The Gold Standard: MINOS

Long Baseline Neutrino Experiments, The Gold Standard : MINOS 1995-2023

Jenny Thomas, Stanford 10th November 2023

The Gold Standard: MINOS

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- The scientific topic
- The history
- The politics
- The money
- Construction
- The experiment
- The results
- Some unexpected developments along the way

Neutrino Oscillations

What they are and how we measure them

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata : 1957-1967

$c_{12}=\cos\theta_{12}$, $s_{12}=\sin\theta_{12}$
δ=CP violating phase

- The PMNS matrix factorises into three separate matrices
- These represent (usefully) the three discrete experimental areas of interest and measurement
- 23 = atmospheric, 13 = reactor, 12 solar
- Time evolution introduces dependence on difference of mass squareds
- We still do not know which is the heaviest! (3=normal hierarchy, 1=inverted hierarchy)

Neutrino Oscillations

What they are and how we measure them

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata : 1957-1967

$c_{12}=\cos\theta_{12}$, $s_{12}=\sin\theta_{12}$

δ=CP violating phase

$$|\psi(t)\rangle = \sum_j U_{\alpha j} e^{(-i[m_j^2/2p_\alpha]x)} |\nu_j\rangle$$

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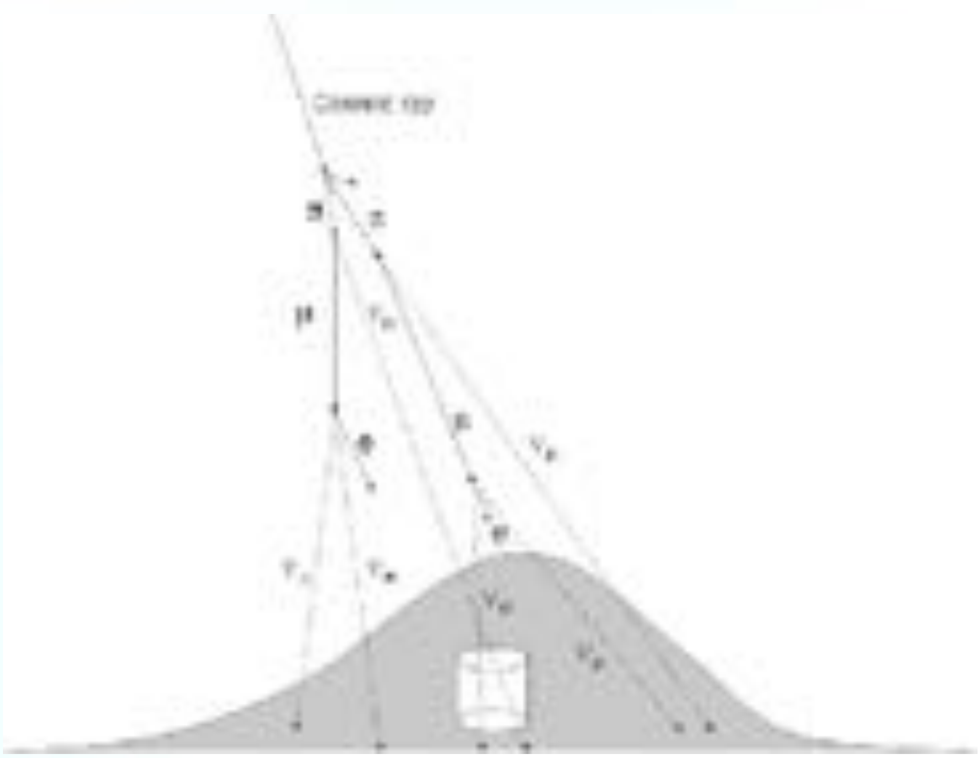
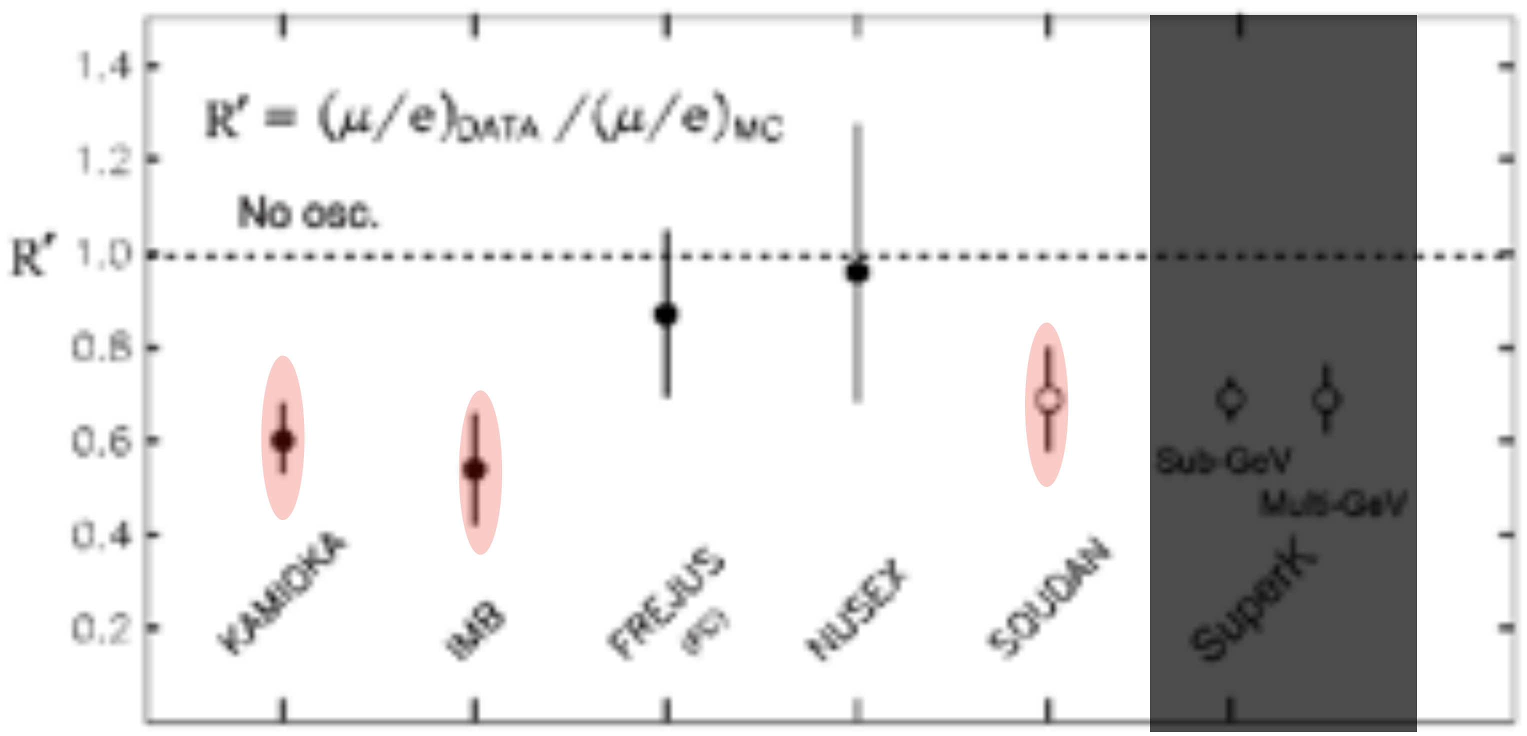
1991 cast your mind back

SSC was being built in Dallas, Tx

- LEP had measured number of light neutrinos = 3
  - Radiative Corrections were being used to tease out new information from the Z mass and width
  - SSC was going to go after the Higgs
  - Only a small number of people had eyes on another anomaly….
  - Proton Decay Experiments

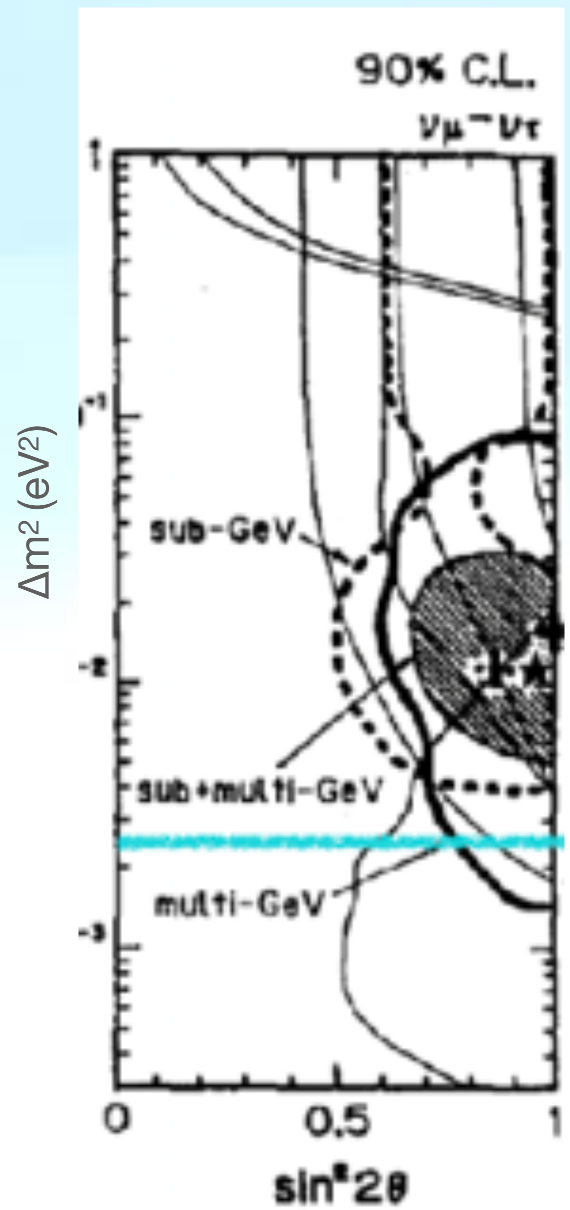




The conventional wisdom at the time

The Kamiokande Experiment

- In 1991 Kamiokande had shown that if neutrino oscillations were the cause of the missing atmospheric neutrinos in their water Cherenkov detector, then the Δm^2 (difference in mass squared of the two types of neutrinos) was ~10^{-2} eV^2



- The Japanese funding agency took it seriously….

"The Super-Kamiokande project was approved by the Japanese Ministry of Education, Science, Sports and Culture in 1991 for total funding of approximately $100 million."

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267\Delta m^2 L / E)$$

The Beginning of MINOS

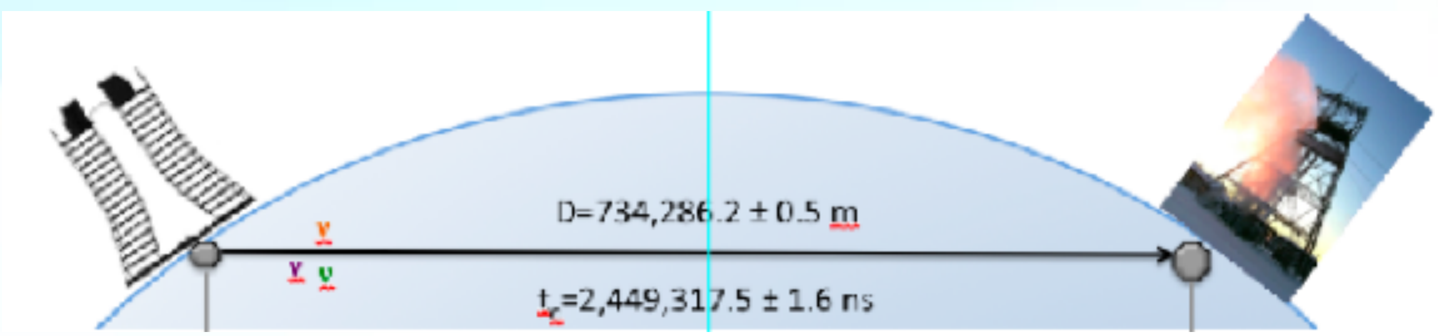
The end of the SSC and the start of NuMI

- There was a call for LOIs in 1994 (3 years after the Kamiokande result) for a long baseline experiment at the planned neutrino facility (NuMI) at FNAL: there was already a short baseline experiment planned
  - COSMOS - later cancelled
- There were three EoIs for LBL experiments
  - Barry Barish and Doug Michael + ex-MACRO collaboration (50-60 people) (Tracker Calo, 15kT)
  - Maury Goodman + Soudan2 collaboration (about 50 people) (Tracker Calo, 1KT)
  - Stan + 0 other people 😀 (Cherenkov Detector at SLAC)
- **All proposed to be sensitive to Kamiokande Δm^2, 700km baseline**

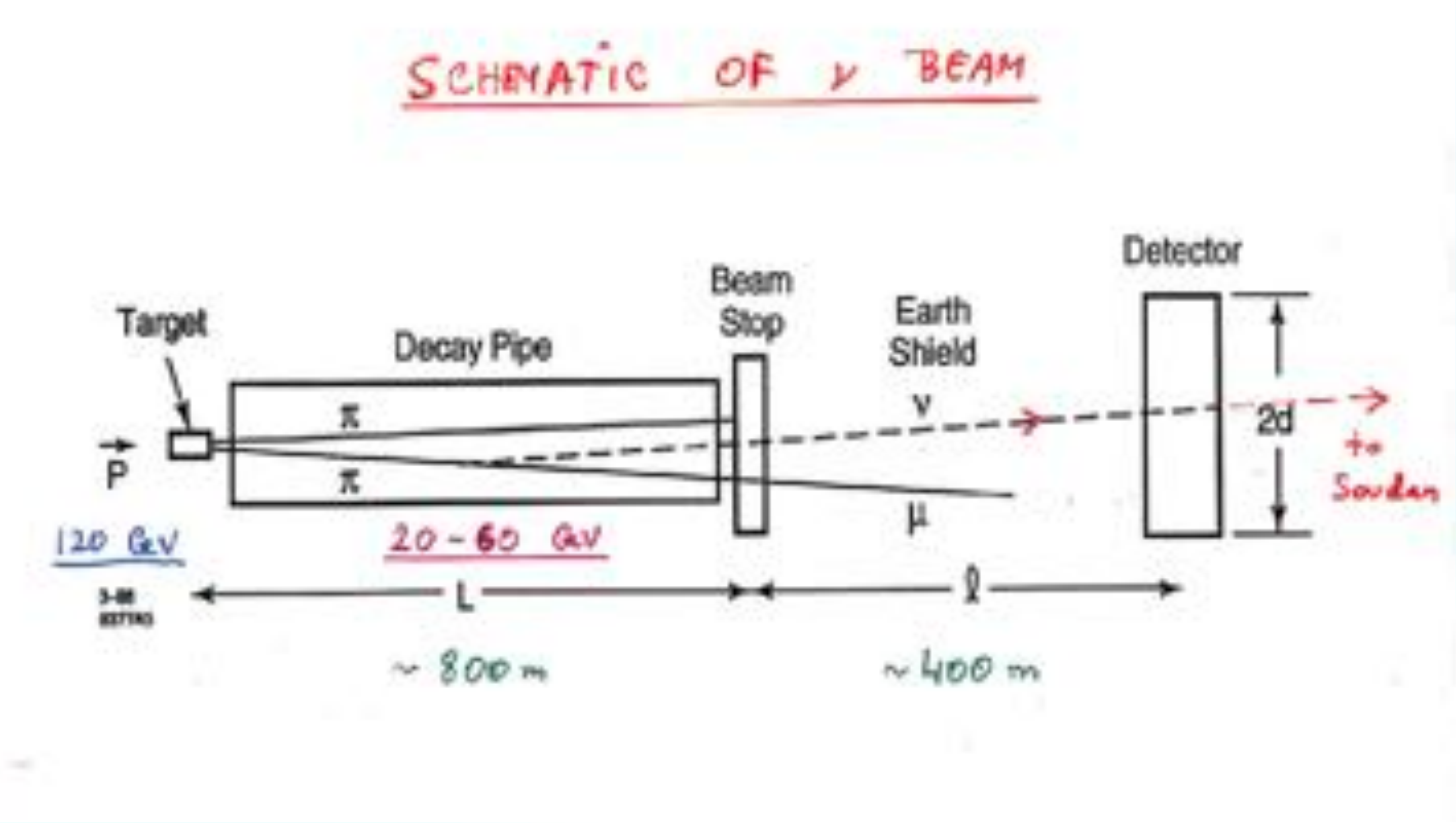
The MINOS Experiment

1995 P-875

- MINOS was born with Stan as appointed-by-FNAL leader
- We had a competition for the name
- MINOS was the winner (Main Injector Neutrino Oscillation Search), for yes, we did not know for sure they existed yet!
- And we got a logo! courtesy Angela M. Gonzales, FNAL
- Beam would point at Soudan, Mn



- Huge $$$ contribution from U.Minn made that happen and helped the decision along
- Original 15 kton detector reduced to 5kt
- Detector $50M Beam $70M



- Produce muon neutrinos to check if they were disappearing

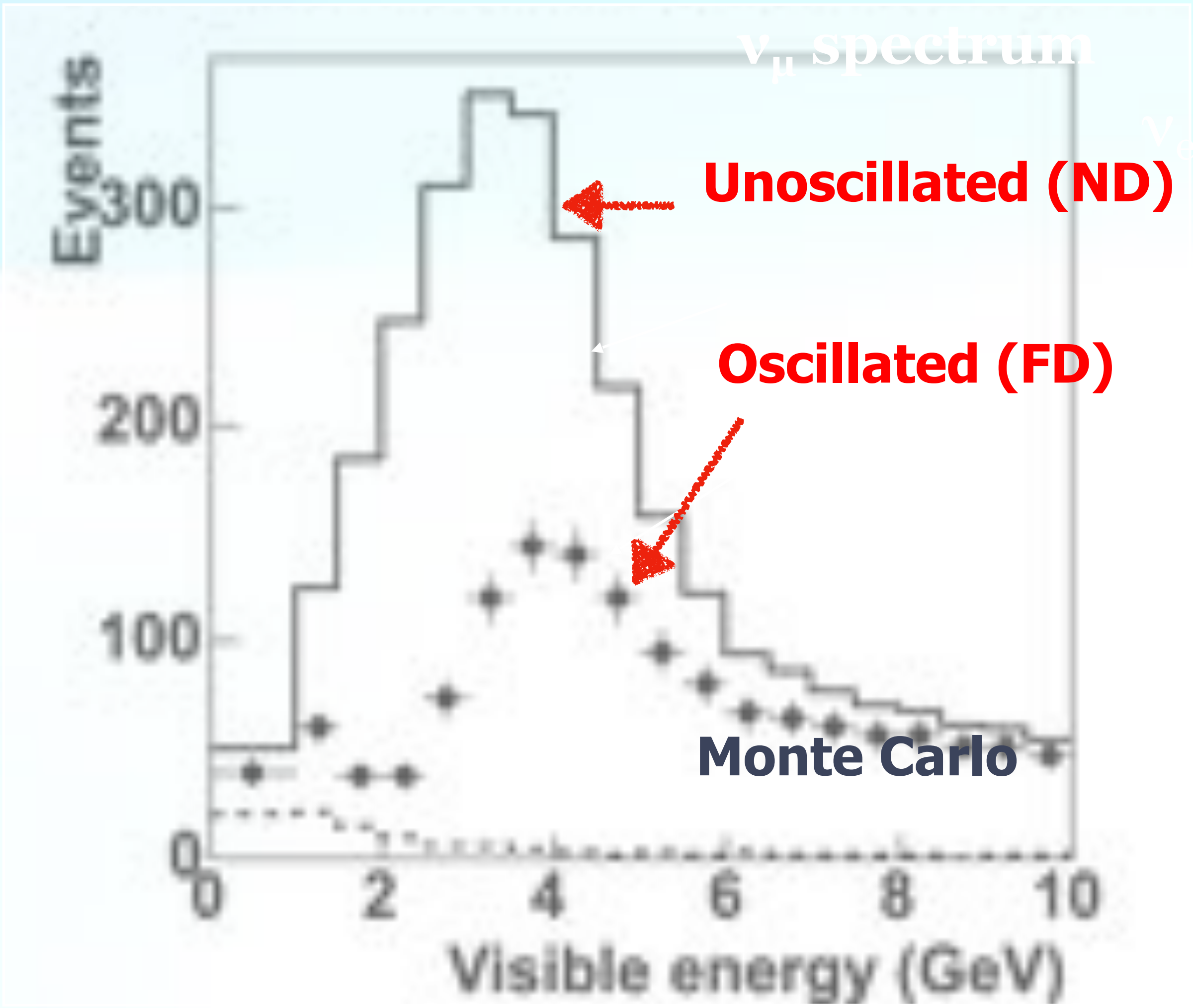
The NuMI Beam

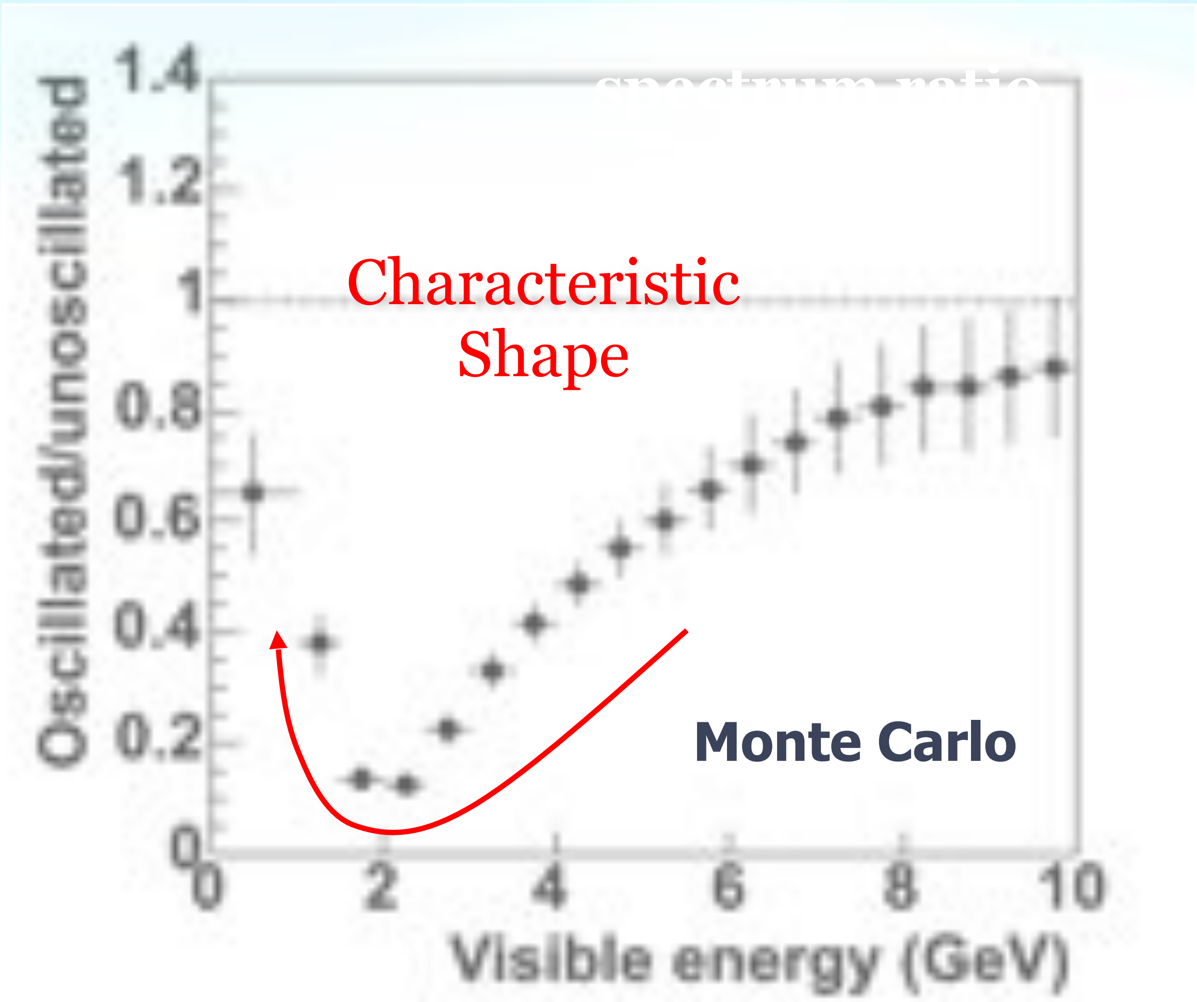
An integral part of the MINOS story

Accelerator Neutrino Disappearance

The simplest experiment

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

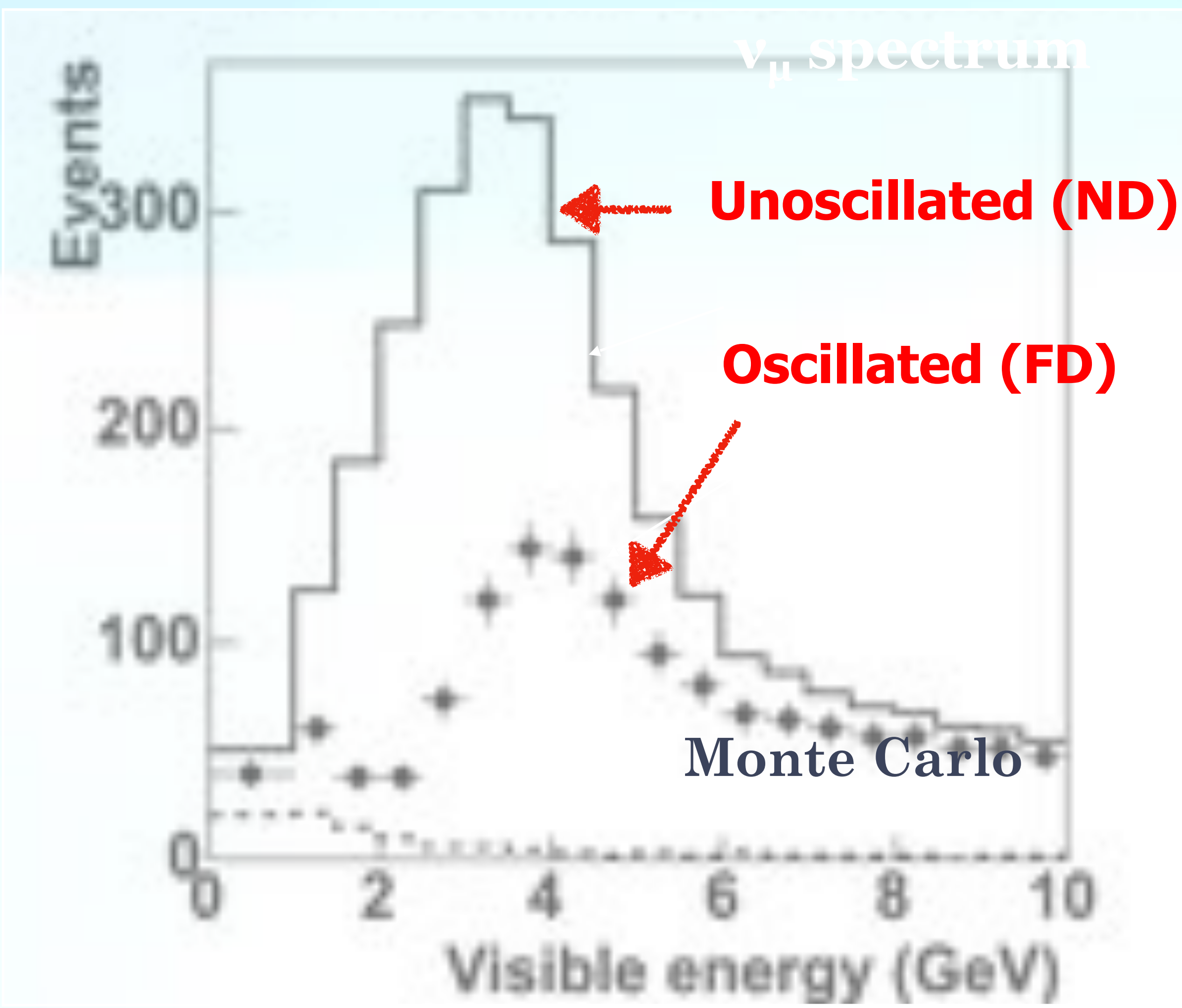


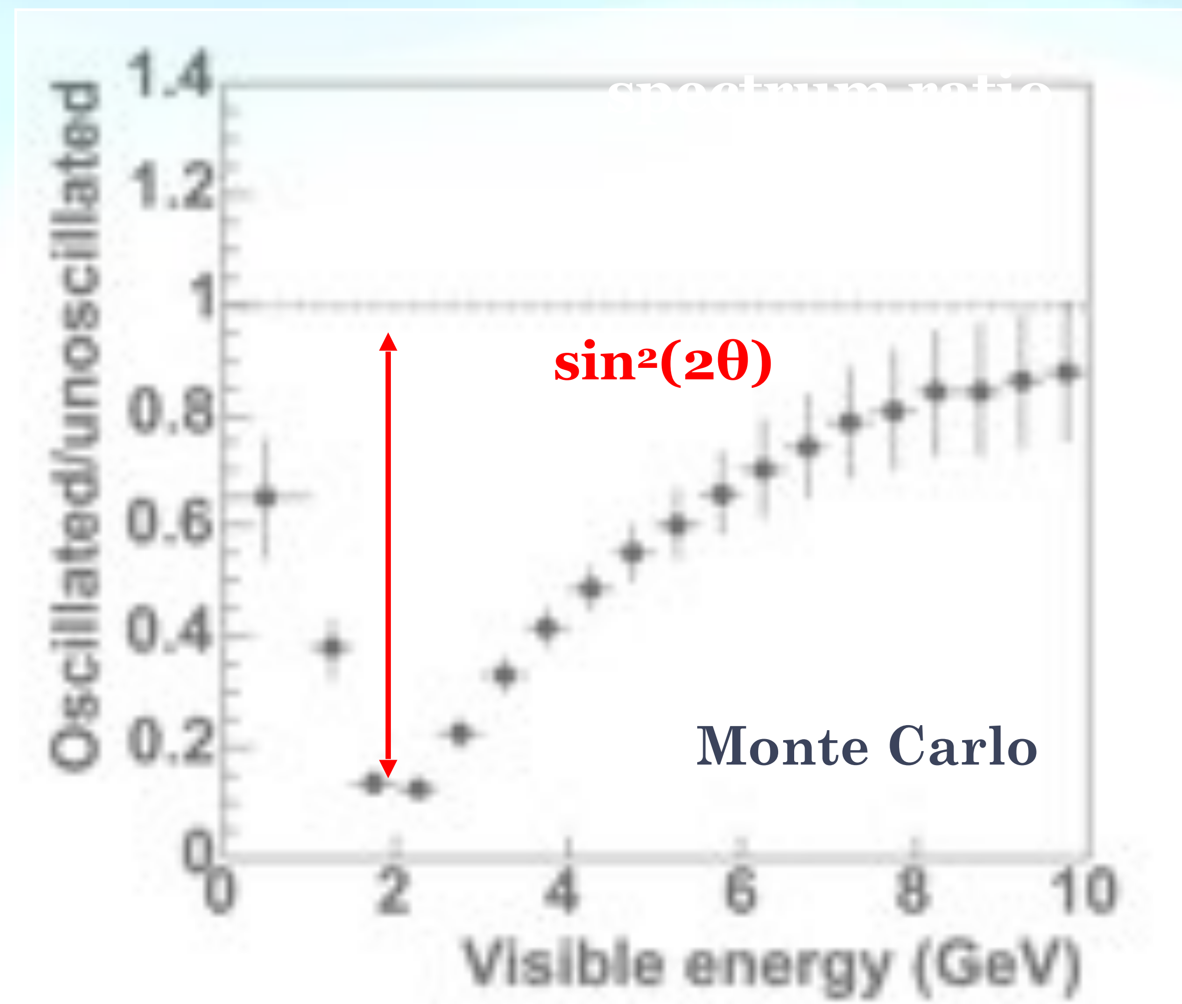


Accelerator Neutrino Disappearance

The simplest experiment

$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2 2\theta} \sin^2(1.267 \Delta m^2 L / E)$$

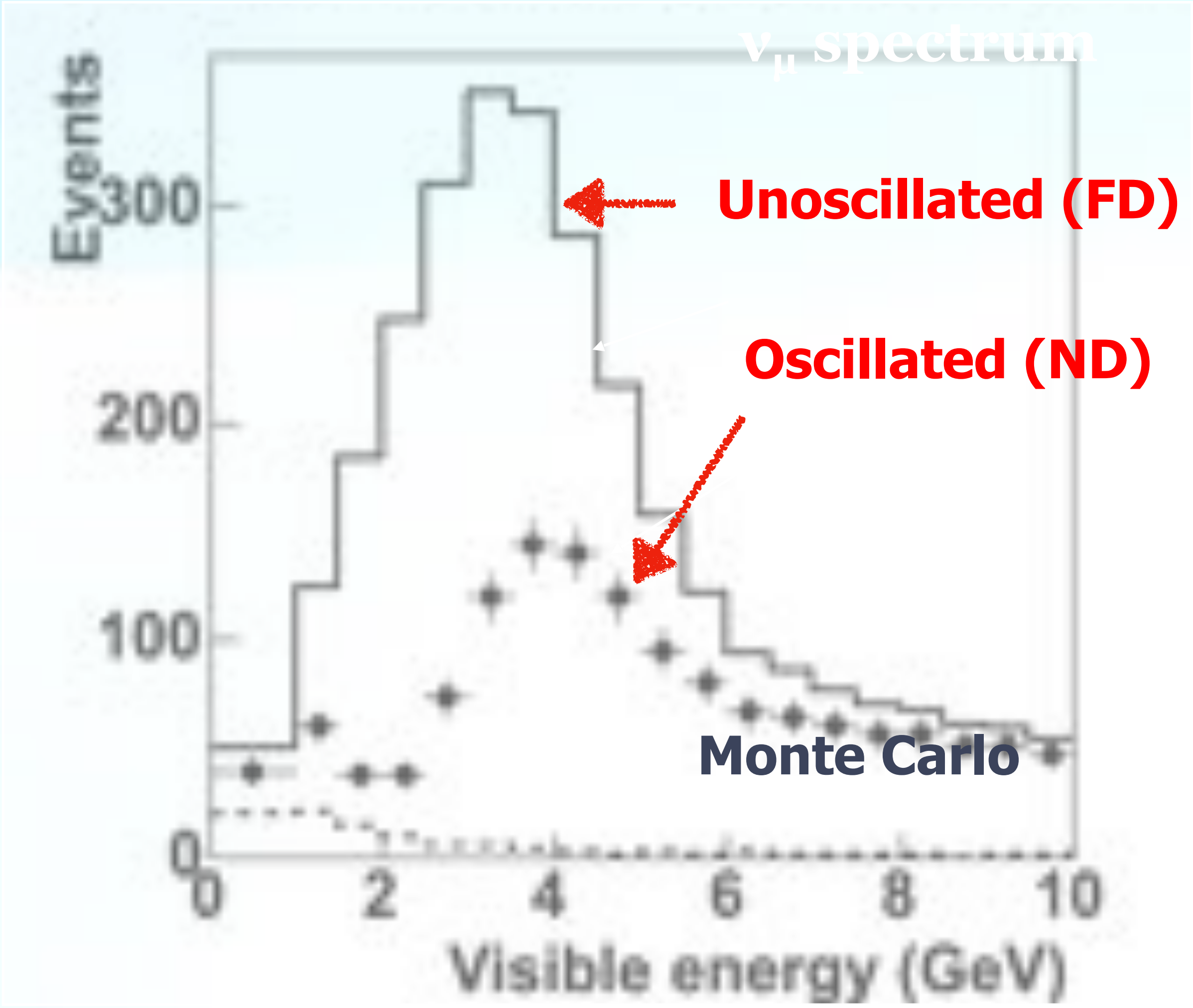


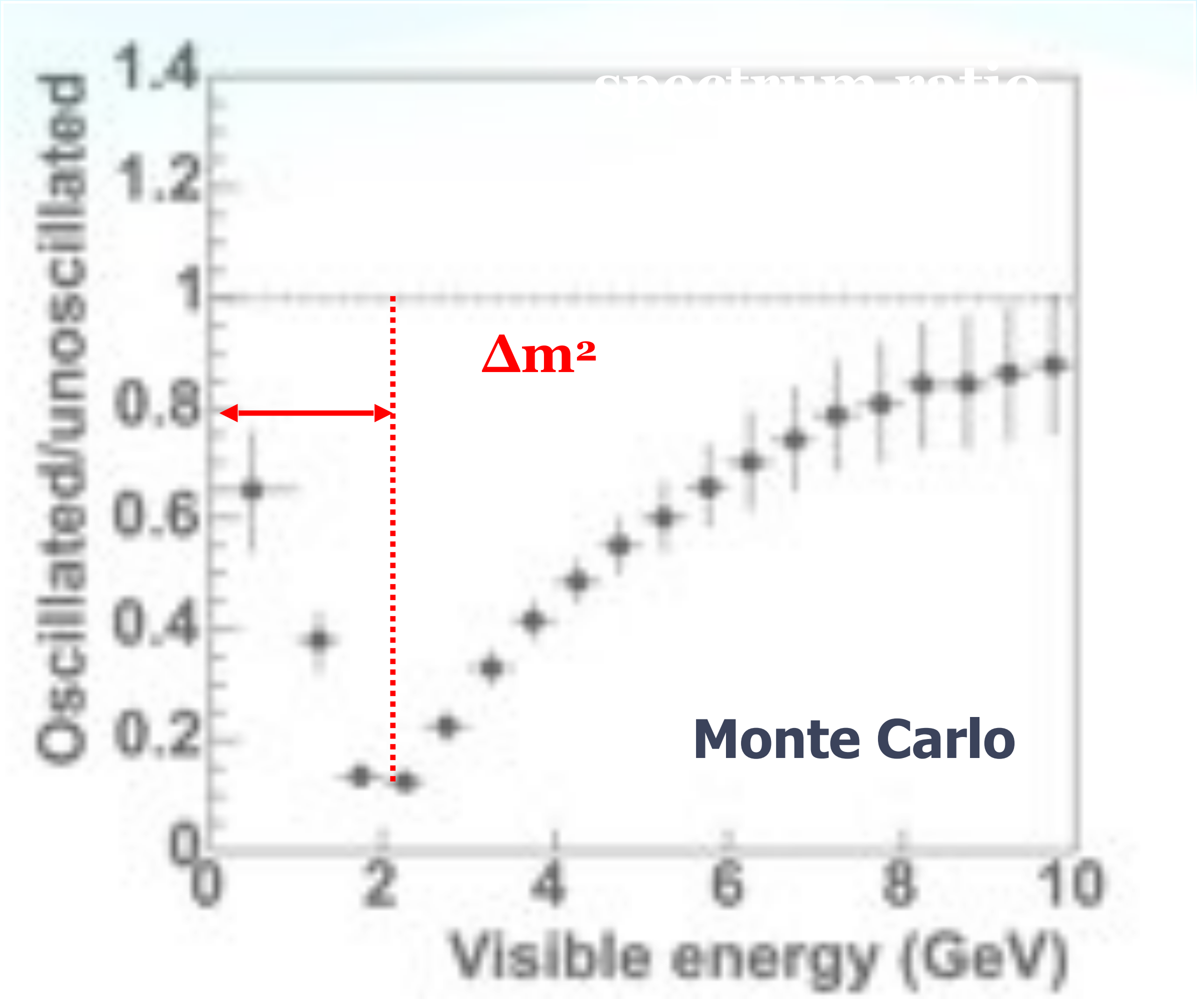


Accelerator Neutrino Disappearance

The simplest experiment

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \, \sin^2(1.267 \Delta m^2 L / E)$$



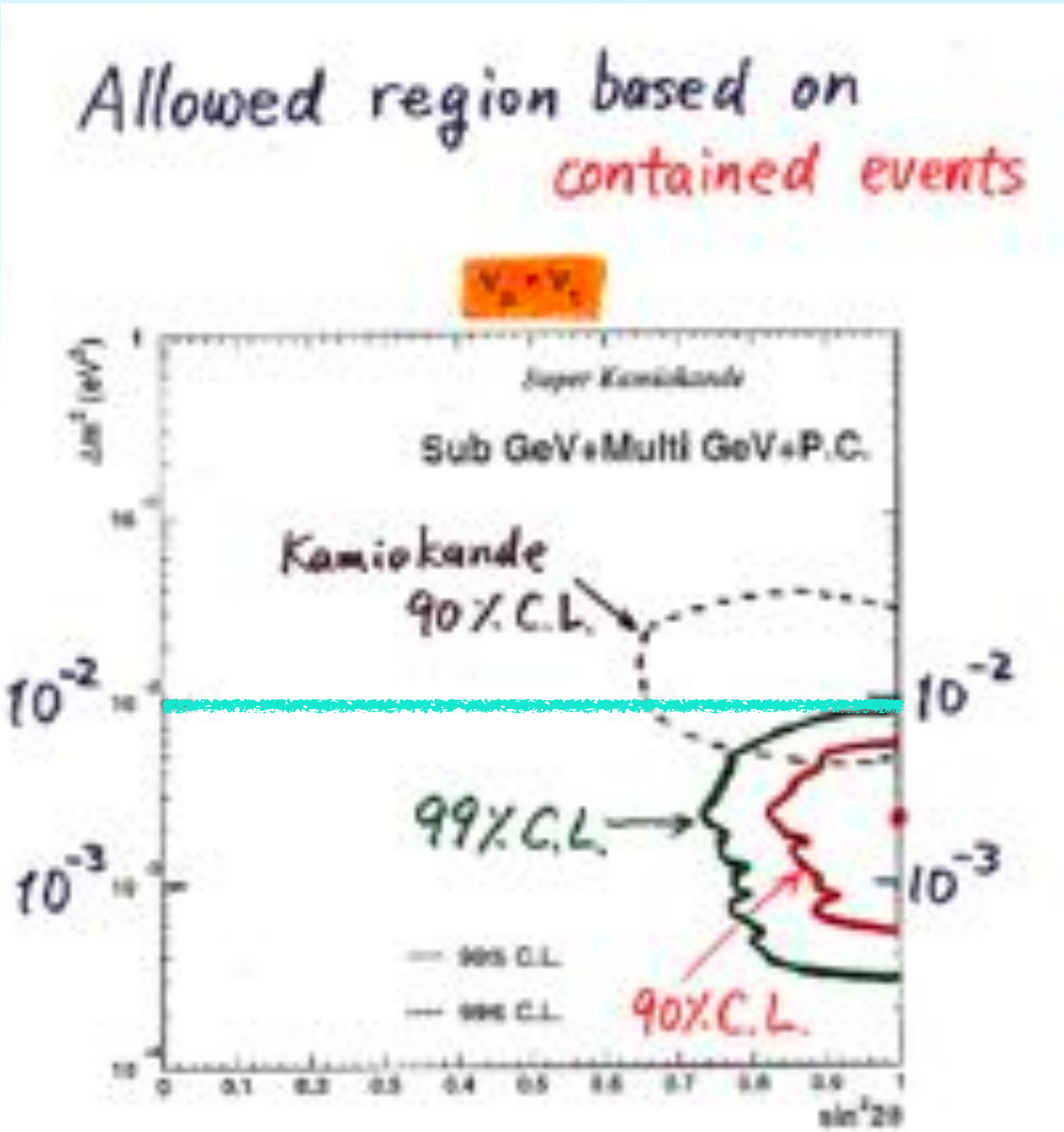


(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2)

Baltay Review 1998

a near catastrophic experience

- Super-K first result showed potential for Δm^2 to be well below $10^{-3}eV^2$
- It was asserted in the review that we would not be sensitive, and therefore should be cancelled
- Huge difference from Kamiokande result!
- Super-K people on the review team!!
- Luckily, Charlie came to his senses…..



1998

Ground Breaking Day, 1999

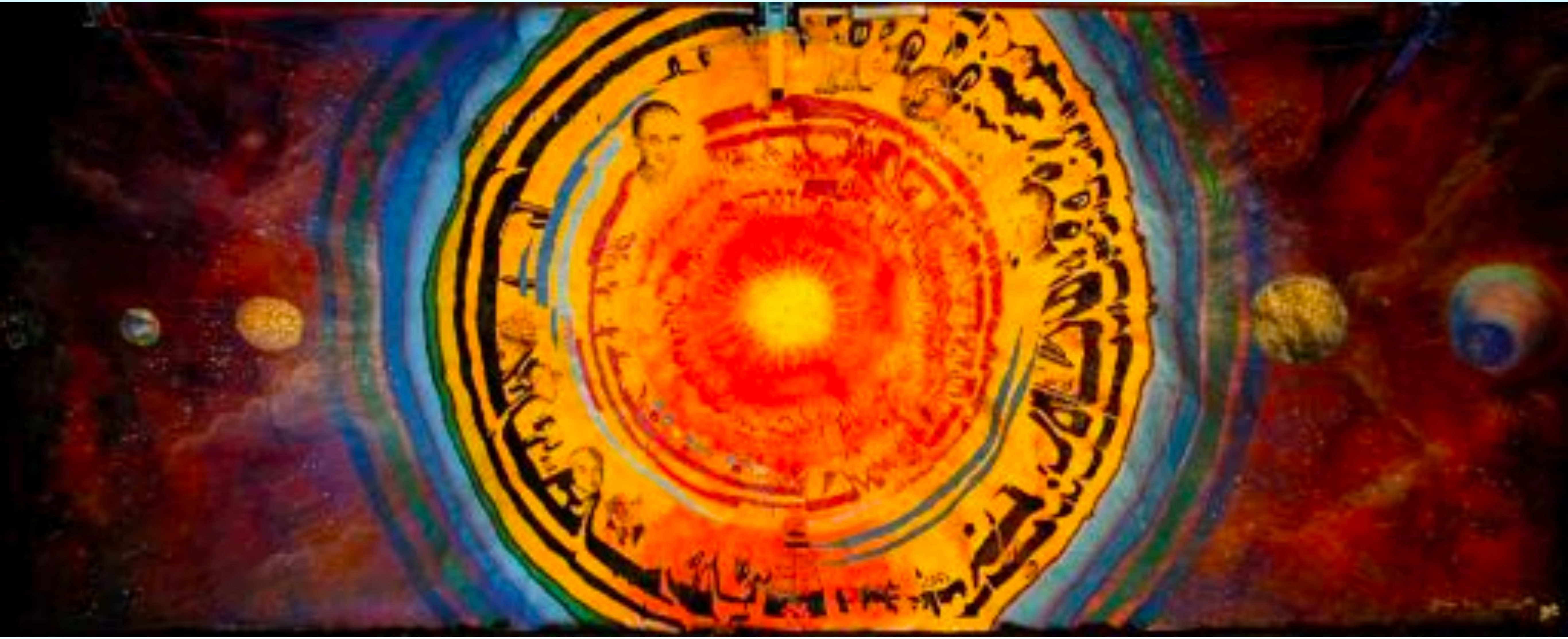
Ground Breaking Day

Construction 1999-2003

- Lehman reviews every 6 months
- Both detector and beam projects
- Beam was discovered to need a re-design
- 3 year delay resulted in beam delivery

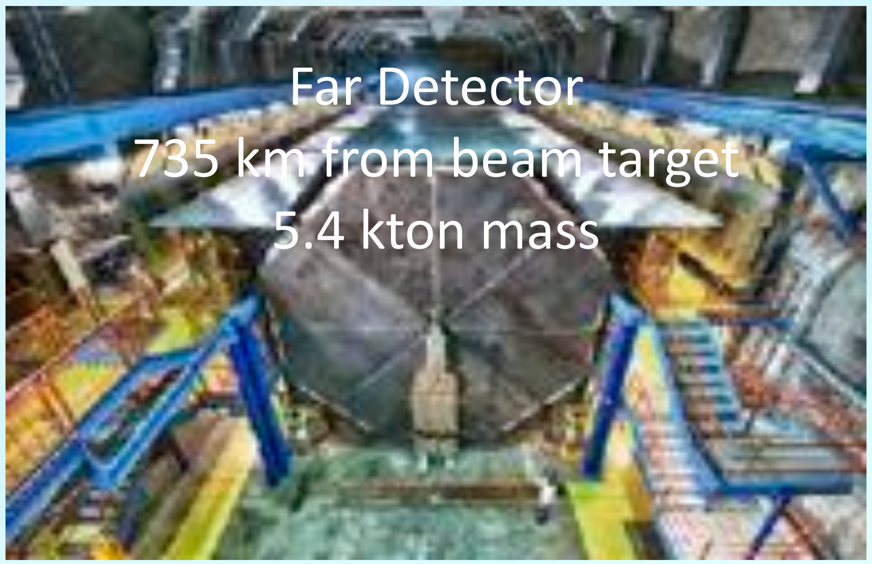
Developments unforeseen, 2002

Art came to the Soudan Mine

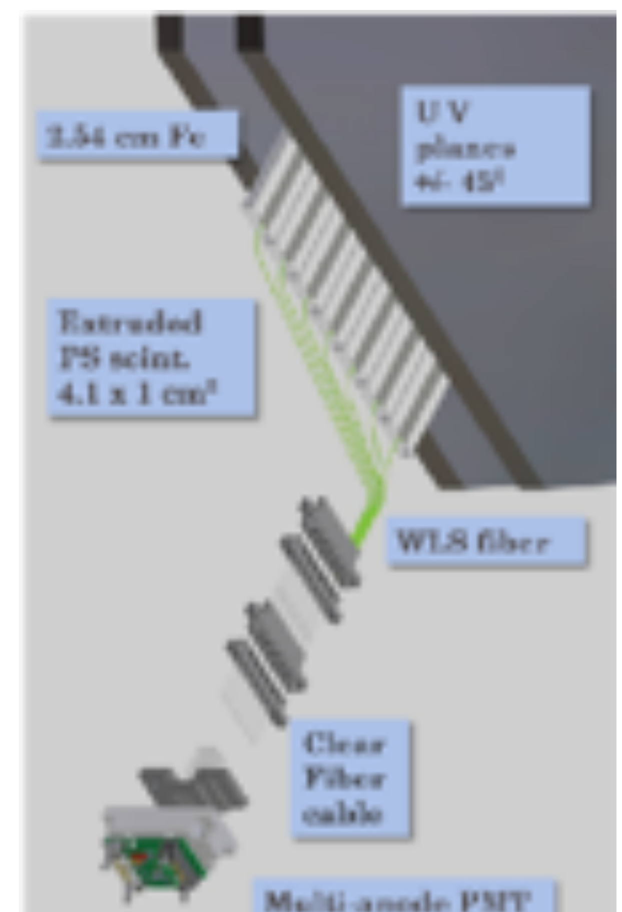


The MINOS/MINOS+ Experiment

On time, on budget! (beam was late)

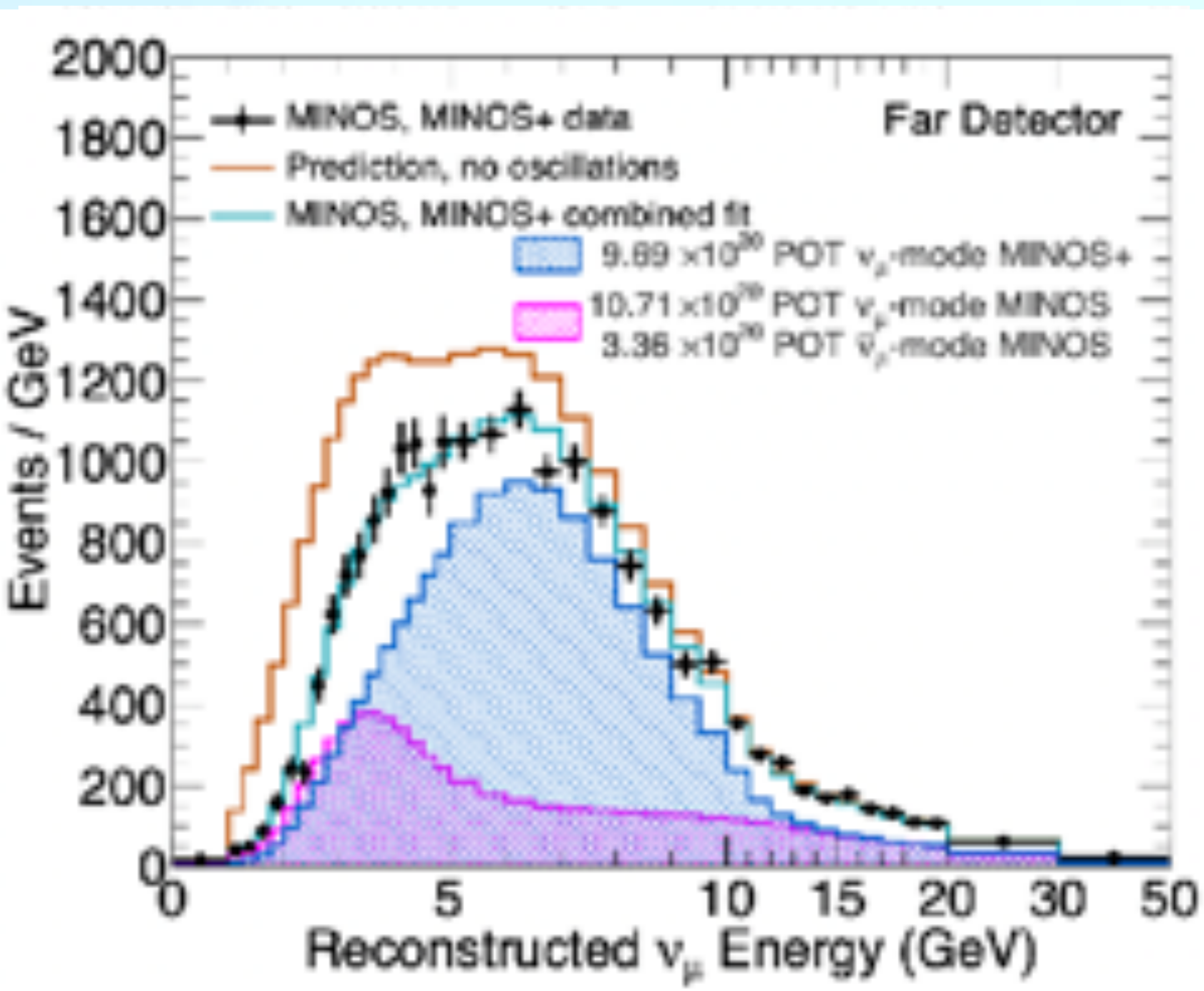


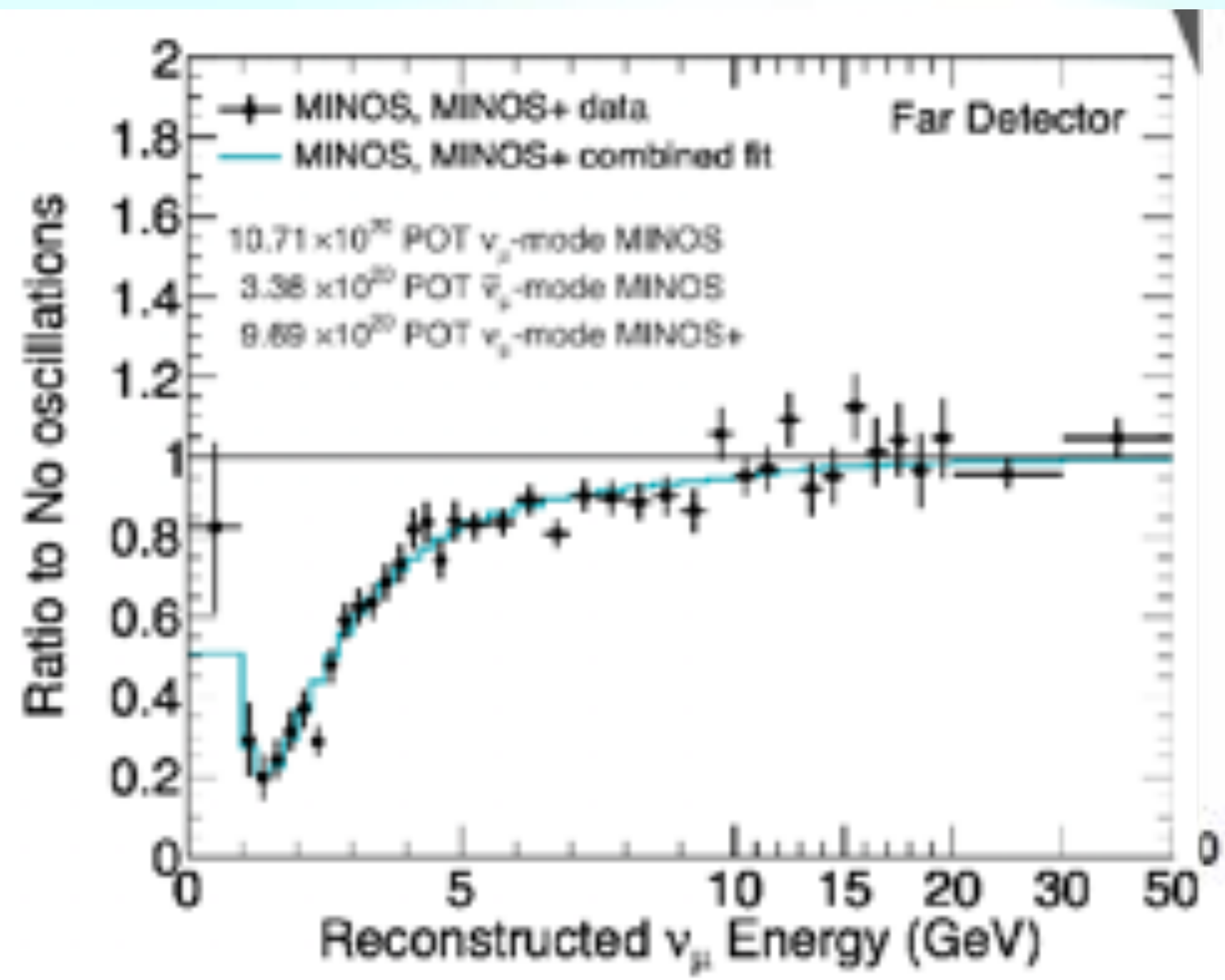
- MINOS had two functionally identical, magnetised, tracking, sampling calorimeters.
  - Can distinguish muon charge from the curvature.
- Exposed to the NuMI beam at Fermilab.
- MINOS+ continued the running of the MINOS detectors into the NOvA era at FNAL.



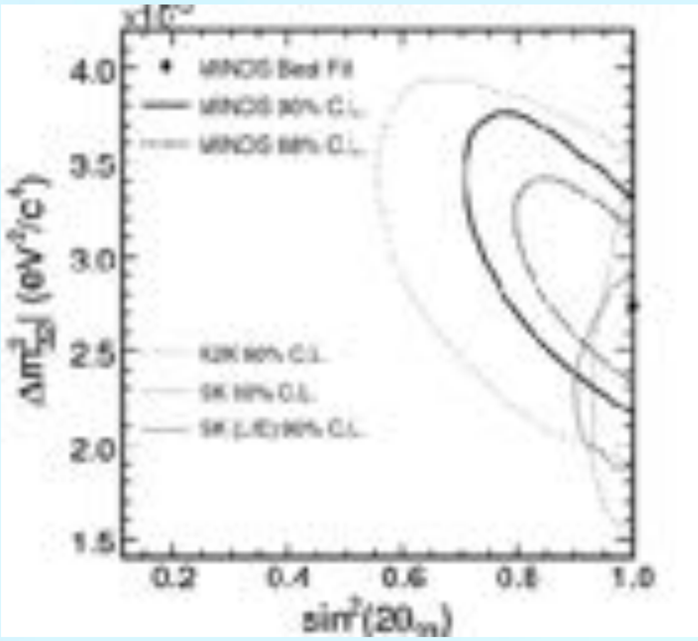
Three Flavour Oscillations

- MINOS was designed to measure the atmospheric scale oscillation parameters Δm^2_{32} and $\sin^2 2\theta_{23}$
  - Look for disappearance of CC ν_μ interactions in the FD relative to ND.
  - Continue the search with MINOS+ above oscillation max

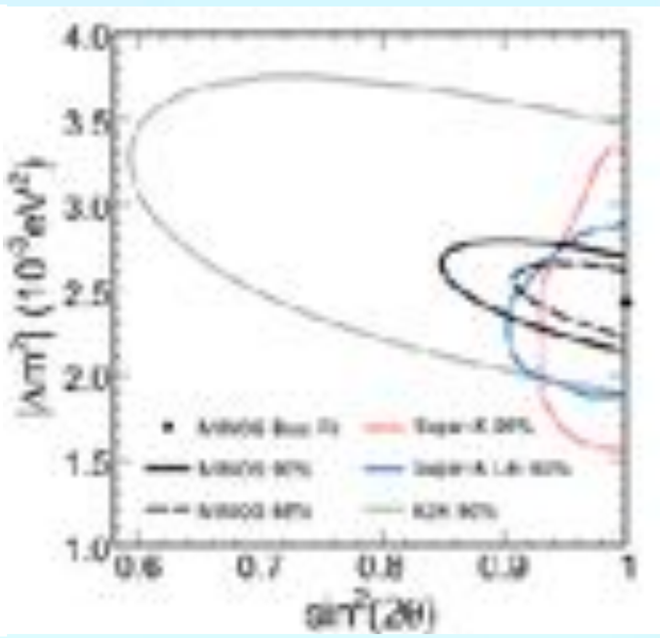




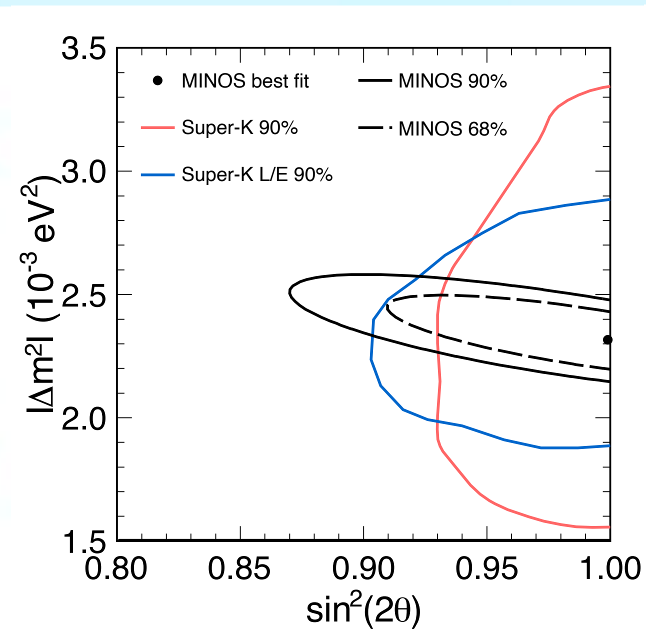
MINOS 2006



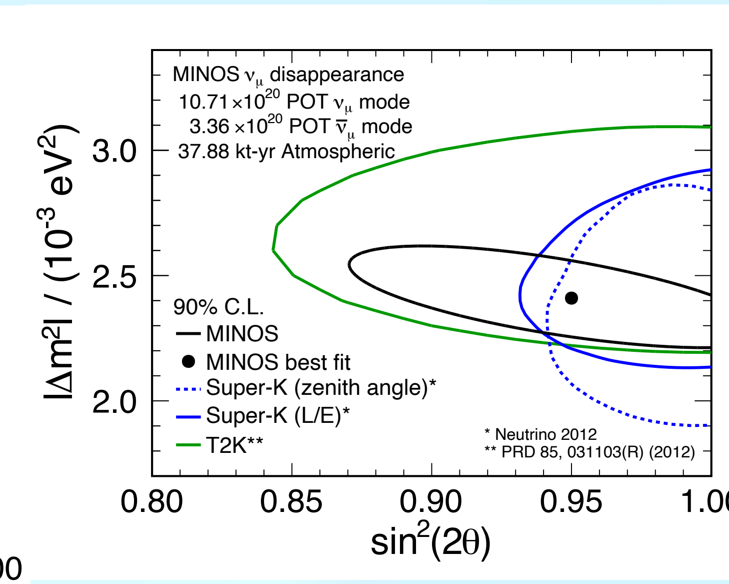
MINOS 2008

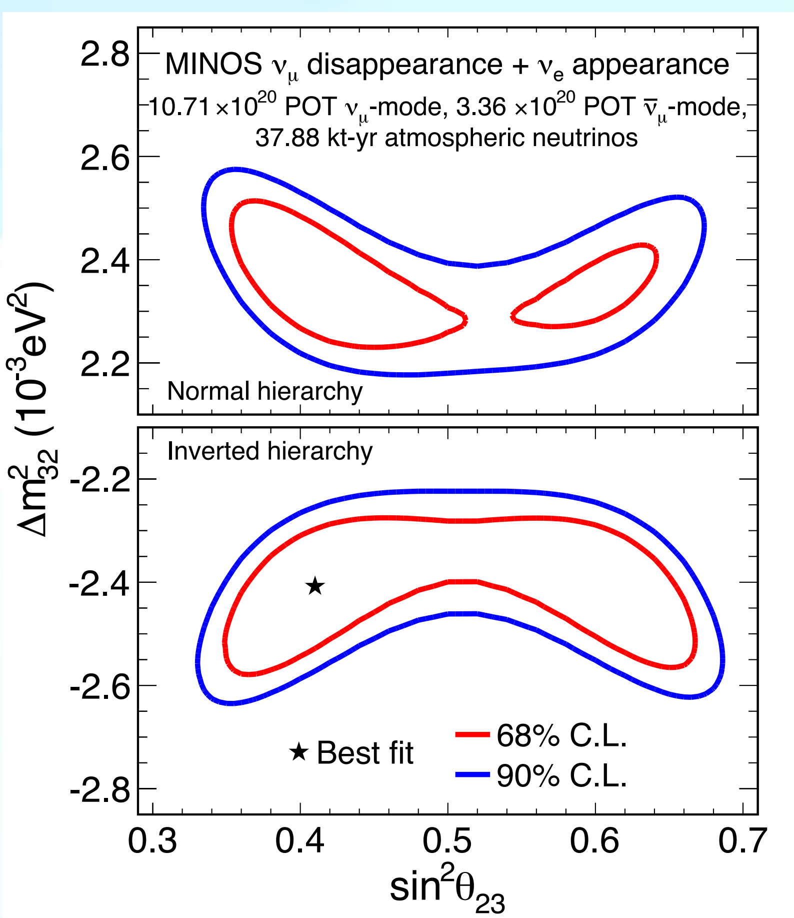


MINOS 2011

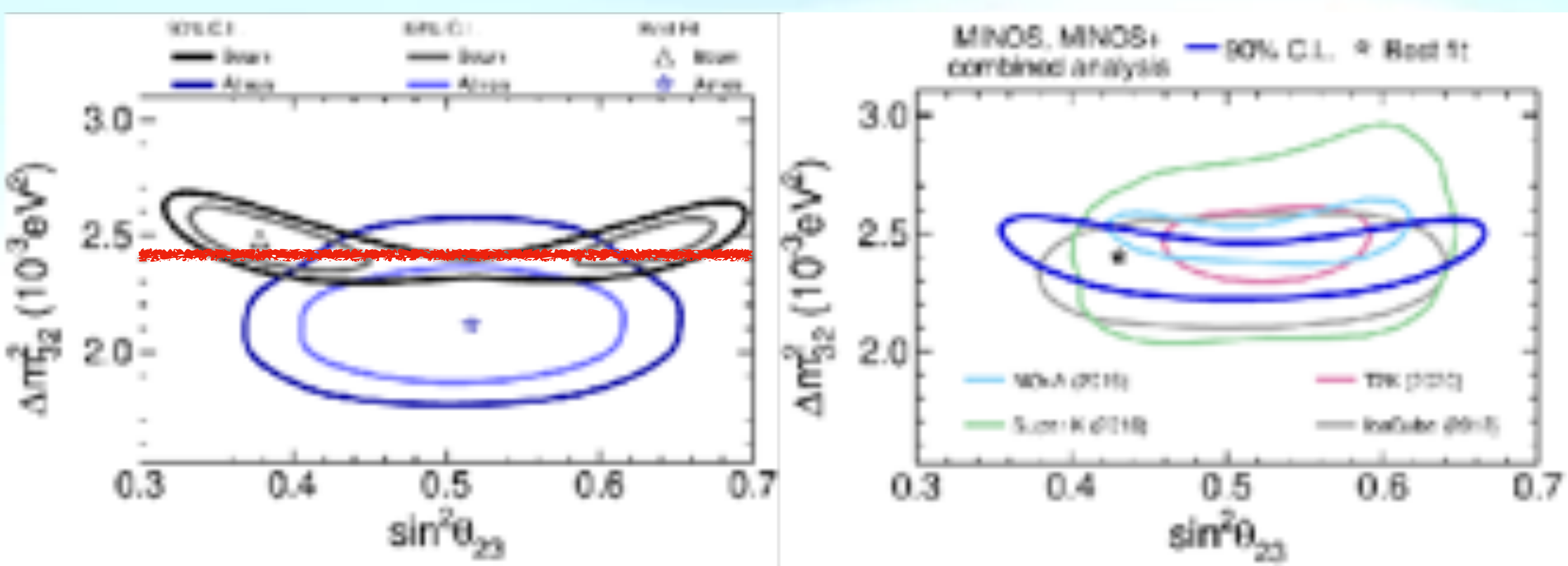


MINOS 2013





MINOS 2014



MINOS+ 2020

- MINOS dominated the neutrino oscillation parameter measurement for 6-7 years before T2K came online.

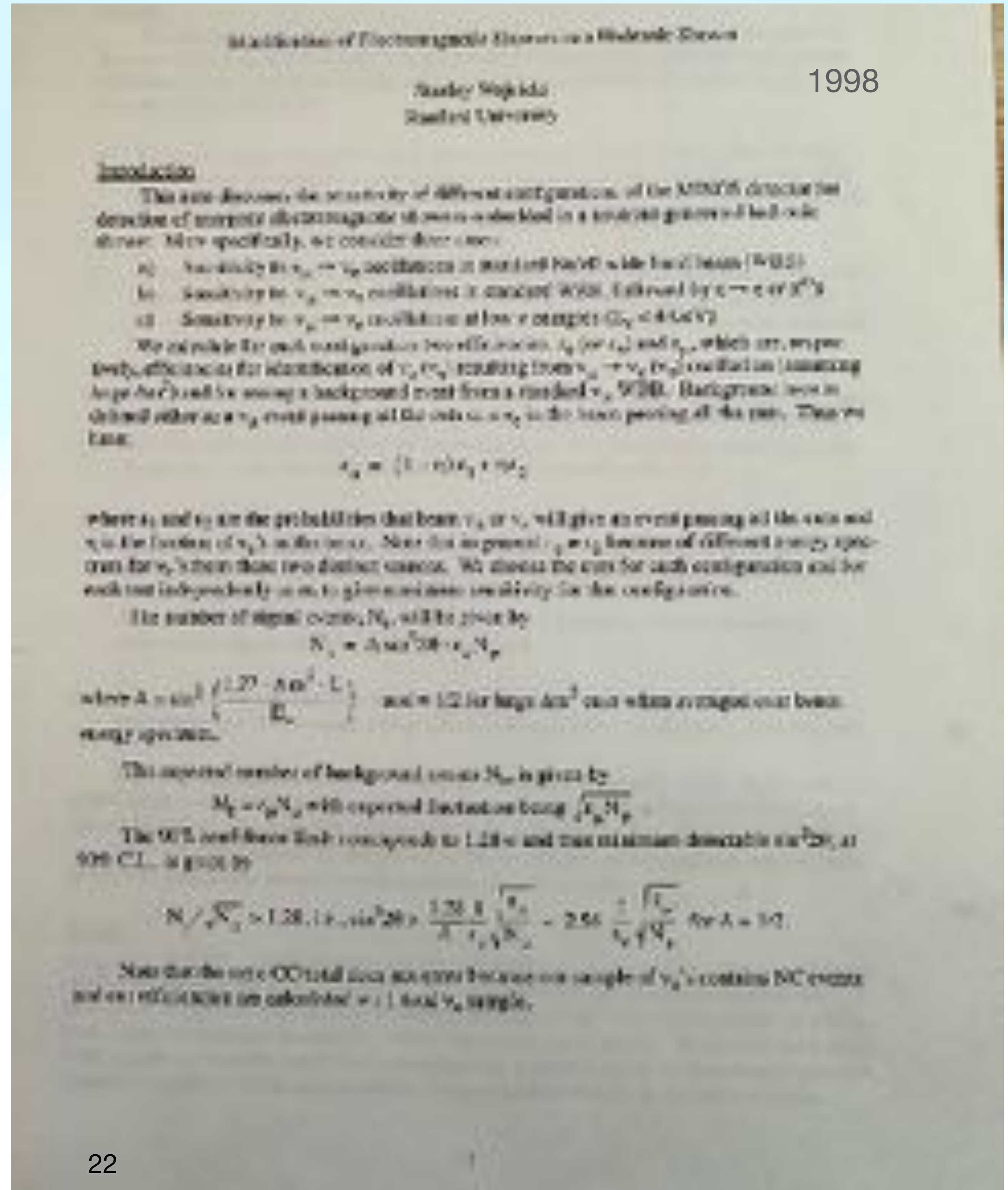
Developments unforeseen

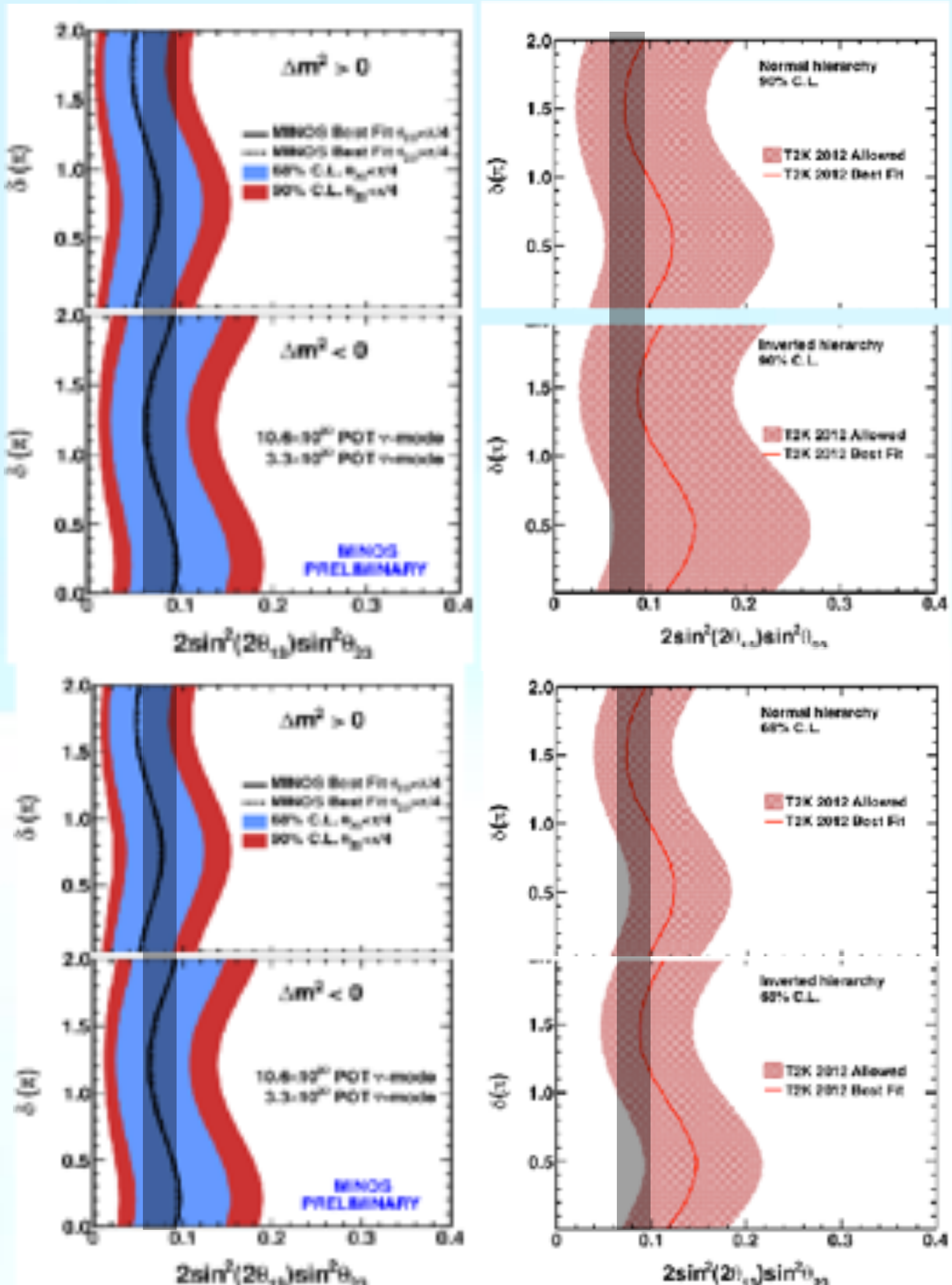
The best looking building on FNAL site

Developments unforeseen

electron neutrino appearance

- Stan pioneered measuring electron neutrino appearance in the MINOS detector
- 1” thick steel planes and 4cm wide scintillator strips could be turned into a great electron detector!
- Development of LEM (Library Event Matching) enabled the analysis, an early precursor to ML





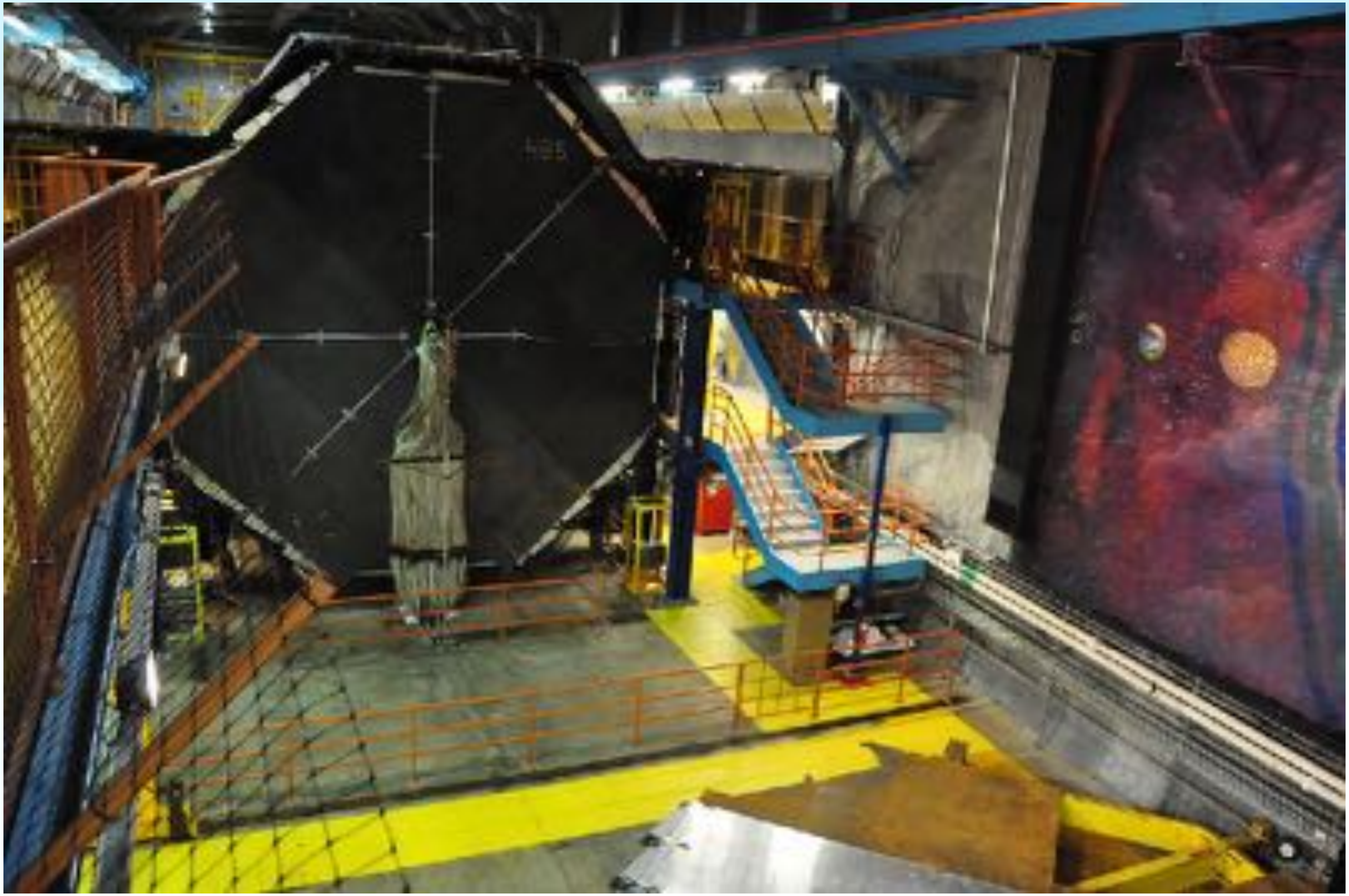
- MINOS and T2K had similar precision the value of the product $2\sin^2(2\theta_{13})\sin^2\theta_{23}$ was lower for MINOS
- Daya Bay came online in 2012 and made the definitive measurement

Developments unforeseen, 2011

No-one expected a fire in the mine!

Developments unforeseen

No-one expected such a great clean up operation!



Developments unforeseen, 2011

That neutrinos might go faster than light!!!

The New York Times

Particles Faster Than the Speed of Light? Not So Fast, Some Say

Share full article

OPERA

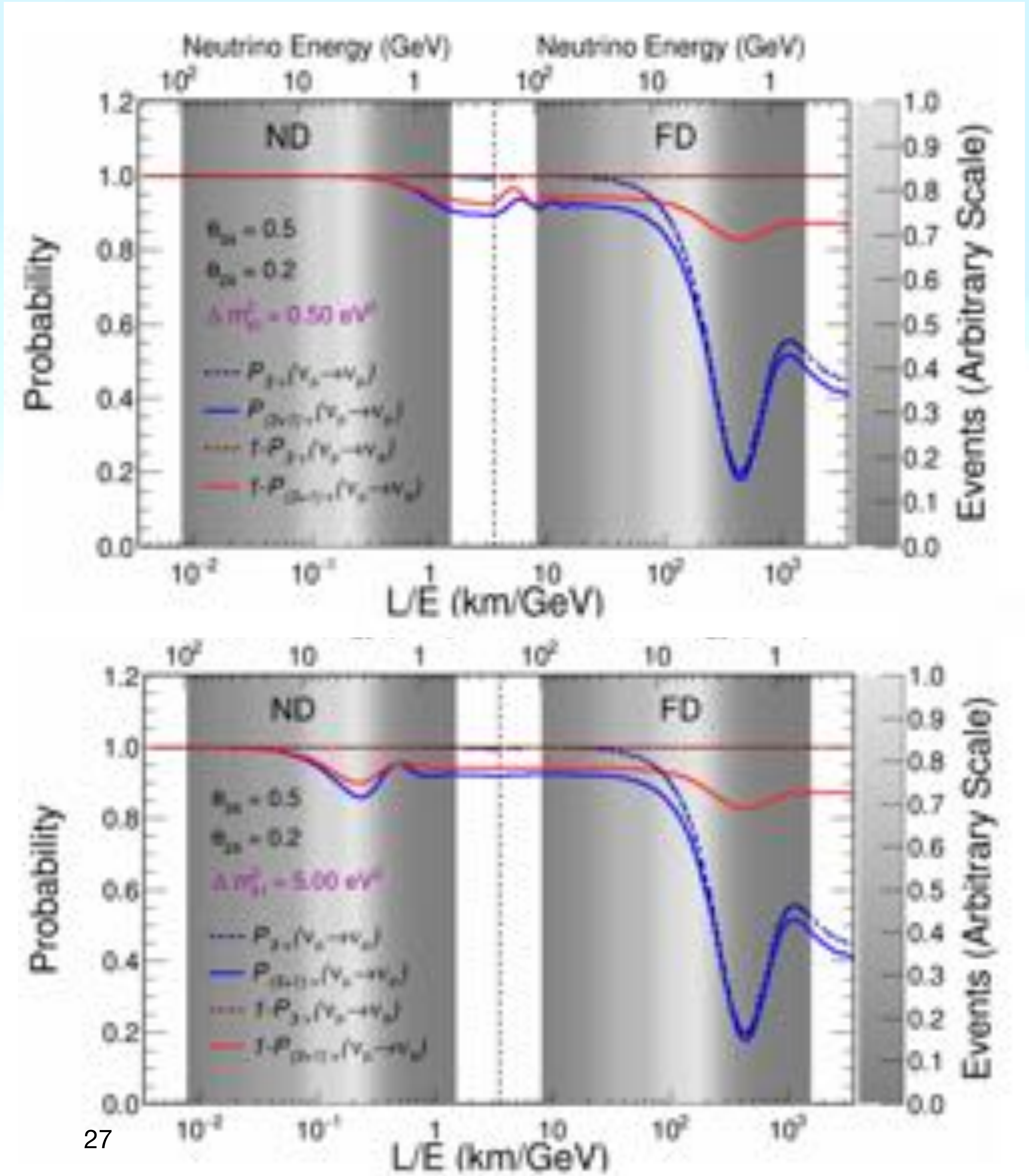
- MINOS was encouraged with $$ to remake their old measurement
- $v_{\nu} = c \pm 1 \times 10^{-6}$
  Phys.Rev.D 92 (2015) 5, 052005
- MINOS best measurement existing of actual travel time of the neutrino

Neutrino time-travel jokes have proliferated on the Internet. Example: “We don’t serve faster-than-light neutrinos here,” said the bartender. A neutrino walks into a bar.

Developments Unforeseen

The power of the 2 detector sterile neutrino search

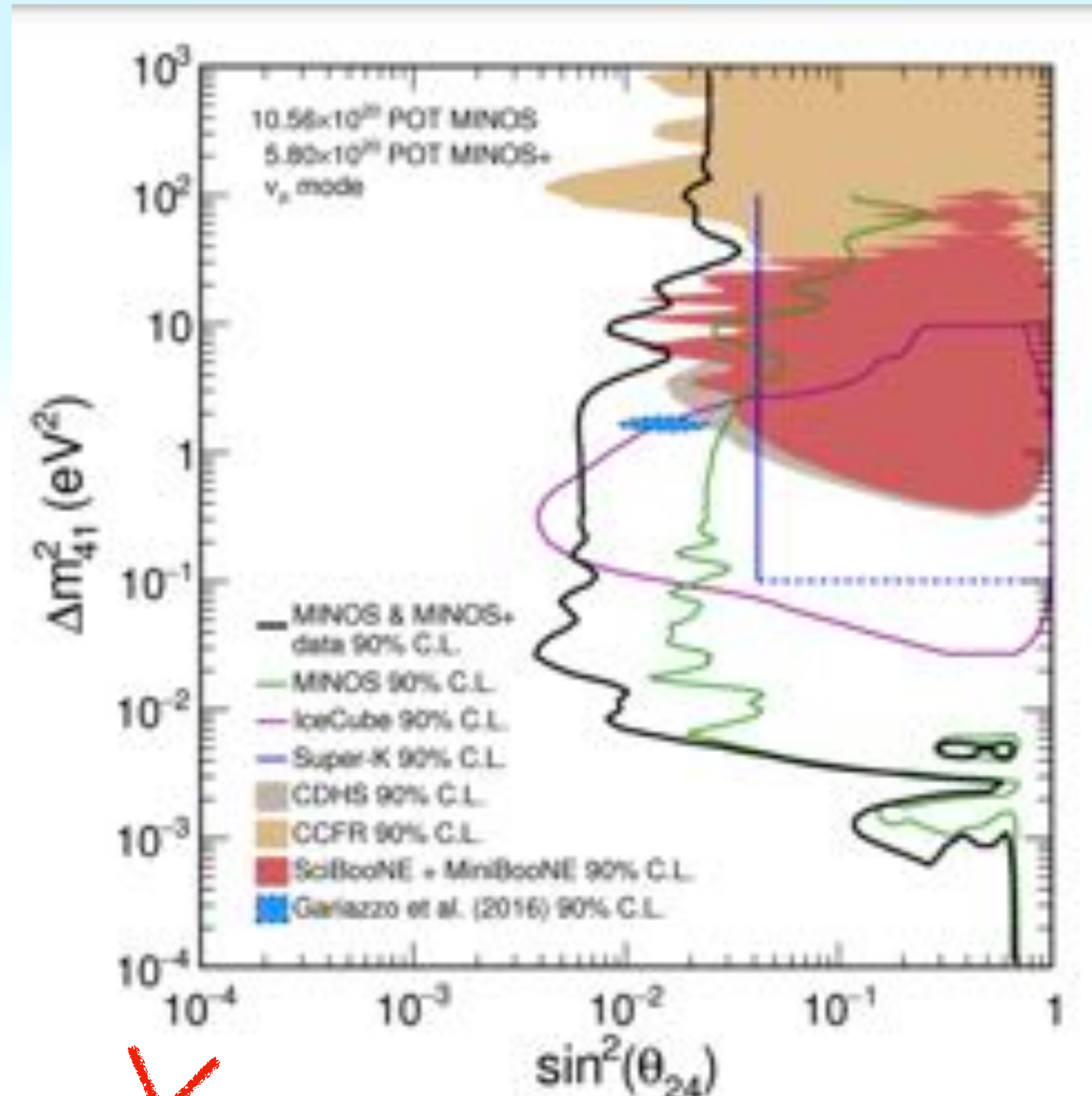
- MINOS is sensitive to three sterile neutrino parameters
    - θ_{24} , θ_{34} and Δm^2_{41}
- Oscillations visible in ND also have a measurable effect in the FD
- Low Δm^2_{41} only affects FD
- High Δm^2_{41} causes rapid oscillations in the ND and a constant deficit in FD
- Using covariance matrix to constrain the signal allowed in both detectors means there is nowhere to hide in such an experiment over large parameter range

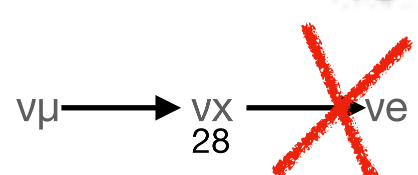


Unitarity and Disappearance

Is there any room for a 4th neutrino?

- Previous experiments looked for ν_μ disappearance but with only one detector
- MINOS/MINOS+ put a large foot print on this plot using newly realised power of the 2 detector covariance technique to weigh in with some very large exclusions
- Blue area was the theorists attempt to combine all existing “positive hints” of the day onto this parameter space
- Clearly, all ruled out

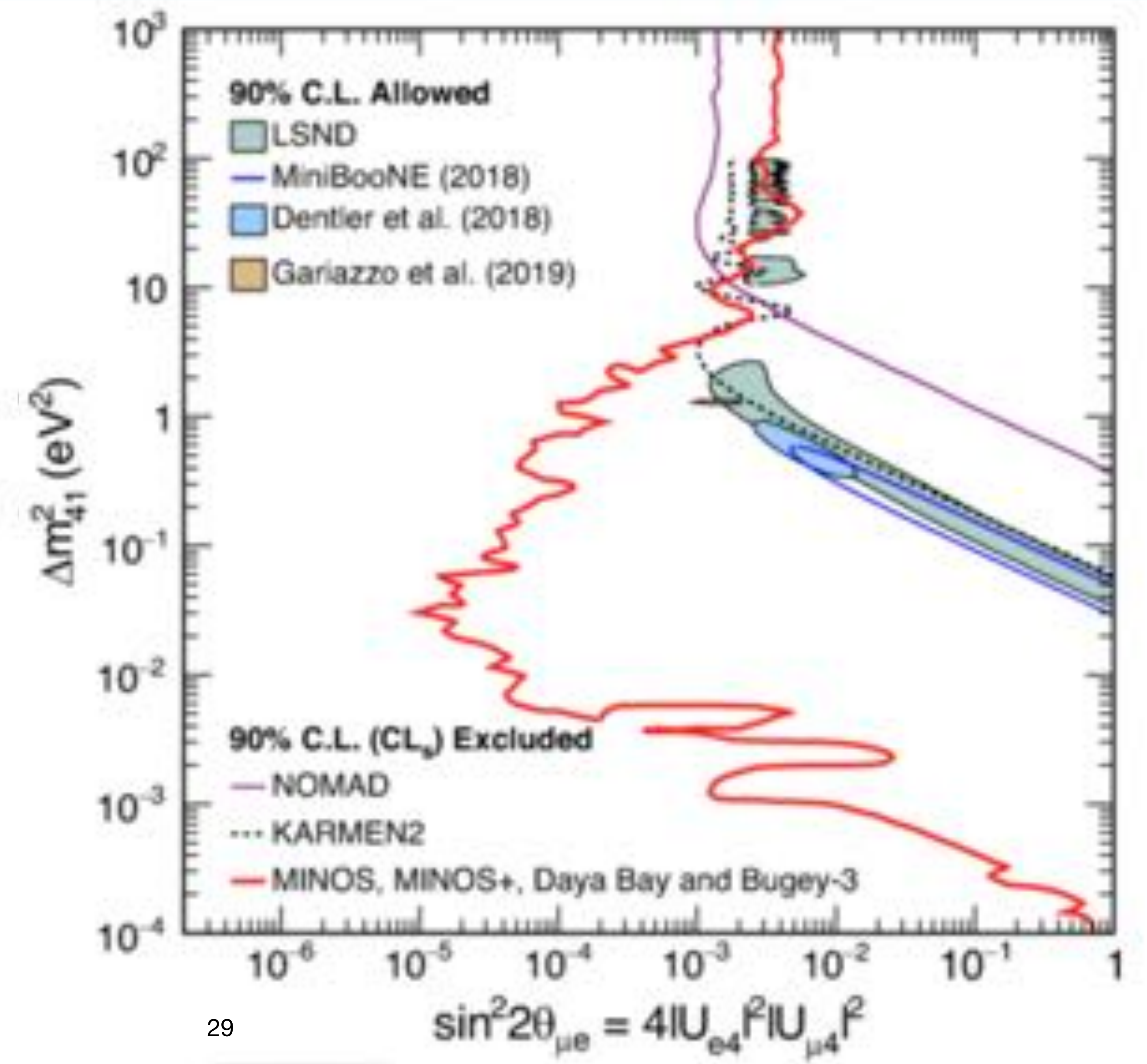




Sterile Neutrinos

They just wont go away

- MINOS/MINOS+ when combined with Daya Bay and Bugey3 reactor experiments, transforms the disappearance parameter space to the appearance parameter space
- at 90% everything observed was ruled out

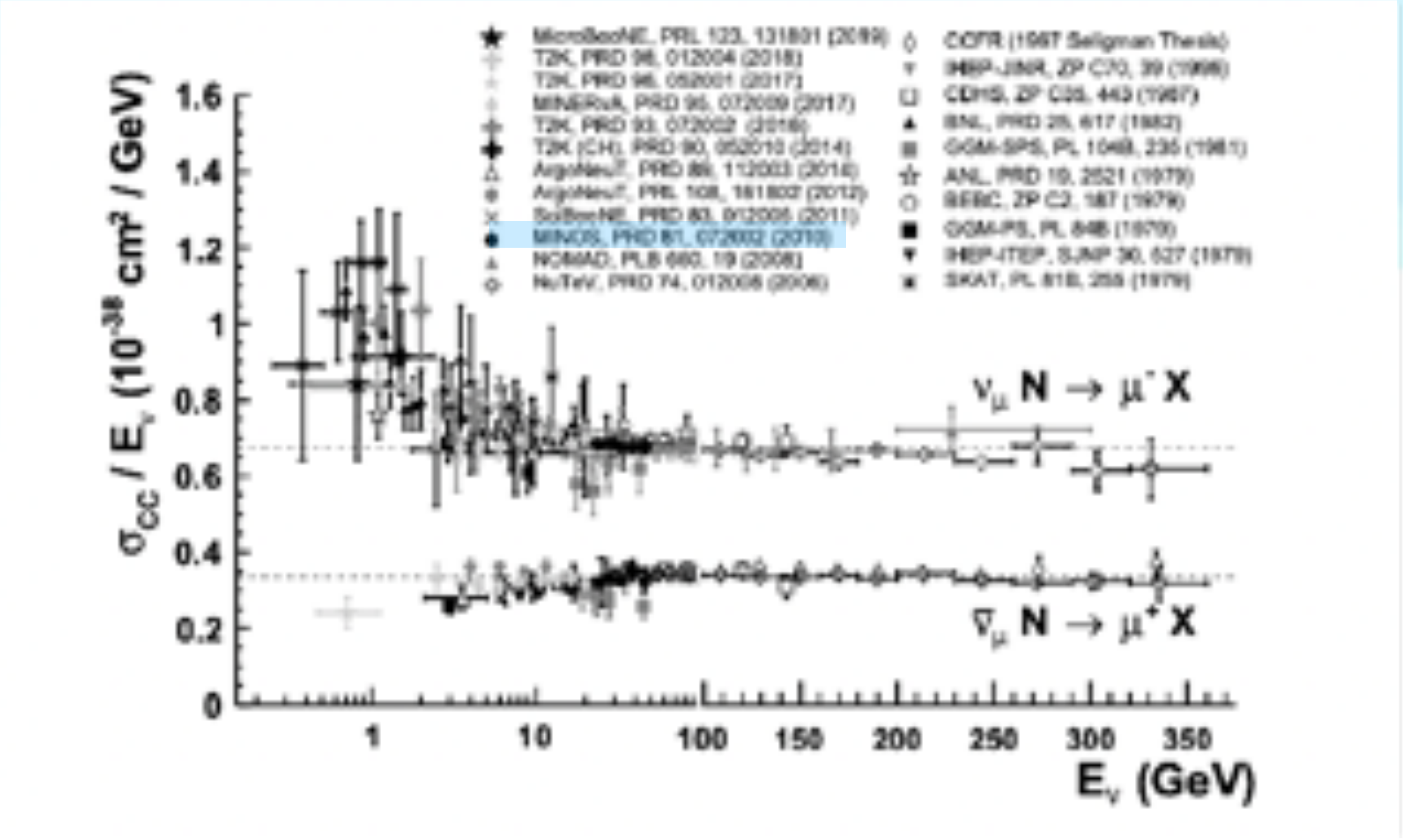


Cross Sections

No neutrino experiment would be complete without

- MINOS contributed cross sections measurements with its near detector across large range of energy

- Dominates still between 10-50 GeV



Cross Sections

No modern experiment would be complete without

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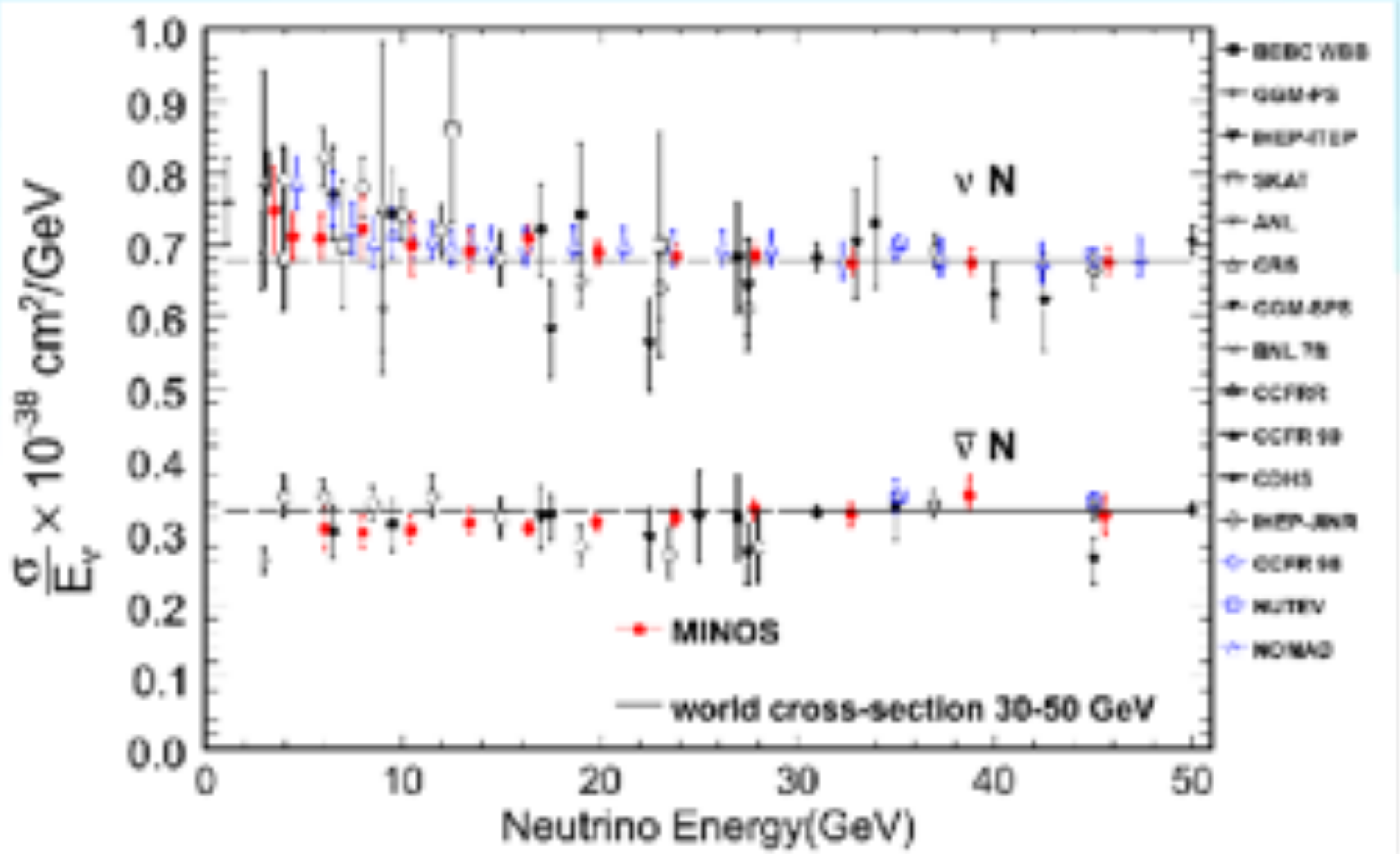


The Numbers

- 250 collaborators (at the peak)
- 10 years from proposal to beam (1995-2005)
- 11 years to collect data (2006-2016)
- 8 Targets (8 MINOS, 1 NOVA)
- 4 horns
- 4 FNAL Directors
- 5 Co-Spokespeople
- 42 papers (so far…)

Improved search for muon-neutrino to electron-neutrino oscillations in MINOS #1

MINOS Collaboration • P. Adamson (Fermilab) et al. (Aug, 2011)

Published in: *Phys.Rev.Lett.* 107 (2011) 181802 • e-Print: 1108.0015 [hep-ex]

pdf links DOI cite claim reference search 910 citations

Observation of muon neutrino disappearance with the MINOS detectors and the NuMI neutrino beam #2

MINOS Collaboration • D.G. Michael (Caltech) et al. (Jul, 2006)

Published in: *Phys.Rev.Lett.* 97 (2006) 191801 • e-Print: hep-ex/0607088 [hep-ex]

pdf links DOI cite claim reference search 895 citations

Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam #3

MINOS Collaboration • P. Adamson (Fermilab) et al. (Jun, 2008)

Published in: *Phys.Rev.Lett.* 101 (2008) 131802 • e-Print: 0806.2237 [hep-ex]

pdf links DOI cite claim reference search 552 citations

Search for sterile neutrinos in MINOS and MINOS+ using a two-detector fit #9

MINOS+ Collaboration • P. Adamson (Fermilab) et al. (Oct 17, 2017)

Published in: *Phys.Rev.Lett.* 122 (2019) 9, 091803 • e-Print: 1710.06488 [hep-ex]

pdf links DOI cite claim reference search 198 citations

The Numbers

2008 paper : 42 individuals moved into academia

FERMILAB-PUB-08-168-E, BNL-xxxx, arXiv:hep-ex/0806.2237

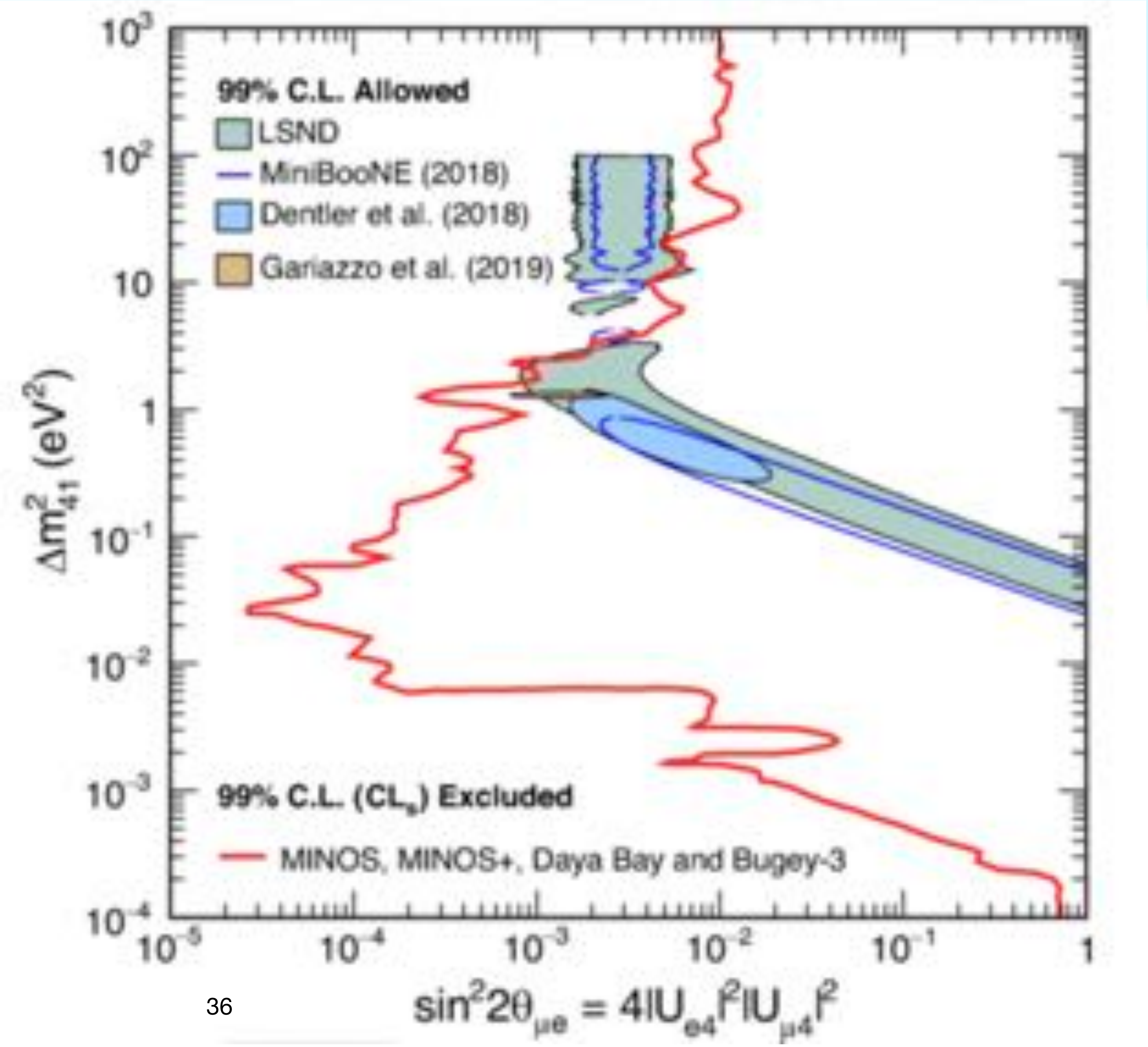
Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam

P. Adamson,[9] C. Andreopoulos,[22] K. E. Arms,[18] R. Armstrong,[12] D. J. Auty,[26] D. S. Ayres,[1] B. Baller,[9] P. D. Barnes Jr.,[16] G. Barr,[20] W. L. Barrett,[31] B. R. Becker,[18] A. Belias,[22] R. H. Bernstein,[9] D. Bhattacharya,[21] M. Bishai,[4] A. Blake,[6] G. J. Bock,[9] J. Boehm,[10] D. J. Boehnlein,[9] D. Bogert,[9] C. Bower,[12] E. Buckley-Geer,[9] S. Cavanaugh,[10] J. D. Chapman,[6] D. Cherdack,[29] S. Childress,[9] B. C. Choudhary,[9] J. H. Cobb,[20] S. J. Coleman,[32] A. J. Culling,[6] J. K. de Jong,[15] M. Dierckxsens,[4] M. V. Diwan,[4] M. Dorman,[17,22] S. A. Dytman,[21] C. O. Escobar,[7] J. J. Evans,[17,20] E. Falk Harris,[26] G. J. Feldman,[10] M. V. Frohne,[3] H. R. Gallagher,[29] A. Godley,[24] M. C. Goodman,[1] P. Gouffon,[23] R. Gran,[19] E. W. Grashorn,[18] N. Grossman,[9] K. Grzelak,[30,20] A. Habig,[19] D. Harris,[9] P. G. Harris,[26] J. Hartnell,[26,22] R. Hatcher,[9] K. Heller,[18] A. Himmel,[5] A. Holin,[17] J. Hylen,[9] G. M. Irwin,[25] M. Ishitsuka,[12] D. E. Jaffe,[4] C. James,[9] D. Jensen,[9] T. Kafka,[29] S. M. S. Kasahara,[18] J. J. Kim,[24] M. S. Kim,[21] G. Koizumi,[9] S. Kopp,[28] M. Kordosky,[32,17] D. J. Koskinen,[17] S. K. Kotelnikov,[15] A. Kreymer,[9] S. Kumaratunga,[18] K. Lang,[28] J. Ling,[24] P. J. Litchfield,[18] R. P. Litchfield,[20] L. Loiacono,[28] P. Lucas,[9] J. Ma,[28] W. A. Mann,[29] A. Marchionni,[9] M. L. Marshak,[18] J. S. Marshall,[6] N. Mayer,[12] A. M. McGowan,[1,18] J. R. Meier,[18] G. I. Merzon,[15] M. D. Messier,[12] C. J. Metelko,[22] D. G. Michael,[5,*] J. L. Miller,[14,*] W. H. Miller,[18] S. R. Mishra,[24] C. D. Moore,[9] J. Morfin,[9] L. Mualem,[5] S. Mufson,[12] S. Murgia,[25] J. Musser,[12] D. Naples,[21] J. K. Nelson,[32] H. B. Newman,[5] R. J. Nichol,[17] T. C. Nicholls,[22] J. P. Ochoa-Ricoux,[5] W. P. Oliver,[29] R. Ospanov,[28] J. Paley,[12] V. Paolone,[21] A. Para,[9] T. Patzak,[8] Ž. Pavlović,[28] G. Pawloski,[25] G. F. Pearce,[22] C. W. Peck,[5] E. A. Peterson,[18] D. A. Petyt,[18] R. Pittam,[20] R. K. Plunkett,[9] A. Rahaman,[24] R. A. Rameika,[9] T. M. Raufer,[22] B. Rebel,[9] J. Reichenbacher,[1] P. A. Rodrigues,[20] C. Rosenfeld,[24] H. A. Rubin,[11] K. Ruddick,[18] V. A. Ryabov,[15] M. C. Sanchez,[1,10] N. Saoulidou,[9] J. Schneps,[29] P. Schreiner,[3] S.-M. Seun,[10] P. Shanahan,[9] W. Smart,[9] C. Smith,[17] A. Sousa,[20] B. Speakman,[18] P. Stamoulis,[2] M. Strait,[18] P. Symes,[26] N. Tagg,[29] R. L. Talaga,[1] M. A. Tavera,[26] J. Thomas,[17] J. Thompson,[21,*] M. A. Thomson,[6] J. L. Thron,[1] G. Tinti,[20] I. Trostin,[13] V. A. Tsarev,[15] G. Tzanakos,[2] J. Urheim,[12] P. Vahle,[32,17] B. Viren,[4] C. P. Ward,[6] D. R. Ward,[6] M. Watabe,[27] A. Weber,[20] R. C. Webb,[27] A. Wehmann,[9] N. West,[20] C. White,[11] S. G. Wojcicki,[25] D. M. Wright,[16] T. Yang,[25] M. Zois,[2] K. Zhang,[4] and R. Zwaska[9]

(The MINOS Collaboration)

Sterile Neutrinos

- MINOS delivered a 99%C.L limit in the supplementary information data release.



The cross check

Is the MiniBooNE result consist with oscillations at all?

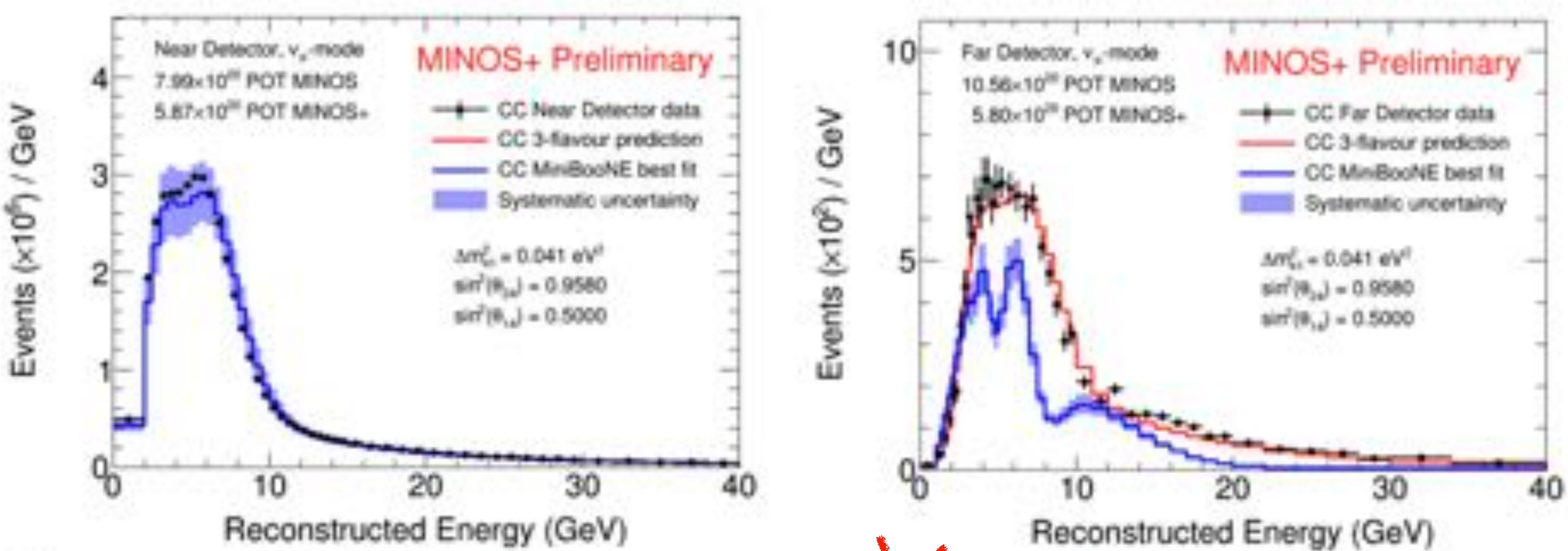
New MiniBooNE paper – arXiv:1805.12028

Best fit: $\Delta m^2 = 0.041\ \mathrm{eV}^2$ and $\sin^2 2\theta_{\mu e} = 0.958$

$$\sin^2_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24}$$

Take $\sin^2 2\theta_{14} = 1$ to minimize ν_μ disappearance

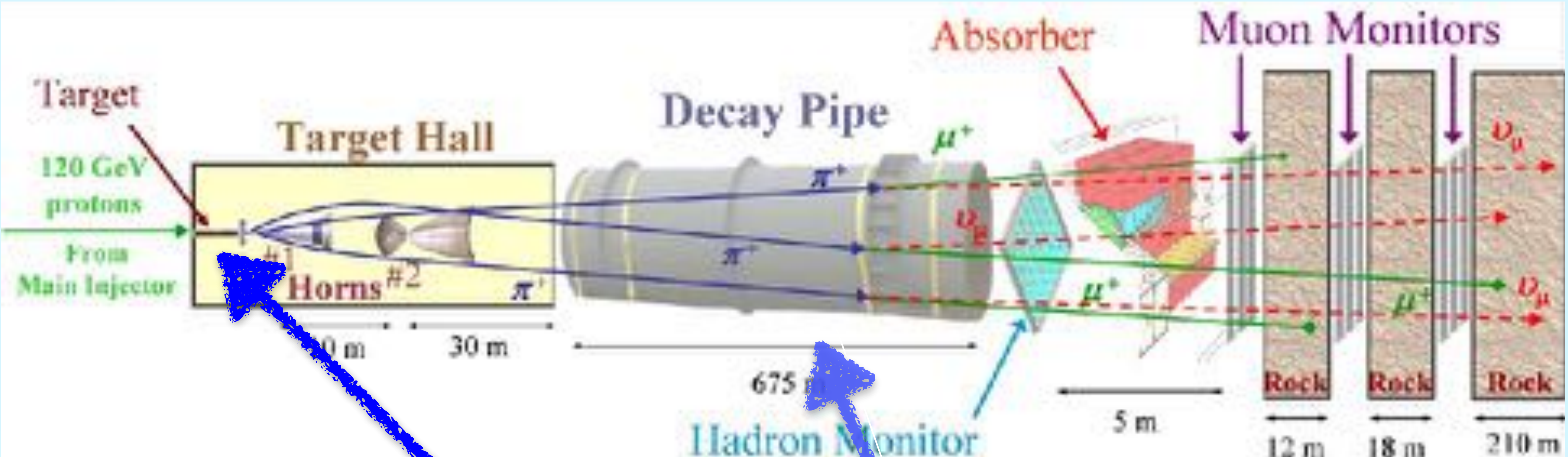
If you accept Unitarity

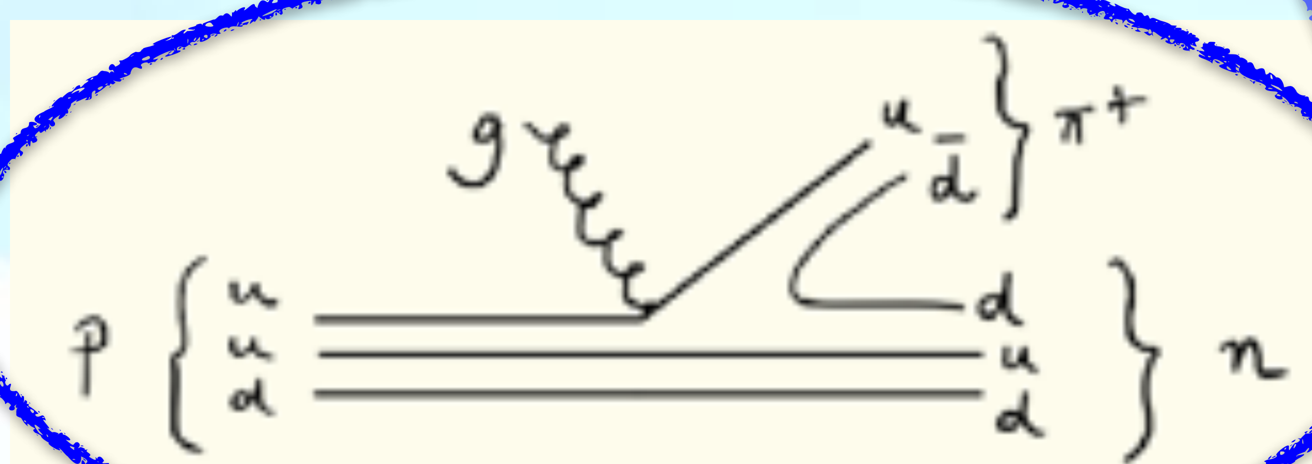


Near Detector

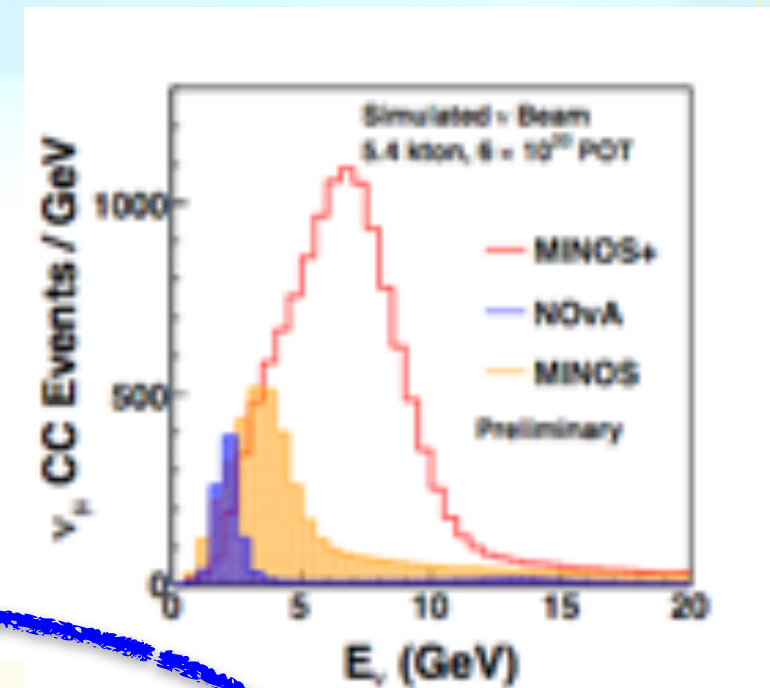
$\nu\mu \rightarrow \nu x \rightarrow \nu e$

Far Detector



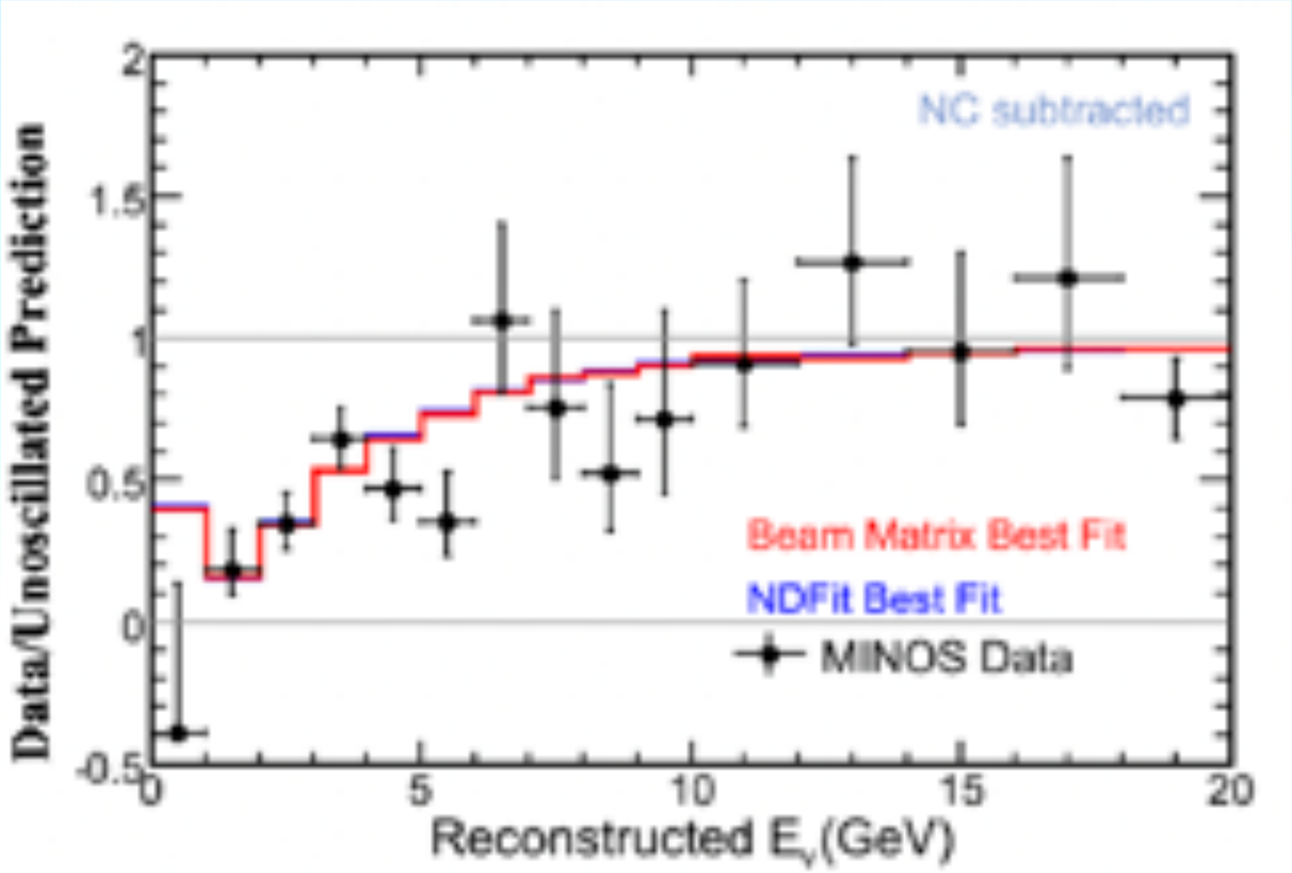


$$\pi^+ \longrightarrow \mu^+ \nu_\mu$$



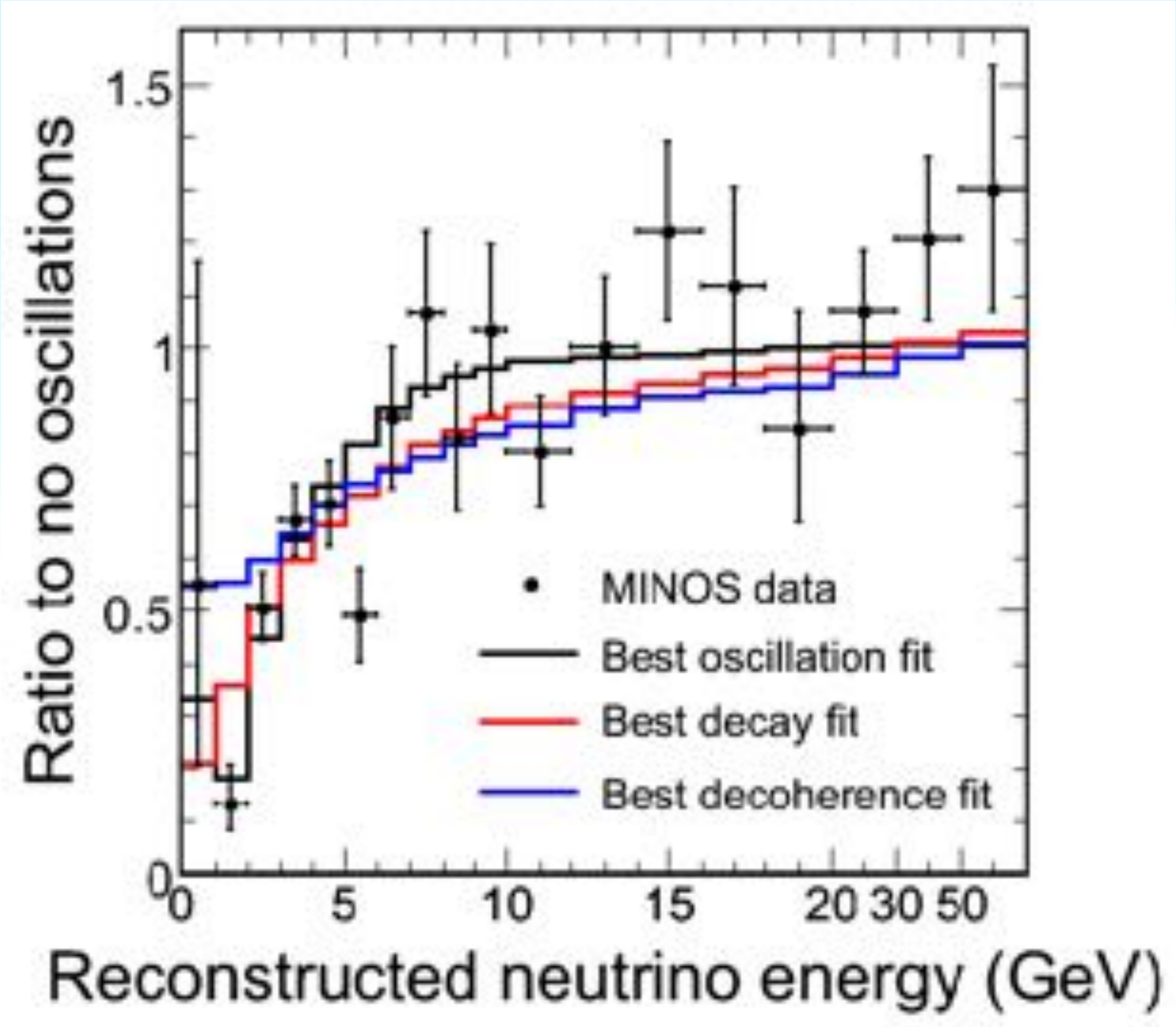
The NuMI Beam

2006

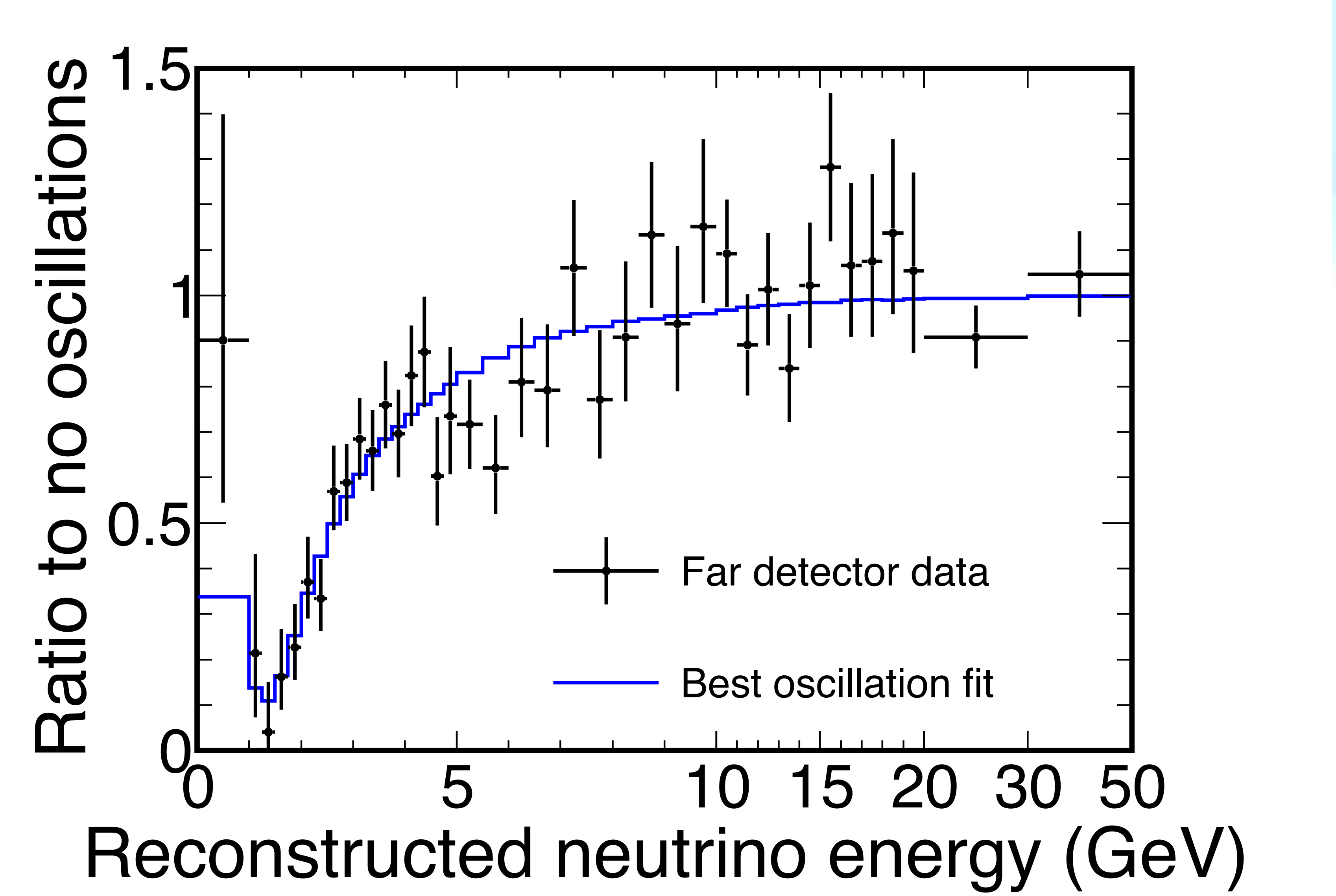


NC subtracted
Beam Matrix Best Fit
NDFit Best Fit
MINOS Data
Data/Unoscillated Prediction
Reconstructed E_ν(GeV)

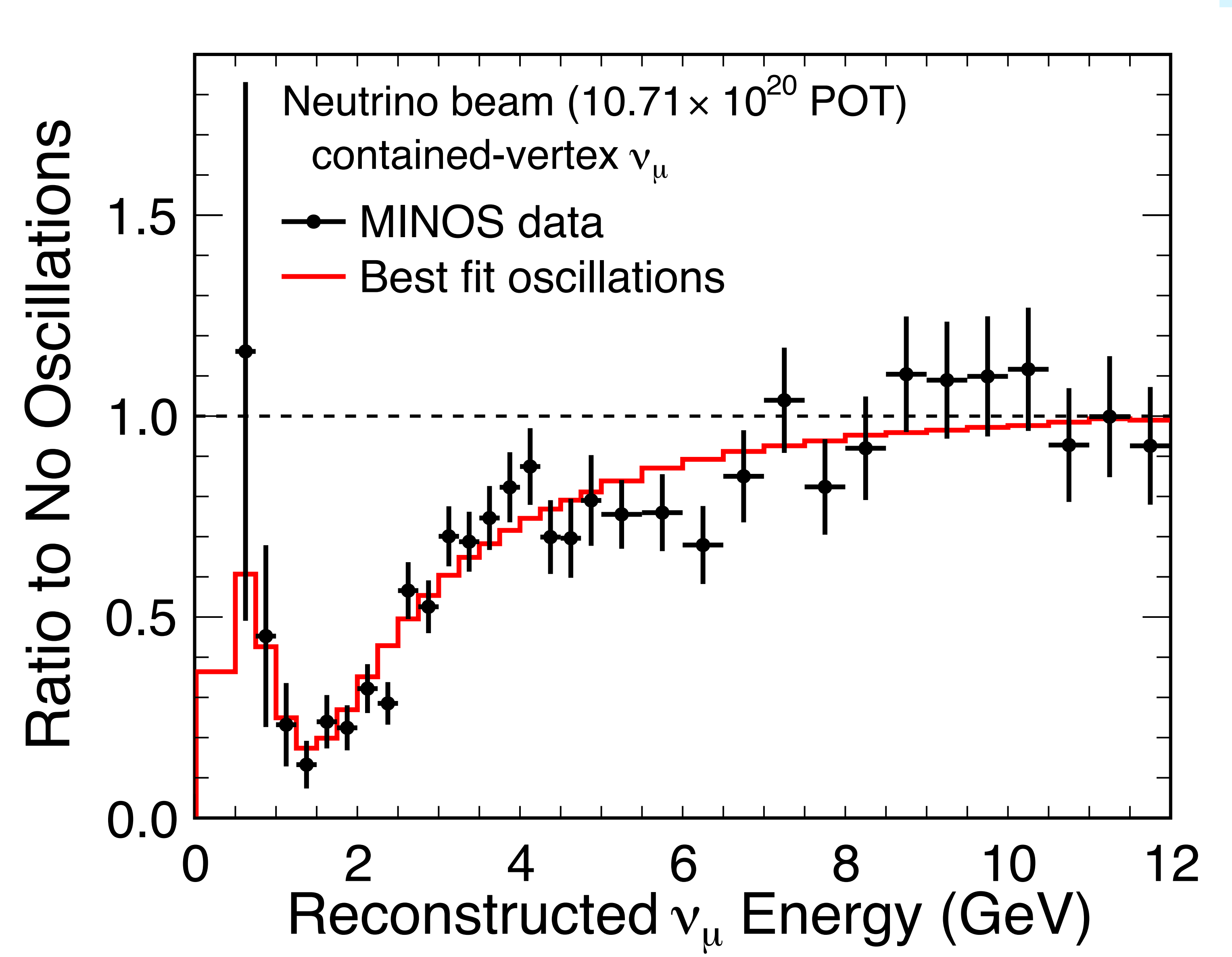
2008

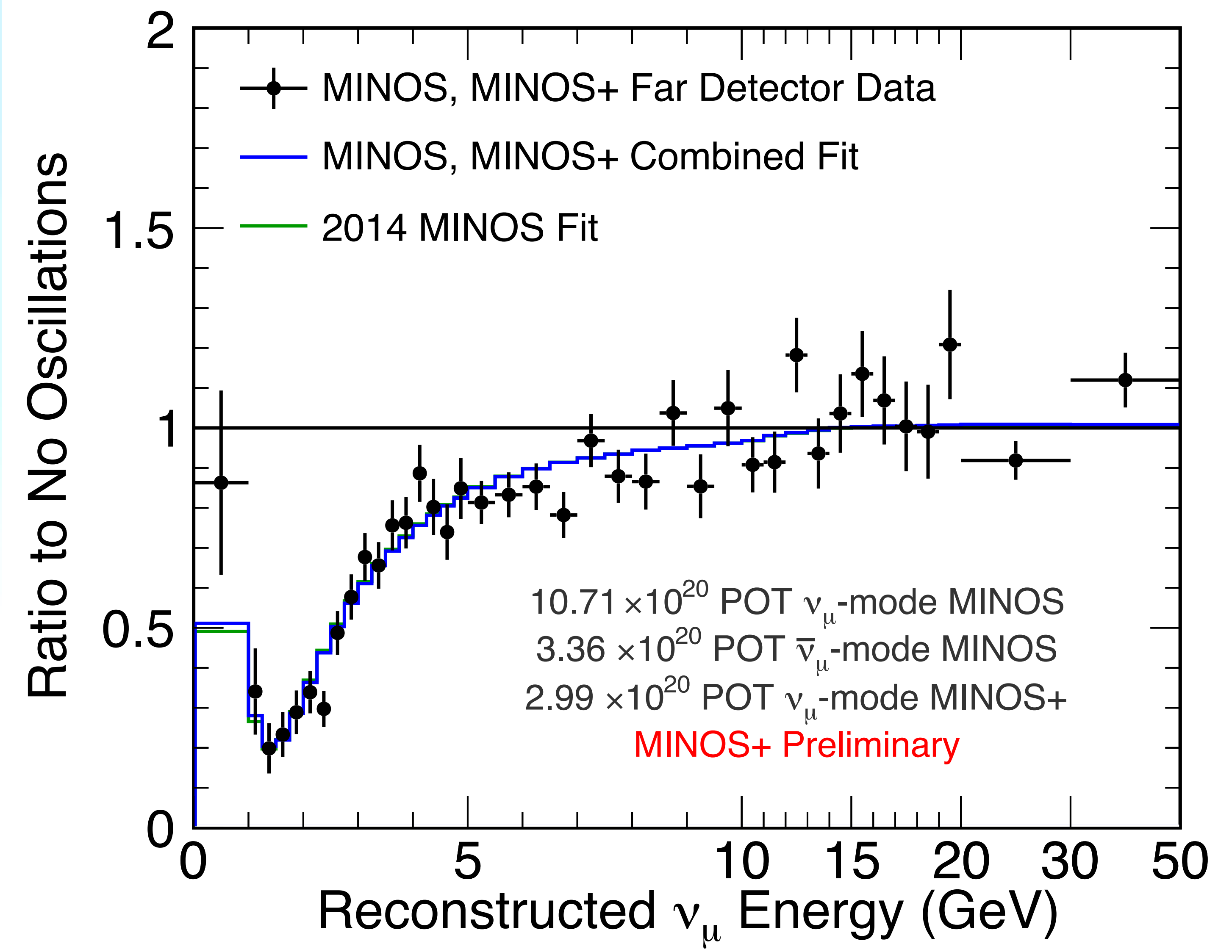


Ratio to no oscillations
1.5
1
0.5
0
0
5
10
15
20 30 50
Reconstructed neutrino energy (GeV)
MINOS data
Best oscillation fit
Best decay fit
Best decoherence fit

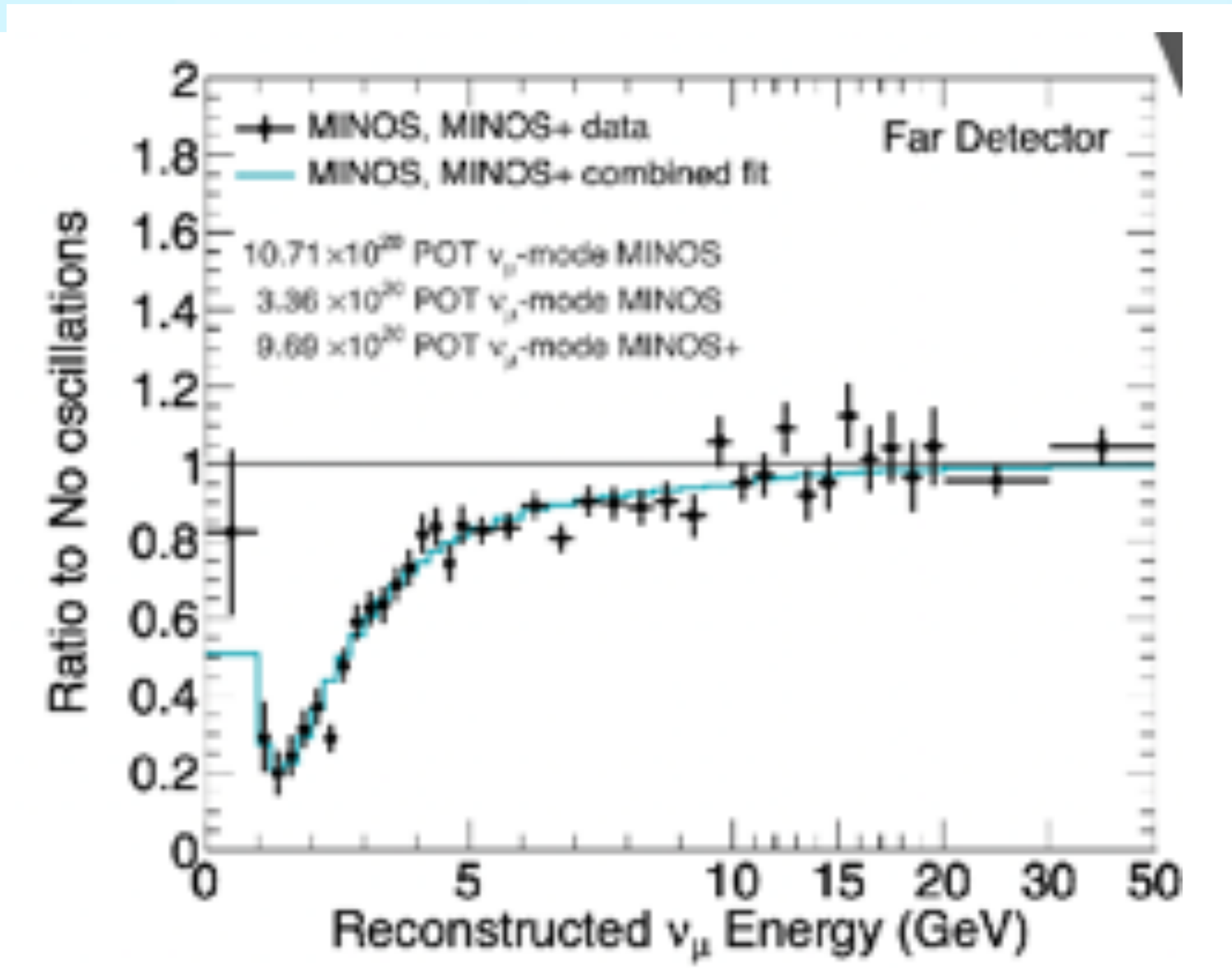

Ratio to no oscillations
1.5
1
0.5
0
Far detector data
Best oscillation fit
0
5
10
15
20
30
50
Reconstructed neutrino energy (GeV)

2014


Neutrino beam (10.71× 10^20 POT)
contained-vertex νμ
MINOS data
Best fit oscillations
Ratio to No Oscillations
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
Reconstructed νμ Energy (GeV)


MINOS, MINOS+ Far Detector Data
MINOS, MINOS+ Combined Fit
2014 MINOS Fit
10.71×10^{20} POT ν_μ-mode MINOS
3.36×10^{20} POT $\bar{\nu}_\mu$-mode MINOS
2.99×10^{20} POT ν_μ-mode MINOS+
MINOS+ Preliminary
Ratio to No Oscillations
Reconstructed ν_μ Energy (GeV)
0
0.5
1
1.5
2
0
5
10
15
20
30
50

2020


MINOS, MINOS+ data
MINOS, MINOS+ combined fit
Far Detector
10.71 ×10^20 POT ν_μ-mode MINOS
3.36 ×10^20 POT ν_μ-mode MINOS
9.69 ×10^20 POT ν_μ-mode MINOS+
Ratio to No oscillations
Reconstructed ν_μ Energy (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
5
10
15
20
30
50