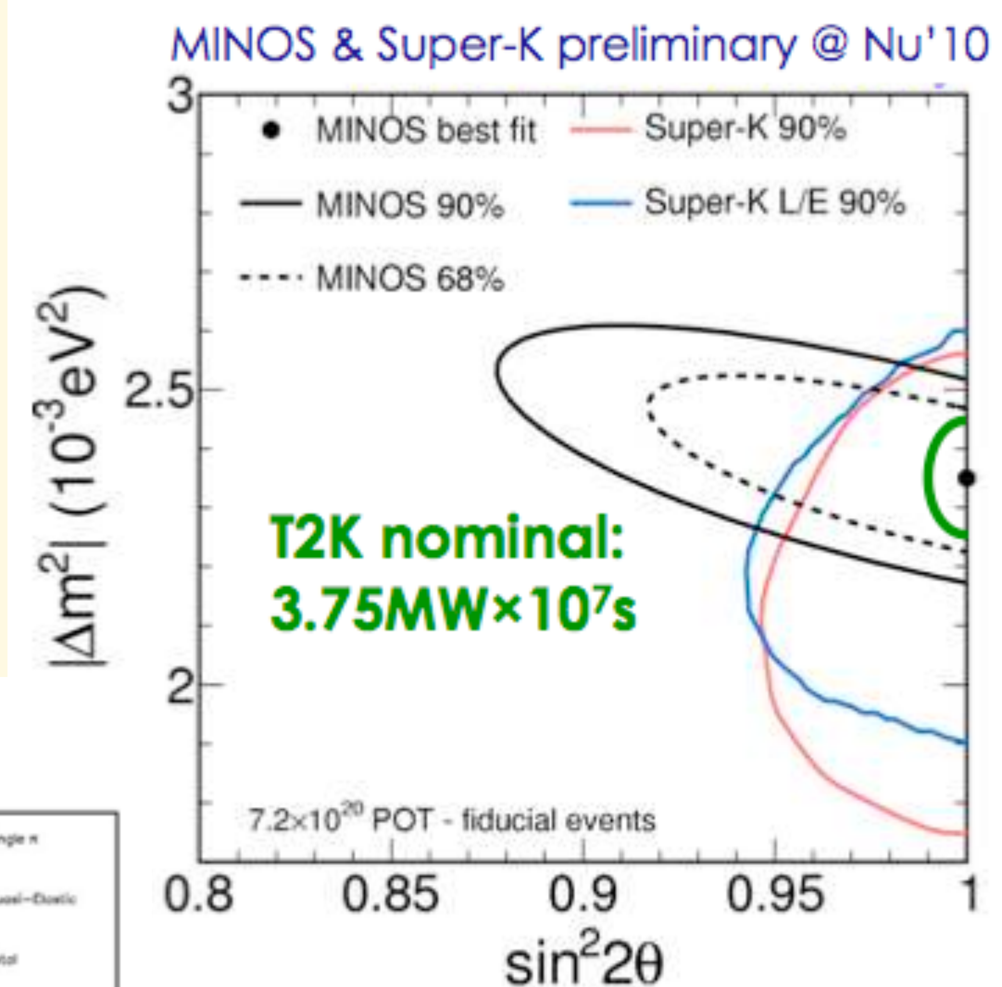

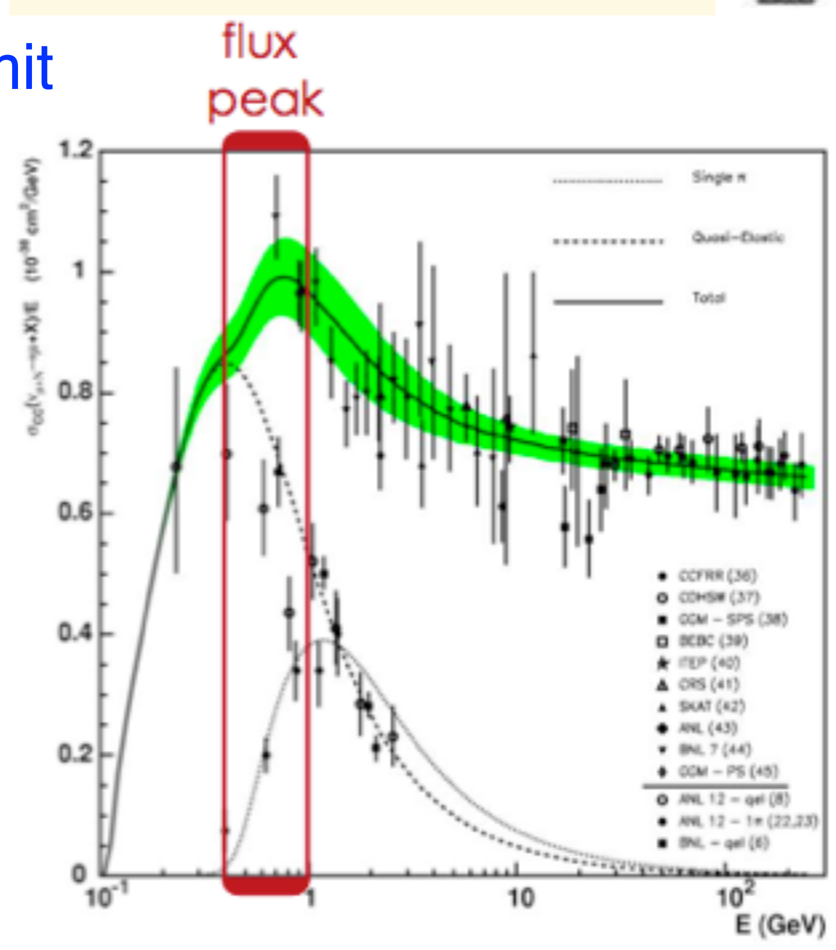

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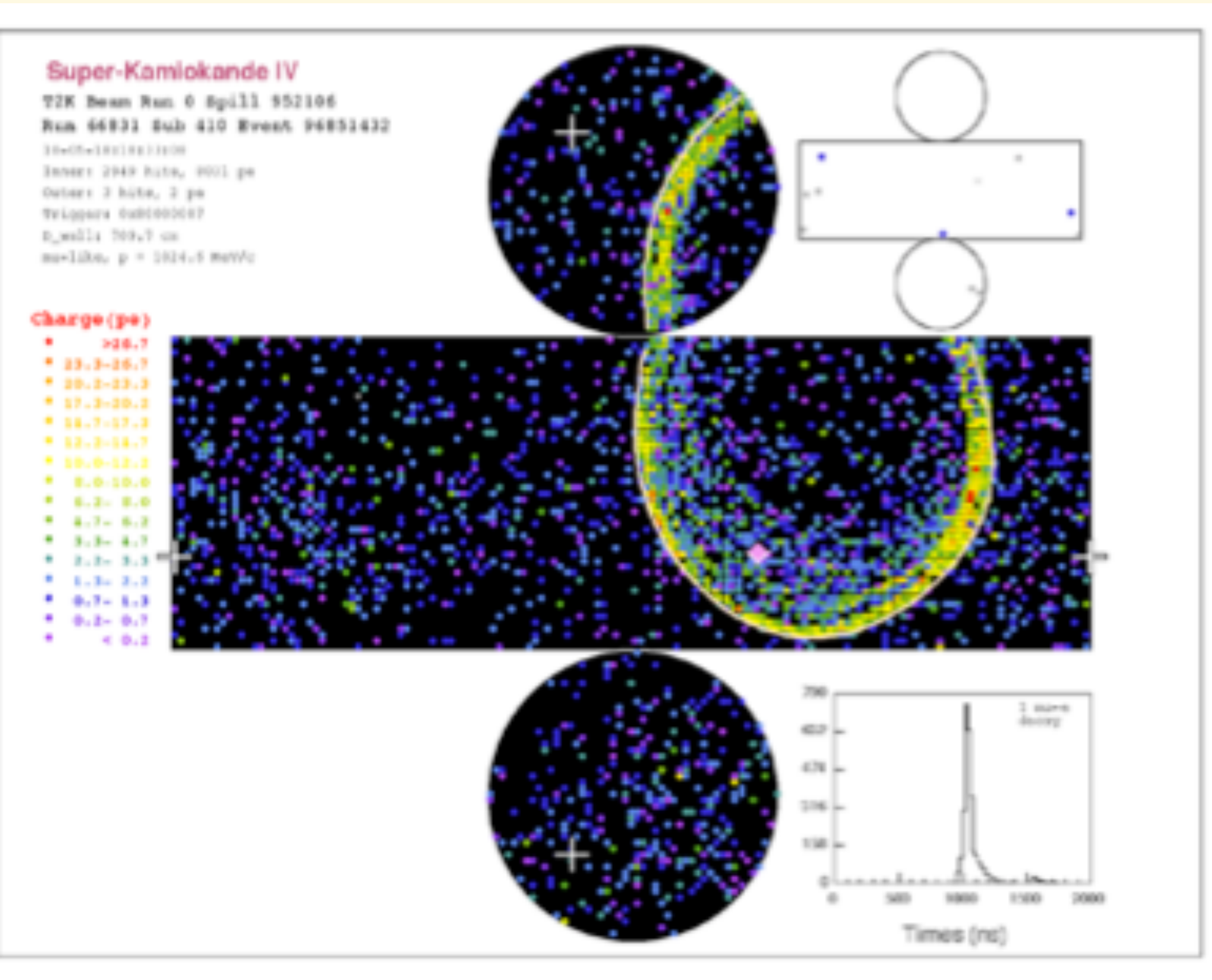

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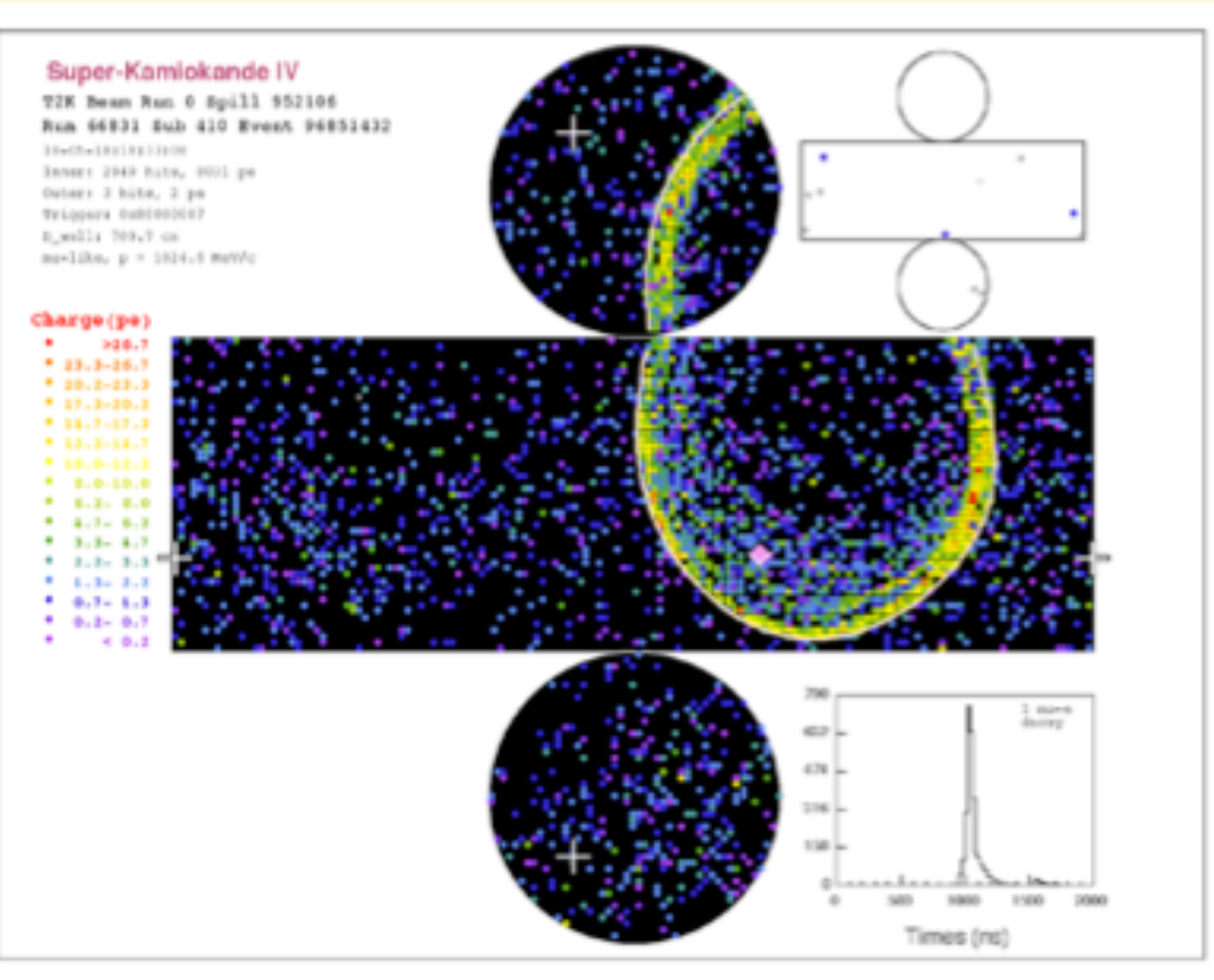

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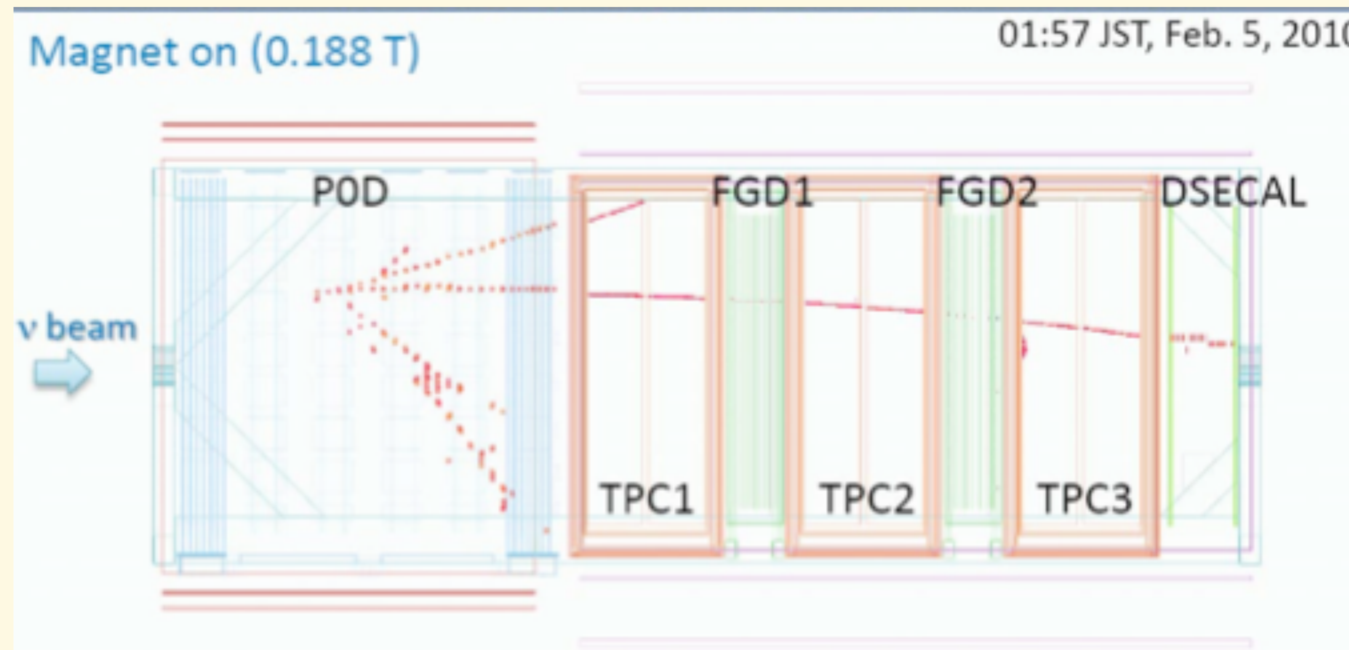

Event in the fine grained Near Detector at 280m

NOvA Detector

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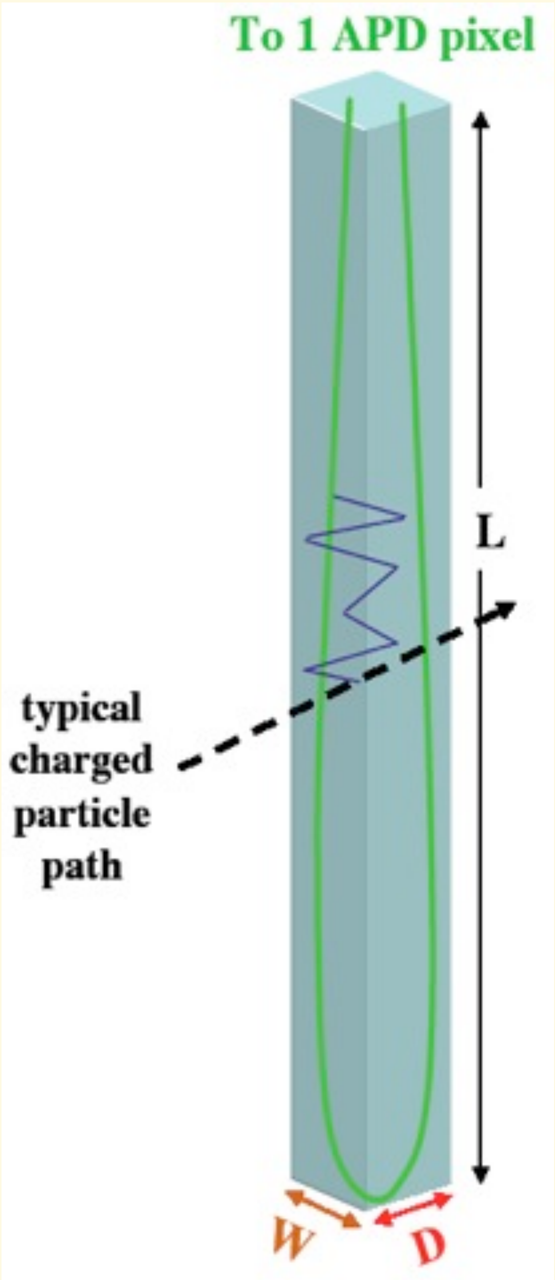
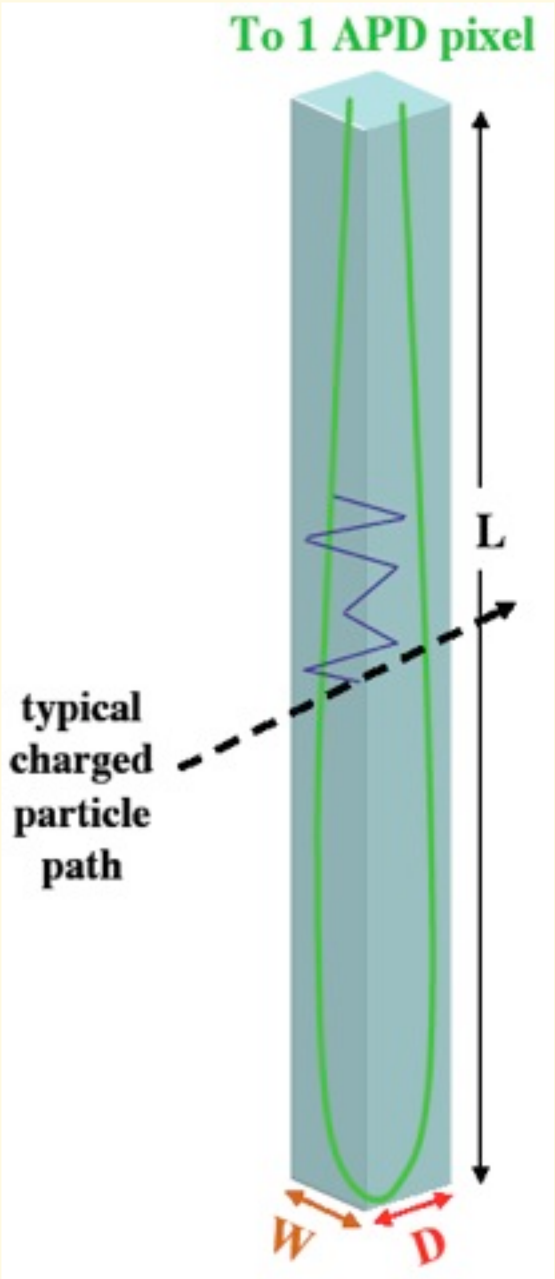
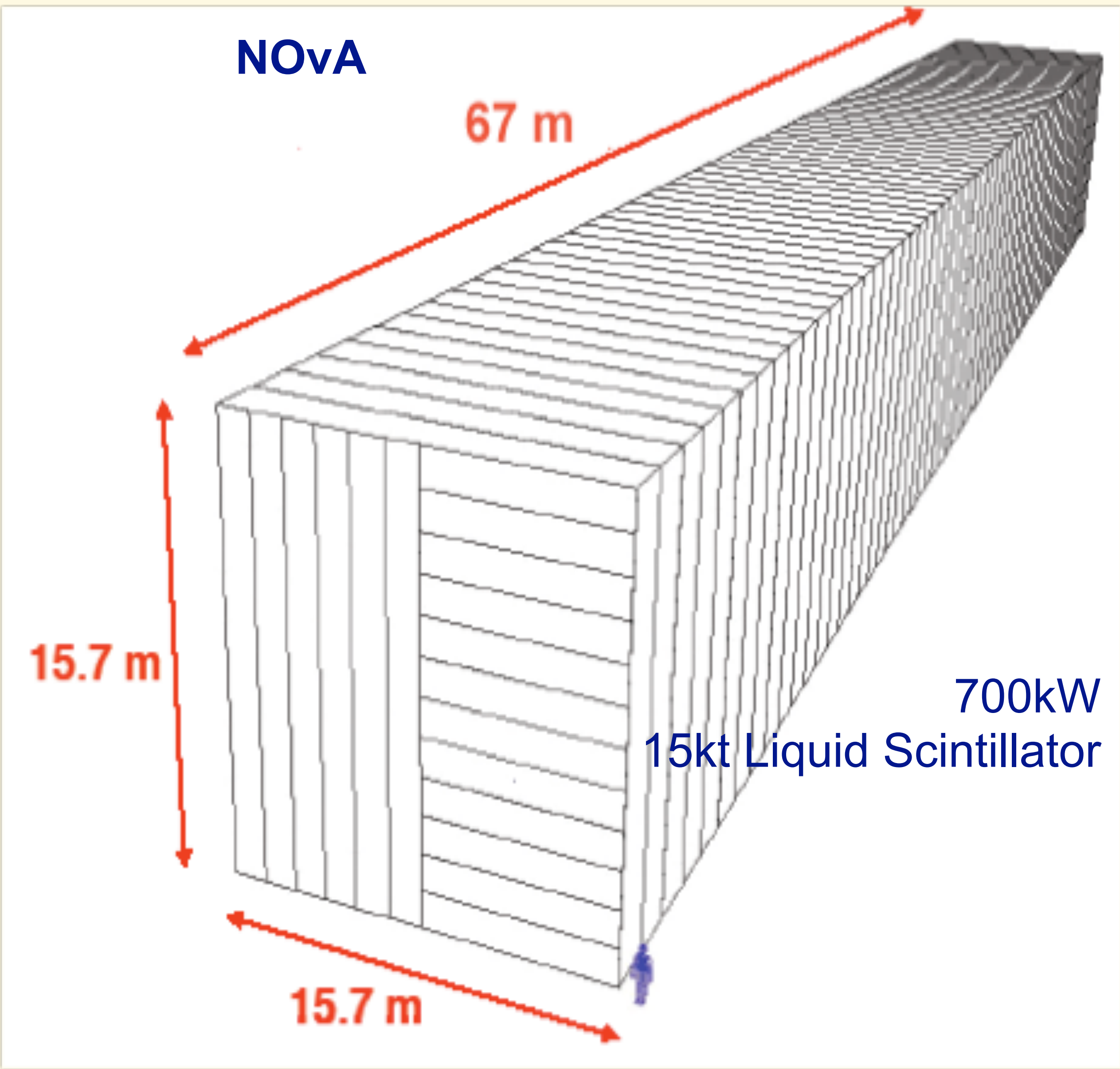


1 cell
L=15.7 m, W=4 cm, D=6 cm

NOvA Detector





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

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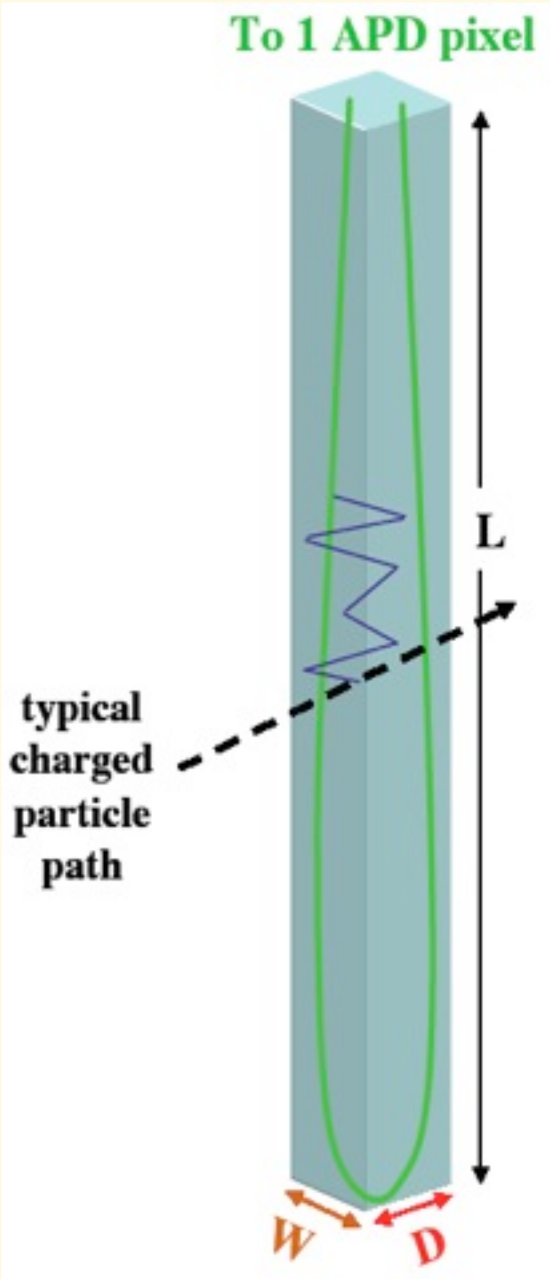

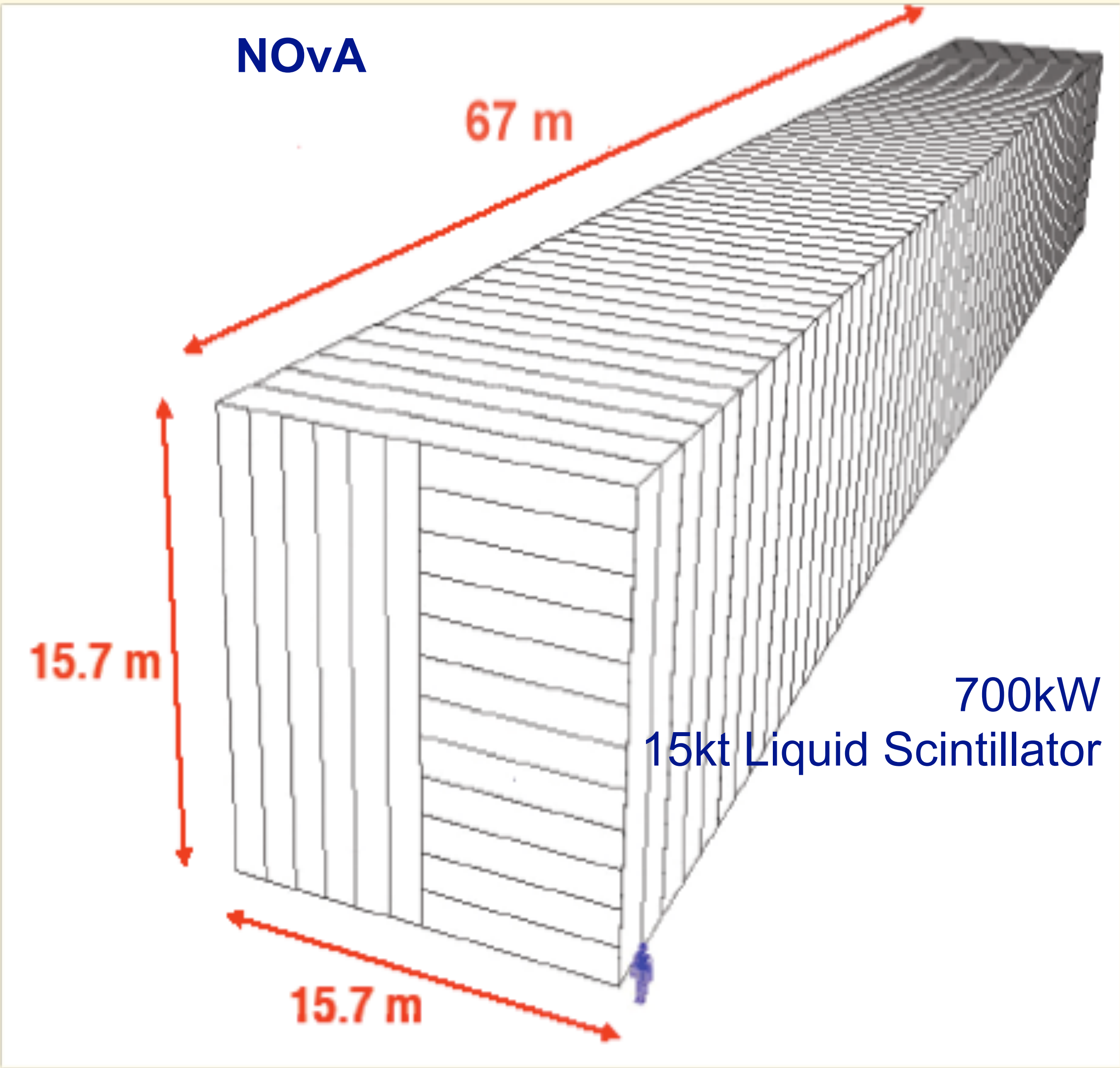

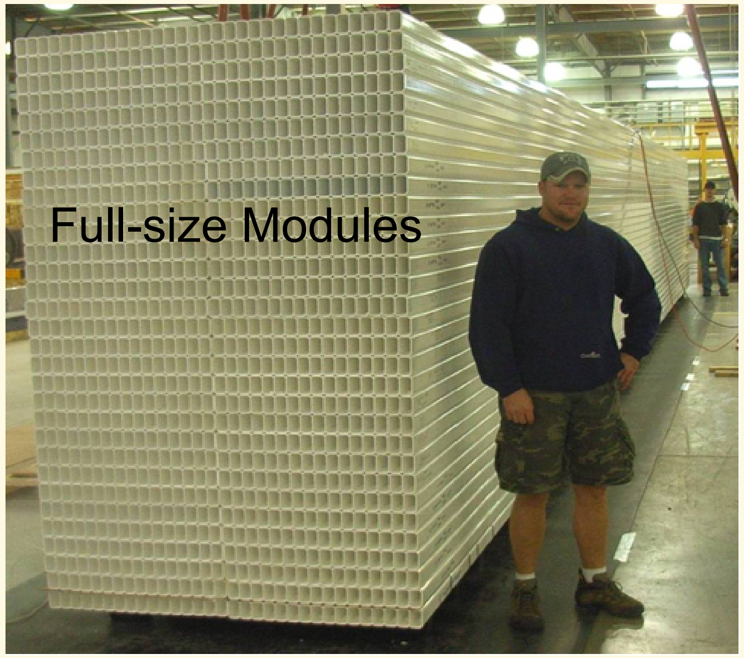

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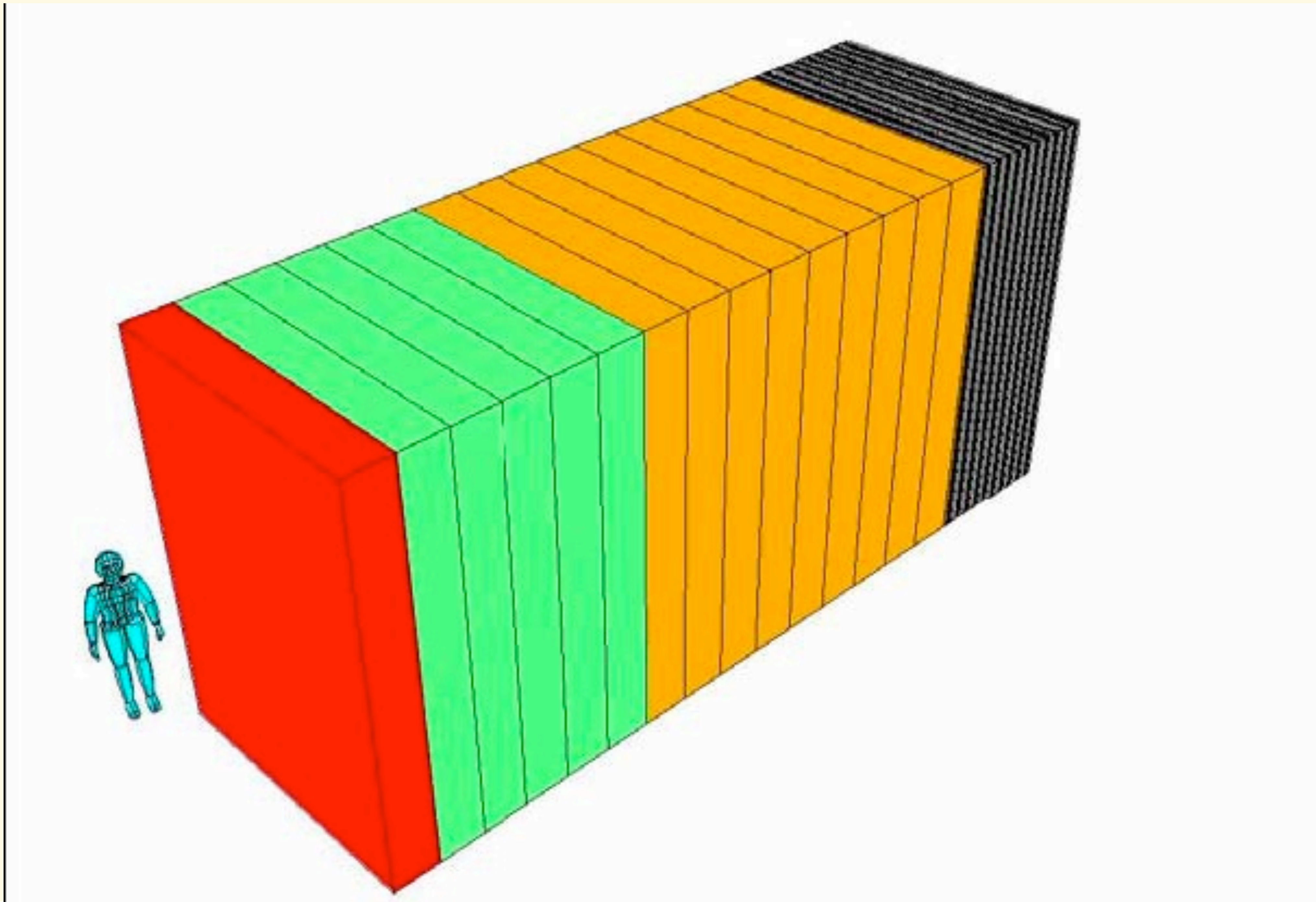

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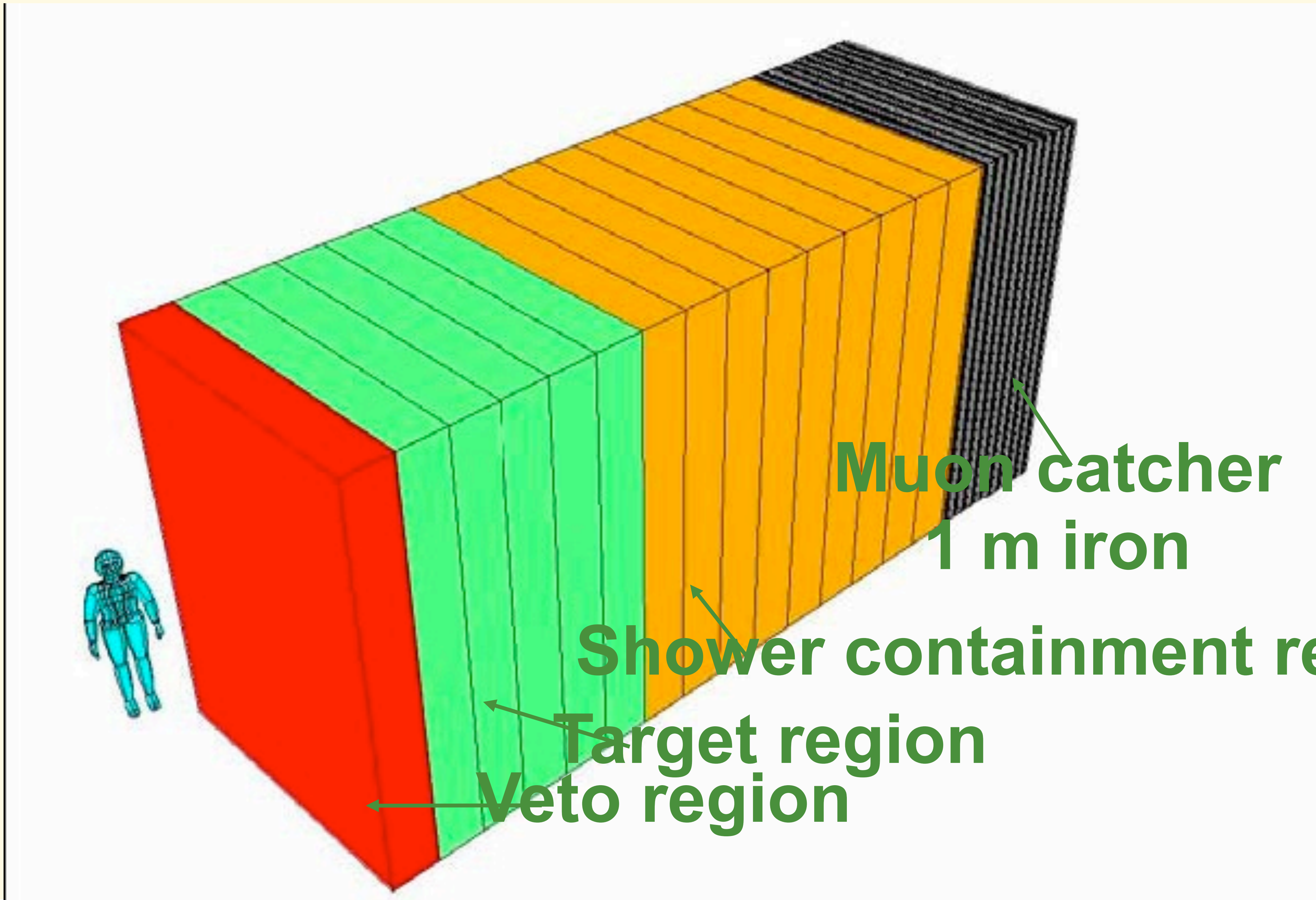

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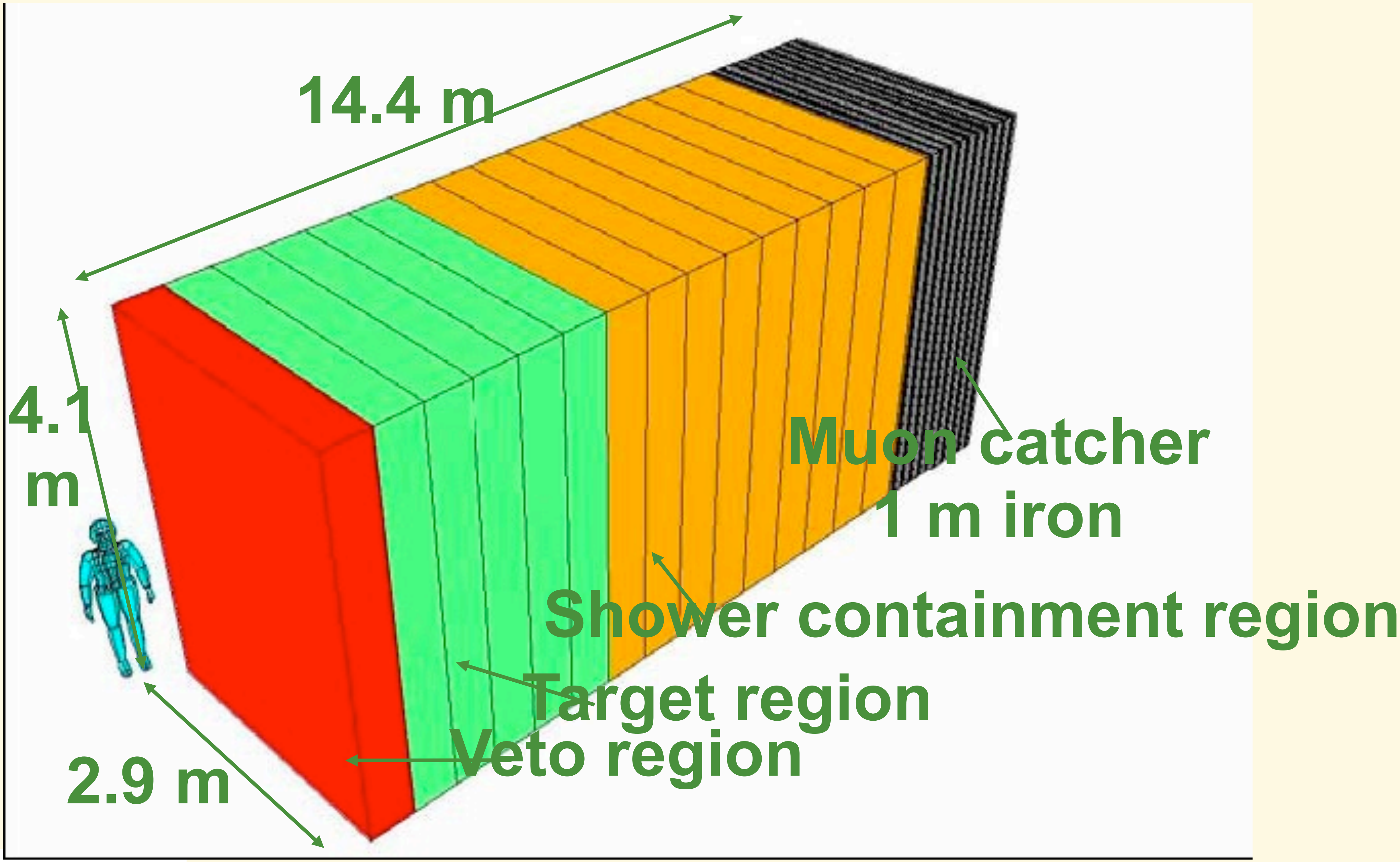

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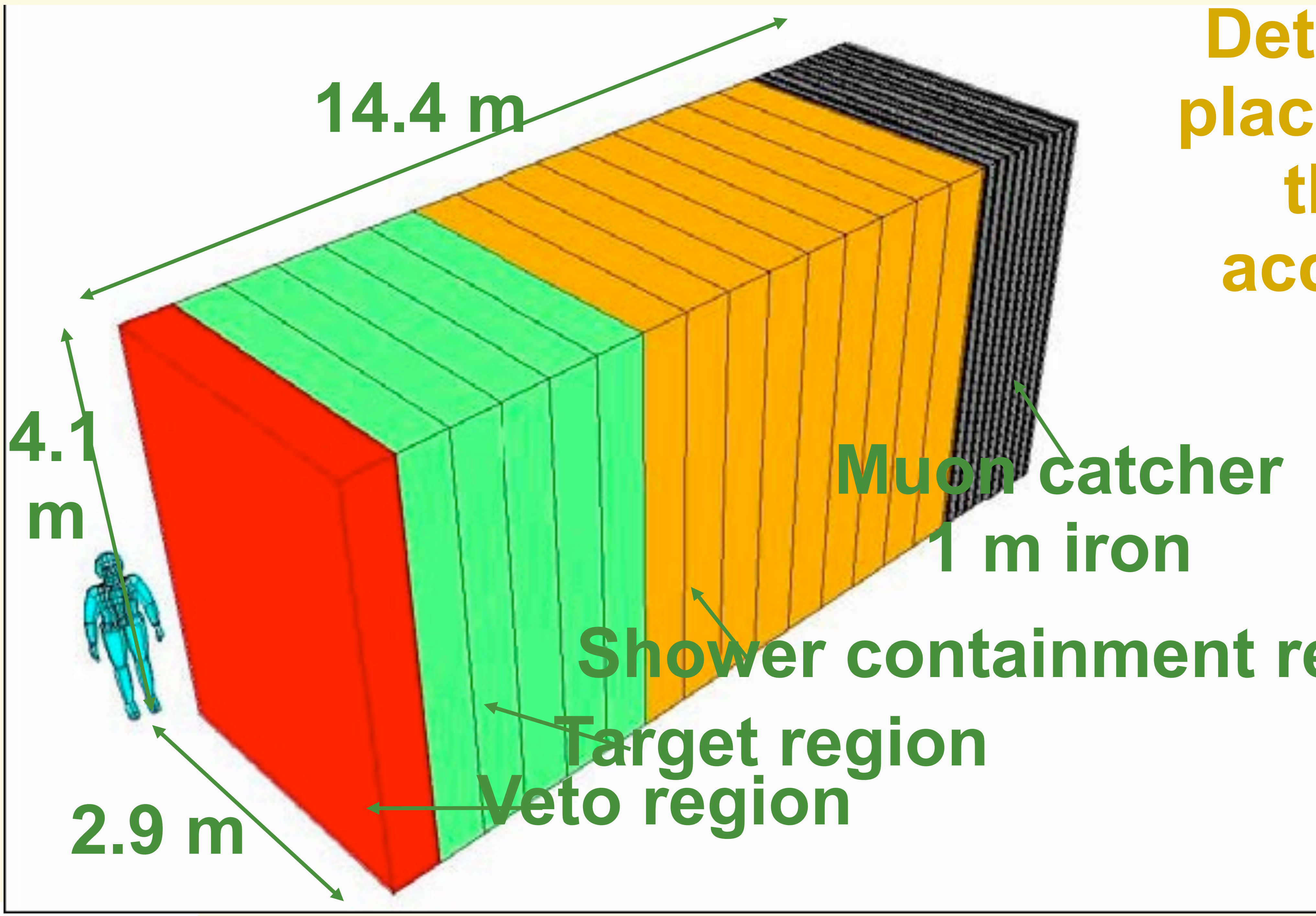

The Near Detector will be placed off-axis in the MINOS access tunnel.

209 T
126 T totally active
23 T fiducial

NOvA FD Status

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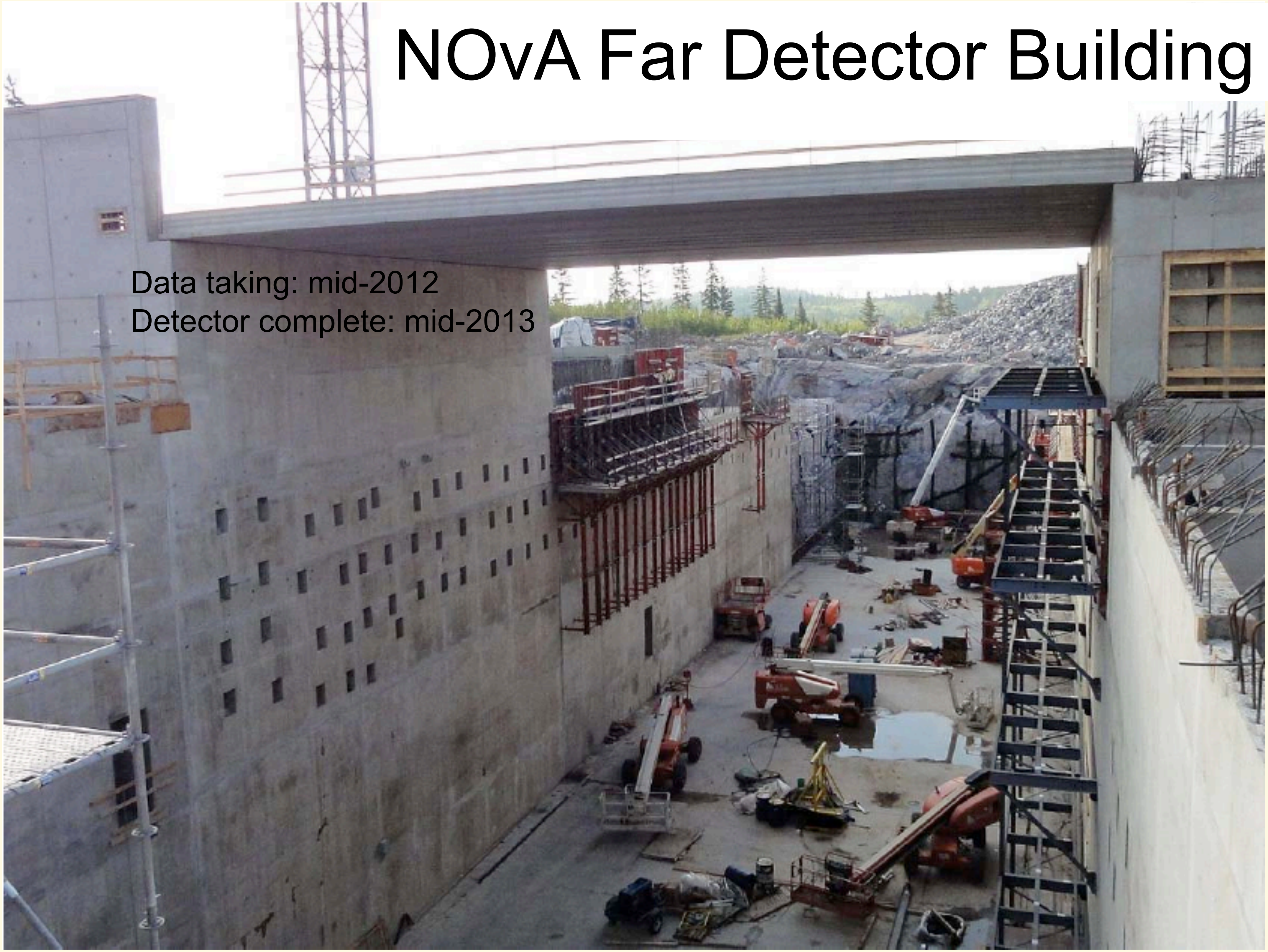
NOvA Far Detector Site - ~3 months ago

NOvA More Recently



NOνA Events (MC)

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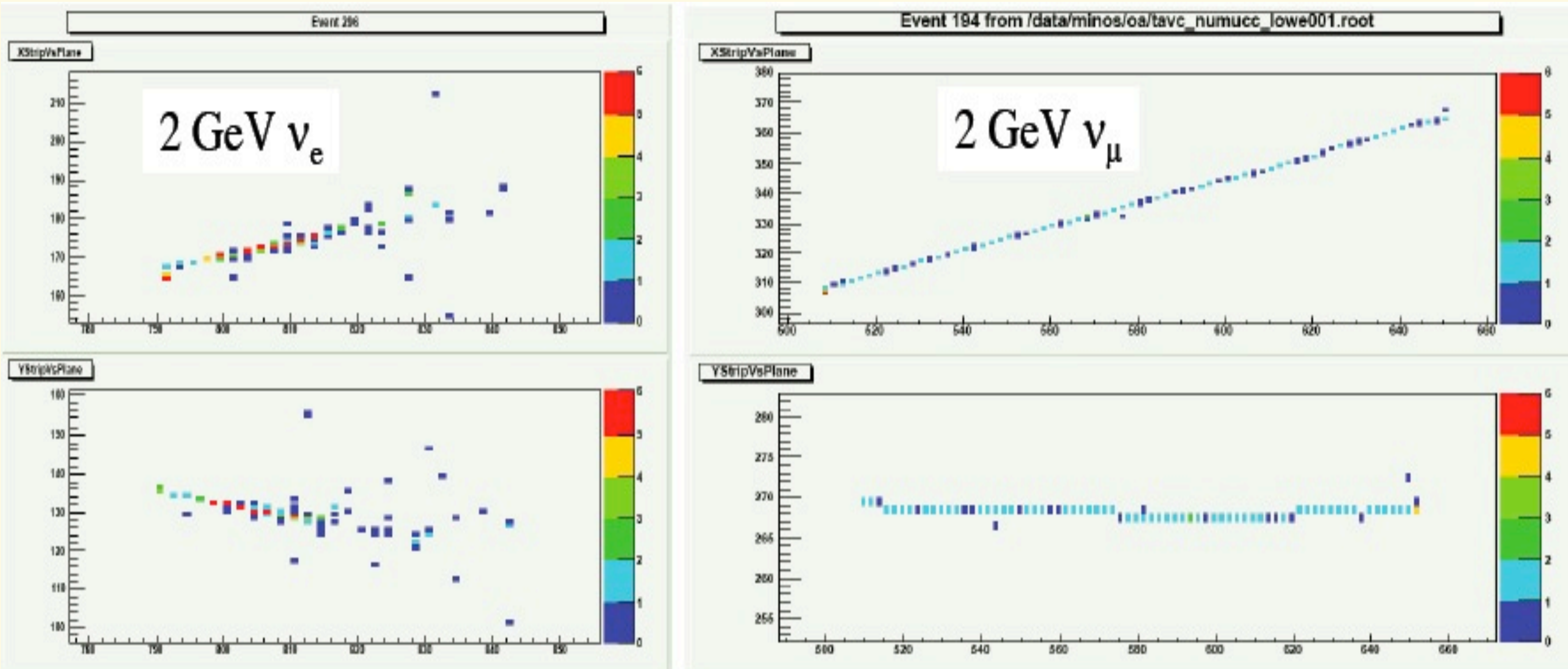

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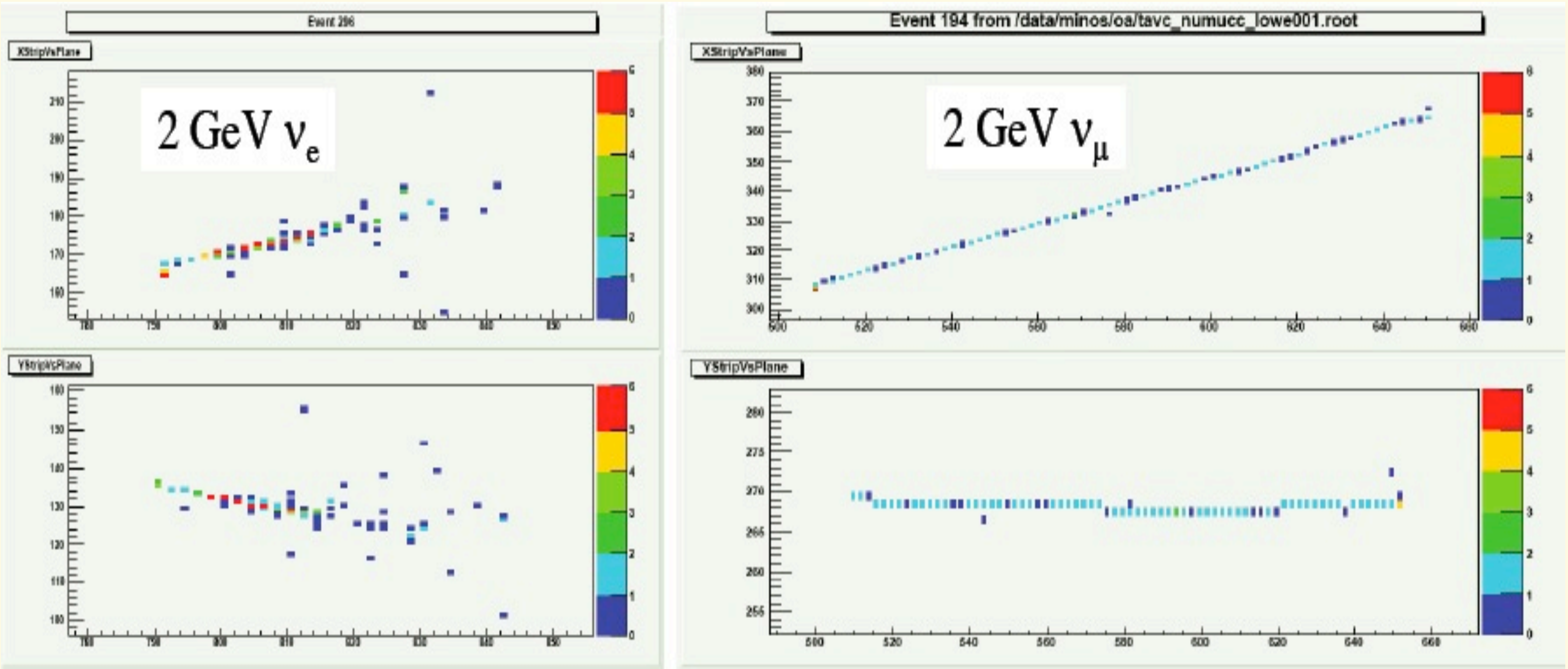


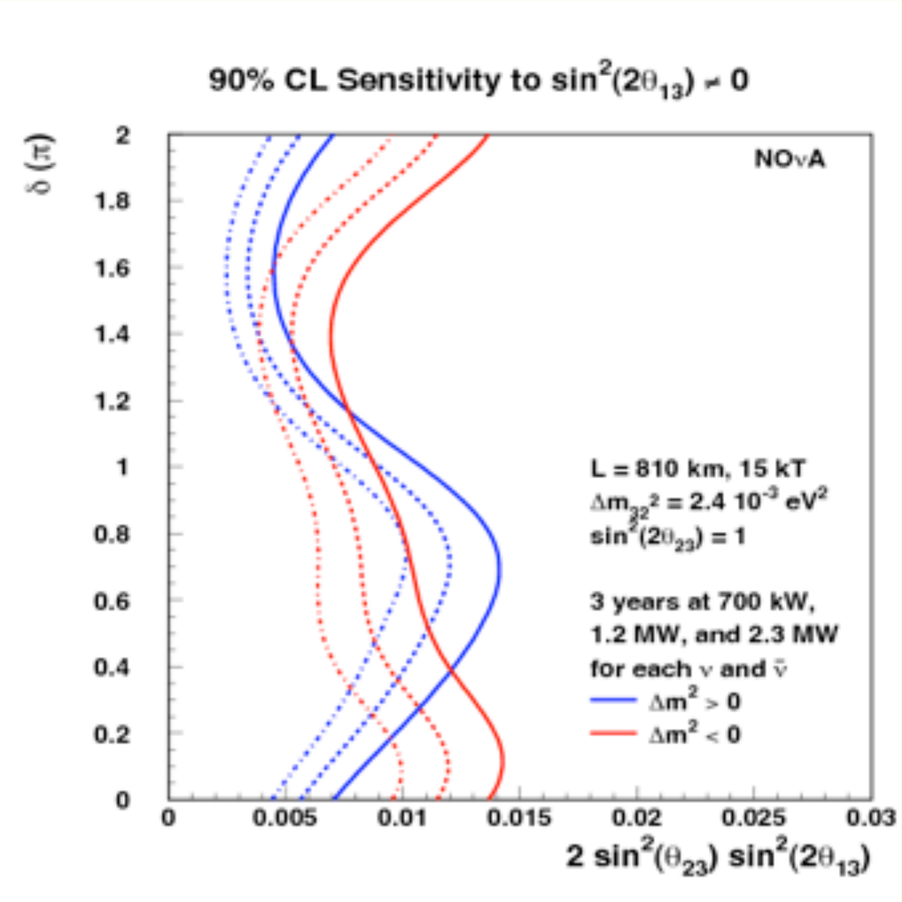
Longitudinal sampling is 0.2 X_0

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

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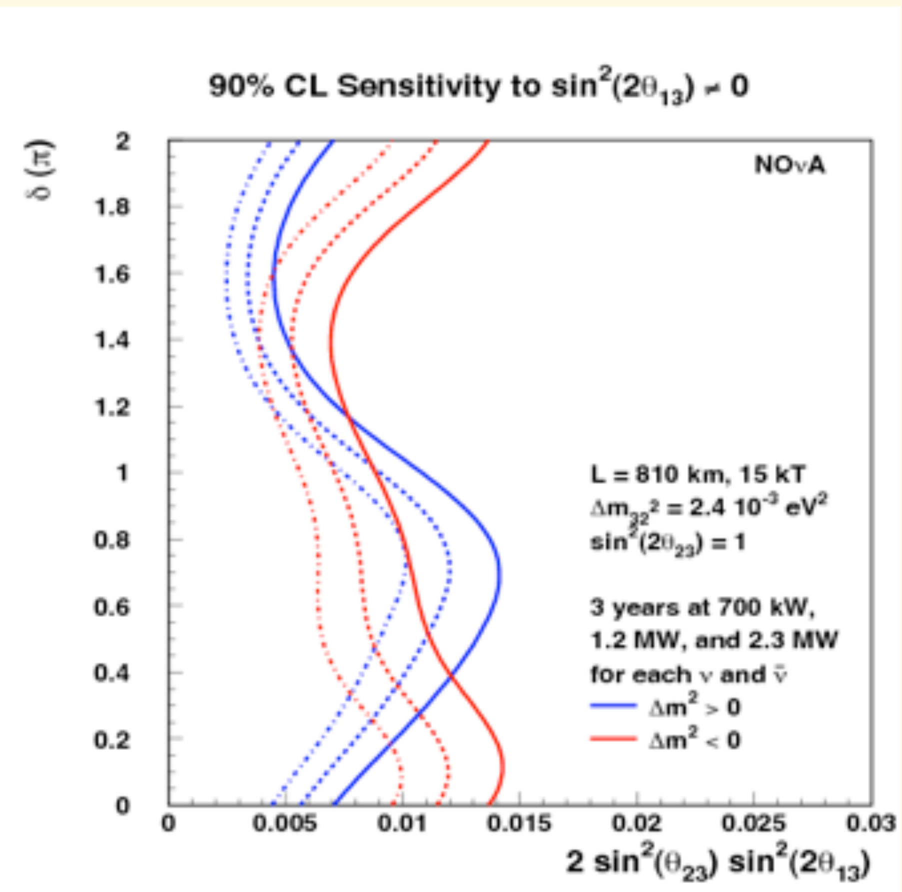

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95% Resolution of Mass Ordering NOvA and T2K combined

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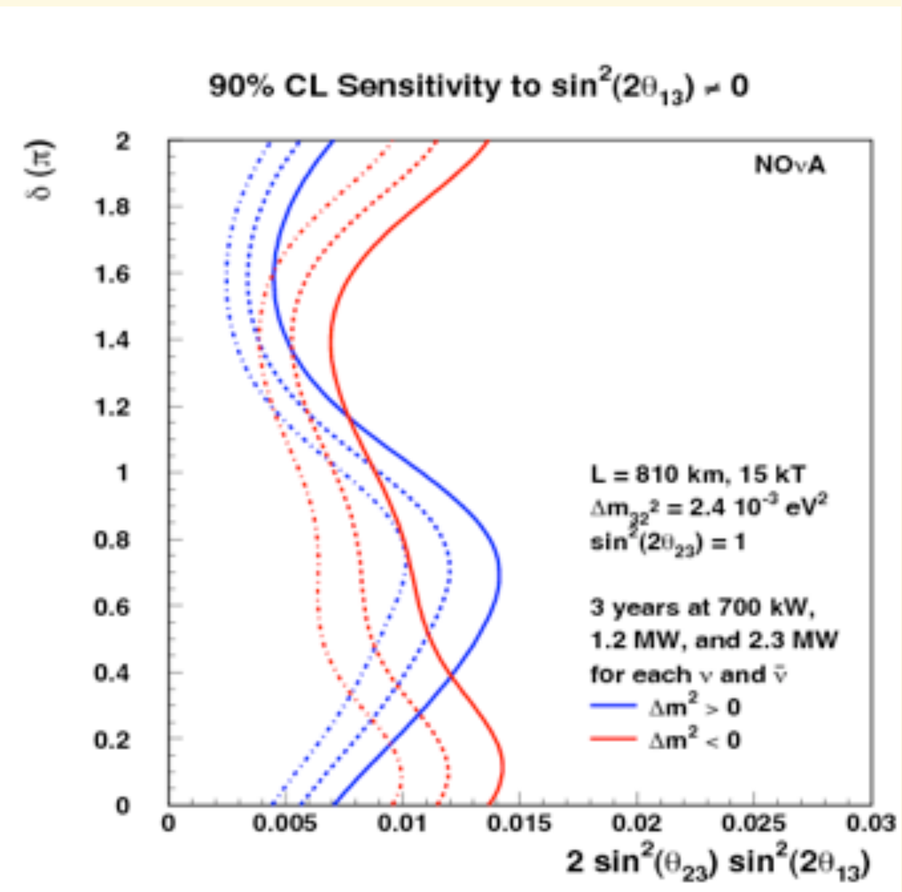

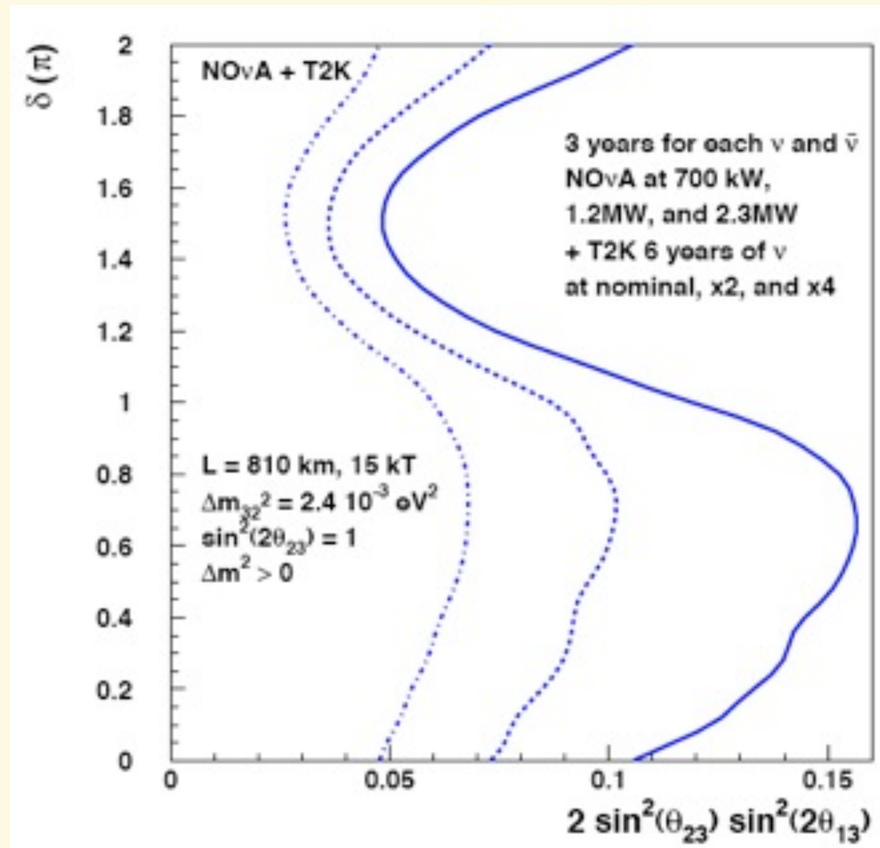

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Normal Hierarchy

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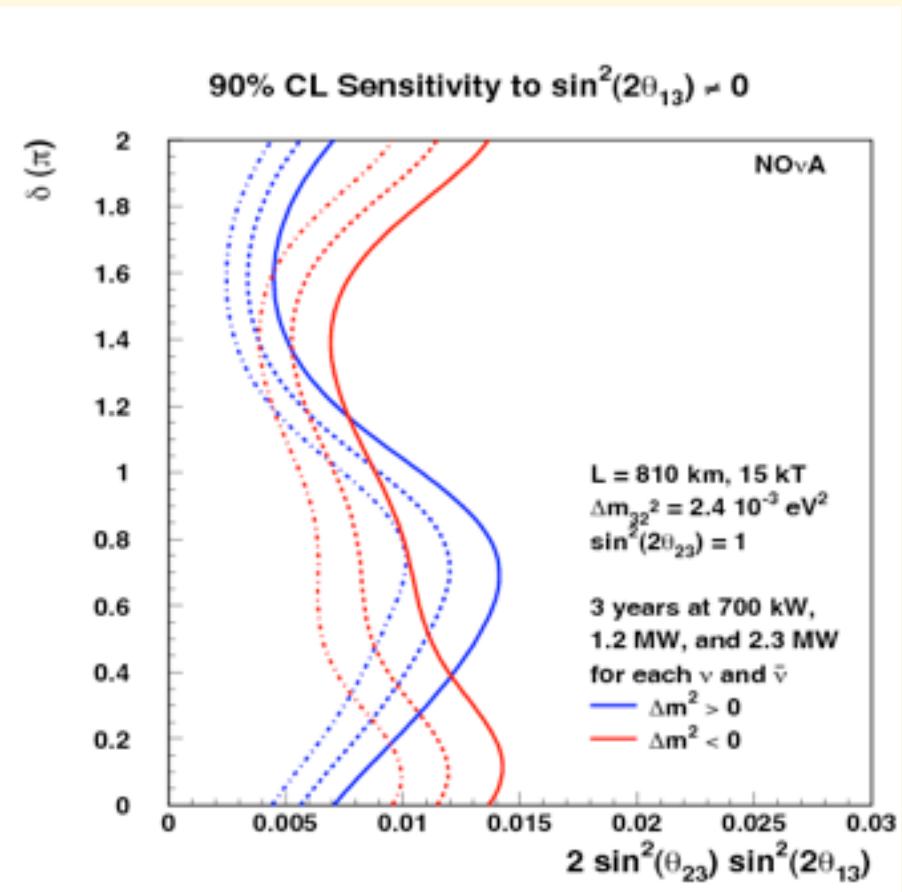

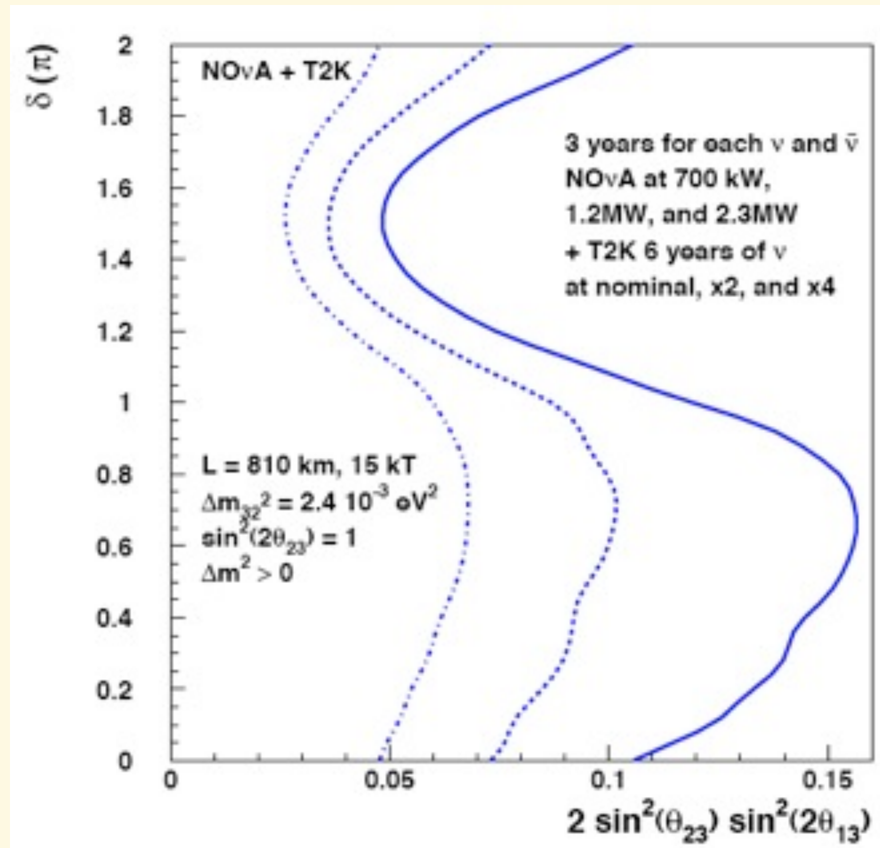

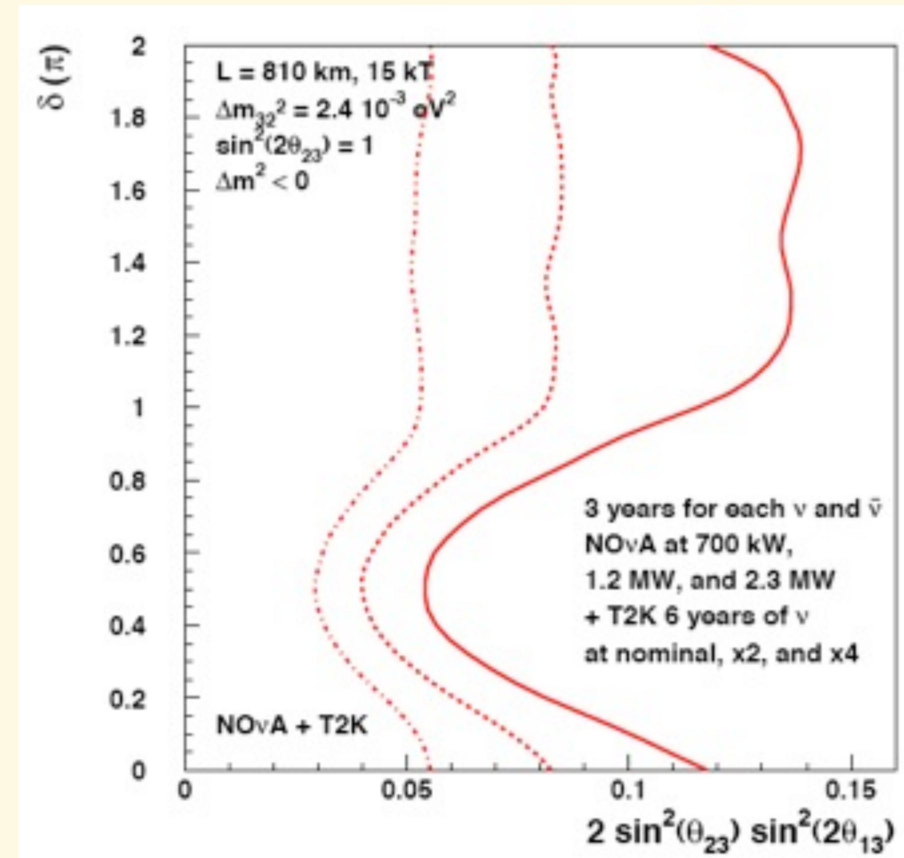

The long distance (810 km) gives it some sensitivity to mass hierarchy

Normal Hierarchy

Inverted hierarchy

Further Future

Further Future

- Next US step?

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  - Upgrade off the accelerator complex (Project X? - 2.2 MW)

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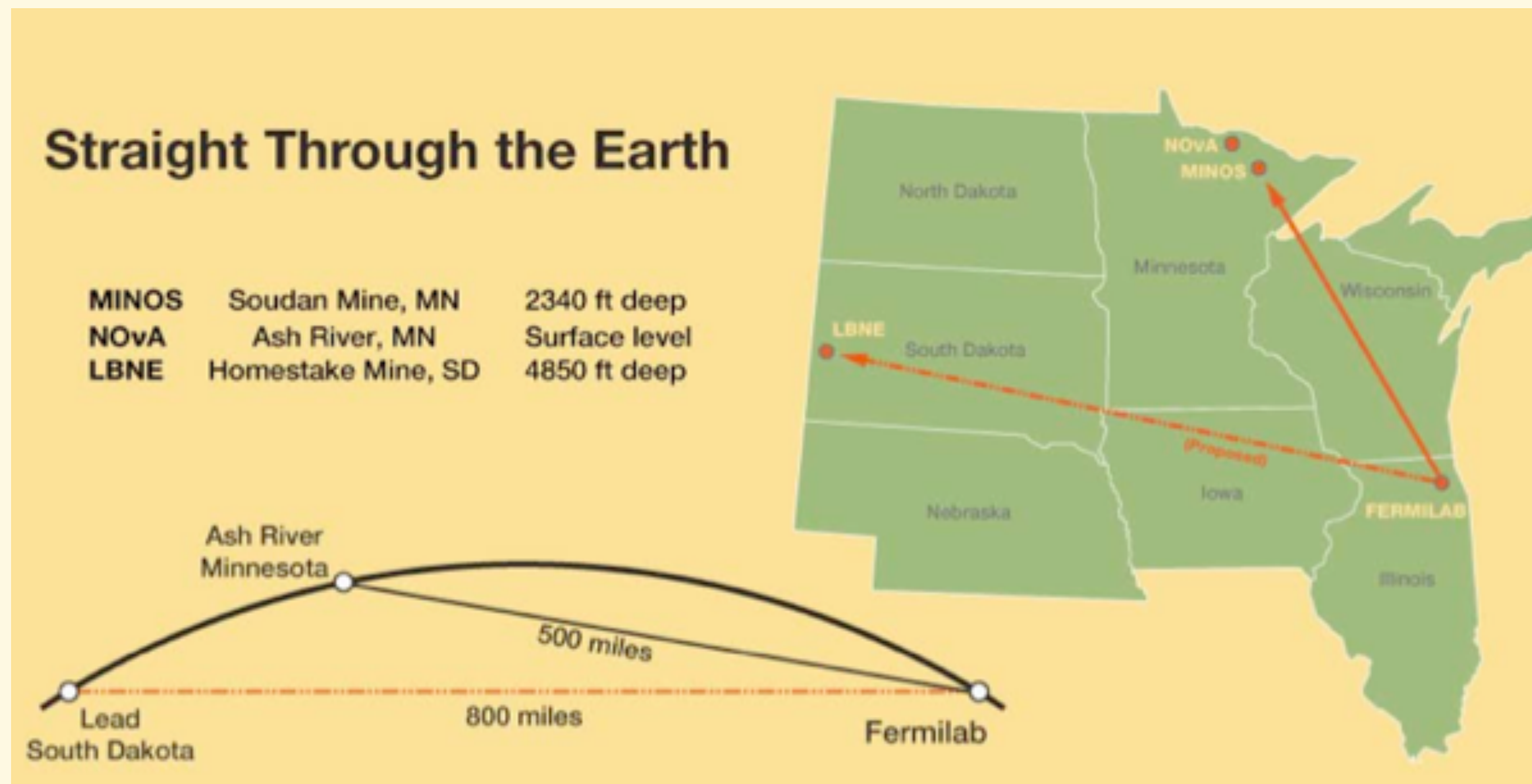

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Long Baseline Neutrino Expt

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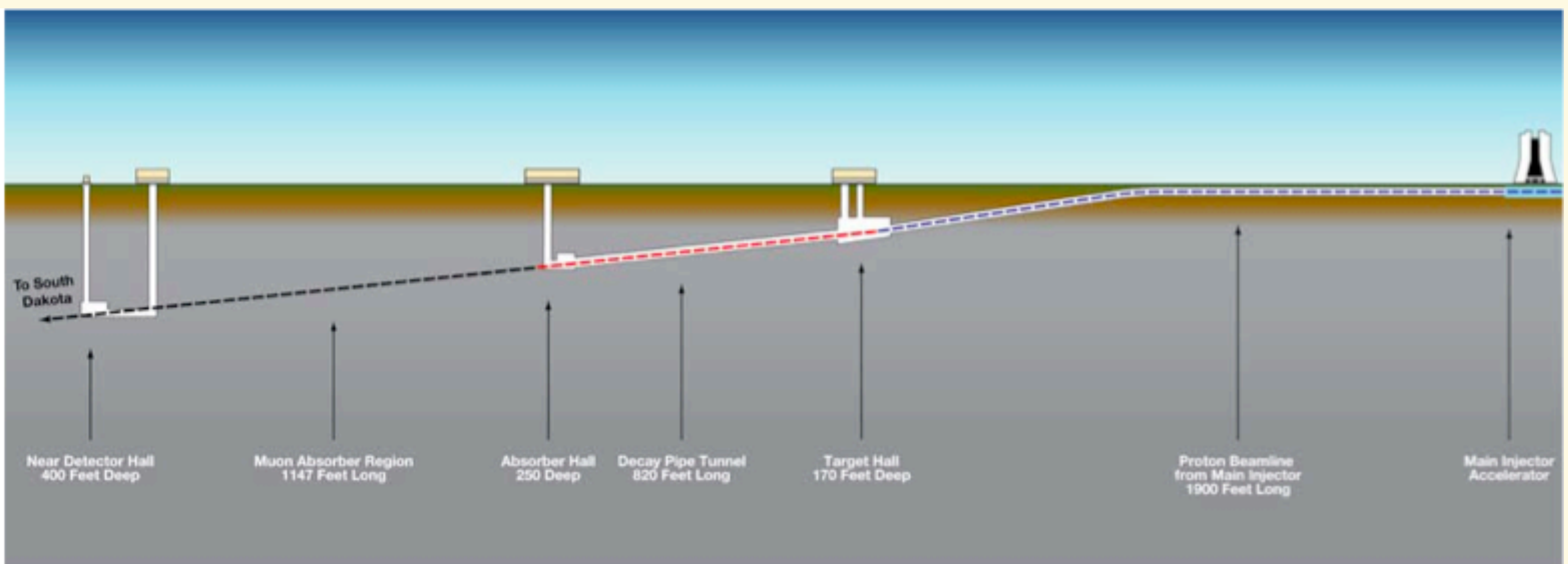
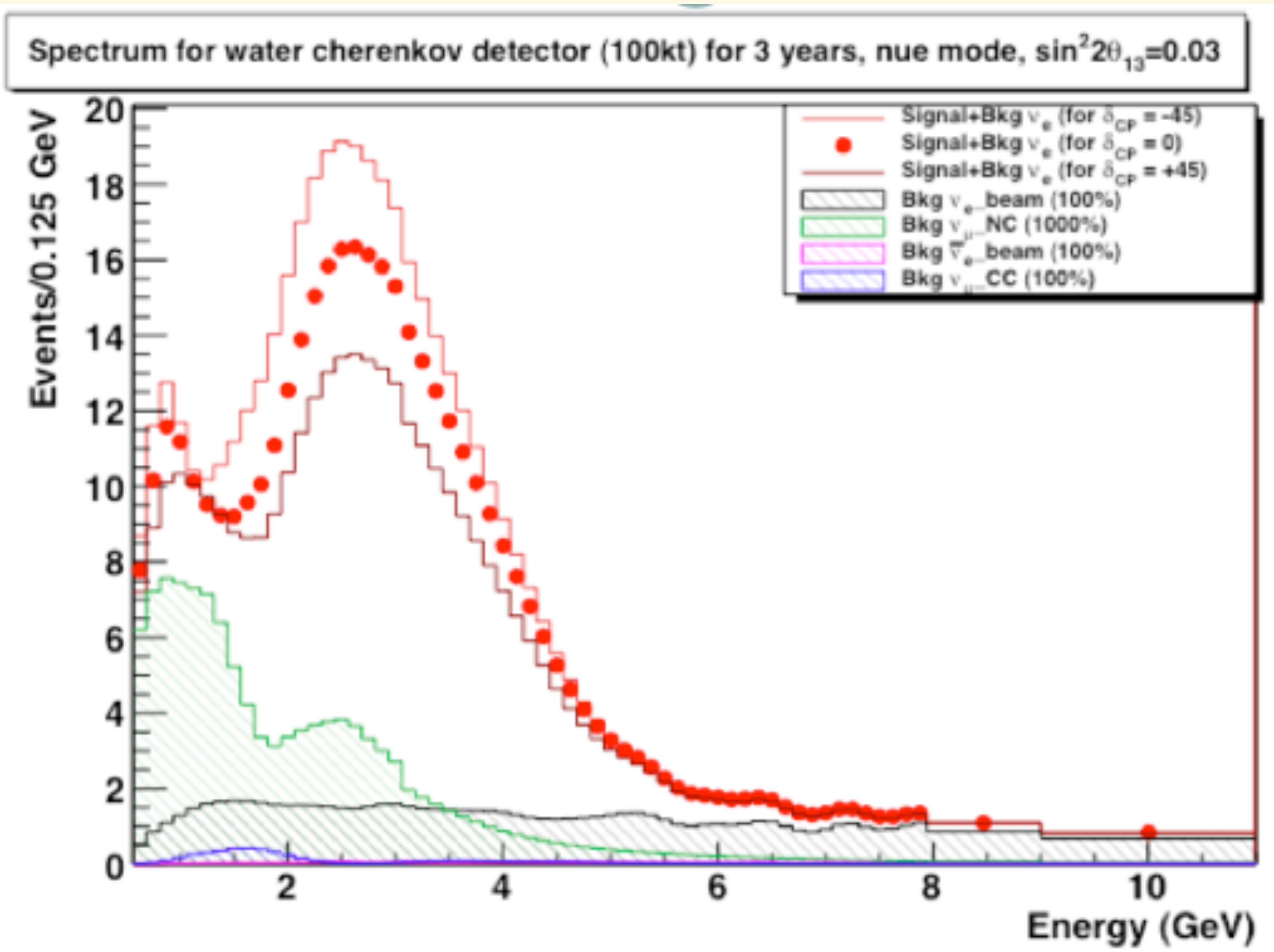


New proposed neutrino beam line

Water or Argon?

Water or Argon?



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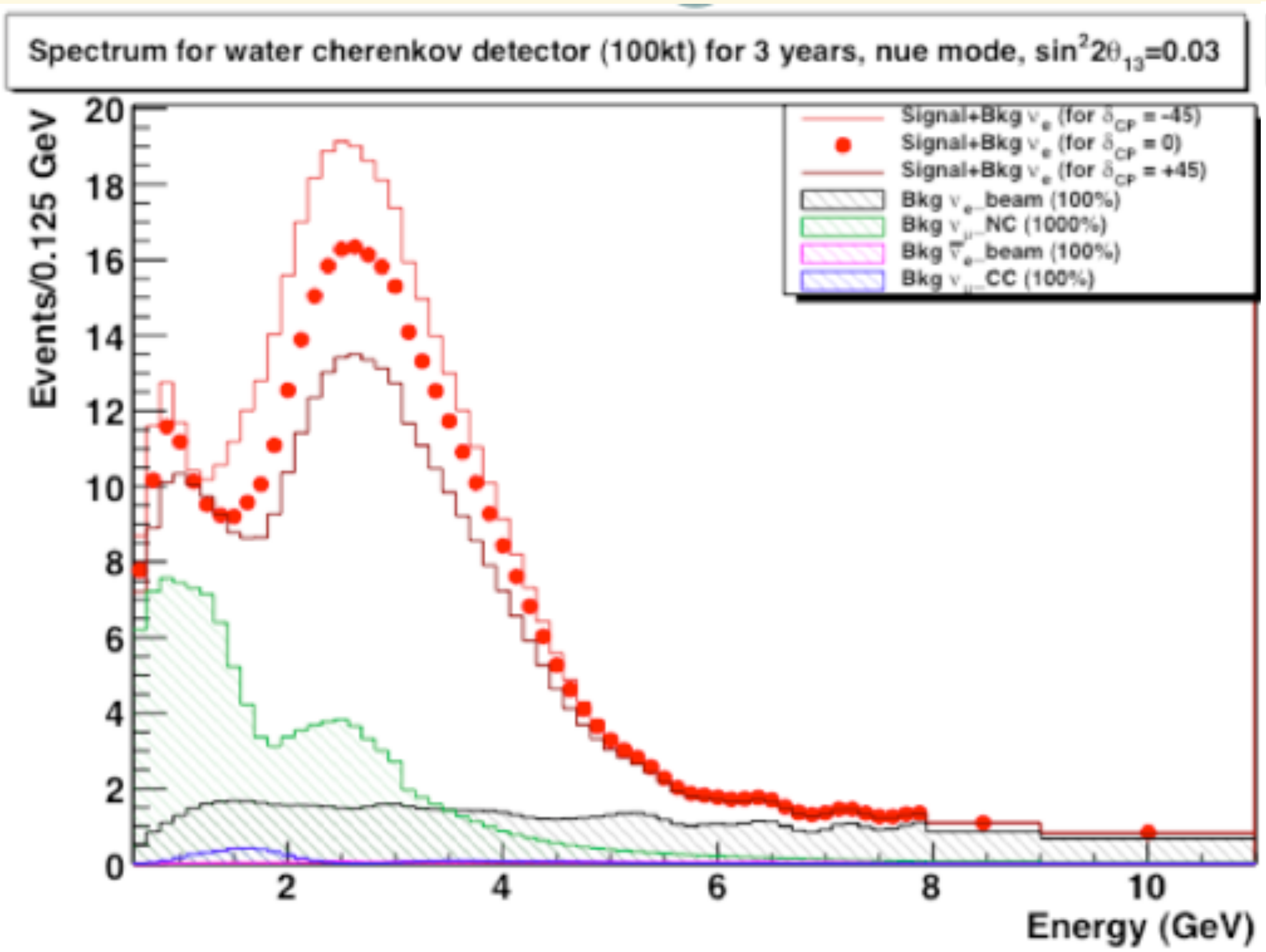

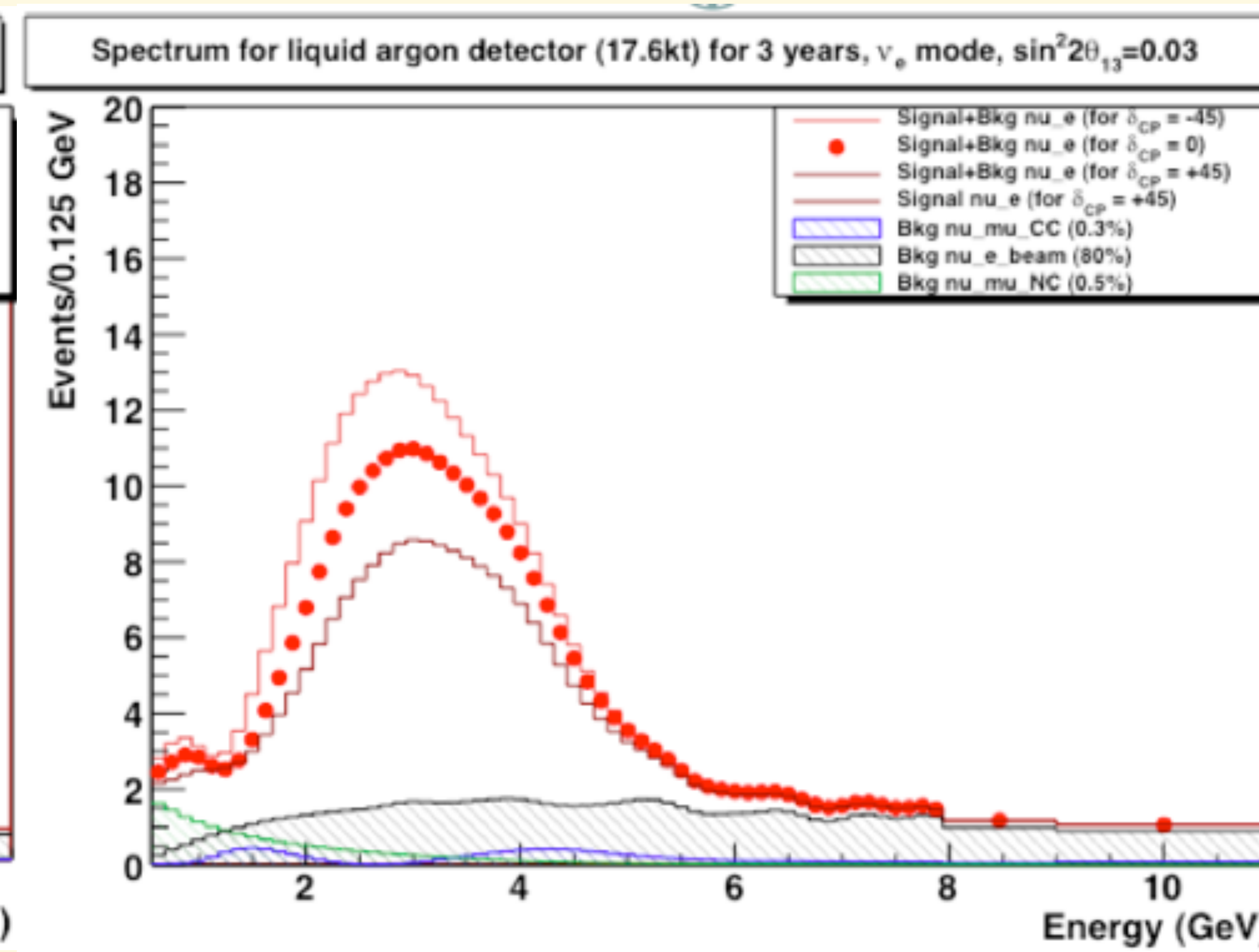

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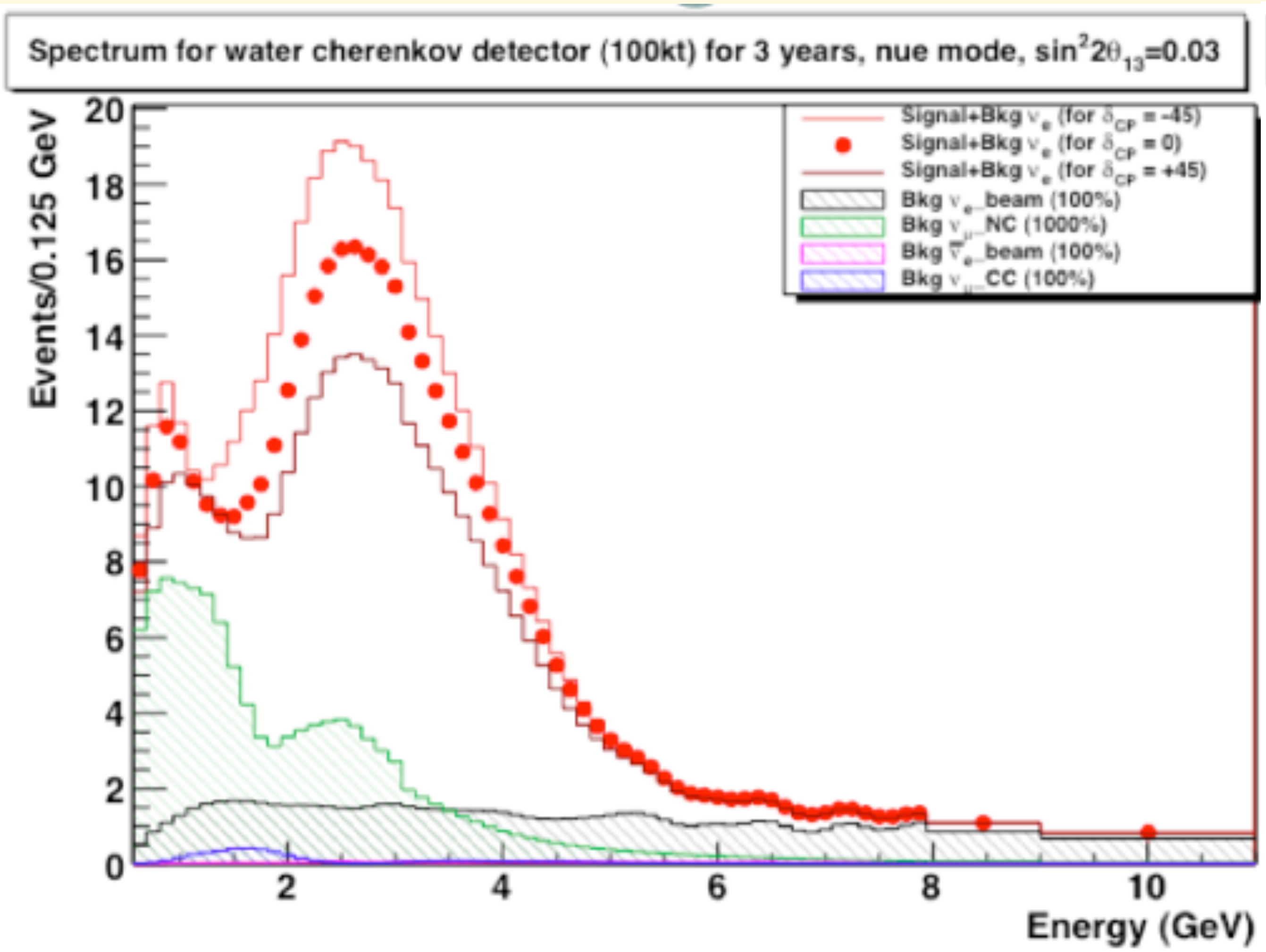

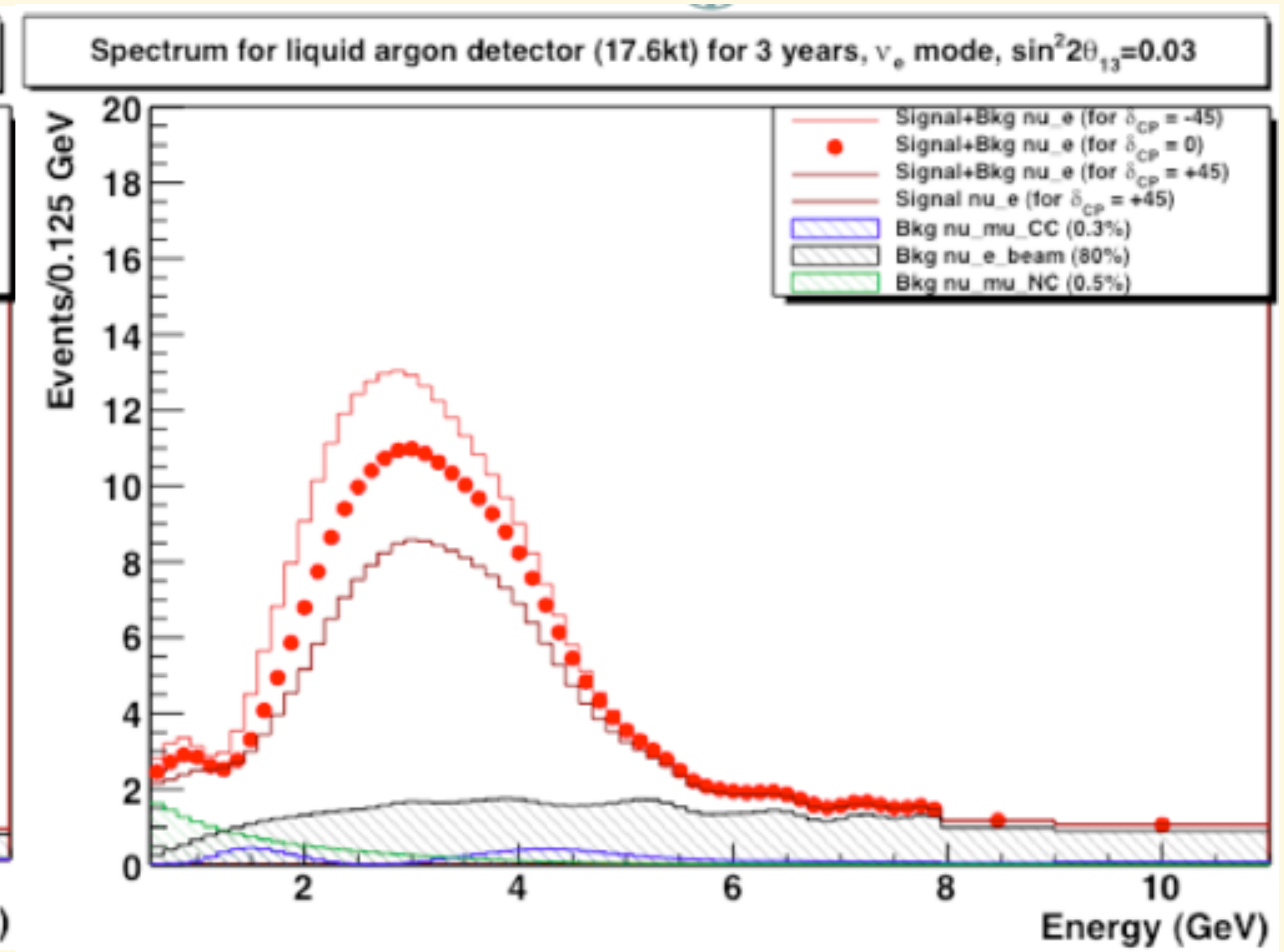

Argon detection efficiency about 5-6 times higher because of much better background rejection

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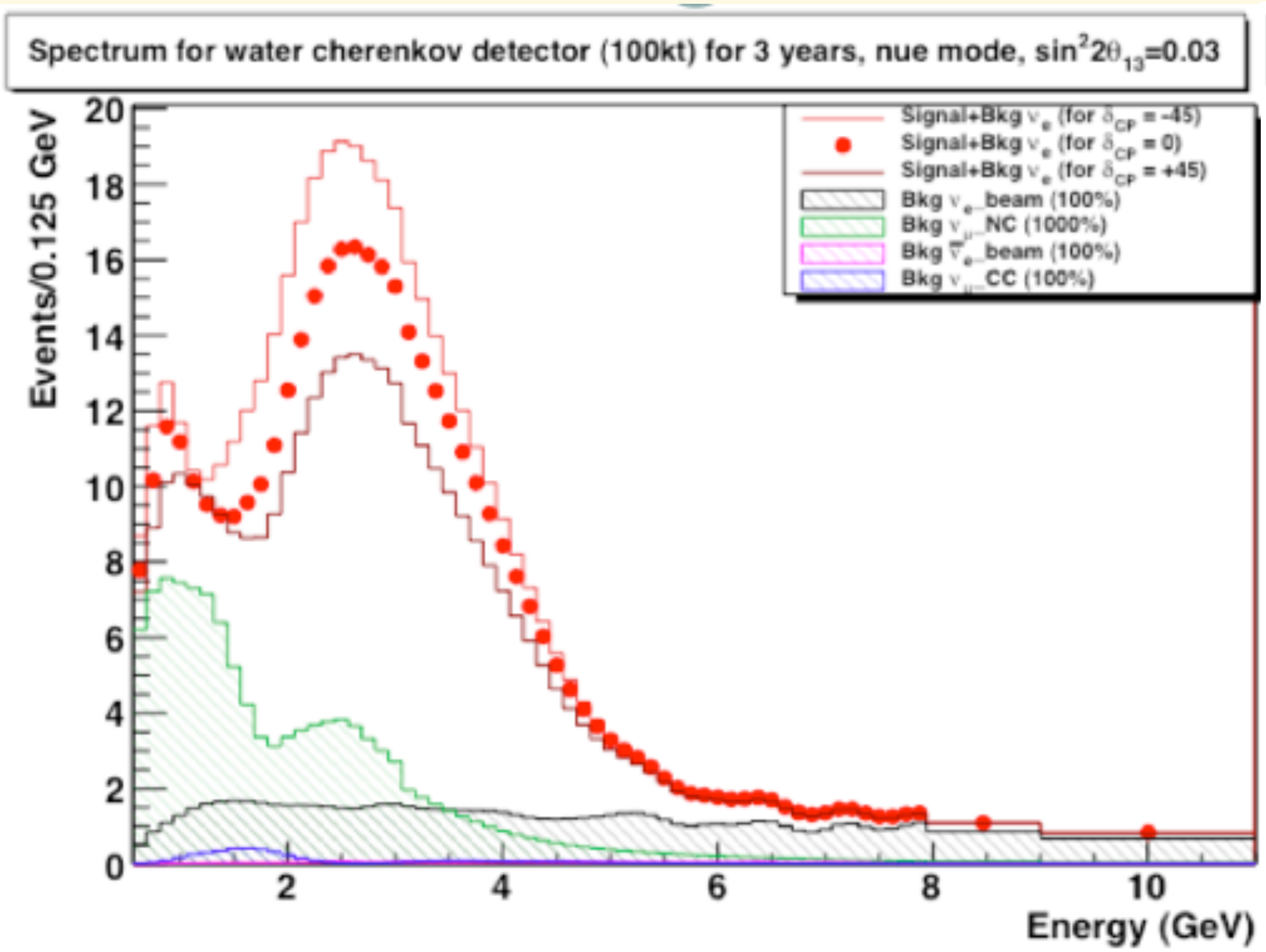

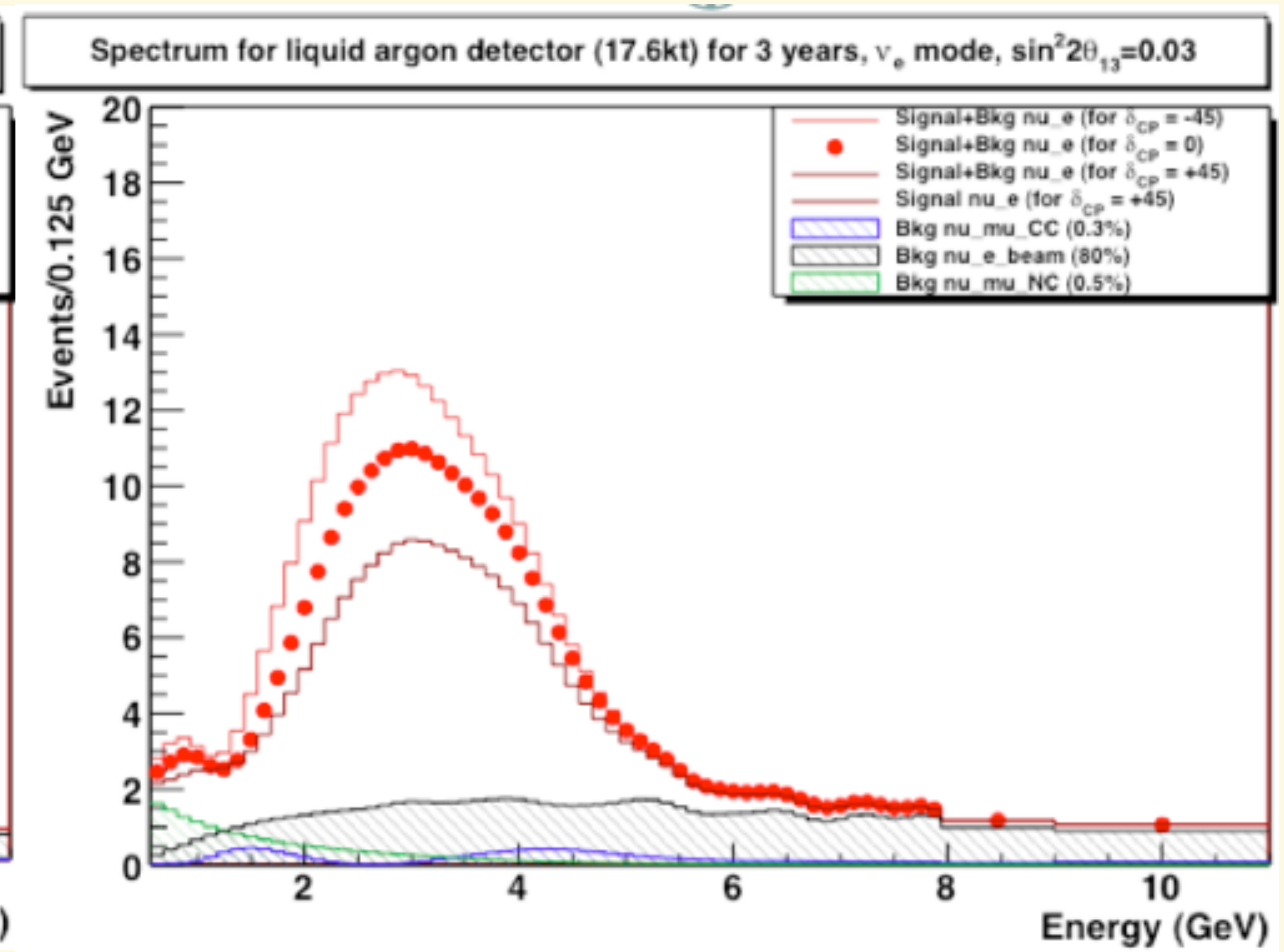

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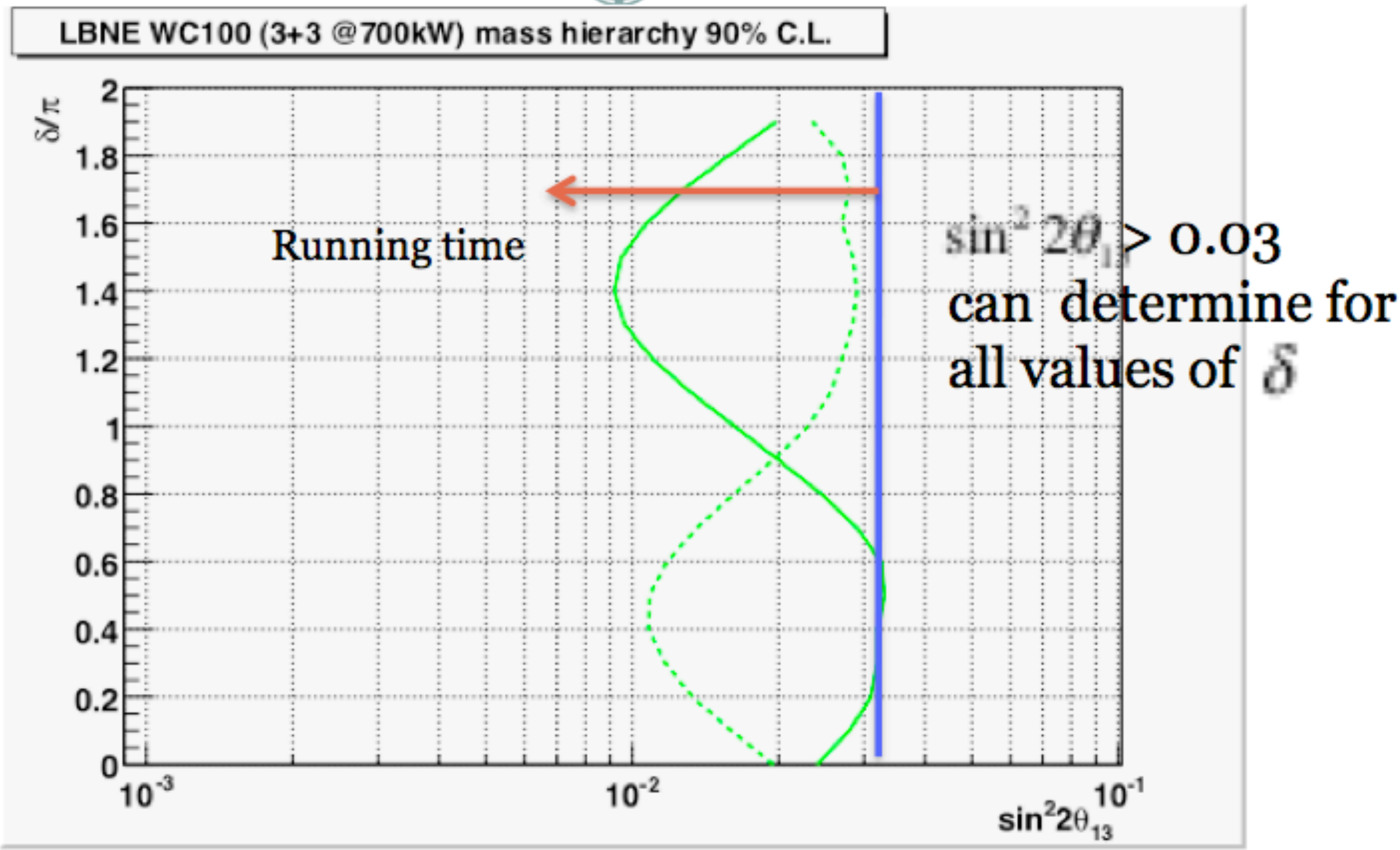
A variety of issues need to be considered before an informed decision can be made

Mass Hierarchy Sensitivity



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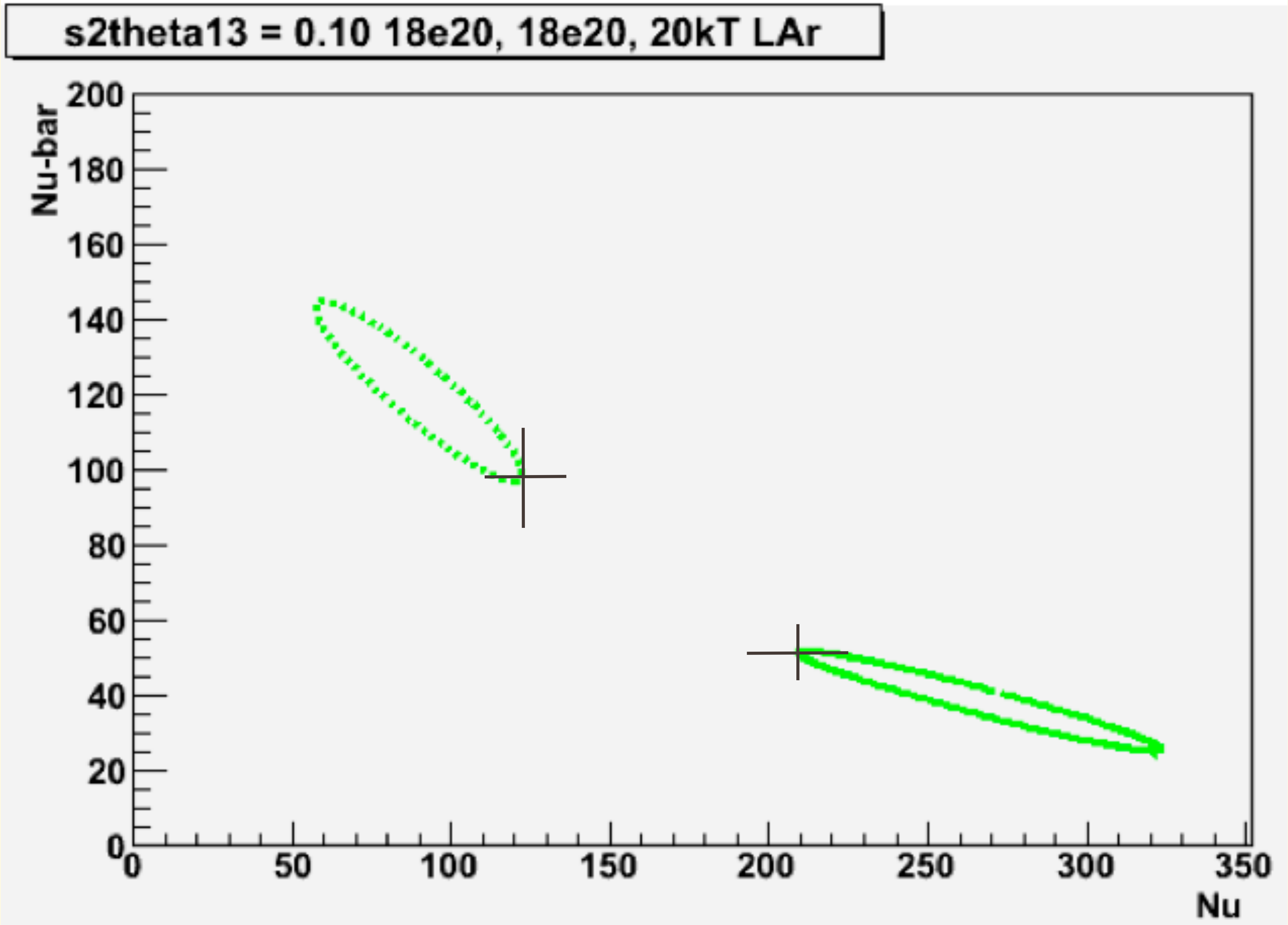

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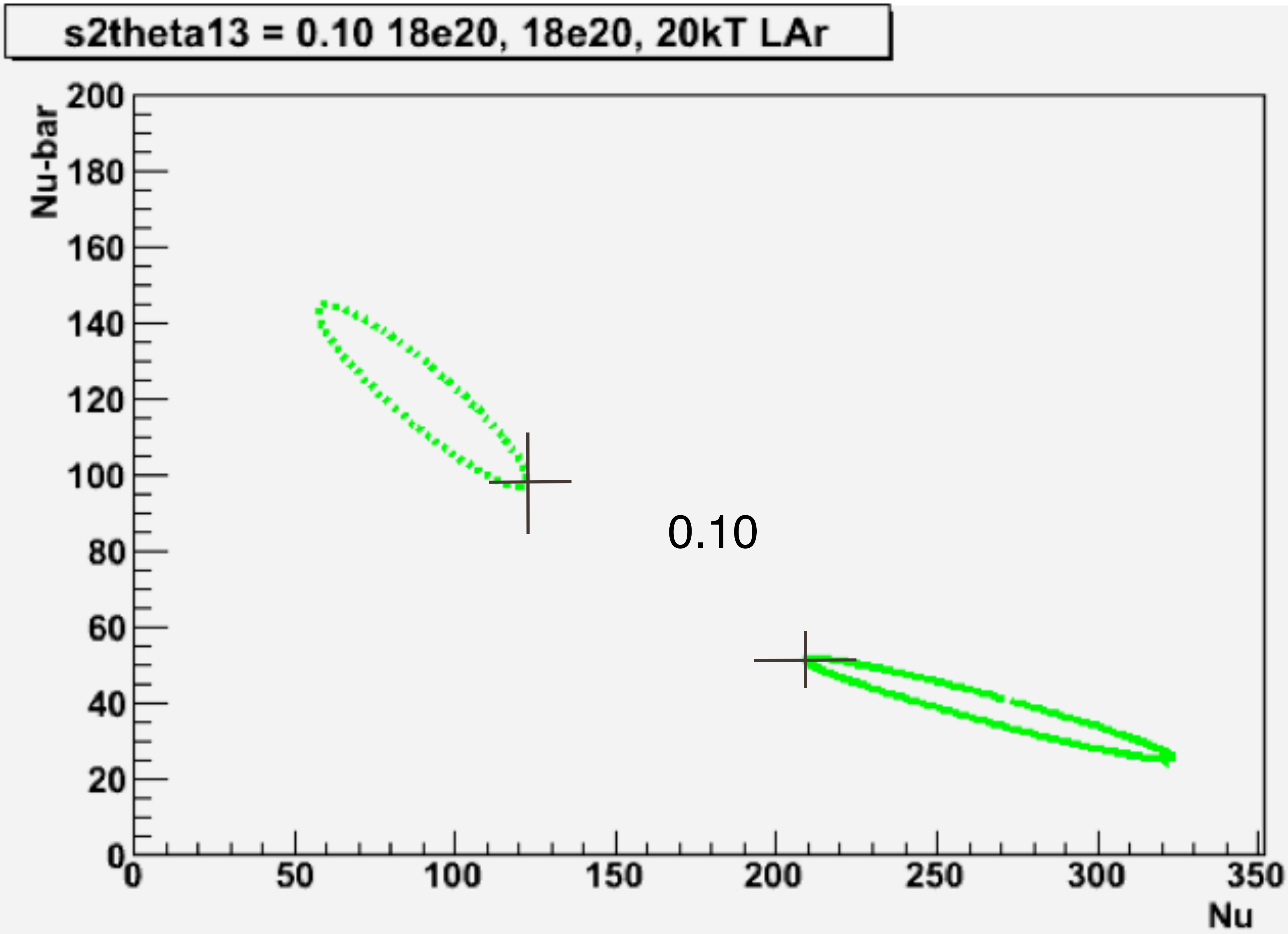

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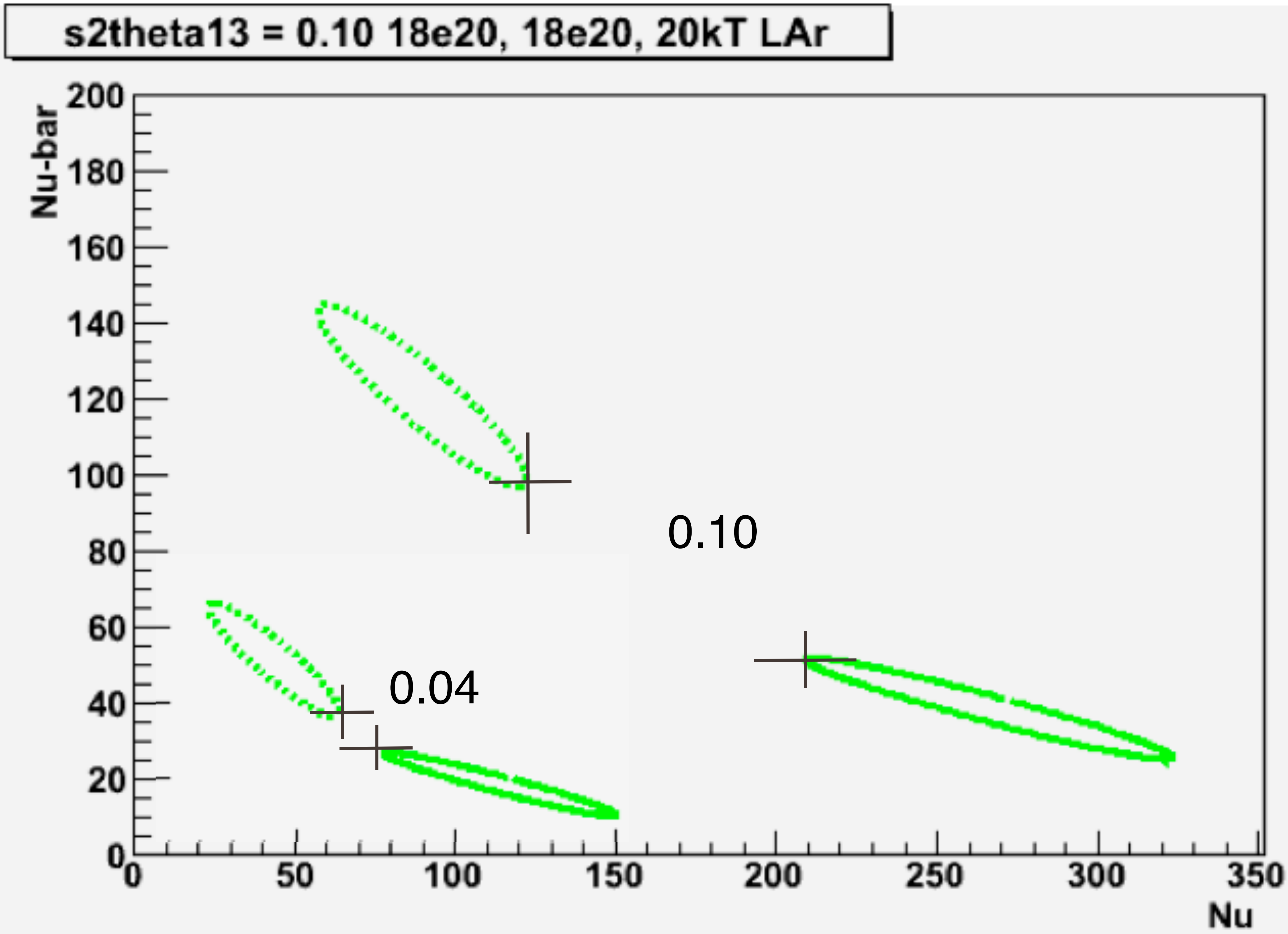

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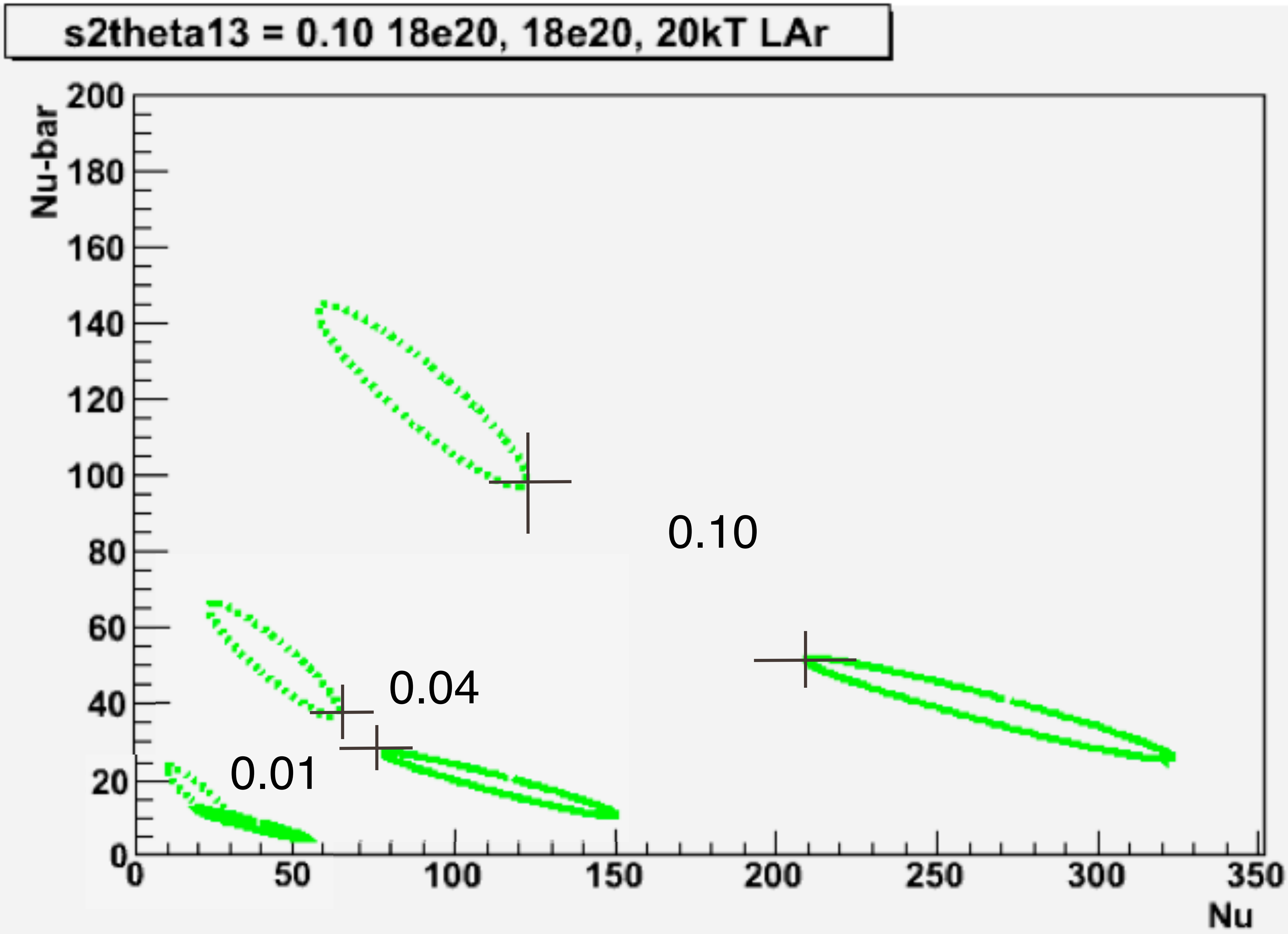

Plans Elsewhere

- Japanese plans are focused currently on a new detector in current JPARC beam line
- Most likely .5-1.0 Mt Water Cerenkov
- European plans are uncertain at this time
- A number of sites have been proposed for a potential underground laboratory

Neutrino Cross Sections

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  - Determination of structure functions
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  - Understanding of backgrounds
  - Determination of neutrino flux

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

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

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None of these is easy; they all present some difficulties

Two Examples

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Examples of possible normalization problems

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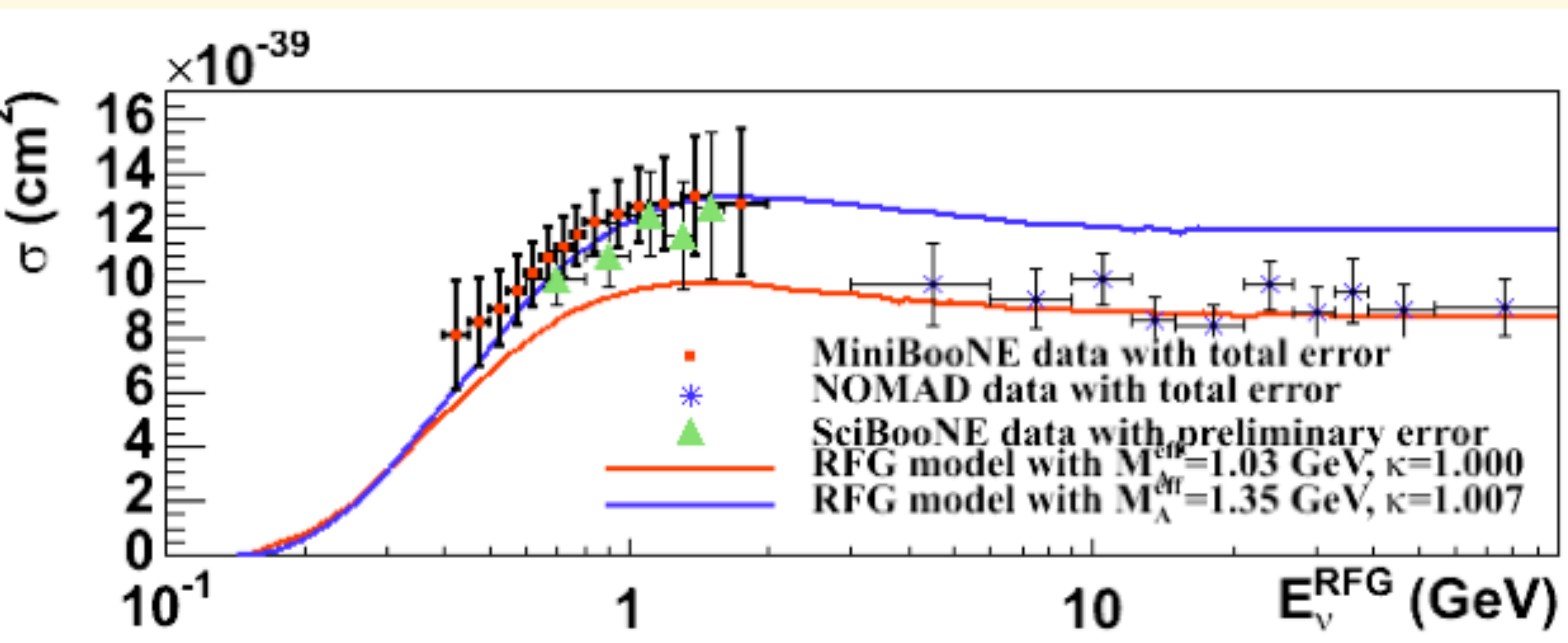

Two Examples

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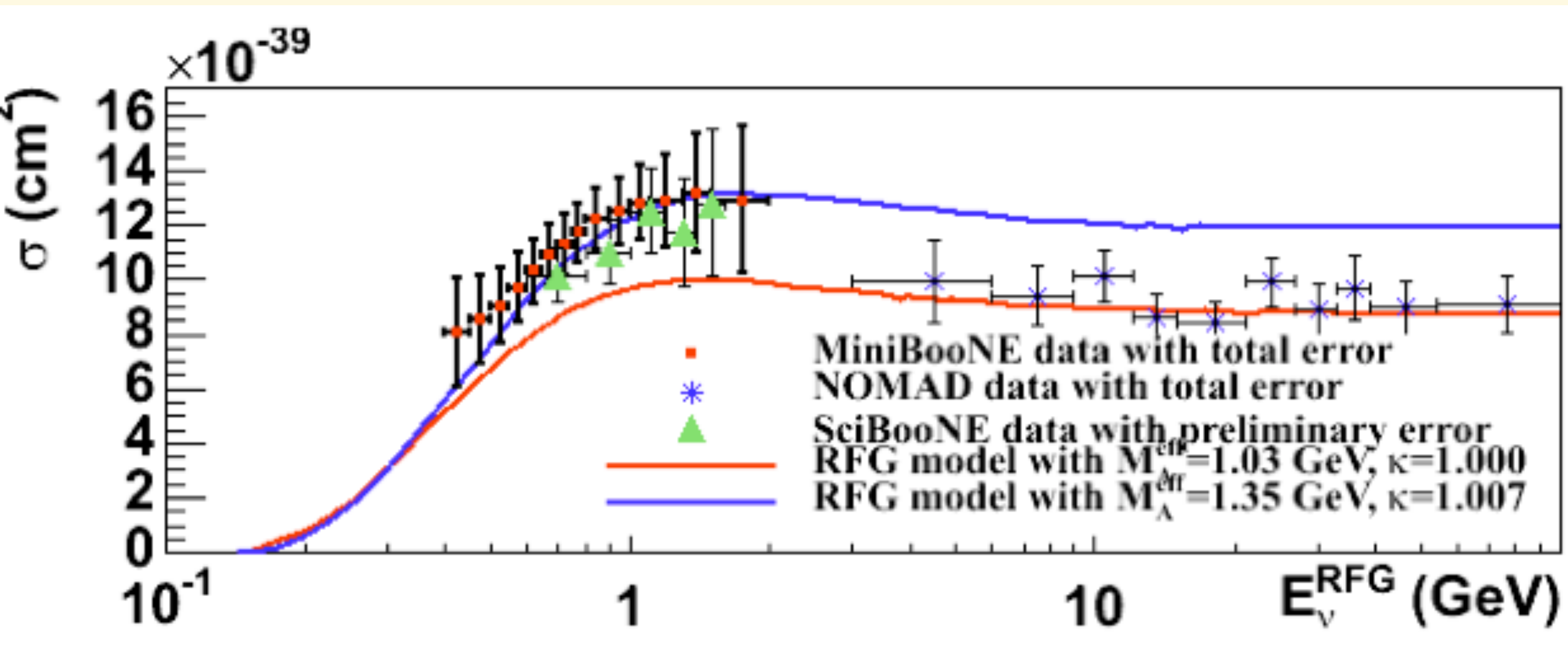

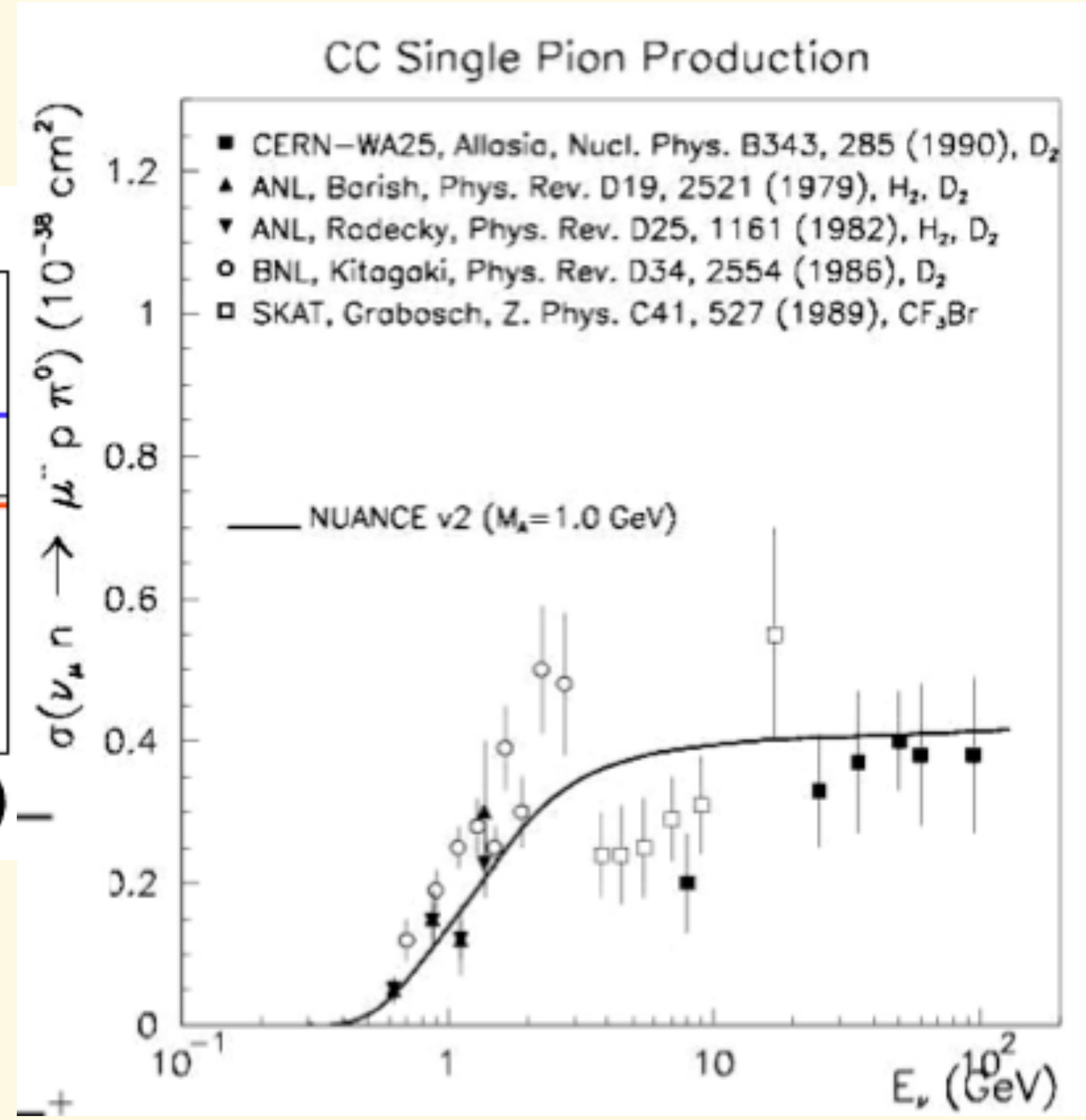

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  - Measurement of differential distributions of π^0's. Important for understanding backgrounds in ν_e appearance experiments
  - Resonance production. If one uses kinematics to deduce neutrino energy, misclassifying resonant event as QE leads to a wrong energy assignment

MiniBooNE Results

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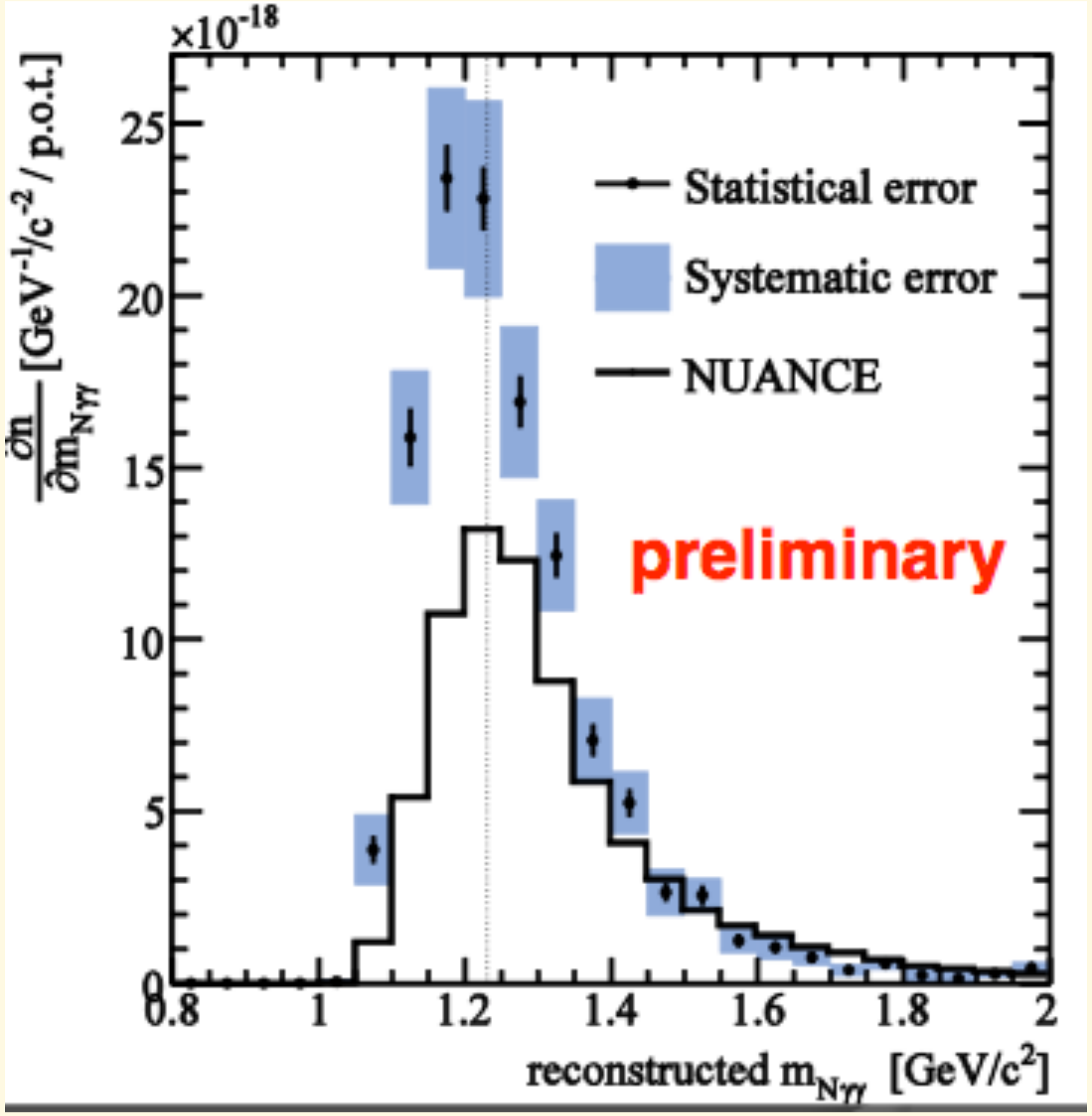

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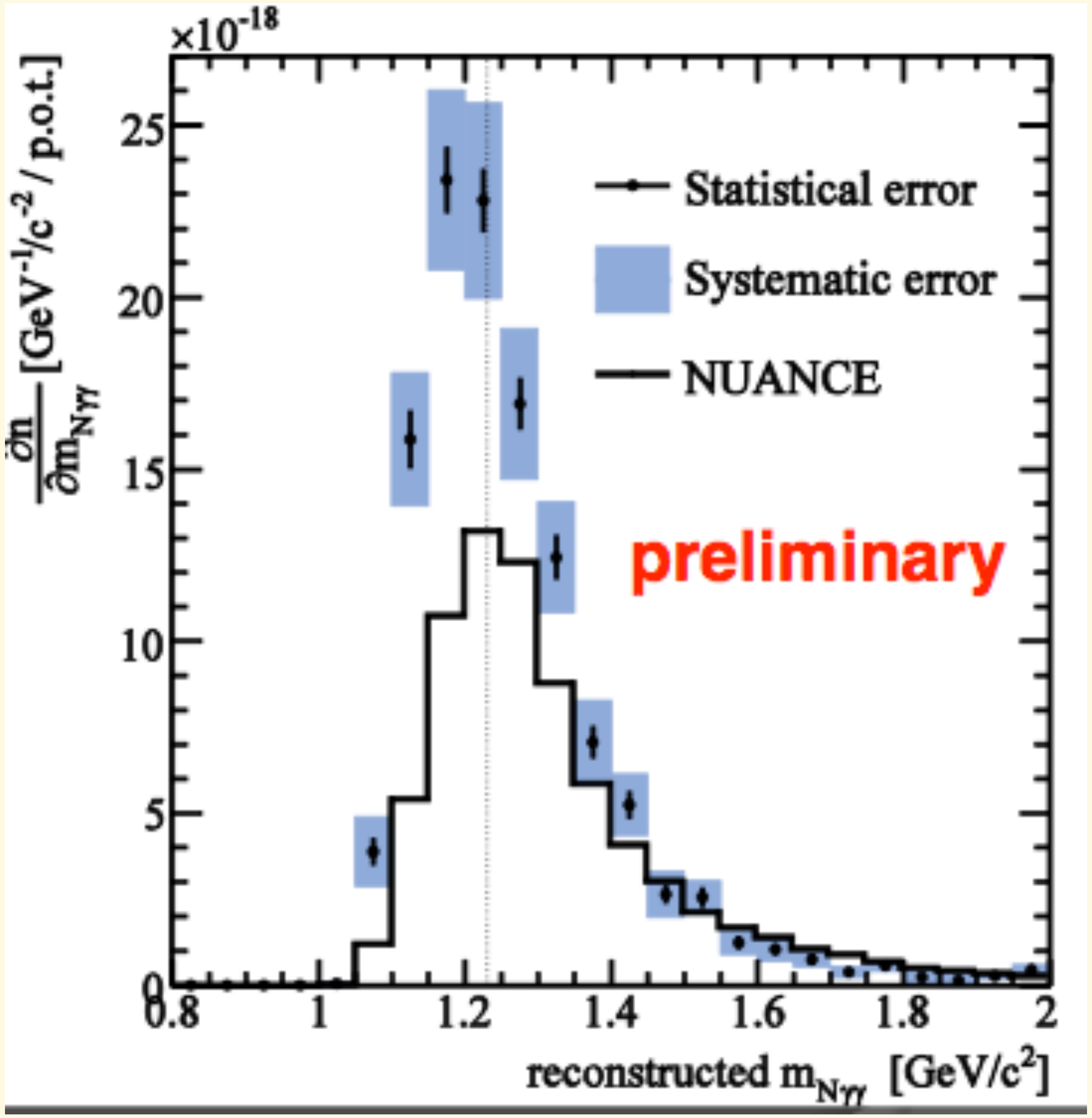

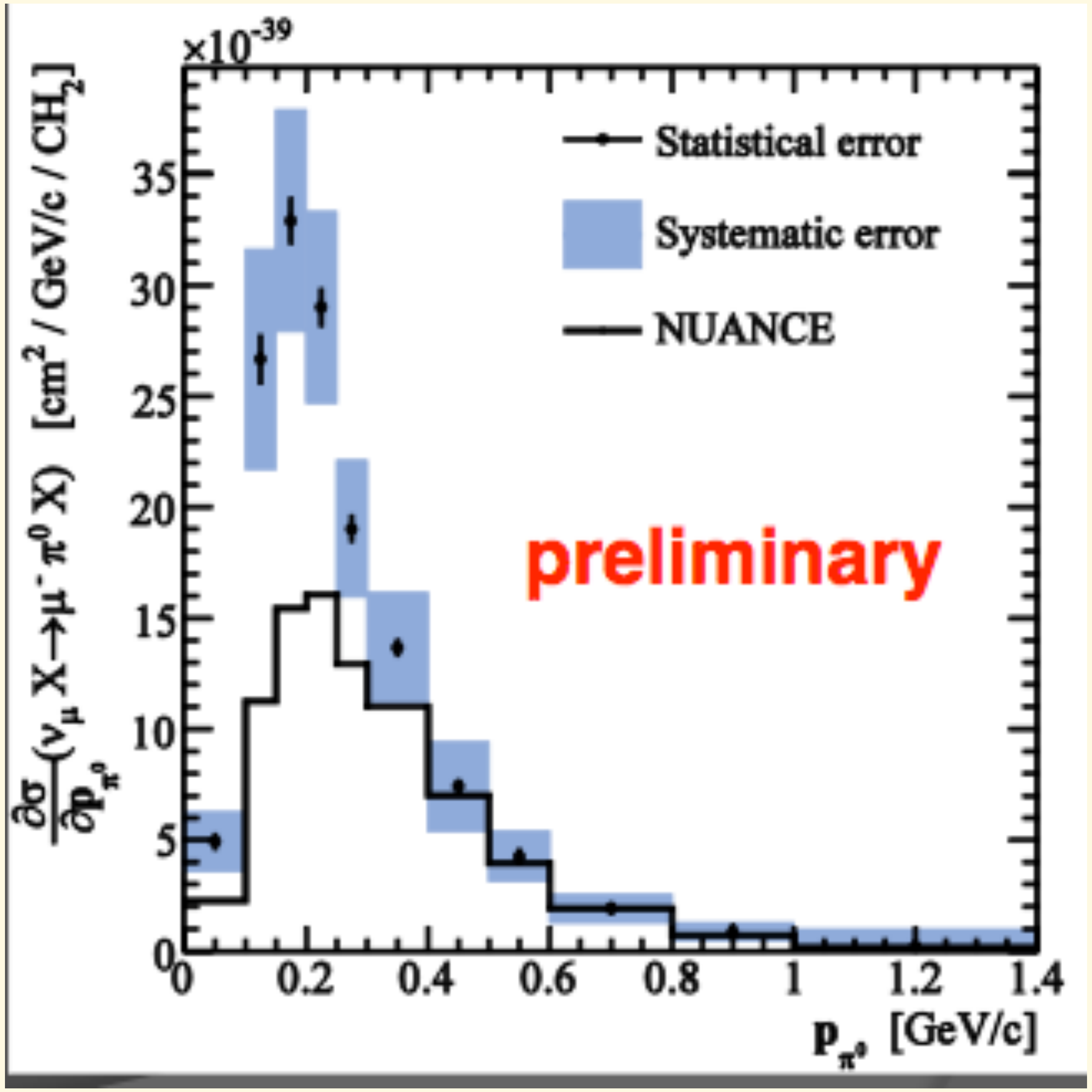

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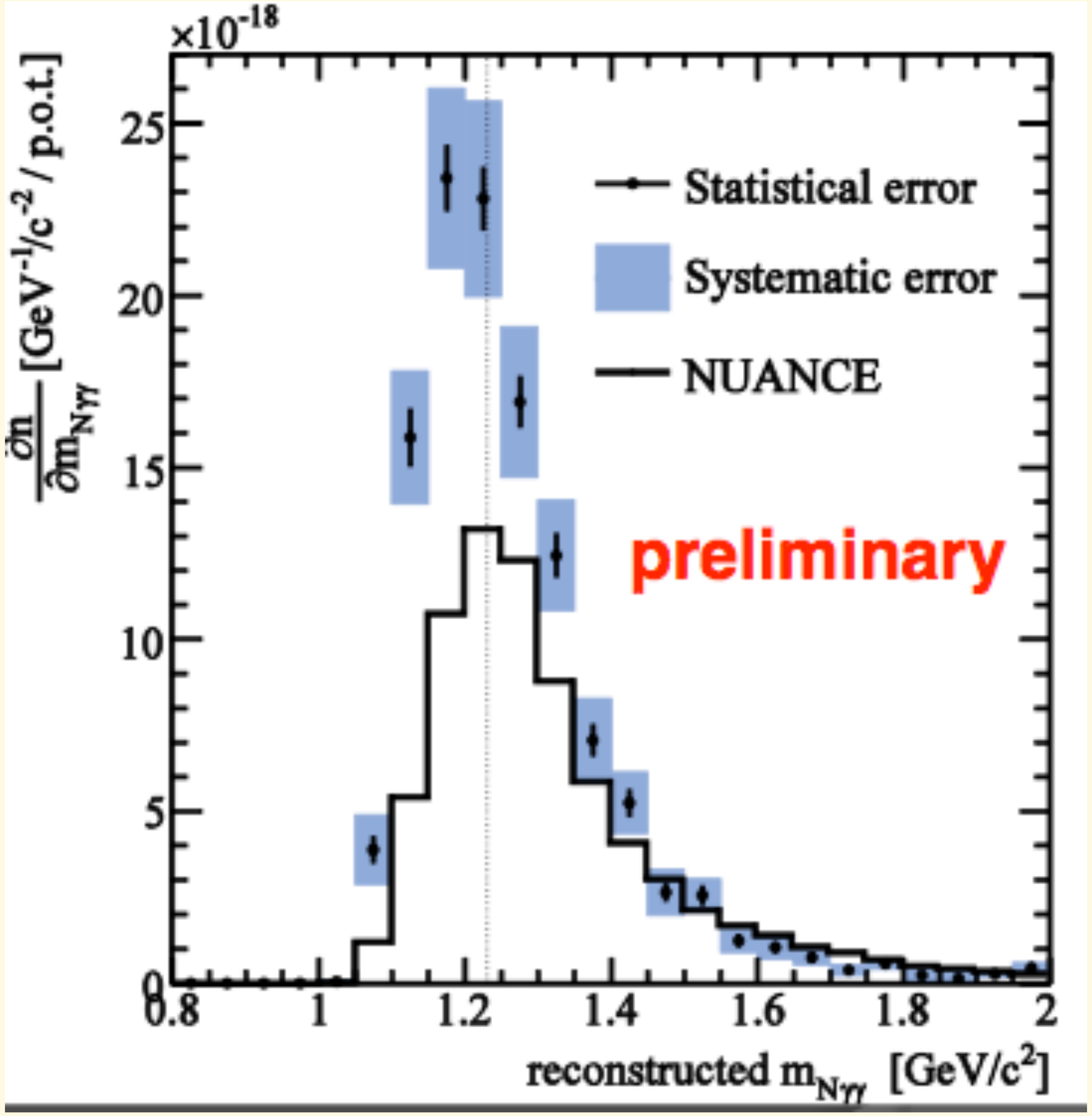

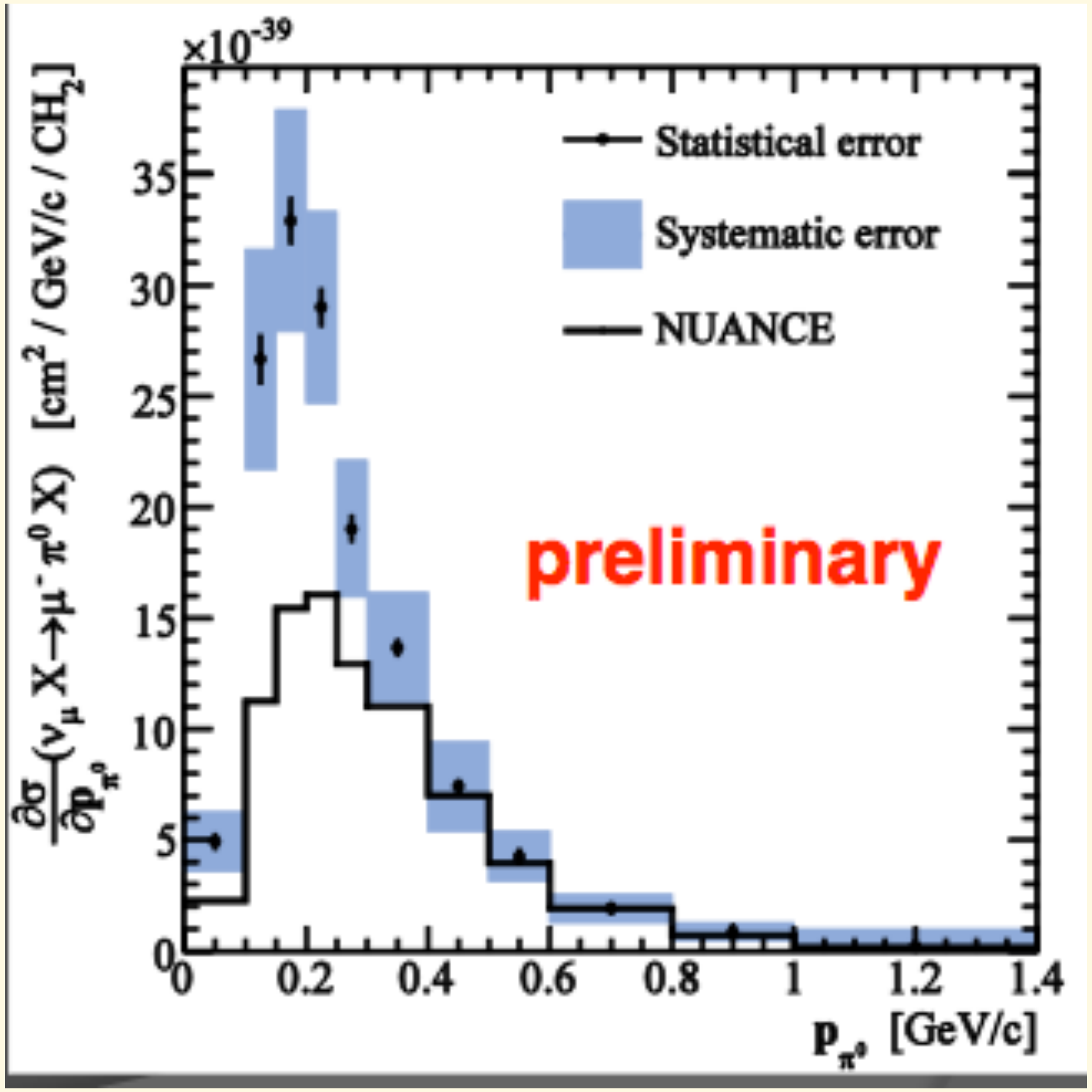

Significant differences between the measurements and the original MC simulation

MINERvA Experiment

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

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- The plan is to use different materials as targets to understand A dependence

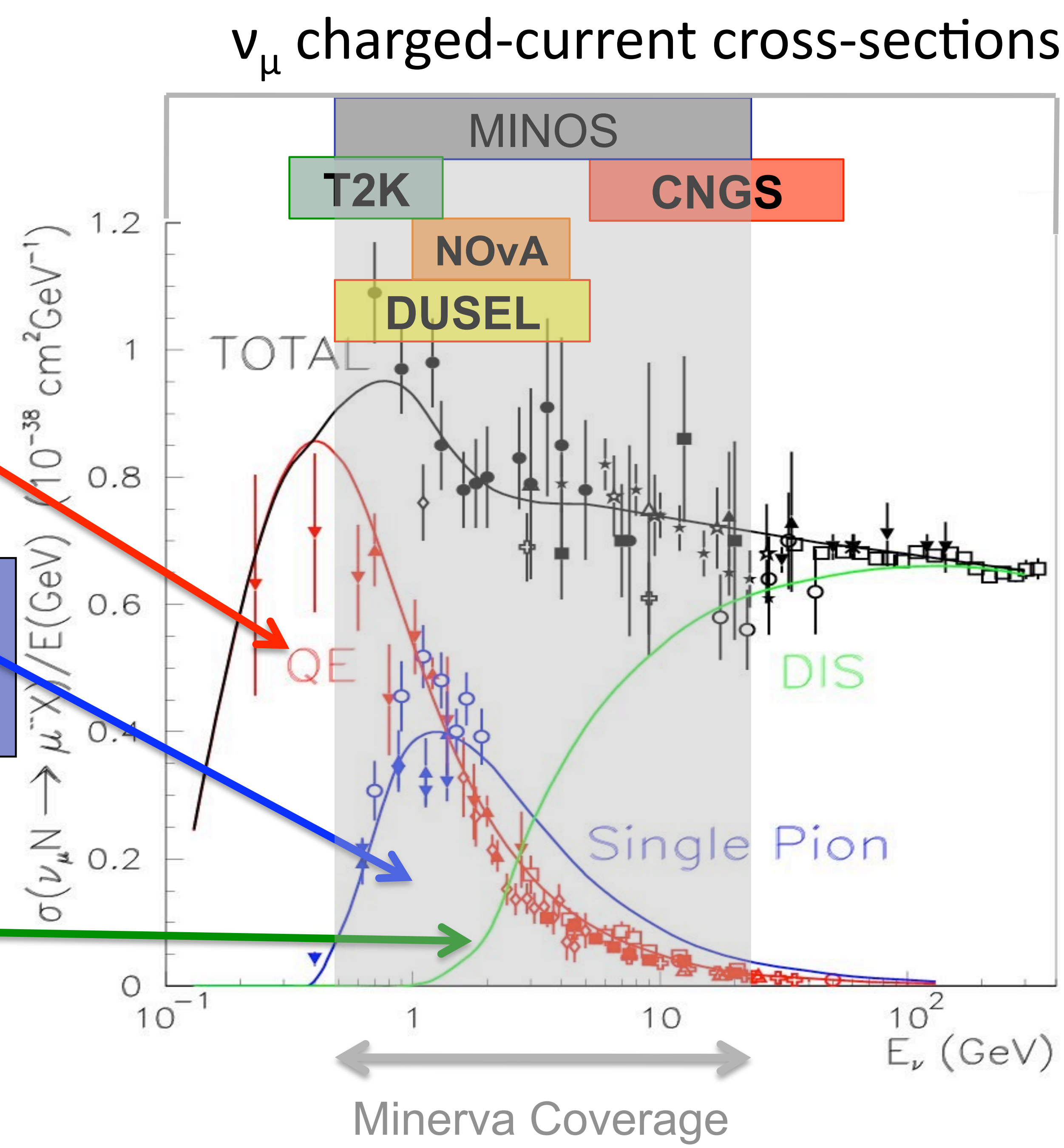
MINERvA Energy Region

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

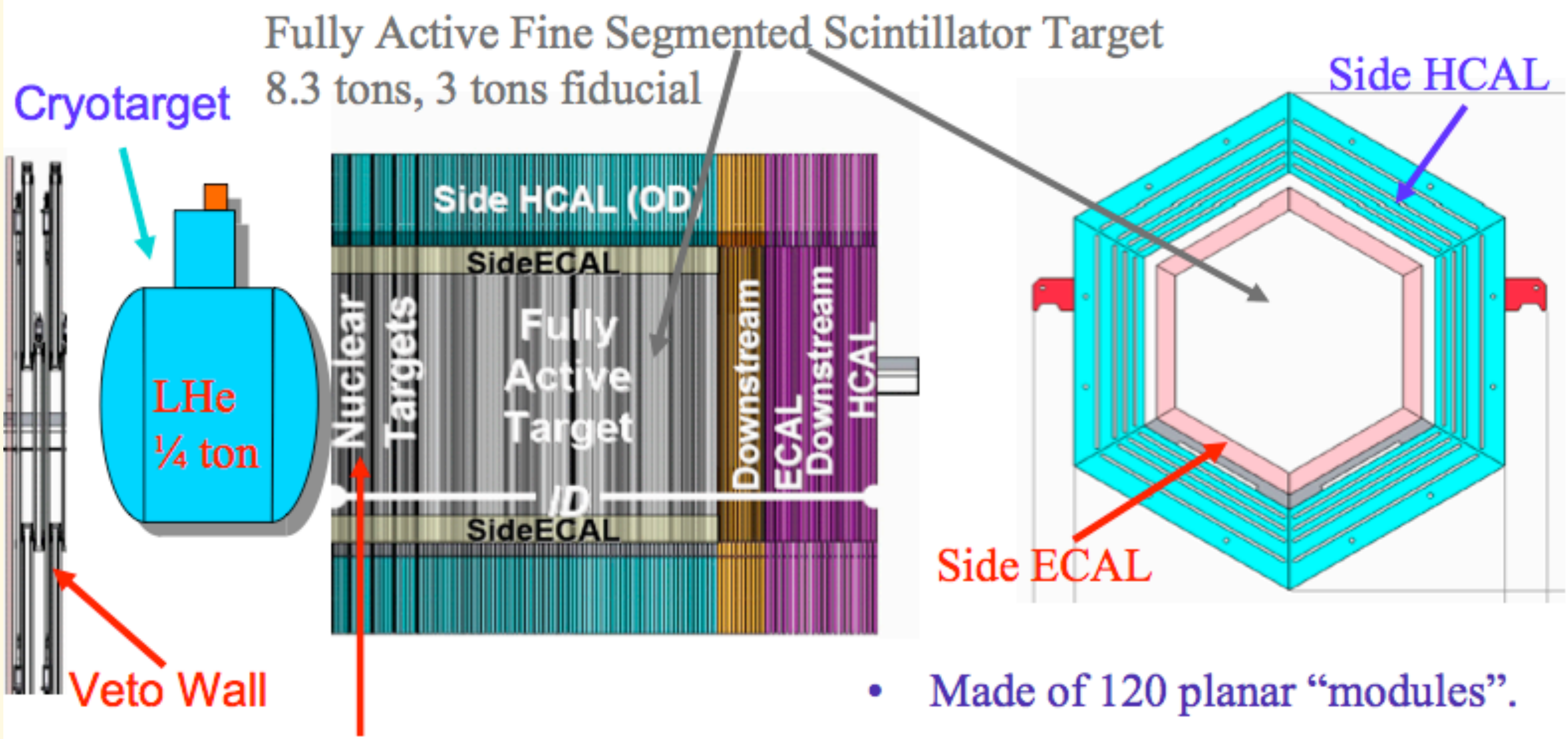


Jeff Hartnell, NOW 2010

Dave Schmitz, MSU Seminar 38

MINERvA Detector

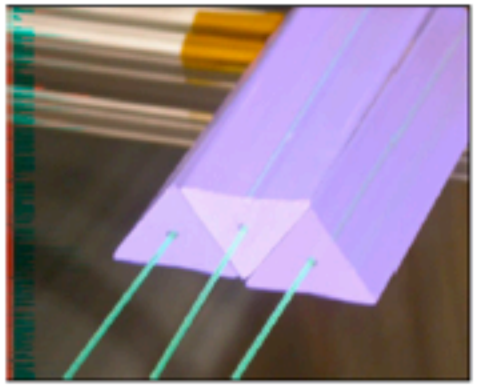
MINERvA Detector



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

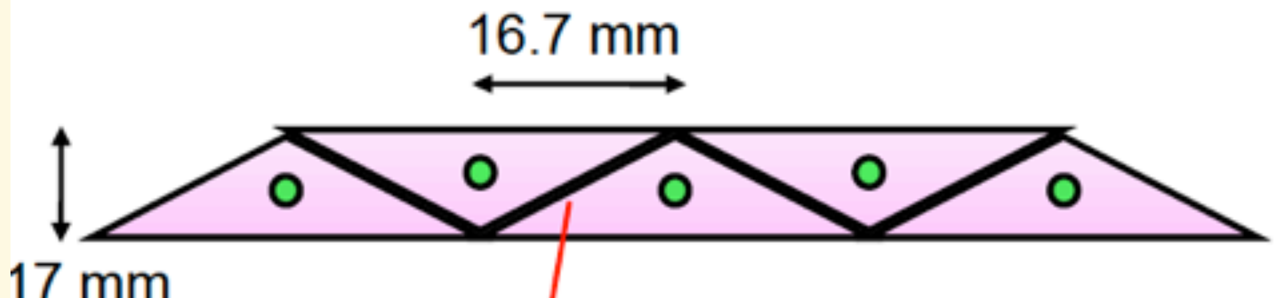
- Made of 120 planar “modules”.
  - Total Mass: 200 tons
  - Total channels: ~32K

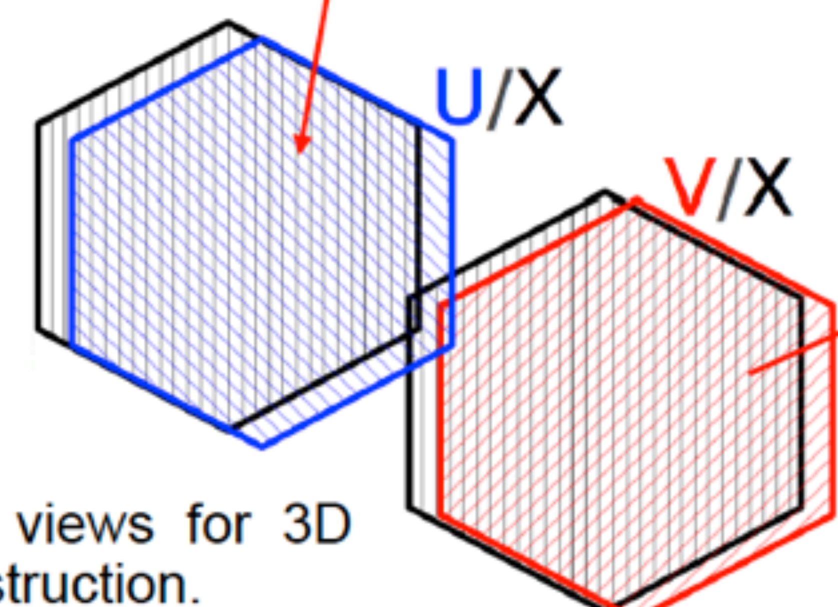
MINERvA Tracking



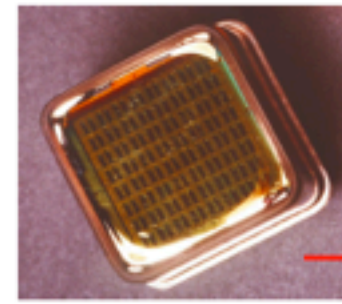
Extruded plastic scintillator + wavelength shifters.

Triangular geometry allows charge sharing for better position resolution.

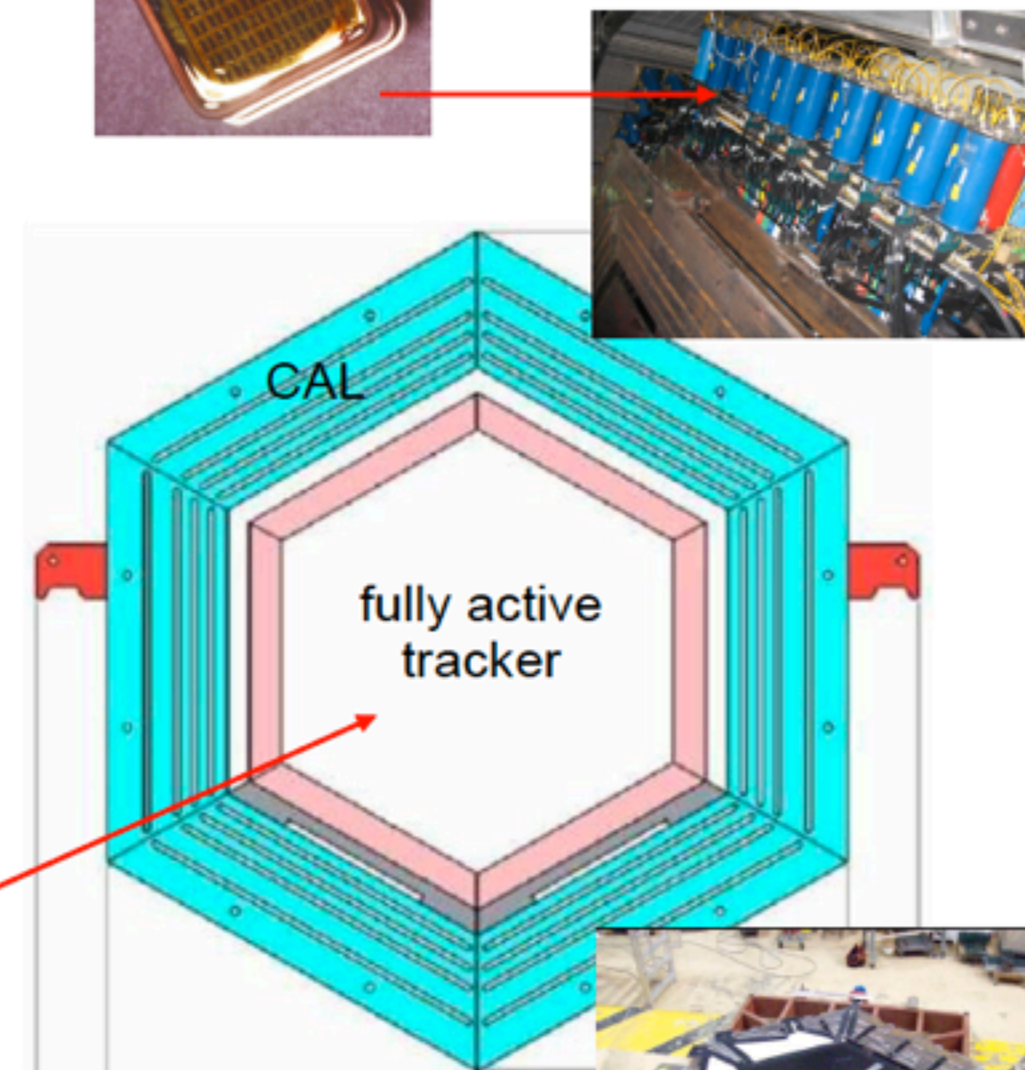




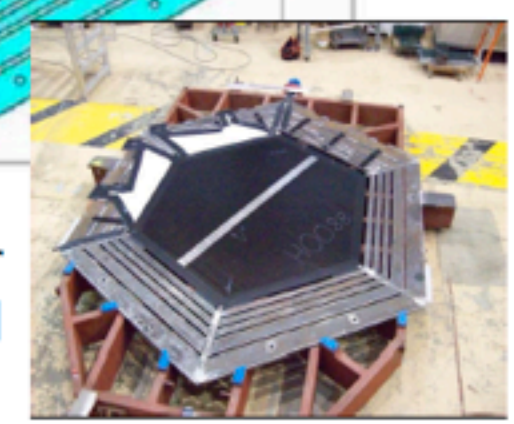
Three views for 3D reconstruction.



64 anode PMT's



Iron outer detector instrumented for EM calorimetry.



Examples of Events

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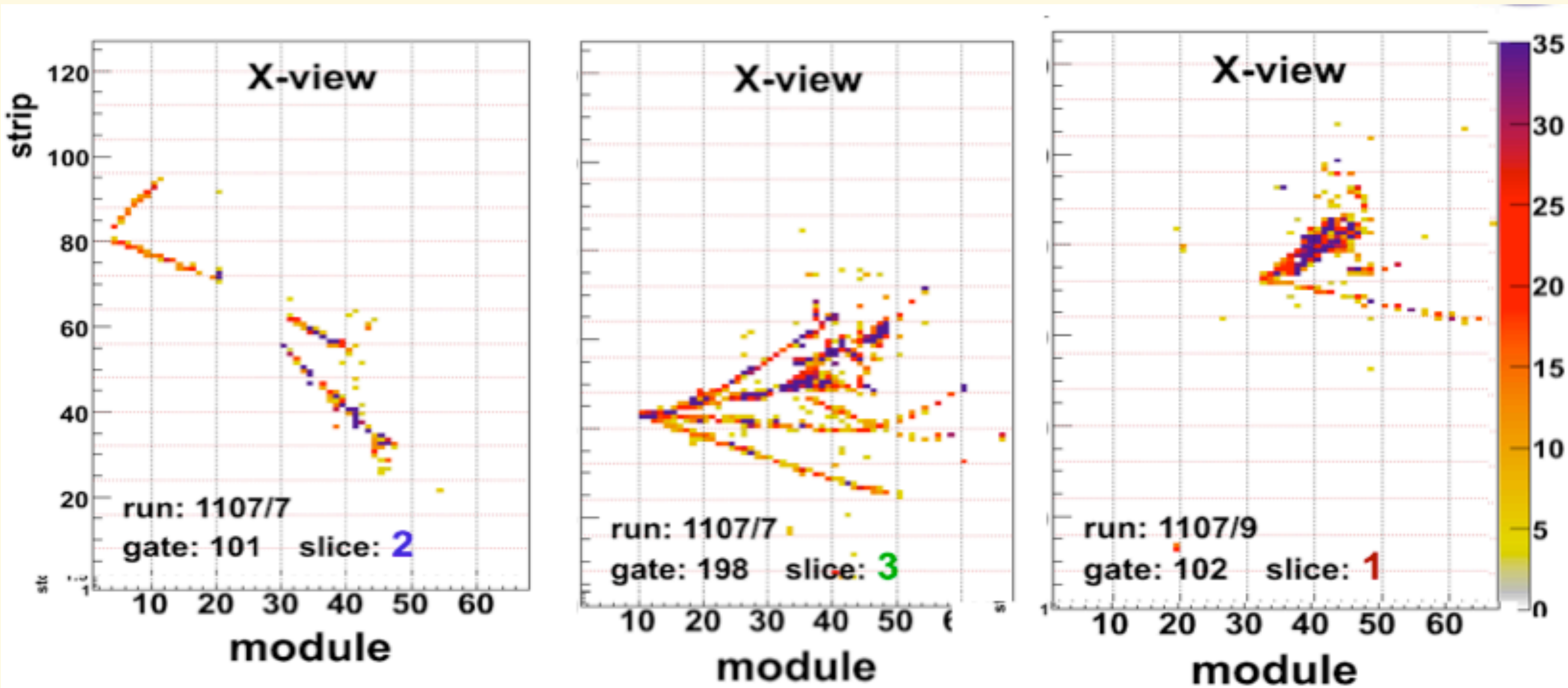
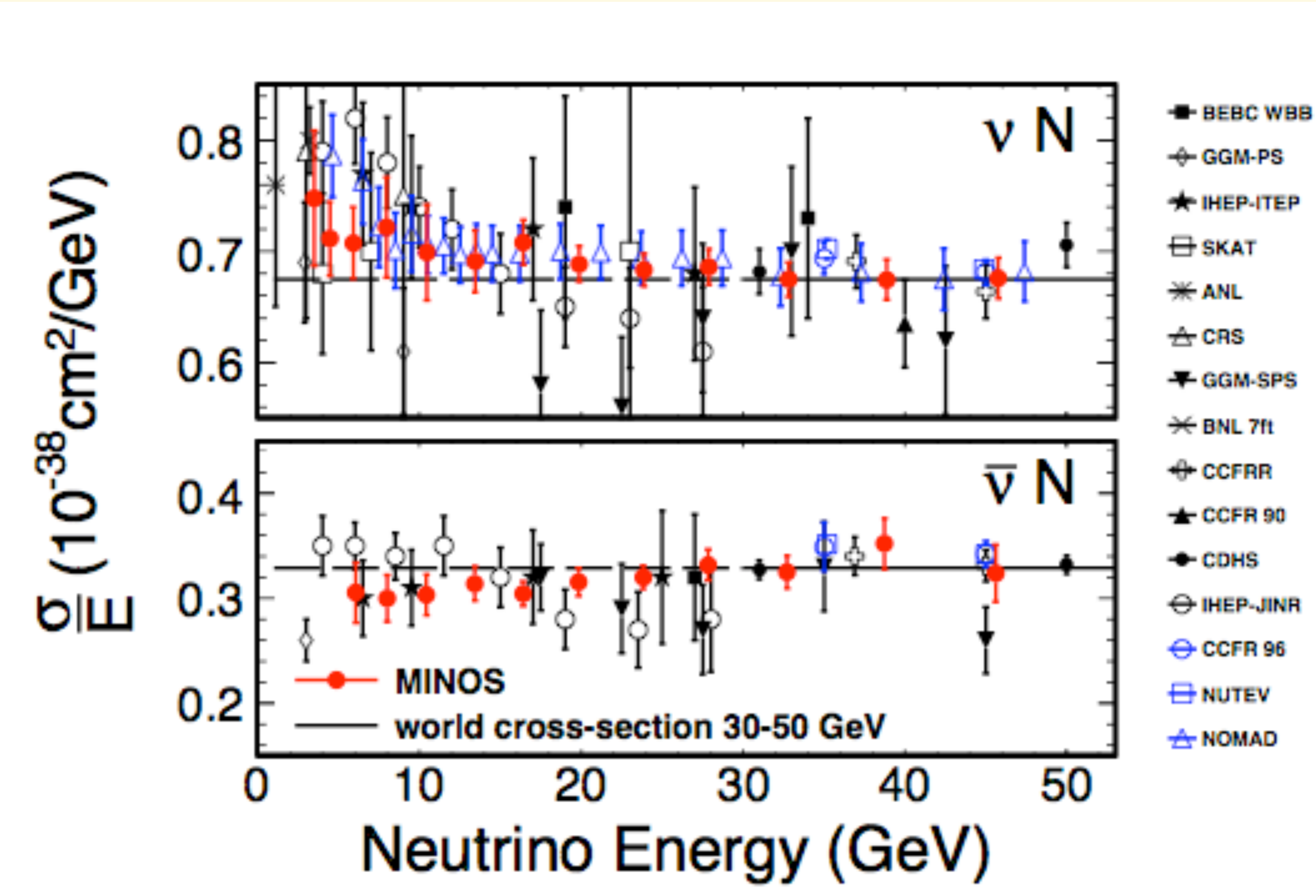


3 different events; same view

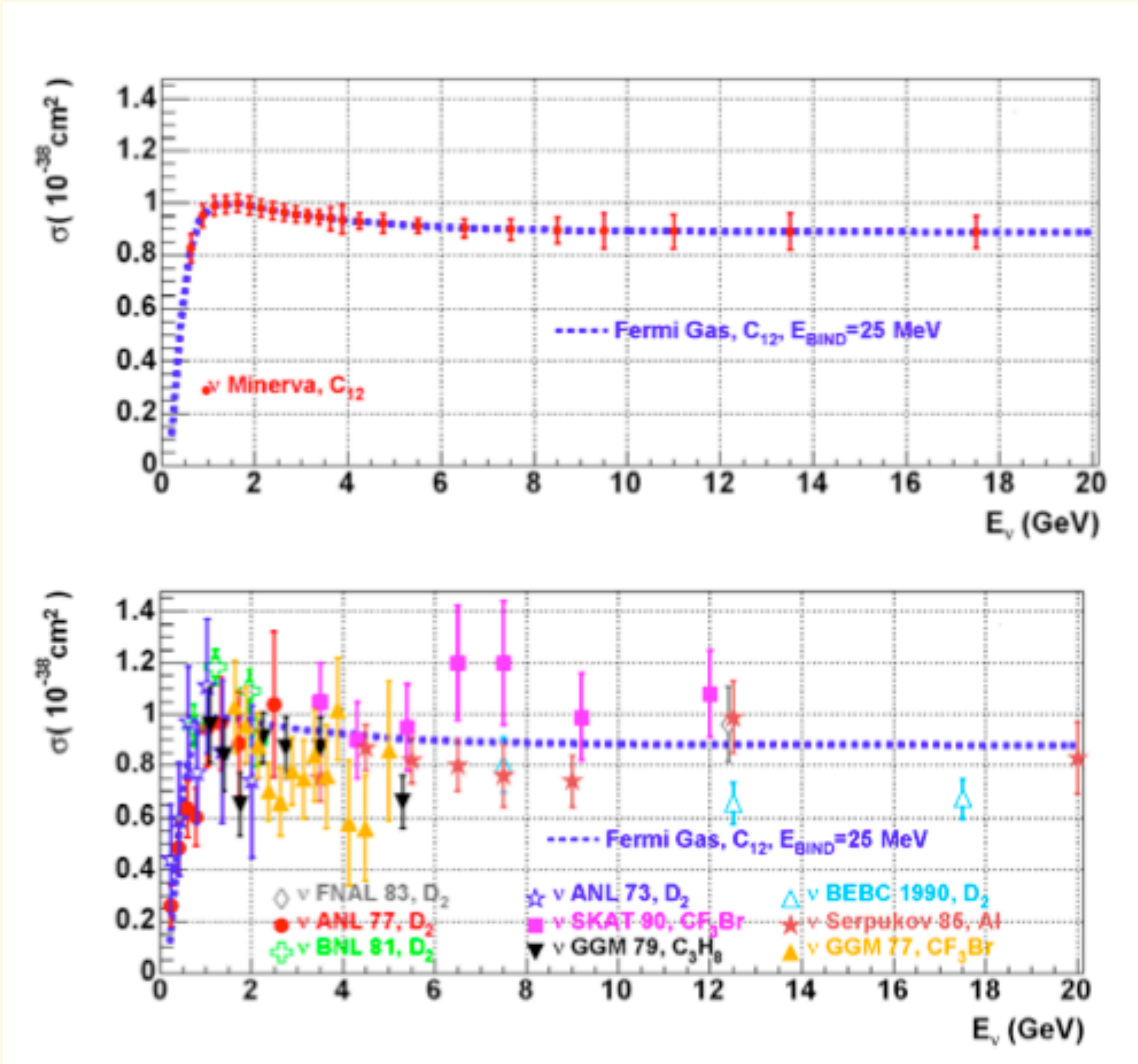
Total x-sections - today

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


σ(10^-38 cm^2)
E_ν (GeV)
Fermi Gas, C_12, E_BIND=25 MeV
ν Minerva, C_12
ν FNAL 83, D_2
ν ANL 77, D_2
ν BNL 81, D_2
ν ANL 73, D_2
ν SKAT 90, CF_3Br
ν GGM 79, C_3H_8
ν BEBC 1990, D_2
ν Serpukov 85, Al
ν GGM 77, CF_3Br

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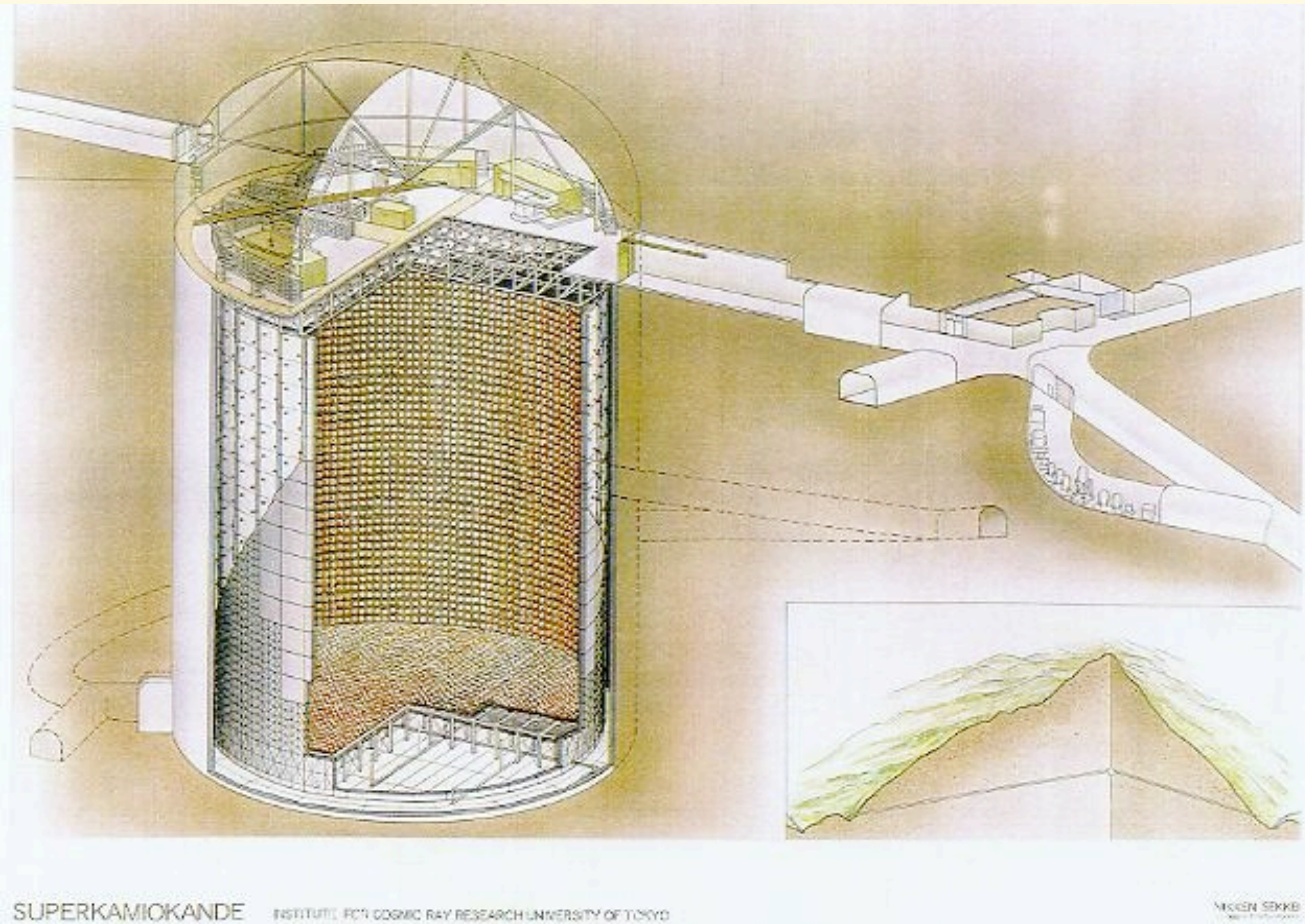
- They will continue to play that role in the future
- Due to technical innovations, their capabilities continue to increase

Backup Slides

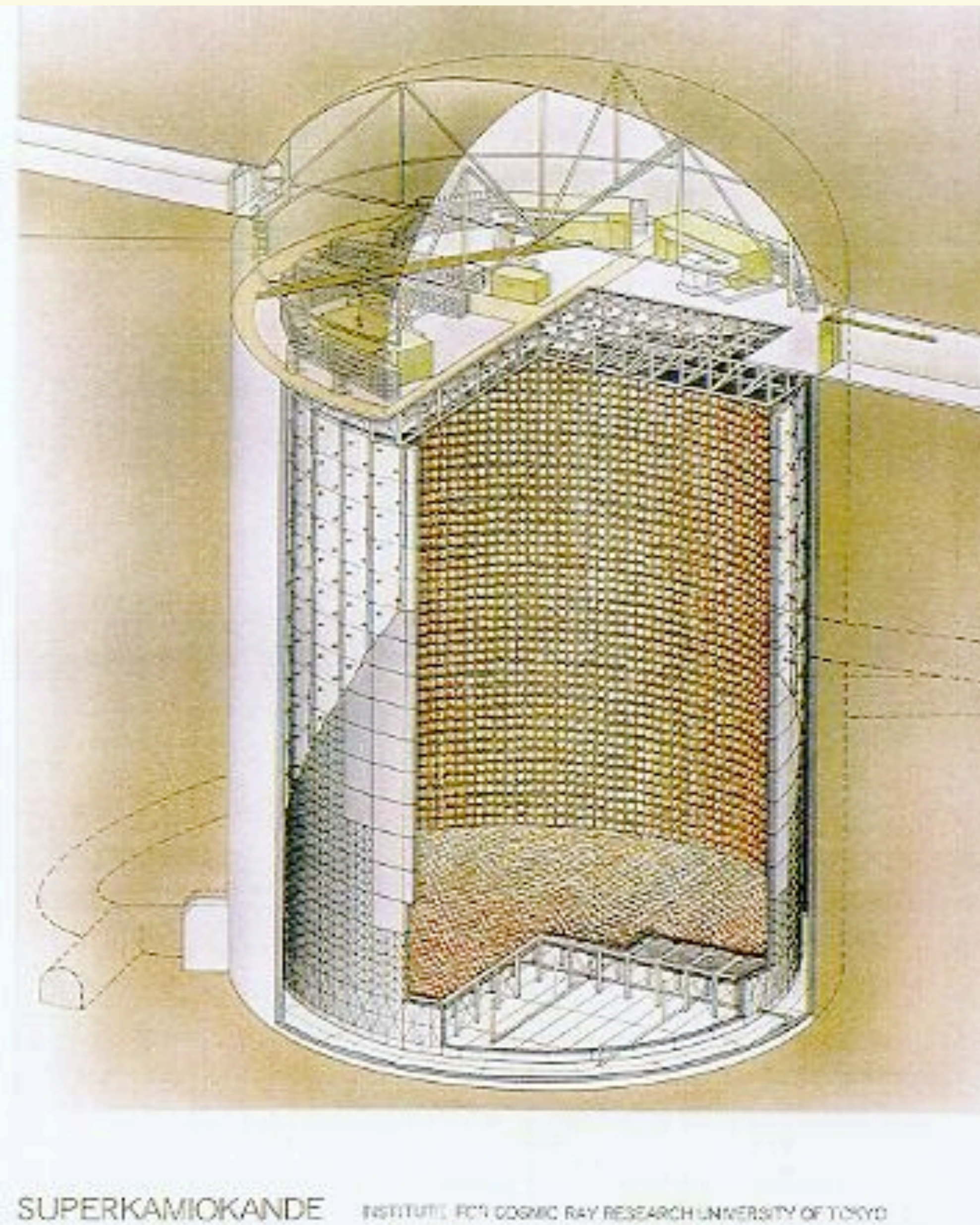
SuperKamiokande

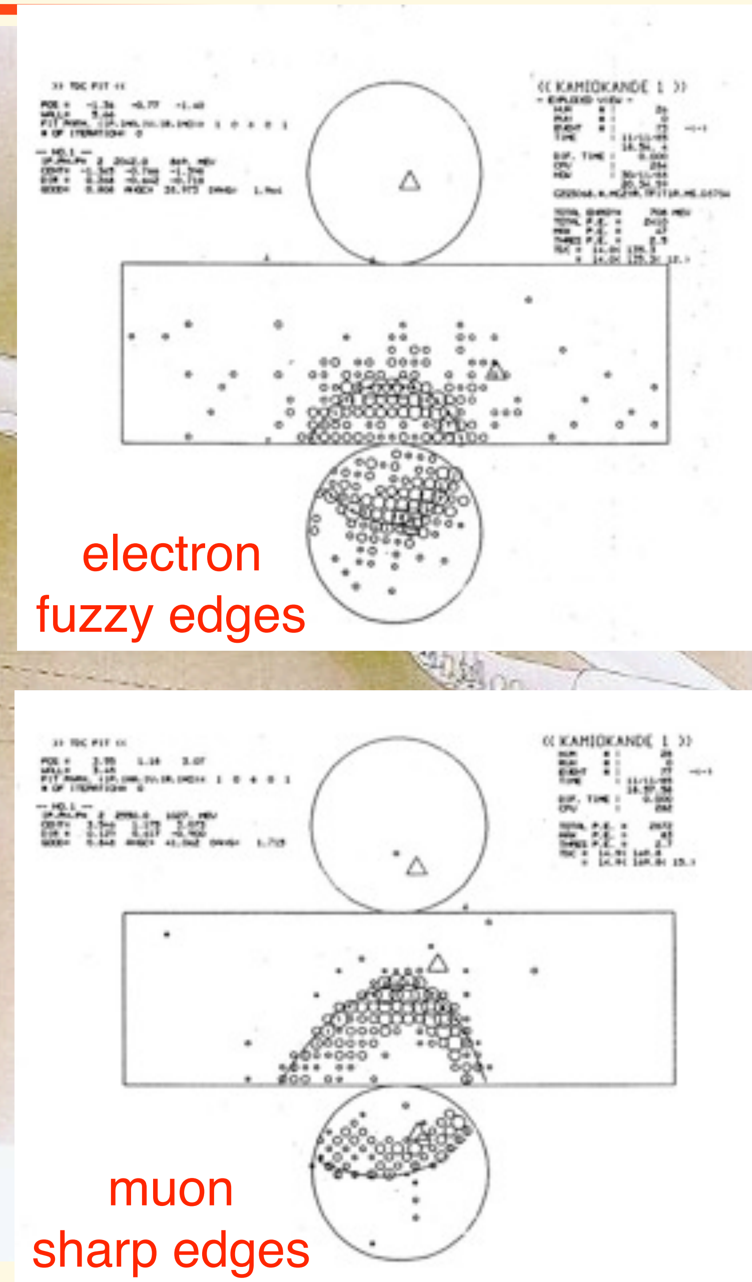
SuperKamiokande



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

SuperKamiokande





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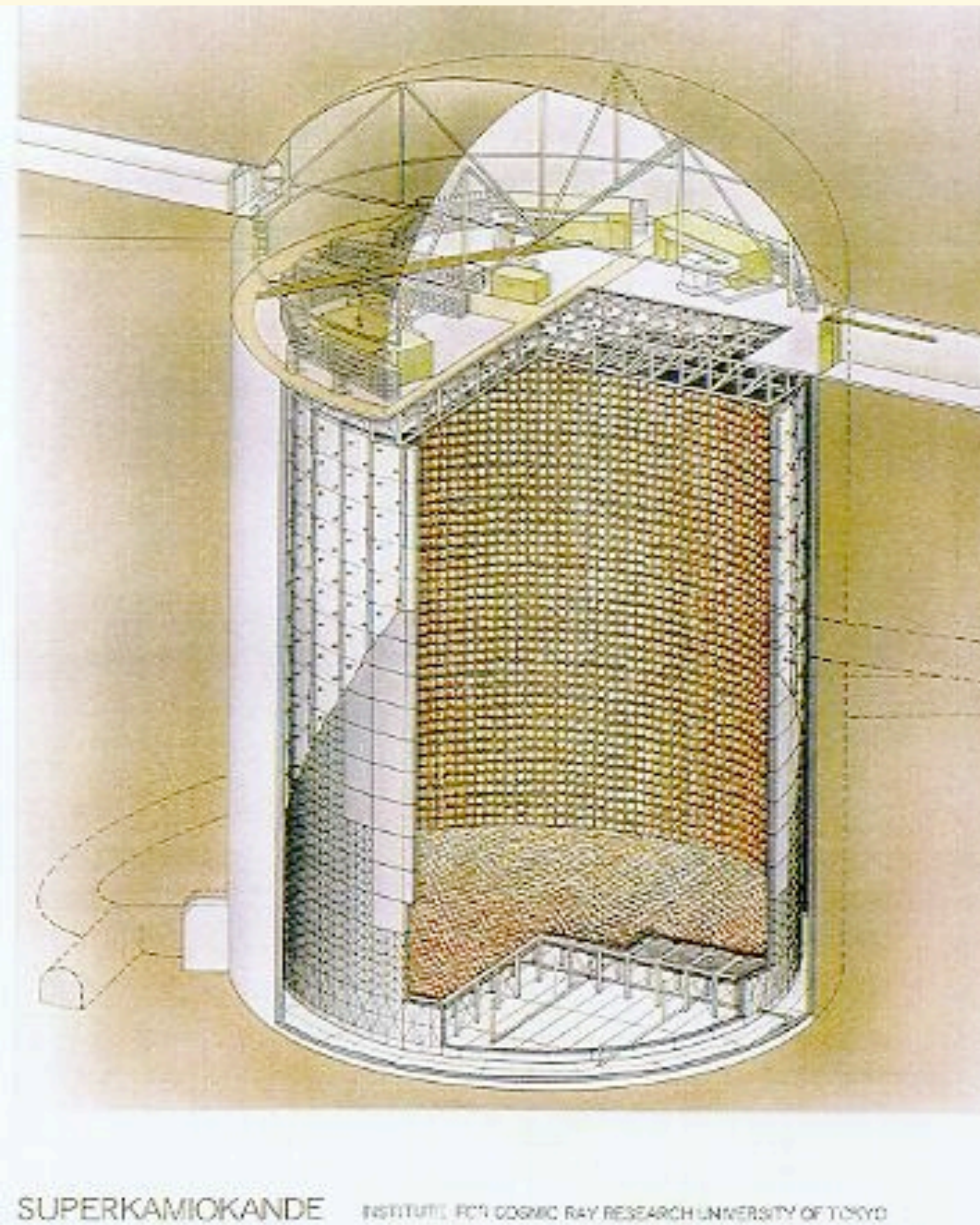

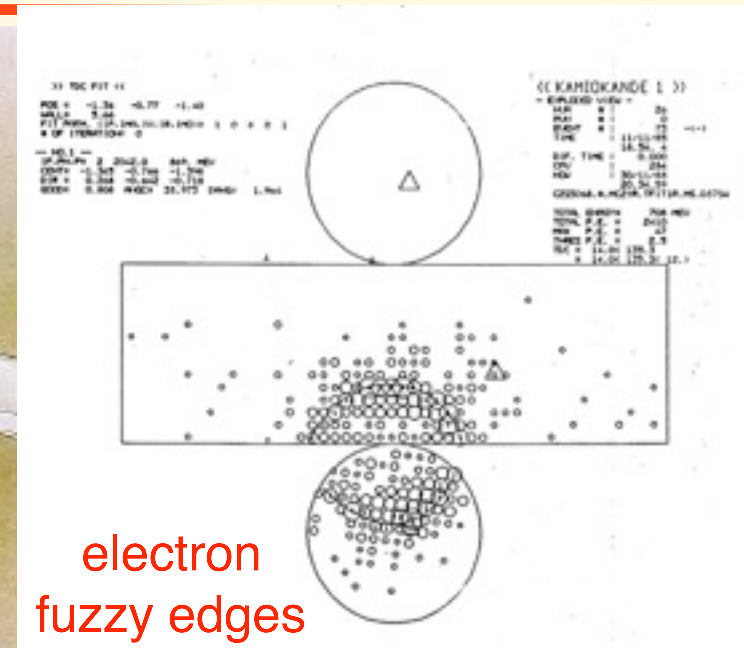

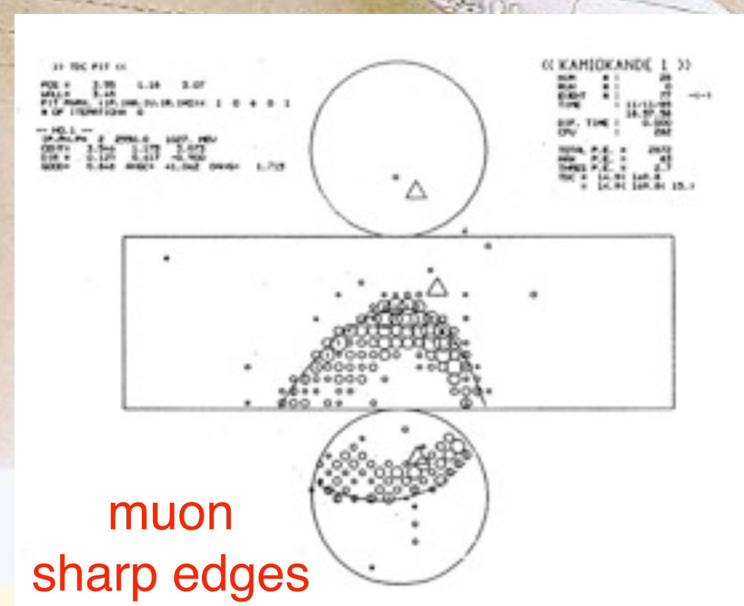

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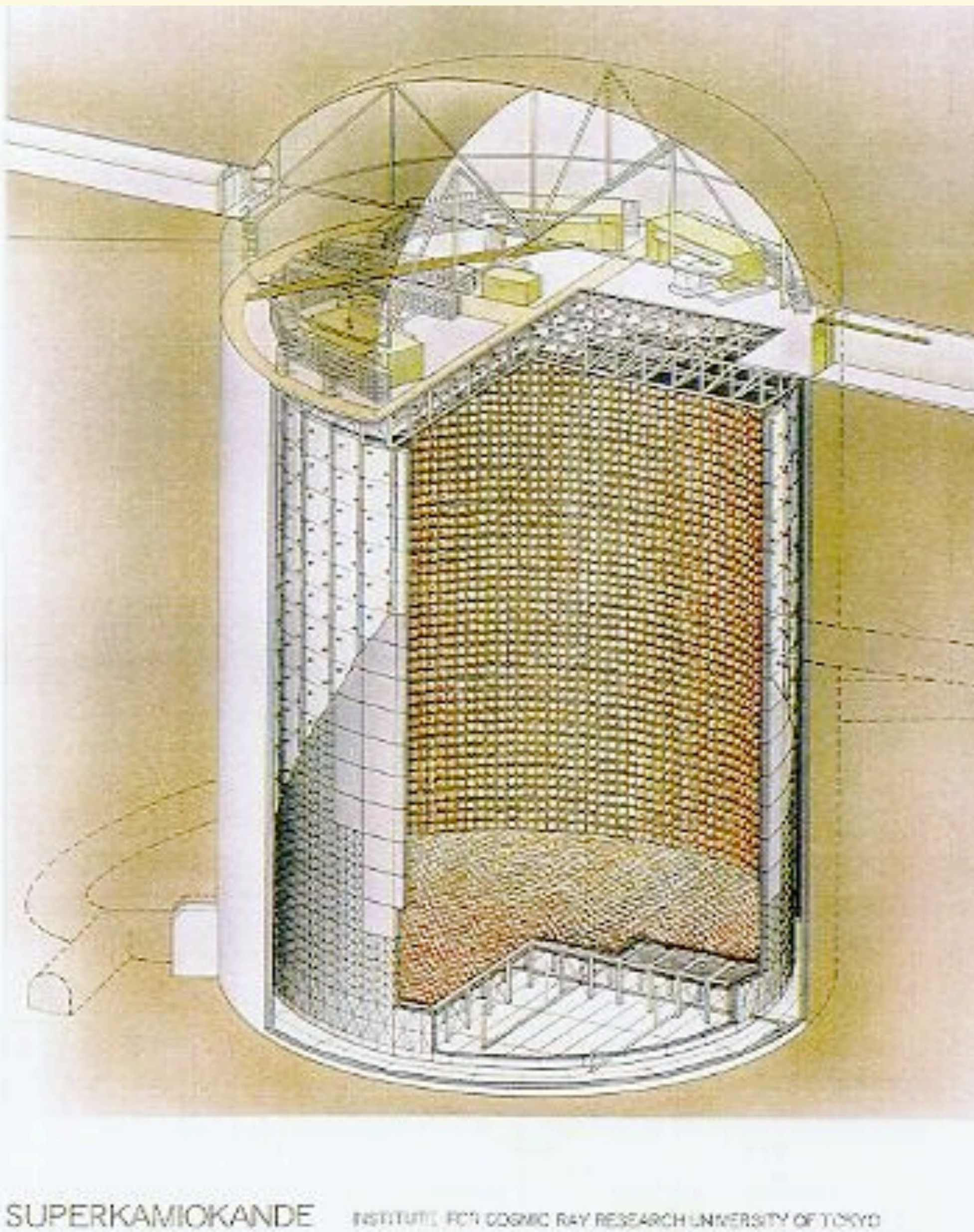
Zenith angle and L/E distributions are used to extract oscillation parameters

SuperKamiokande



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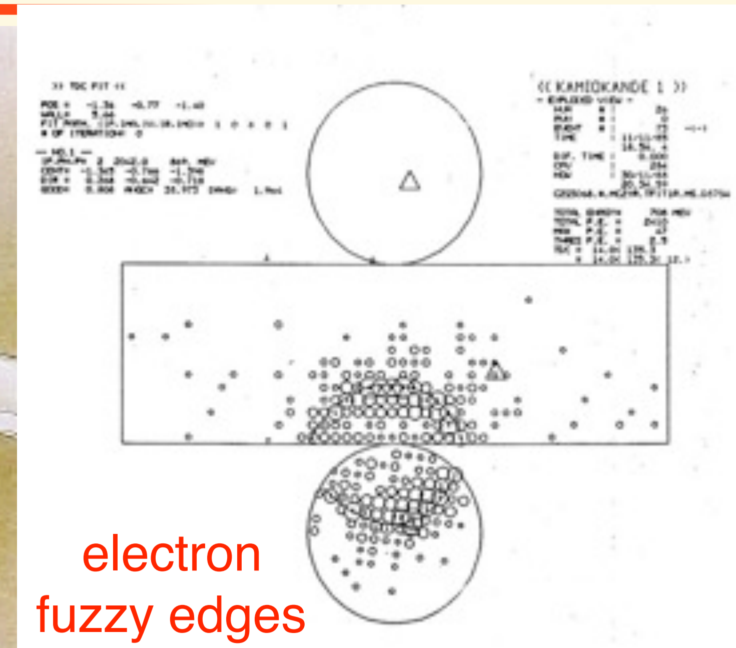
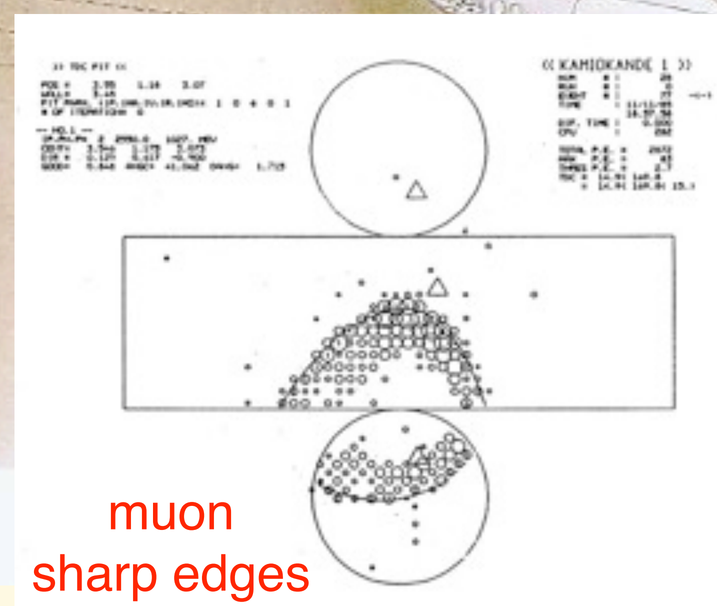
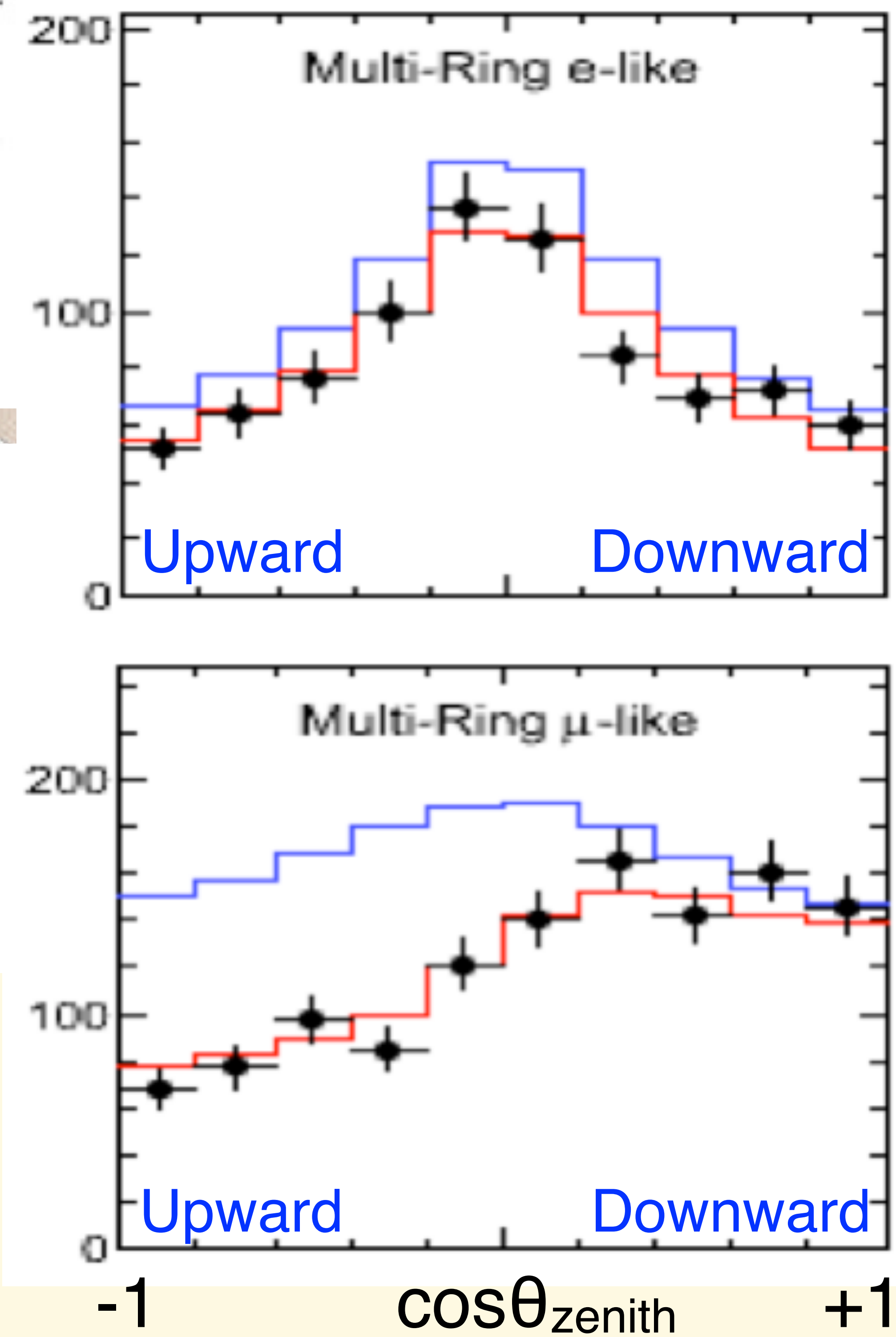
1000m underground





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

Example distributions



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

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