Muon Neutrino Disappearance and Tau Neutrino Appearance

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Physics in Collision 2011 - Vancouver, Canada

Neutrino Oscillations

- The flavor eigenstates are linear combinations of the mass eigenstates.

$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k}|\nu_k\rangle \quad (\alpha = e,\mu,\tau)$$

- There is a non-zero probability of detecting a different neutrino flavor than that produced at the source.

$$\langle \nu_\beta(t)|\nu_\alpha(0)\rangle = \sum_k U^*_{\beta k} U_{\alpha k} e^{-iE_k t}$$

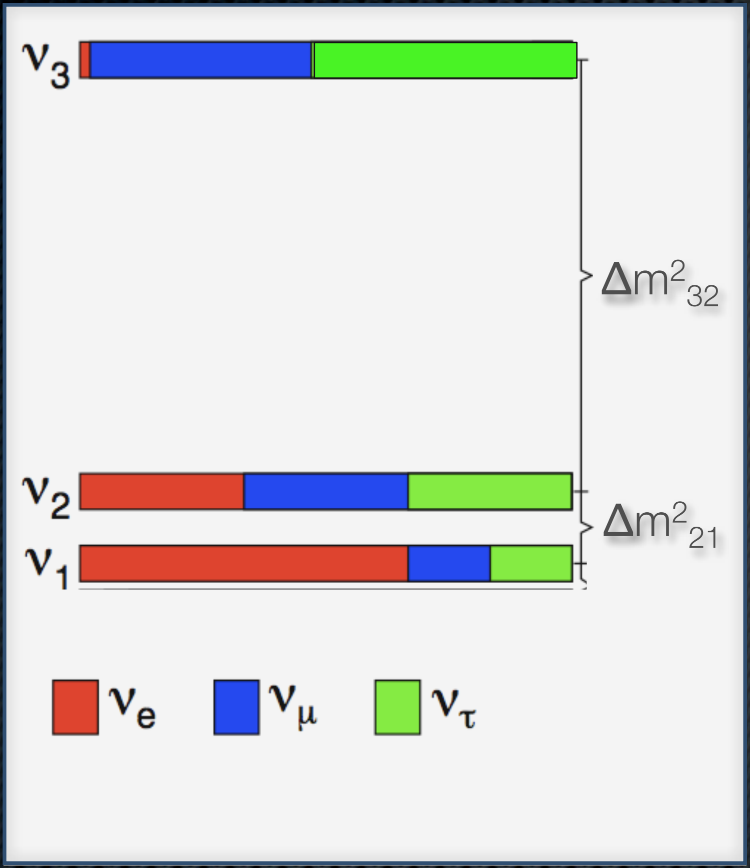
- The PMNS mixing matrix can be factorized into 3 sectors:

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(23) Sector: atmospheric and accelerator, L/E~500 km/GeV
(13) Sector: Reactor+accelerator. See next talk
(12) Sector: Reactor + Solar, L/E~15,000 km/GeV

Neutrino masses and mixing

What is the current experimental picture?

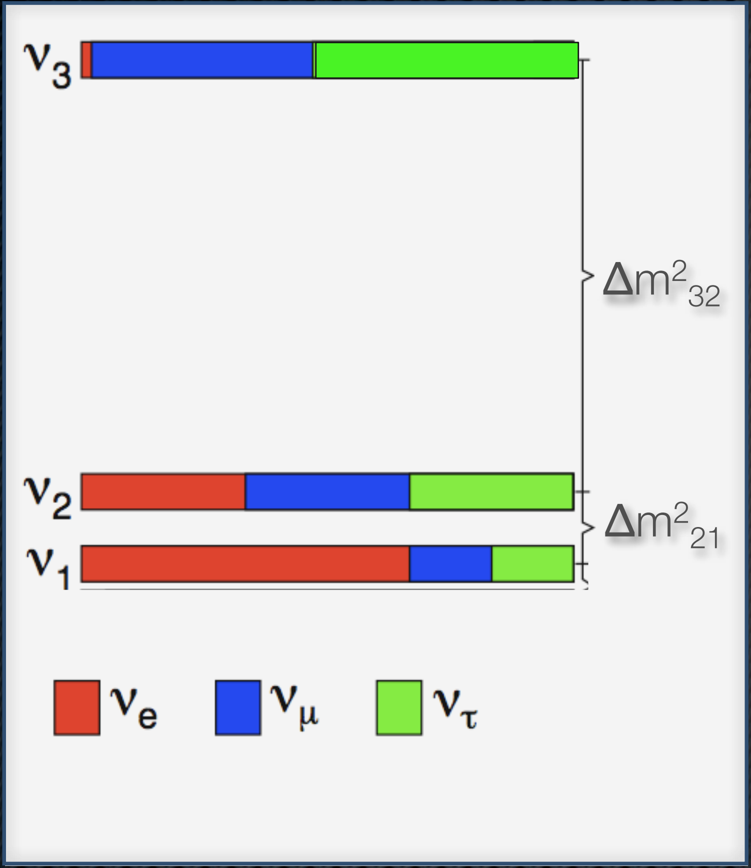


New results from this summer 2011!

- Two mass scales:
  - **The atmospheric mass scale: Δm^2_{32}**
  - The solar mass scale: Δm^2_{21}
- **Large mixing angle for atmospheric neutrino oscillations.**
- Solar neutrino oscillations are subject to matter effects. Non maximal mixing angle.
- Mass ordering known for the solar mass scale. Not known for the atmospheric.
- Third mixing angle is small and has not yet been measured.

What can we do with...

Accelerator neutrinos (long baseline)
and also atmospheric neutrinos (Super-K)



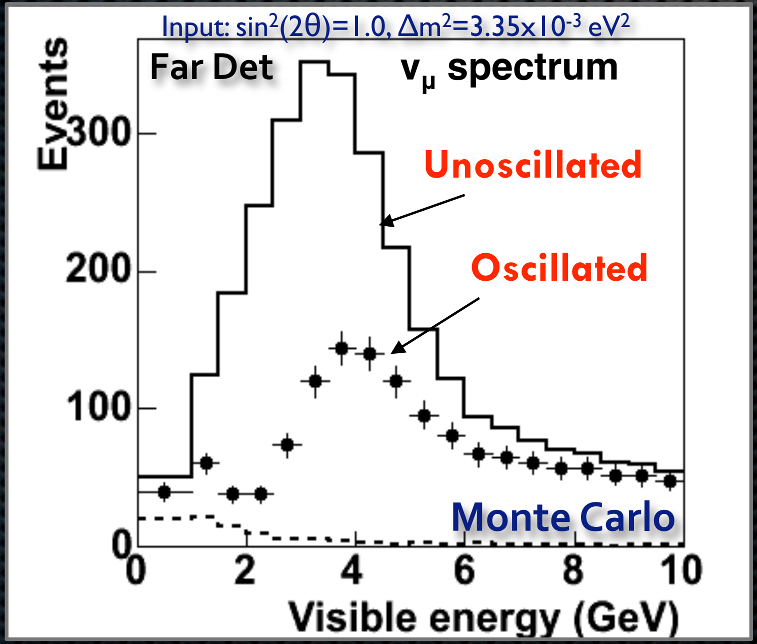
- **The atmospheric mass scale: Δm^2_{32}.**
- **Large mixing angle for atmospheric neutrino oscillations: θ_{23}.**
- **Differences between $\Delta m^2_{32}/\Delta \bar{m}^2_{32}$**
- The third mixing angle: θ_{13}.
- CP violation: δ_{CP}.
- Mass ordering for the atmospheric oscillations: the sign of Δm^2_{32}.

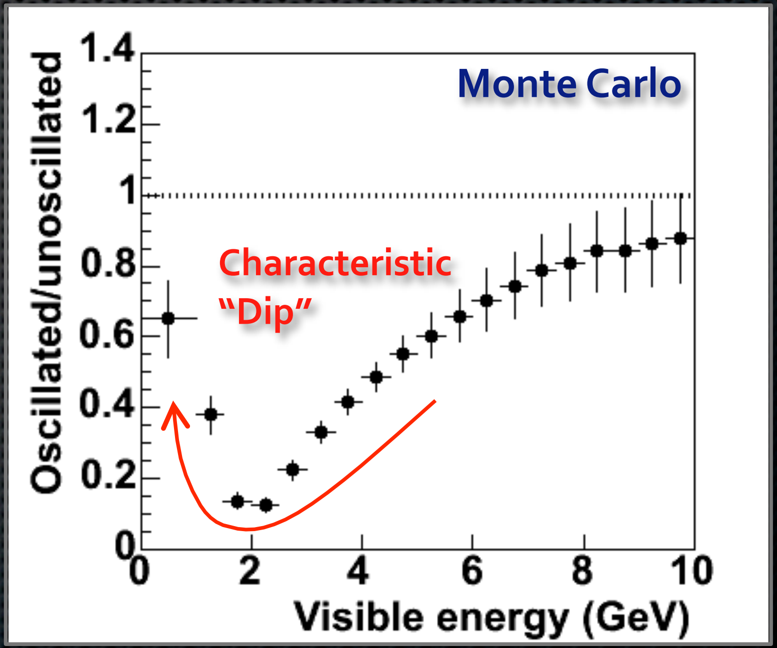
Experiments: MINOS, Super-K, Opera,T2K, NOvA

ν_μ disappearance

- In long baseline experiments, we compare a prediction obtained from Near Detector data with a Far Detector measurement.
  - Neutrino oscillations deplete rate and distort the energy spectrum.

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$





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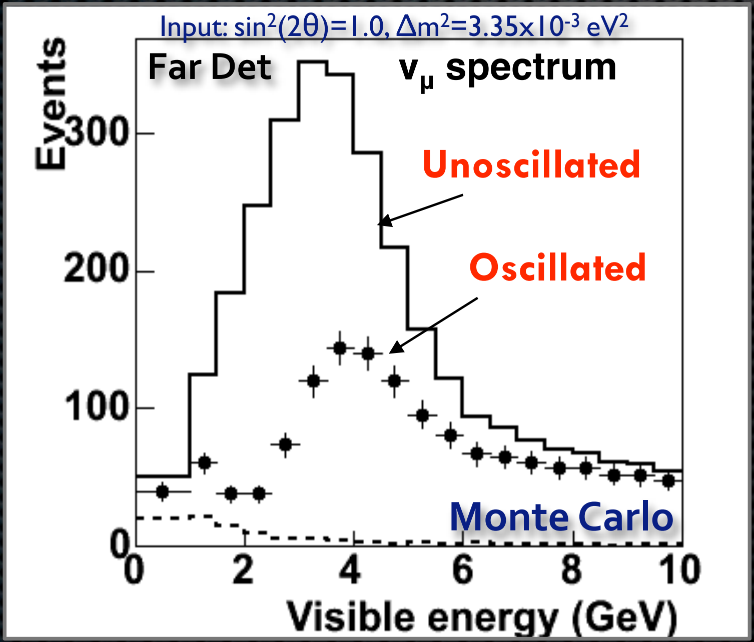
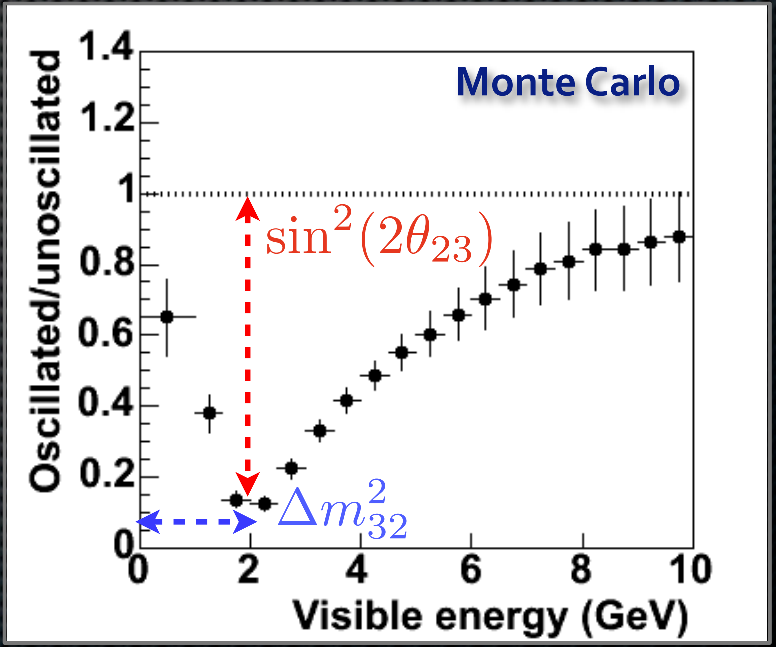




MINOS in a nutshell

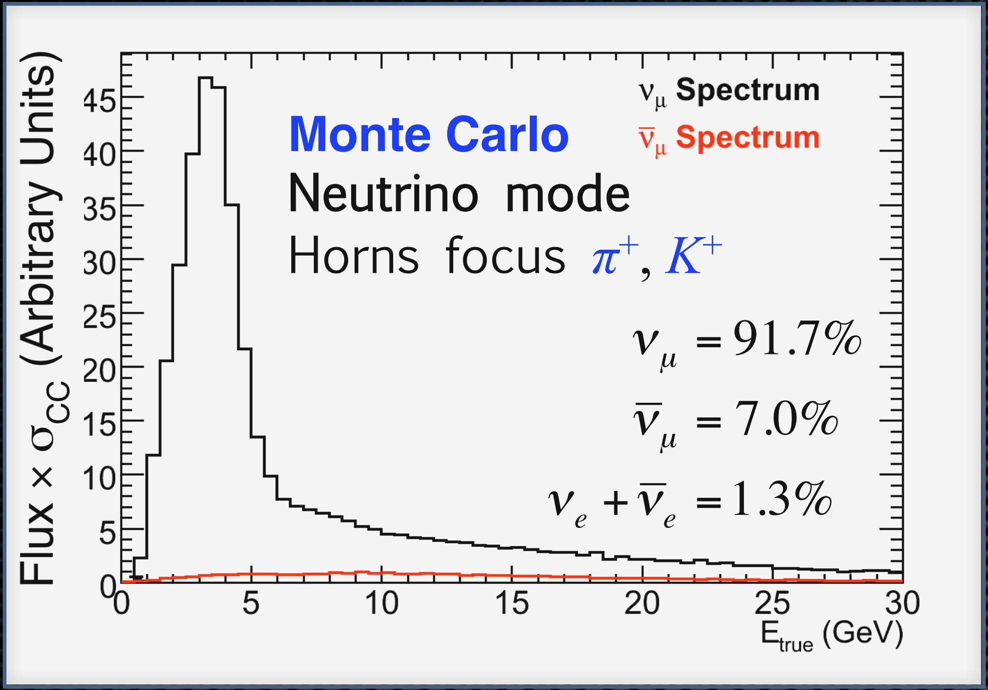
Main **I**njector **N**eutrino **O**scillation **S**earch

- Produce a high intensity beam of muon neutrinos at Fermilab.
- Measure these neutrinos at the Near Detector and use it to predict the Far Detector spectrum.
- If neutrinos oscillate we will observe a distortion in the data at the Far Detector in Soudan.

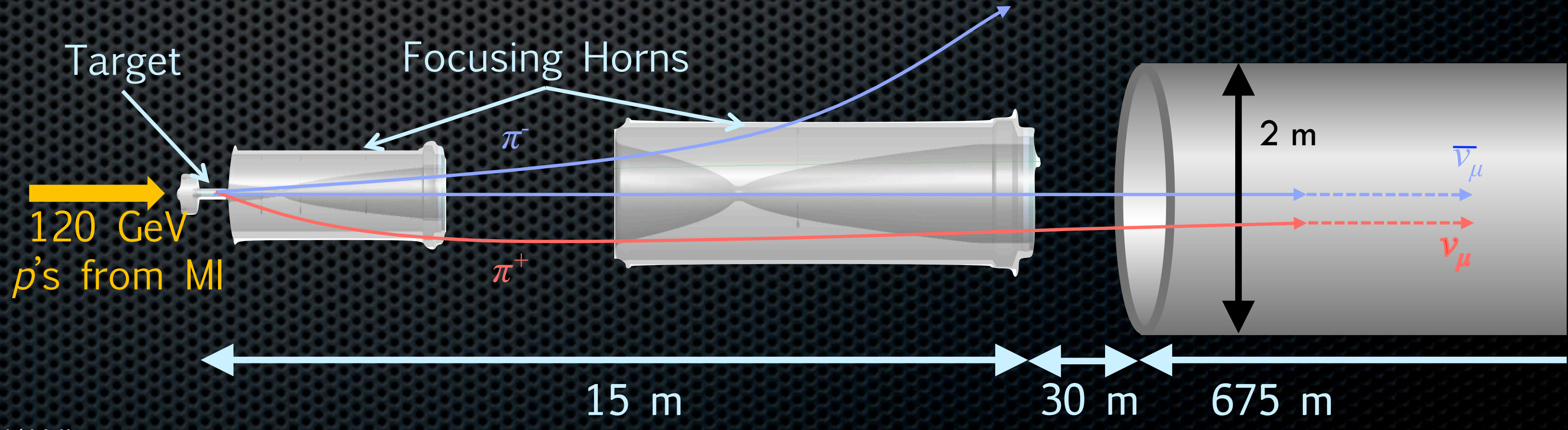
←long baseline→
735 km

Taking data since 2005!

Producing Neutrinos with NuMI



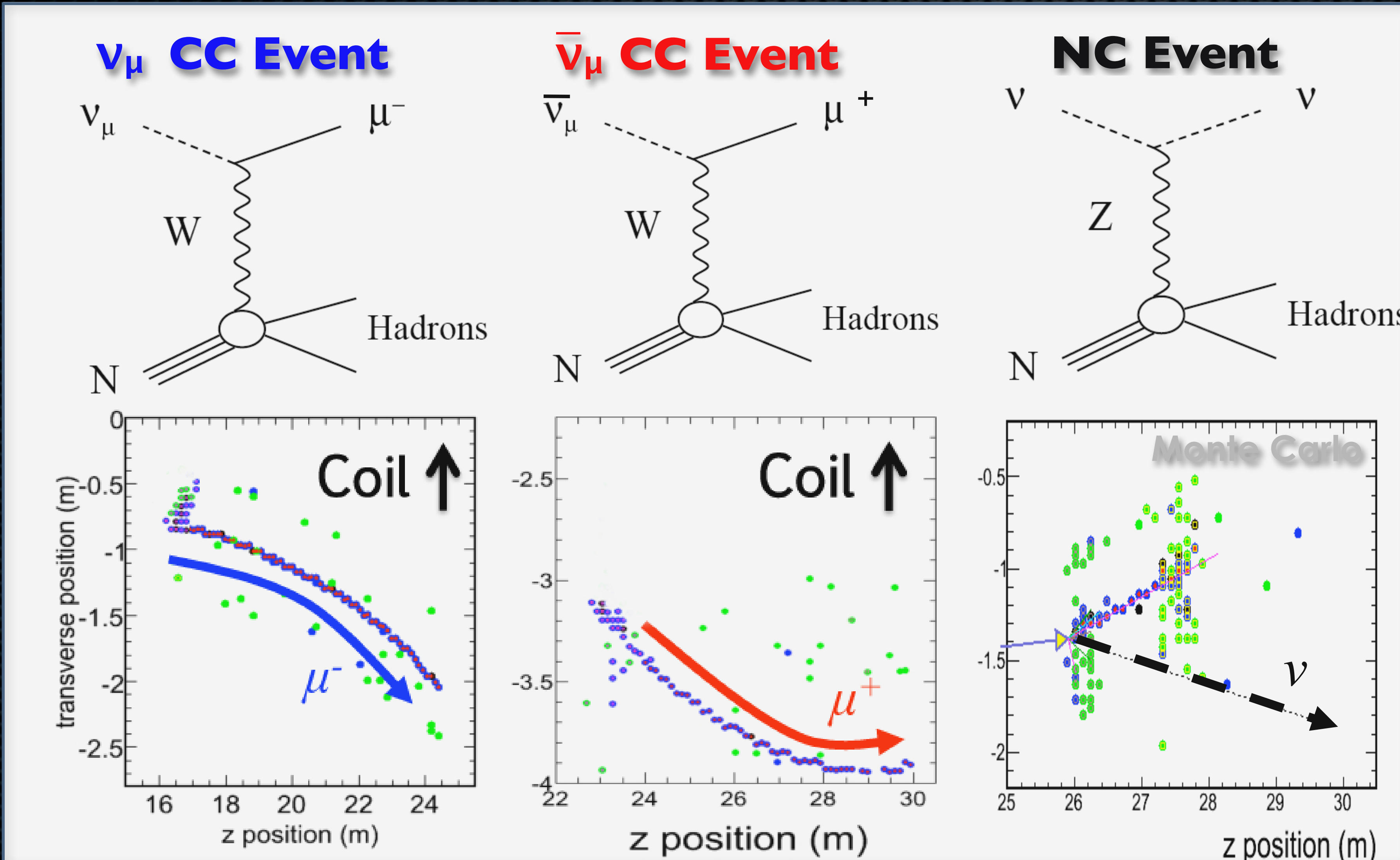
- Horns are positive pions and kaons which decay into neutrinos.
- Higher energy anti-neutrinos from very forward negative pions.
- Most of MINOS data is taken in this configuration.



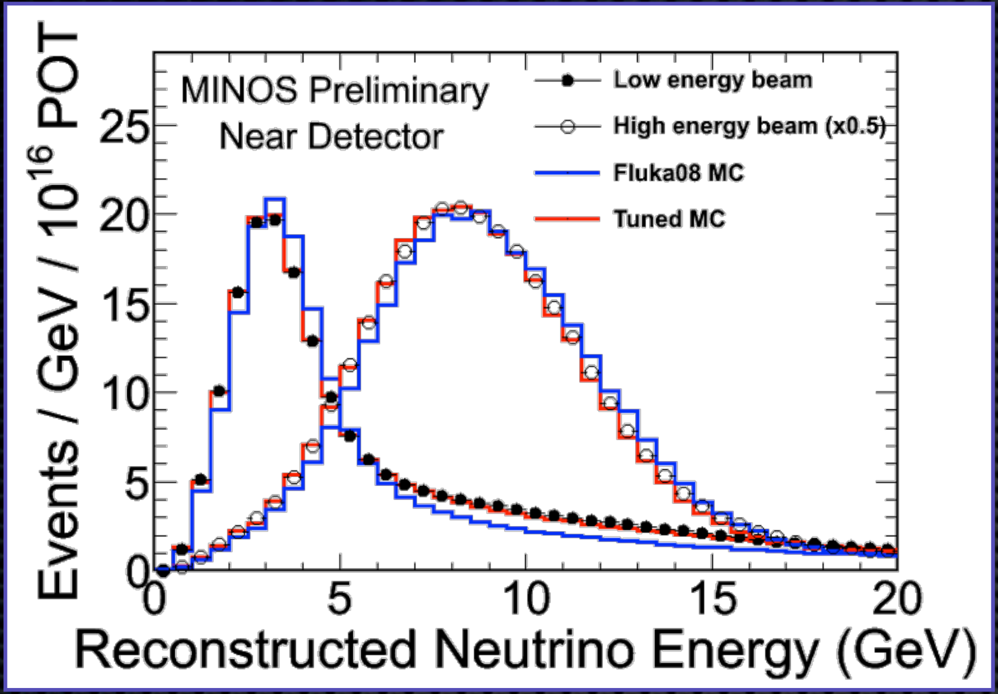
The MINOS detectors

- Functionally identical: **Near and Far detectors**
- Octogonal steel planes (2.54cm thick ~$1.44X_0$). **Magnetized detector.**
- Alternating with planes of scintillator strips (4.12cm wide, Moliere rad ~3.7cm).
  - **Near (ND)**: ~ 1kton, 282 steel squashed octagons. Partially instrumented.
  - **Far (FD)**: 5.4 kton, 486 (8m/octagon) fully instrumented planes.

MINOS Event Topologies



ν_μ CC events in the Near Detector

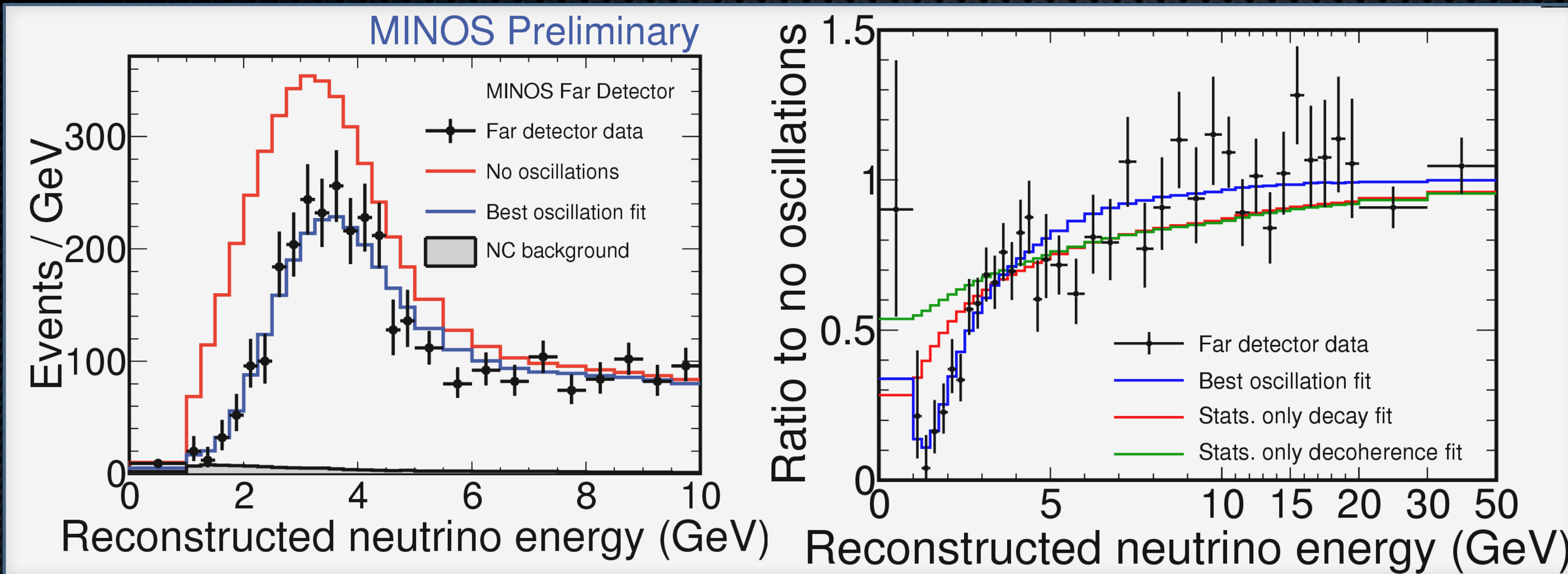


- The beam spectrum can be tuned by varying relative positions of target and magnetic horns.
- We use ν_μ CC events in ND to constrain flux using 7 beam configurations.
- NA49 data used to constrain π^+/π^- and π/K ratios in fits.

- Majority of data is from the low energy beam.
- High energy beam improves statistics in energy above the oscillation dip.
- Additional exposure in other beam configurations for commissioning and systematic studies.

- **Use Near Detector data to predict Far Detector spectrum.**

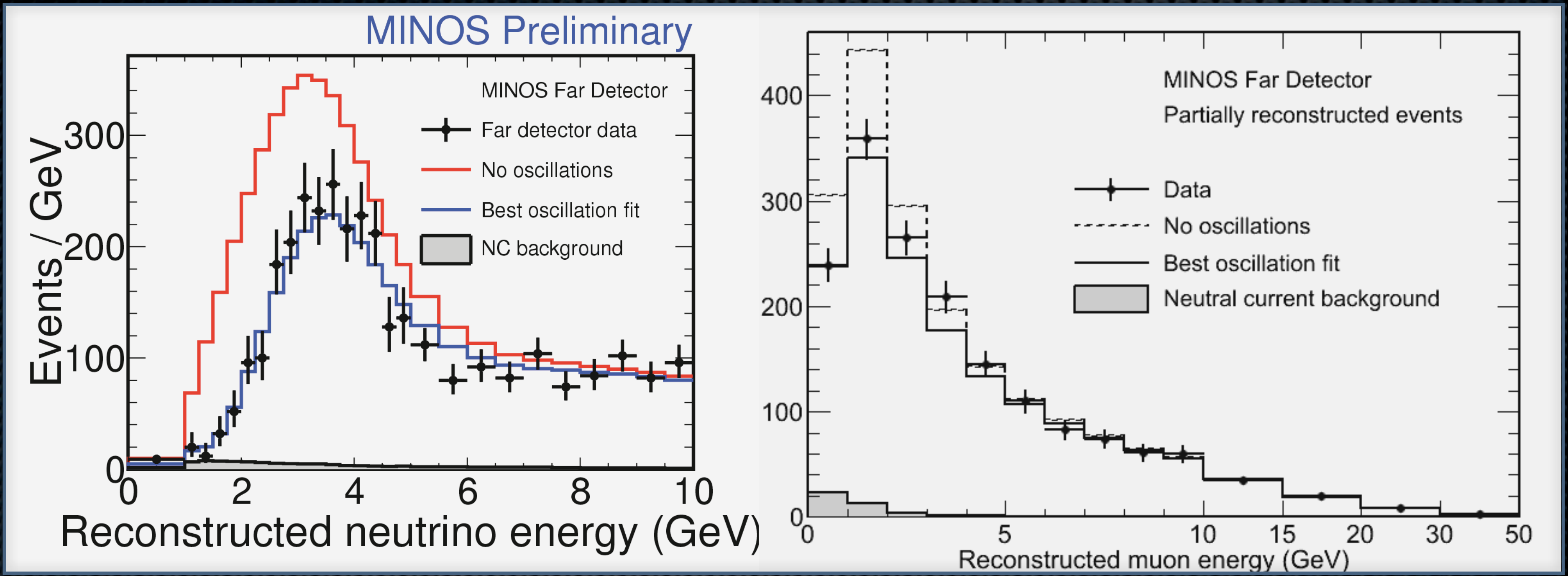
MINOS ν_μ disappearance



Contained: Expect **2451**. Observe **1986.**

- Oscillations fit well.
- Pure decoherence disfavored at 8 σ.
- Pure decay disfavored at 6 σ.

MINOS ν_μ disappearance



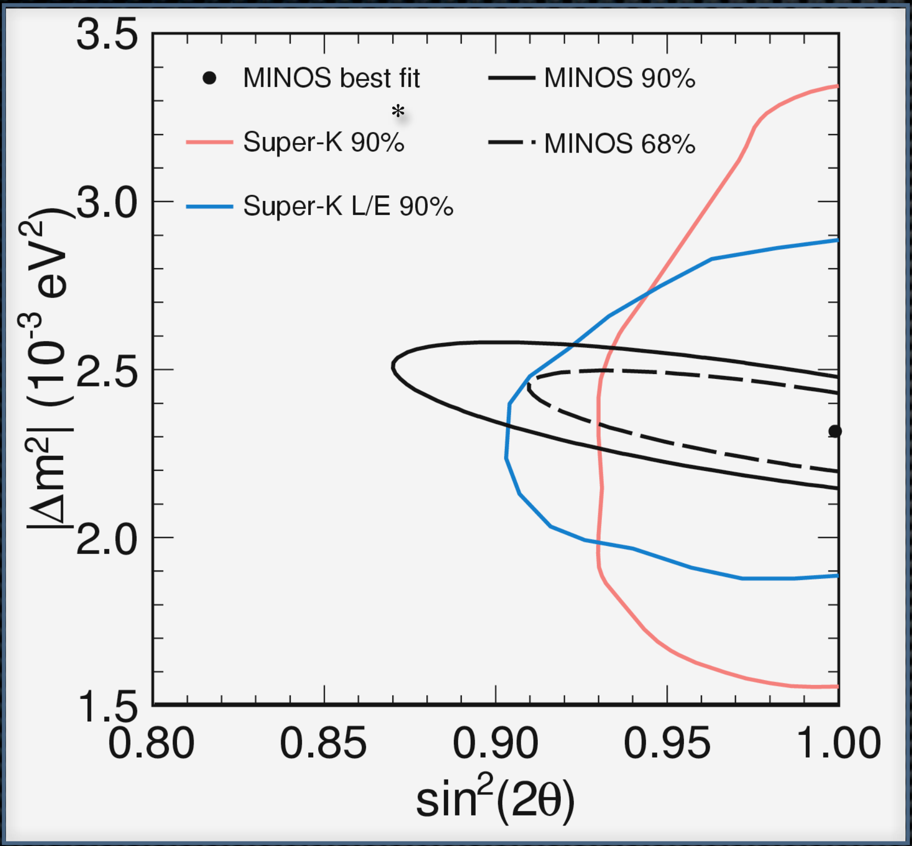
Contained: Expect **2451**. Observe **1986.**

Non-contained: Expect **2206**. Observe **2017.**

- Oscillations fit well. 66% of simulated experiments have worse χ^2 than the data.
- Pure decoherence disfavored at 9 σ (contained only 8 σ).
- Pure decay disfavored at 7 σ (contained only 6 σ).

P. Adamson *et al.*, Phys.Rev.Lett. 106 181801 (2011)

MINOS ν_μ disappearance



- Study ν_μ disappearance as a function of energy.
- Precision measurements of Δm^2_{32} and $\sin^2(2\theta_{23})$.

$$\left|\Delta m^2\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.90 \ (90\%\ \mathrm{C.L.})$$

- World's best measurement: ~ 5% in Δm^2_{32}.

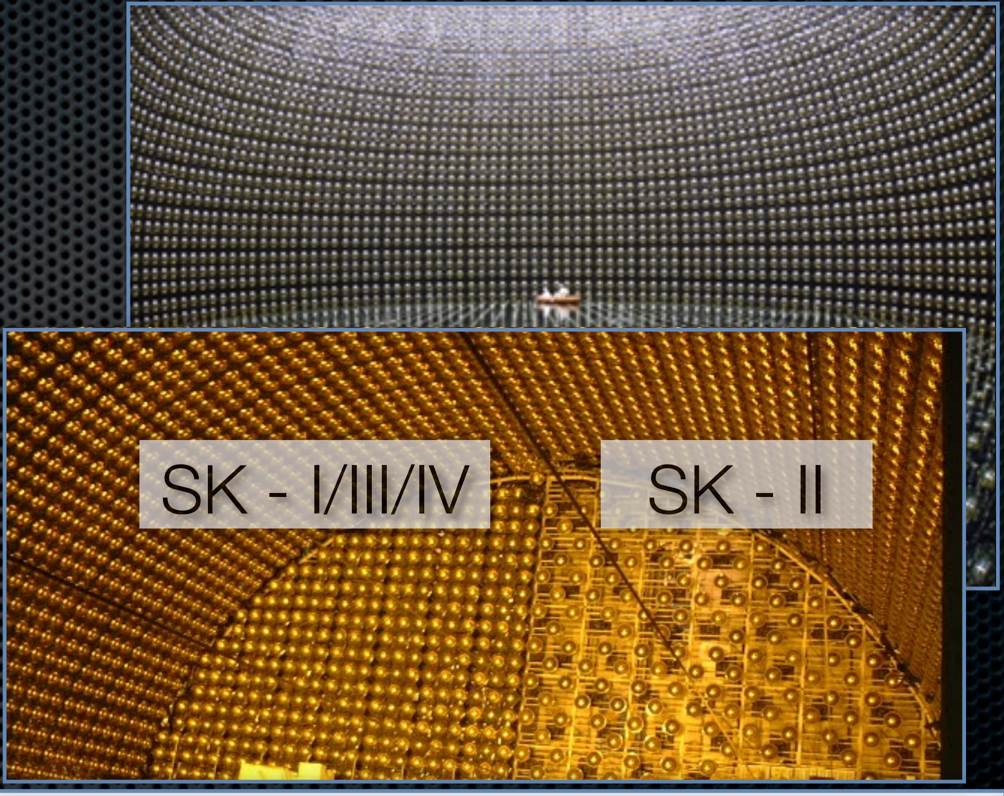
- Contour includes dominant systematic uncertainties:
  - normalization, NC background, shower energy and track energy.

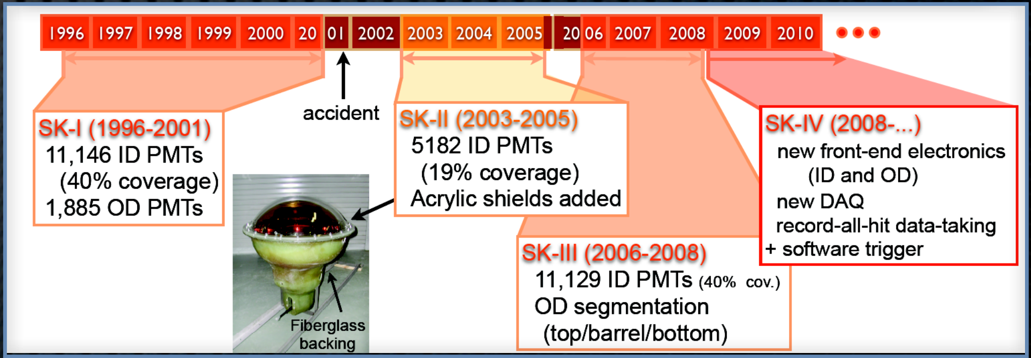
P. Adamson *et al.*, Phys.Rev.Lett. 106 181801 (2011)

Super-K in a nutshell

- 50 kton water Cherenkov detector
  - 22.5 kton fiducial volume
  - Inner detector
    - ~11,146 50 cm PMTs
  - Outer detector
    - 1,885 20 cm PMTs
  - Depth of 2700 m.w.e
    - Cosmic ray background ~3Hz
- Sensitive to a wide range of energies, down to <5 MeV.
- Multi-purpose detector
  - Atmospheric neutrinos: 10/day

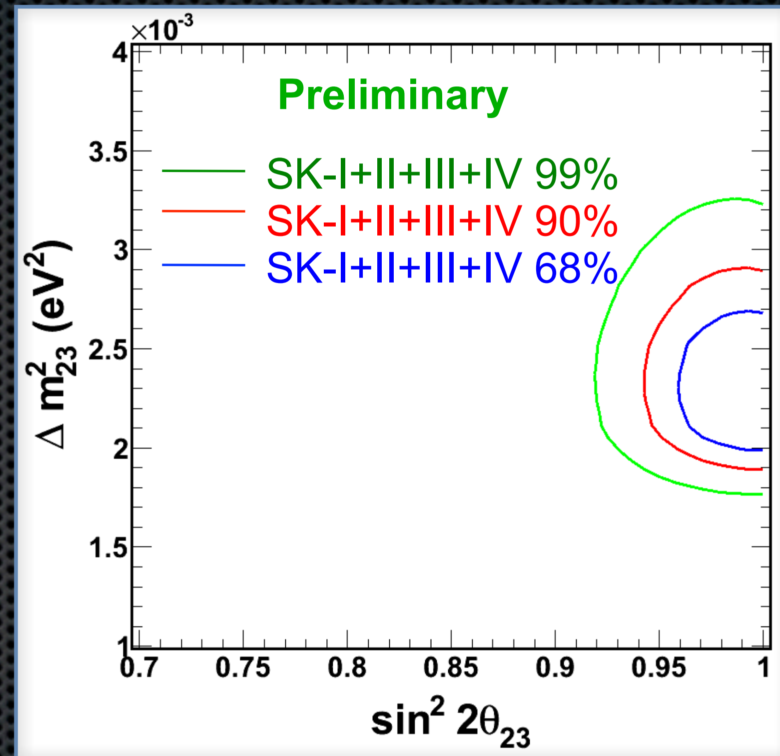
Running since 1996!





Super-K ν_μ disappearance

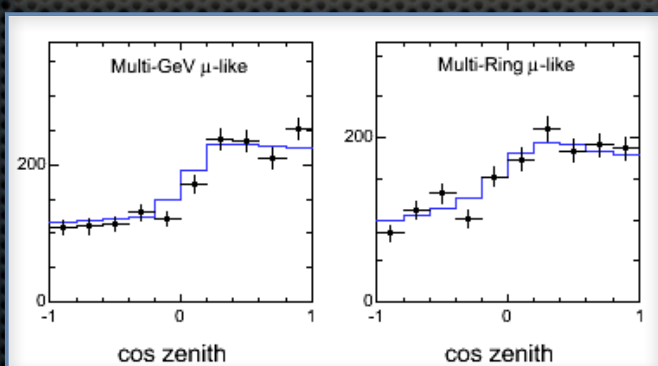
- Large statistics neutrino measurement:
  - 220 kton-year exposure
- Large number of data sample distributions in zenith angle and lepton momentum.
  - Sub-GeV, Multi-GeV, Partially Contained stopping and through going.
- World's best $\sin^2(2\theta_{23})$ measurement.



SK Zenith SK1234(1σ)

$\Delta m_{23}^2 = 2.2^{+0.15}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta_{23} > 0.96$ (90% C.L.)



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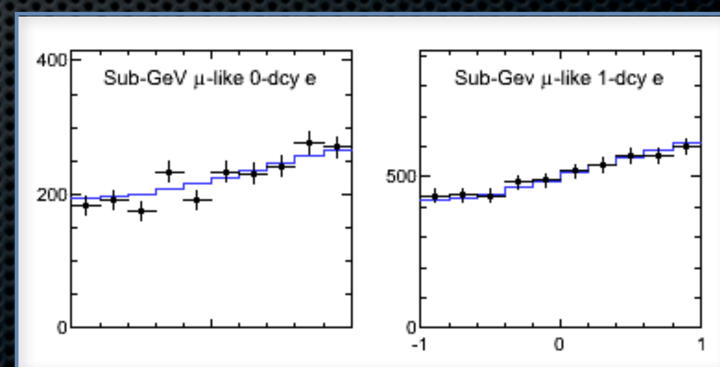
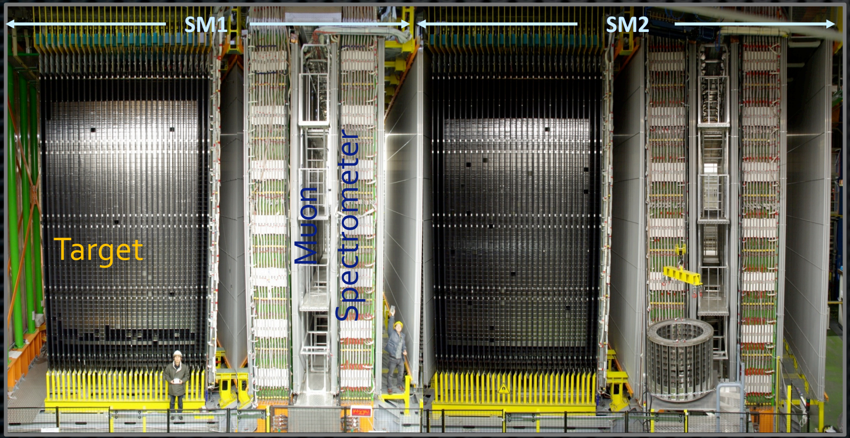


Opera in a nutshell

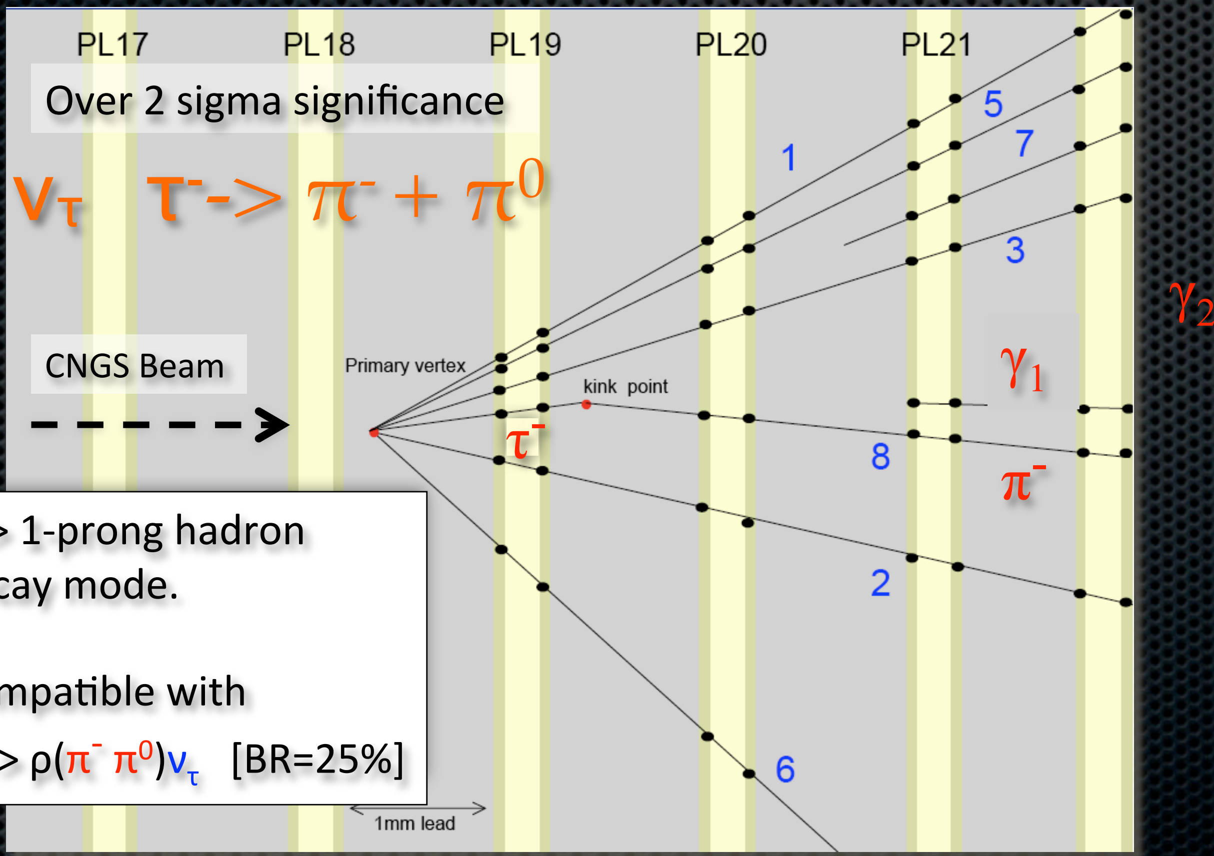


Taking data since 2008!

- Produce a high intensity beam of muon neutrinos at CERN. Distance similar to Fermilab - Soudan.
- If neutrinos oscillate, directly observe resulting tau neutrinos from the dominant oscillation mode.
- Far detector divided in two supermodules.
  - Target composed of lead/emulsion bricks.
  - Muon spectrometers magnetized with 1.5T.

Opera ν_τ appearance

Opera's 1st ν_τ Candidate Event (Spring 2010)



τ -> 1-prong hadron decay mode.

Compatible with

$\tau \to \rho(\pi^- \pi^0)\nu_\tau$ [BR=25%]

Confirming ν_τ appearance with 35% of '08-'09 data

Opera ν_τ appearance

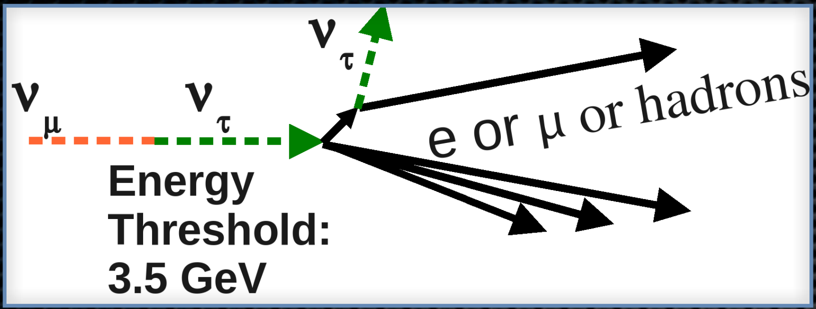
- Analyzed 92% for data '08-'09:
  - 4.8×10^{19} POT.
- Significant improvements in the analysis and simulation chain.
  - Including better charm cross sections and reduction of charm background.
- **No new tau neutrinos found.**

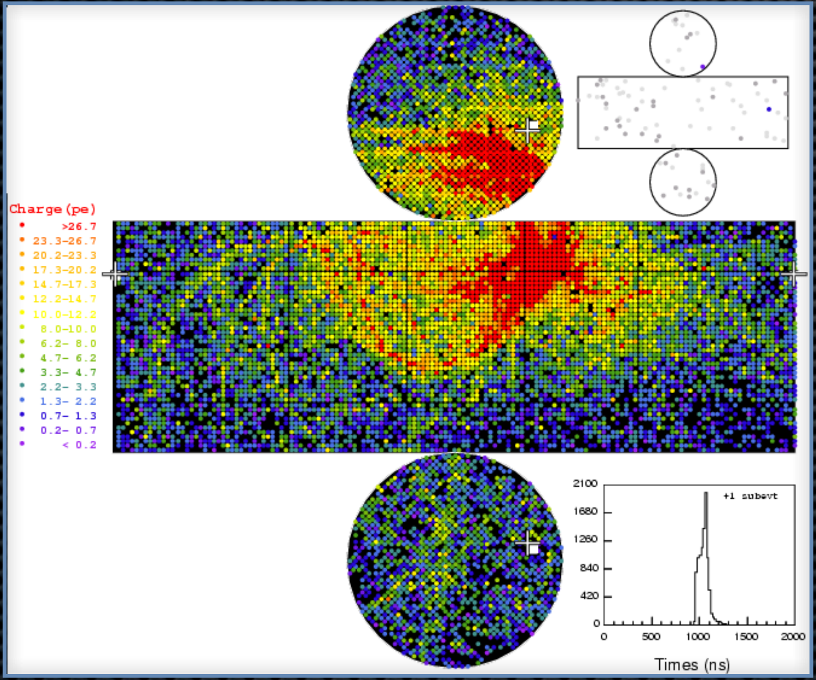
Decay channel	Number of signal events expected for *$Dm^2 = 2.5\times10^{-3}$ eV^2*	
	22.5×10^{19} p.o.t.	Analysed sample
$\tau \to \mu$	1.79	0.39
$\tau \to e$	2.89	0.63
$\tau \to h$	2.25	0.49
$\tau \to 3h$	0.71	0.15
Total	7.63	1.65

- One tau neutrino observed in the $\tau \to h$ channel.
- Observation compatible with expectation of 1.65 signal events and a background of 0.05±0.01.
- Probability of background fluctuation is 5%.
- Significance of observation is 95% (was 98.2% in previous analysis).

S. Dusini EPS 2011/ arxiv 1107.2594

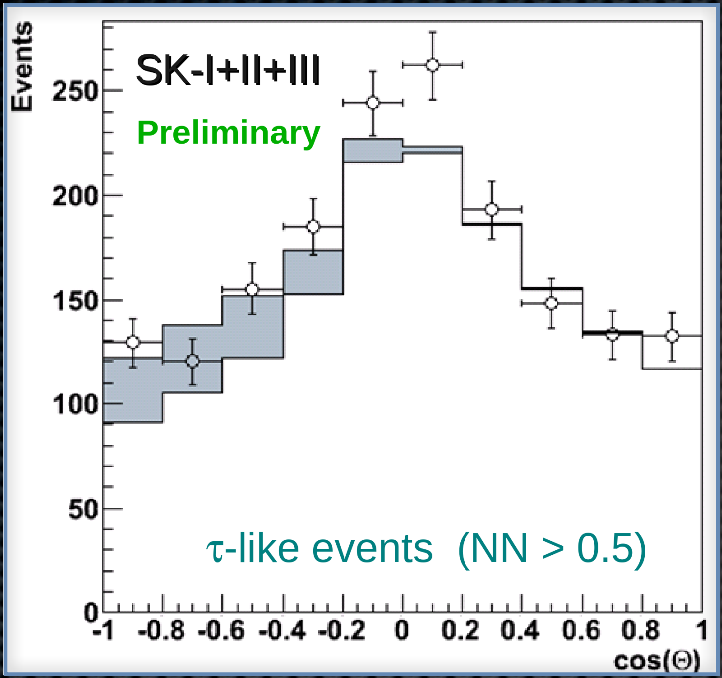
Super-K ν_τ appearance





- Tau neutrinos at Super-K are hard to recognize as it is a complicated event topology where the leading lepton might not be distinguishable.
- Developed a neural net with 80% efficiency.
- Looking for an excess over background which must be oscillation induced.

Super-K ν_τ appearance



- Fit for two parameters: one for background and one for signal.
- Tau signal clearly appears in the upward-going region.
- The data disfavors no tau neutrino appearance at 3.8 σ.

$$Data = \alpha(\gamma) \times bkg + \beta(\gamma) \times signal$$

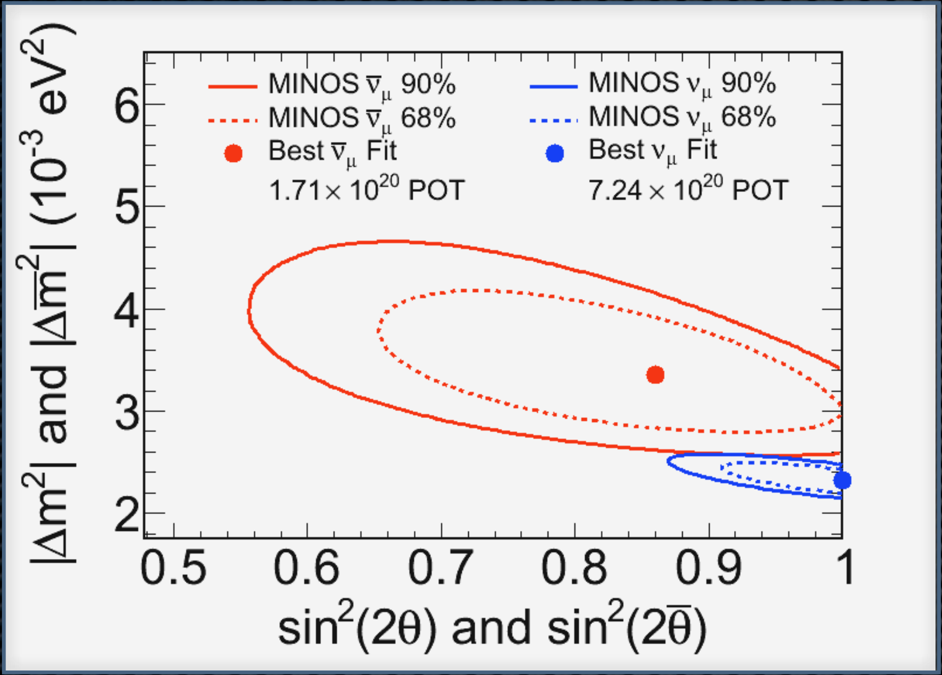
$$\beta = 1.63 \pm 0.35_{(stat)} {}^{+0.10}_{-0.08}(sys) {}^{+0.02}_{-0.22}(3\,flav)$$

This corresponds to 213.6 τ Events 3.8σ excess

(Expected 2.6σ significance)

$\bar{\nu}_\mu$ disappearance

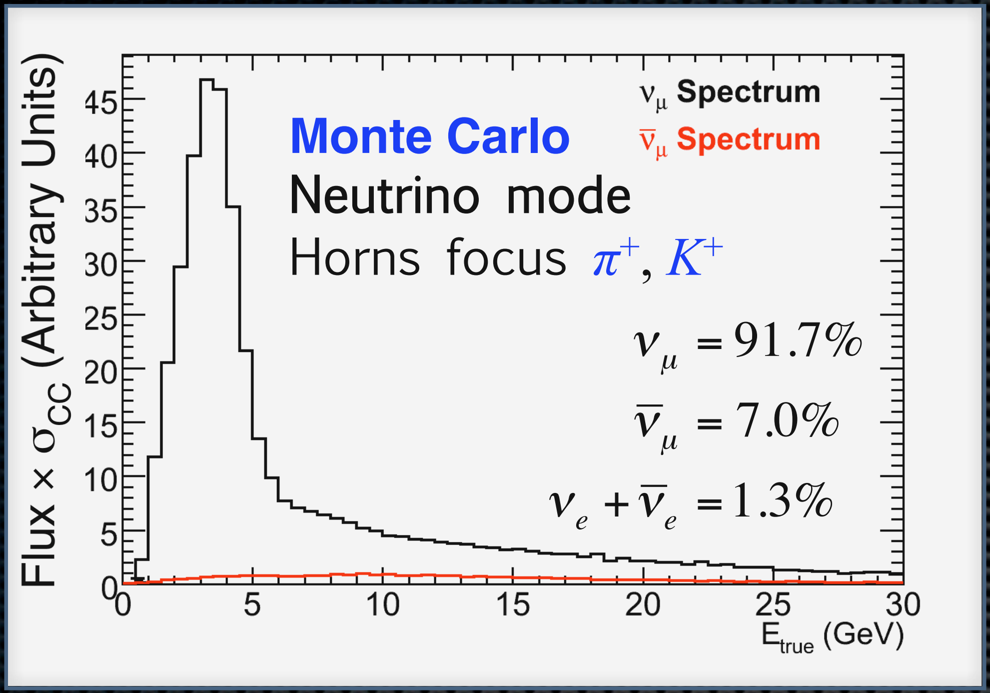
- Last year MINOS observed that the neutrino and anti-neutrino measurements were consistent only at the 2% confidence level.

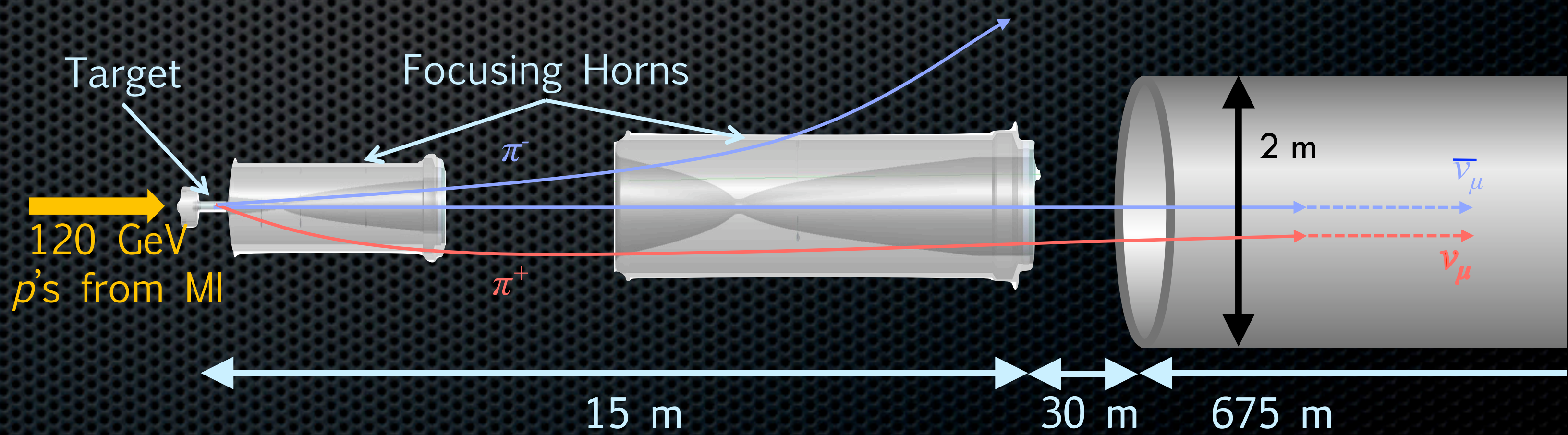


- This result generated significant interest and generated discussion and publications.
- Possible explanations in literature:
  - **CPT and Lorentz Violation**
    L. Liu, et al. Phys.Lett. B702 (2011)
    J.S. Diaz and V.A. Kostelecký arXiv:hep-ph/1108.1799
  - **Non-Standard Interactions**
    J. Kopp, et al. Phys.Rev. D82:113010 (2010)
    W. Mann, et al. Phys.Rev. D82:113002 (2010)

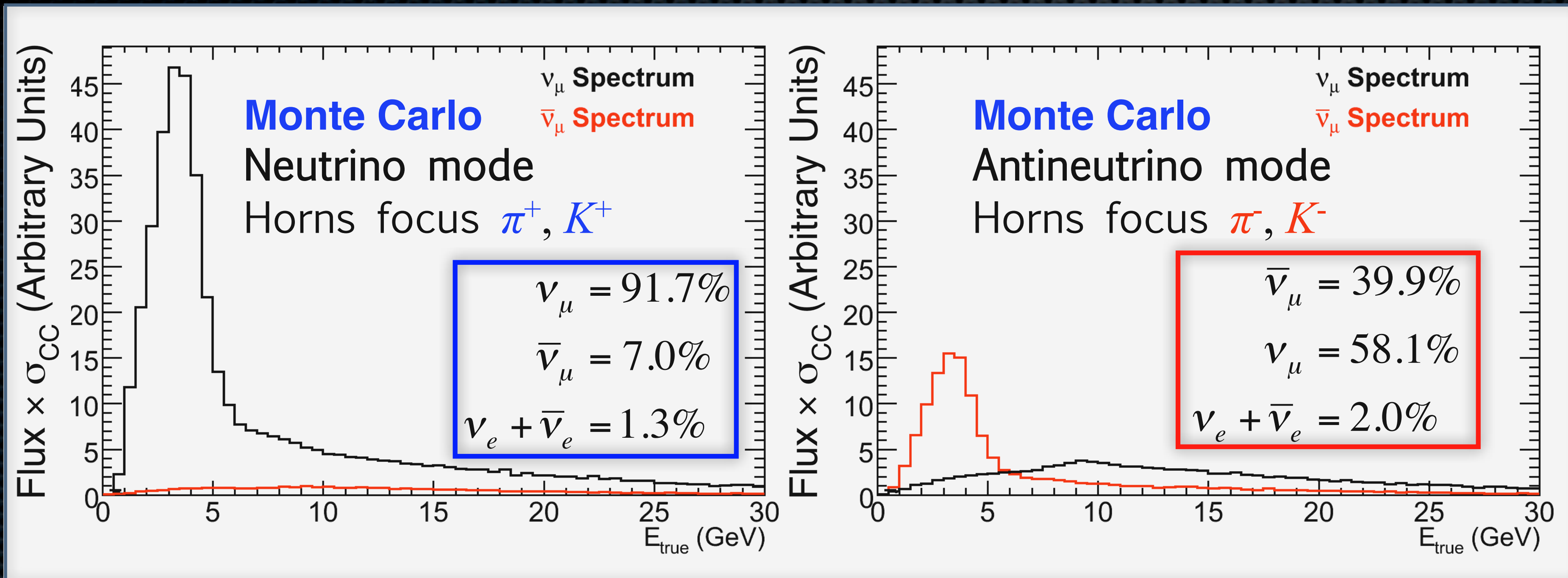
70% more data has been added.
Improved analysis.

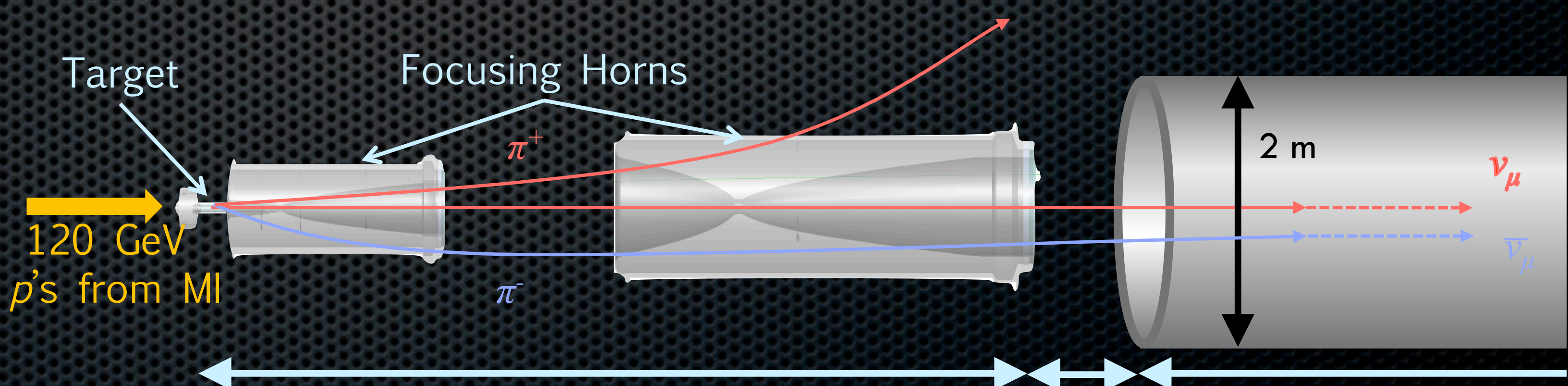
Producing Neutrinos with NuMI



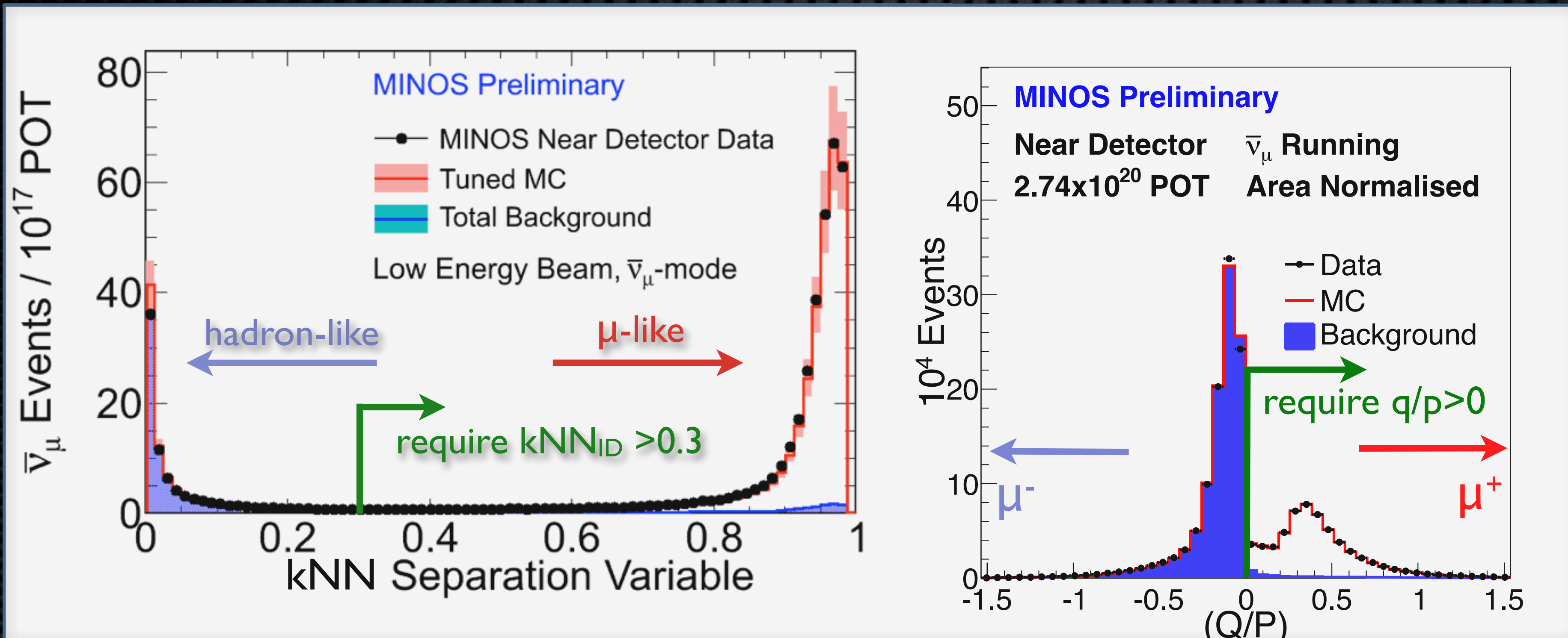


Producing Anti-neutrinos with NuMI



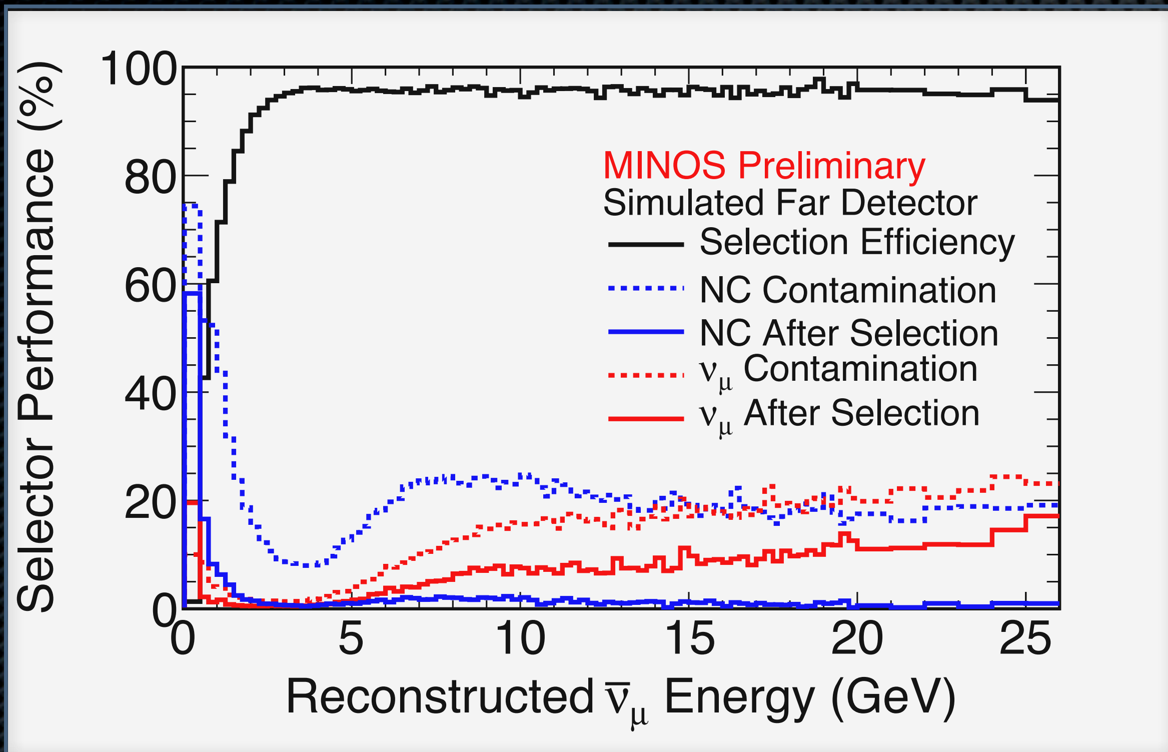


MINOS $\bar{\nu}_\mu$ disappearance



- Muons from charged current interactions are identified as tracks satisfying a multivariate topological ID based on k-nearest neighbors.
  - The input variables include: track length, mean dE/dx along track, energy fluctuations along track and energy deposition in transverse track profile.
- Muon charge/momentum is analyzed by track curvature, we only accept events with positive reconstructed charge.

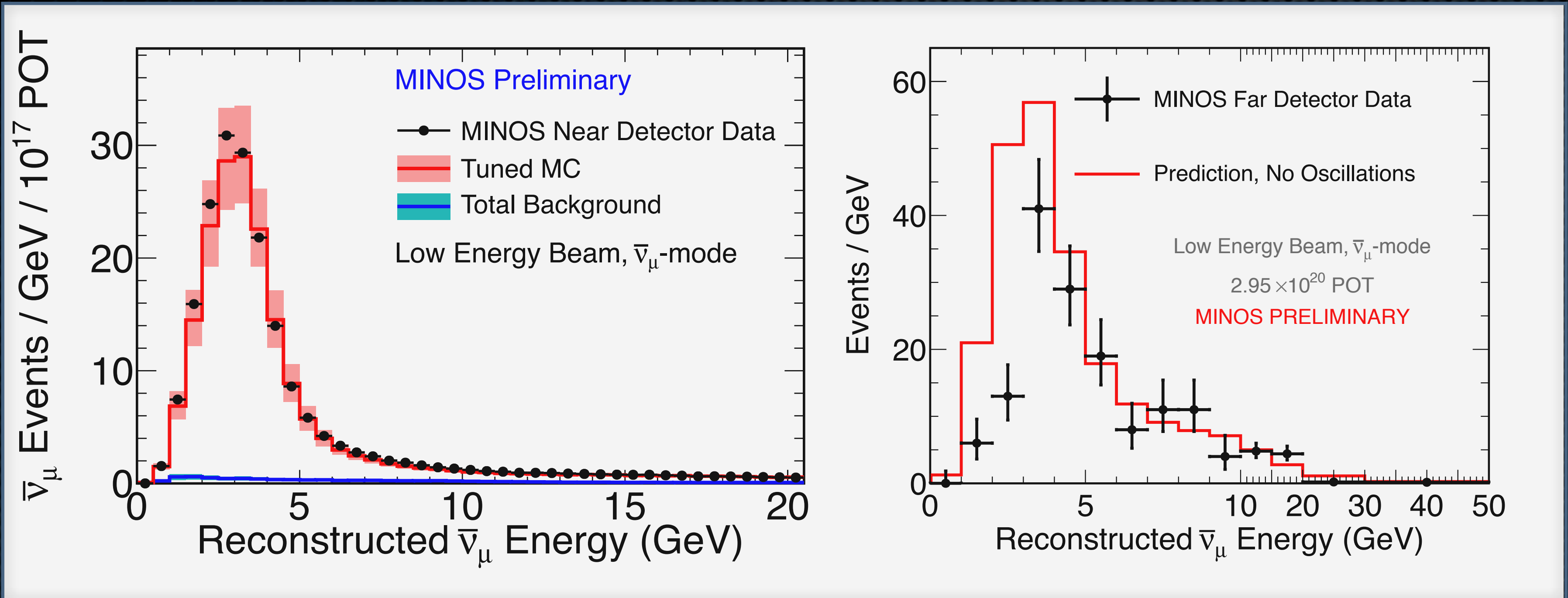
MINOS $\bar{\nu}_\mu$ disappearance



	Eff.	Pur.
0 - 6 GeV	96%	98%
6 -20 GeV	98%	91%
20-50 GeV	98%	78%
0-50 GeV	97%	95%

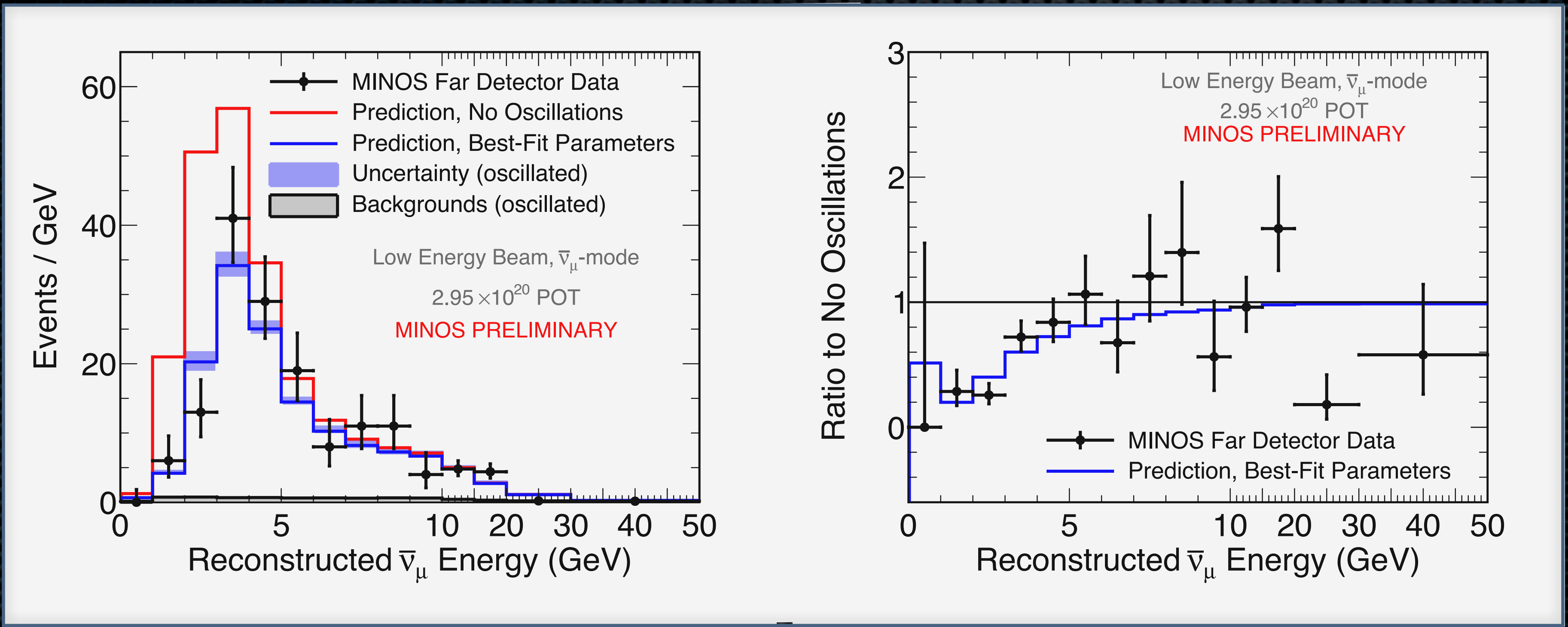
- Antineutrinos in the Far Detector are selected in the same way as in the Near Detector except for tracks ending near the coil.
- Integrated selection efficiency in Far Detector is 97% with 95% sample purity.
  - For the Near Detector it is 53% integrated efficiency, with 94% sample purity.

MINOS $\bar{\nu}_\mu$ disappearance



- Reconstructed neutrino energy uses new shower energy estimator.
- Near detector data matches the expectation well. We use it to predict the Far Detector spectrum with null oscillations.
- Far Detector: expect with no oscillations **273**. Observe **193.**
- No oscillations disfavored at 7.3 σ.

MINOS $\bar{\nu}_\mu$ disappearance

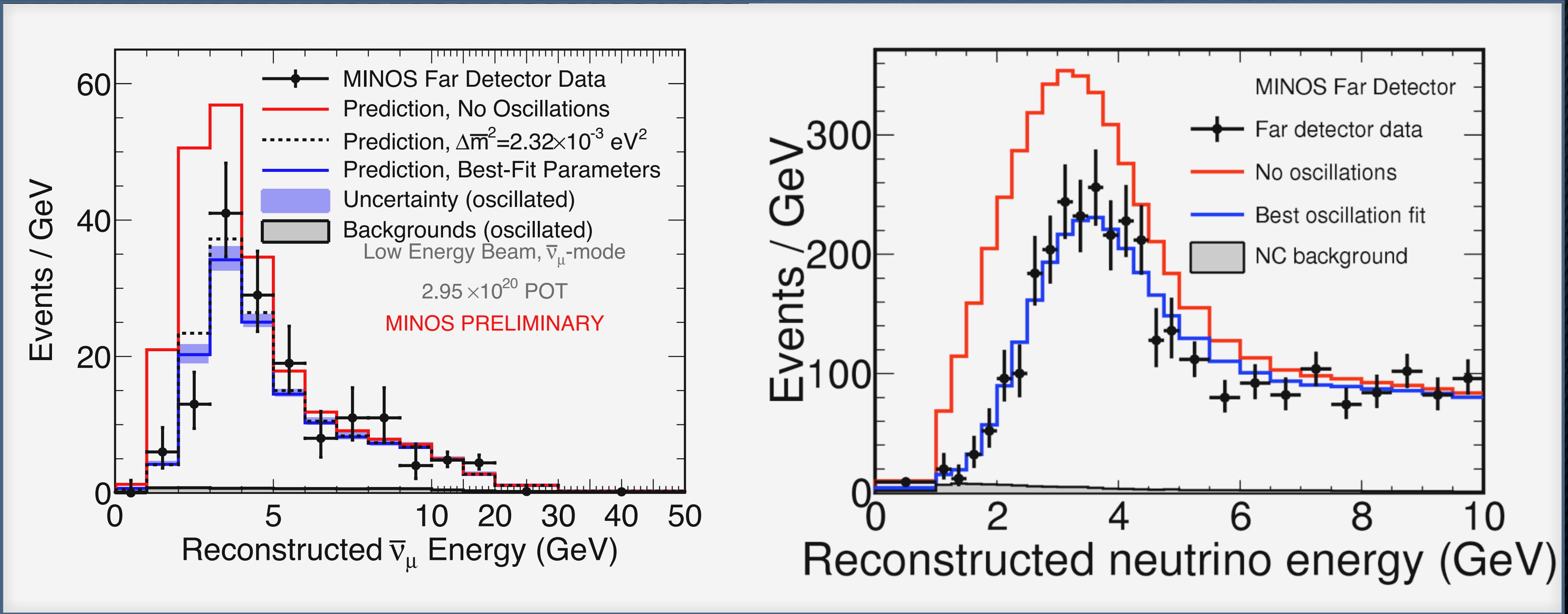


NEW!

$$|\Delta\bar{m}^2_{atm}| = 2.62^{+0.31}_{-0.28} \times 10^{-3} eV^2$$

$$\sin^2(2\bar{\theta}_{23}) > 0.75 \;\; (90\% \text{ C.L.})$$

MINOS $\bar{\nu}_\mu$ disappearance

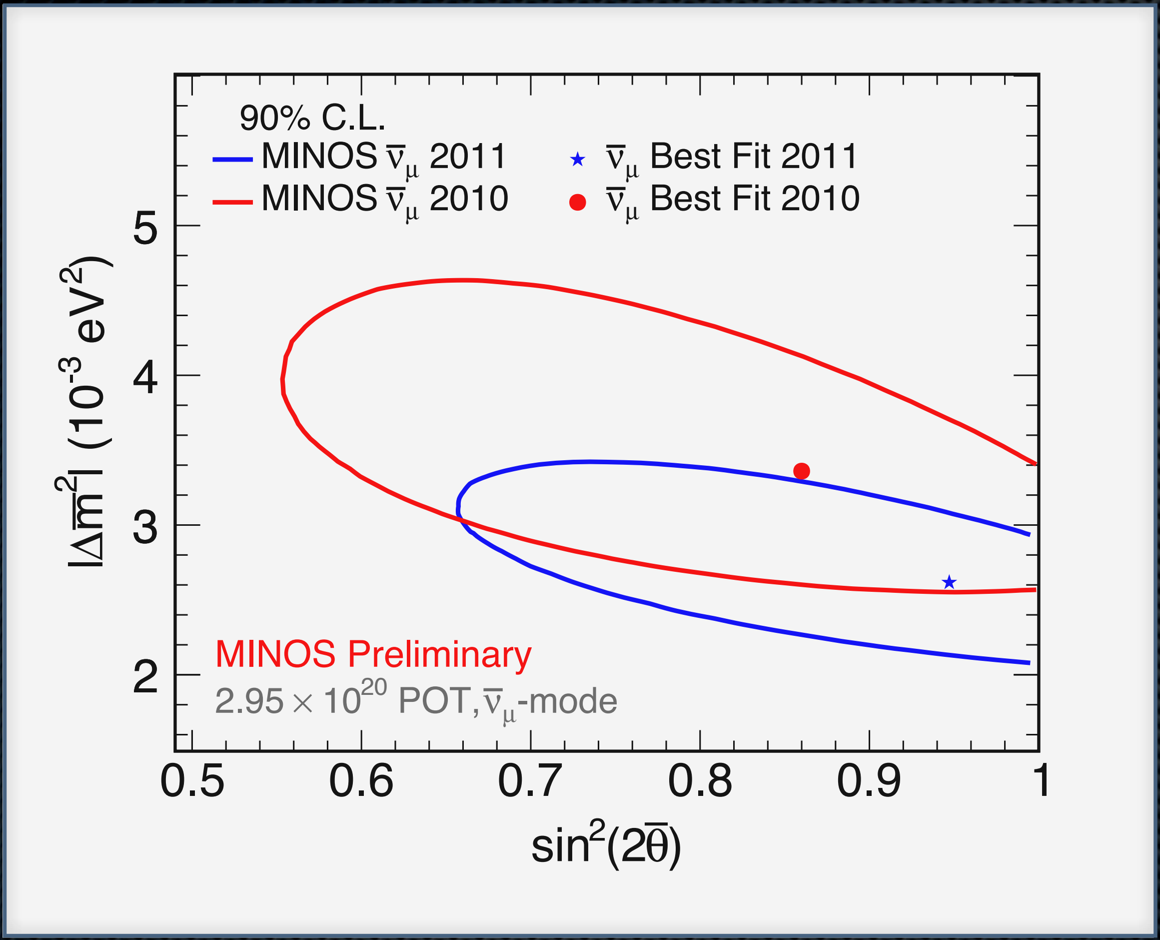


- Comparing to anti-neutrino and neutrino oscillations.

$$|\Delta \overline{m}^2_{atm}| = 2.62^{+0.31}_{-0.28} \times 10^{-3} eV^2$$
$$\sin^2(2\bar{\theta}_{23}) > 0.75 \ (90\% \ C.L.)$$

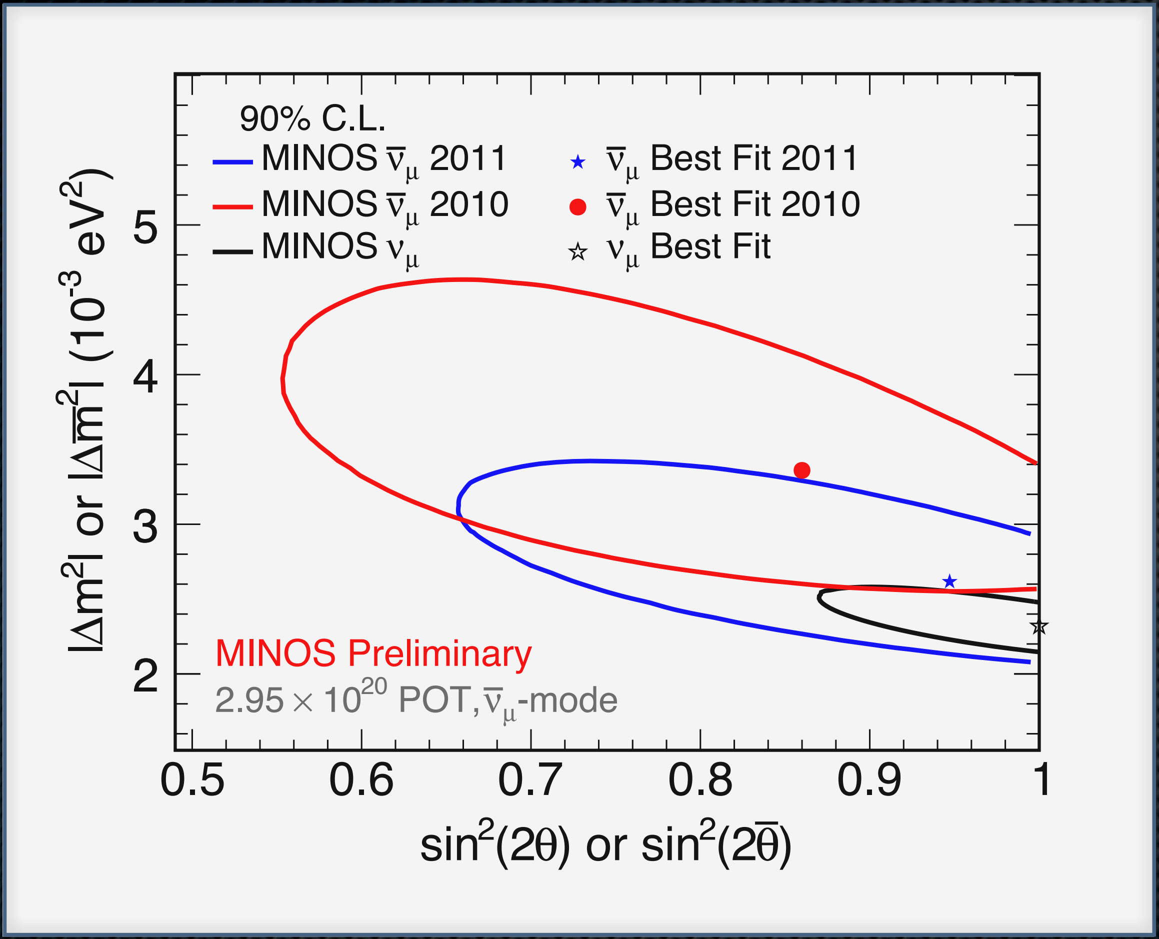
$$|\Delta m^2_{atm}| = 2.32^{+0.12}_{-0.08} \times 10^{-3} eV^2$$
$$\sin^2(2\theta_{23}) > 0.90 \ (90\% \ C.L.)$$

MINOS $\bar{\nu}_\mu$ disappearance



- World's best measurement in $\Delta\bar{m}^2_{32}$.
- Anti-neutrino oscillation parameters consistent with neutrino parameters with p = 42%.
- More anti-neutrino running is under way.

MINOS $\bar{\nu}_\mu$ disappearance



- World's best measurement in $\Delta\bar{m}^2_{32}$.
- Anti-neutrino oscillation parameters consistent with neutrino parameters with p = 42%.
- More anti-neutrino running is under way.

Super-K $\bar{\nu}_\mu$ disappearance

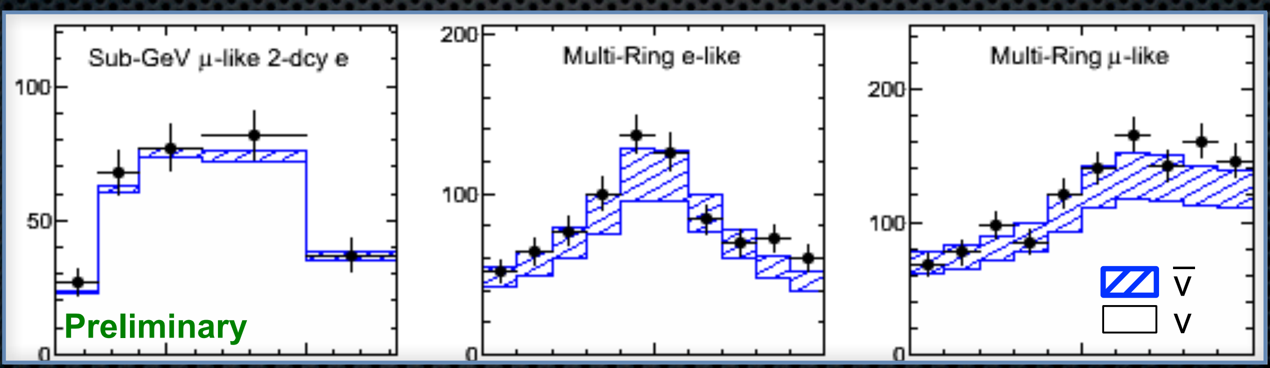
- Atmospheric data carries both neutrinos and anti-neutrinos.
- Super-K cannot distinguish on an event by event basis neutrinos from anti-neutrinos.

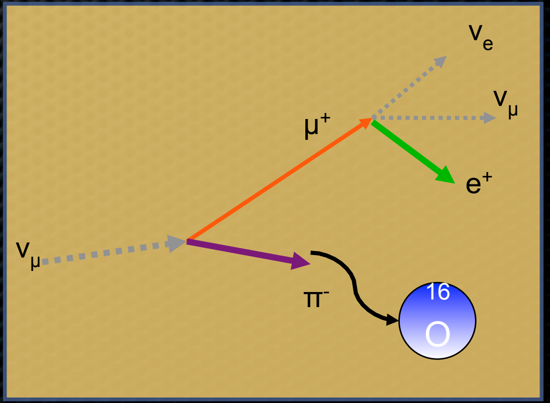
$$p + N_{air} \rightarrow \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

However an indirect measurement is possible:

- Cross-sections differ by a factor of ~2 to 3.
- Neutrino/anti-neutrino flux ratio is energy dependent.

- Distributions of out-going products can differ.
  - Eg. Charged pion absorption affects the number of observed decay electrons.

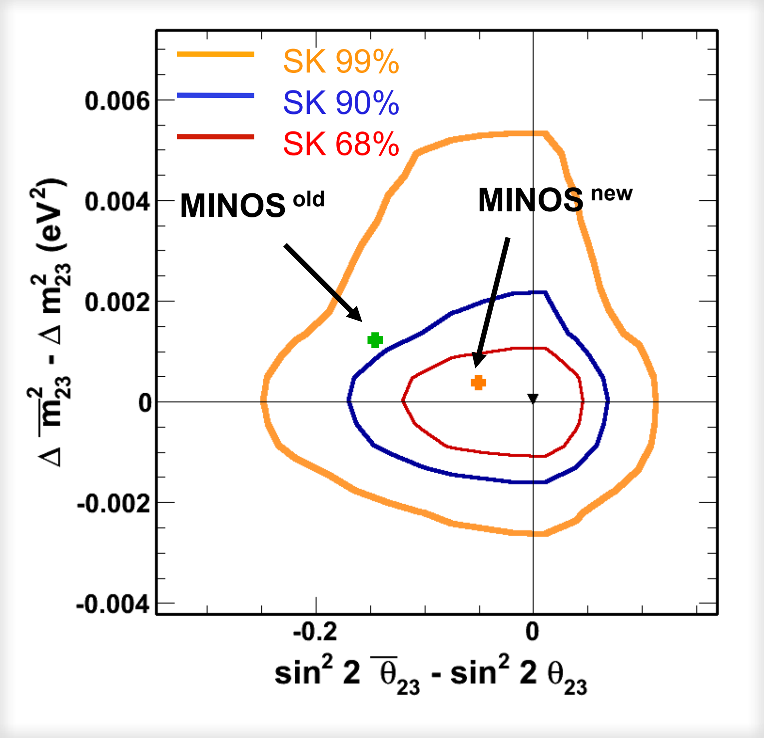




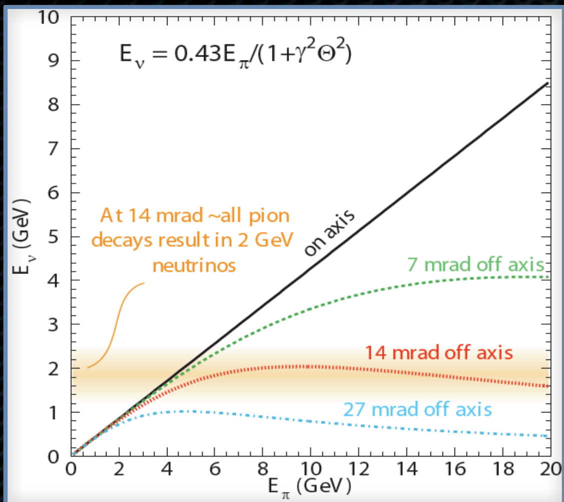
Super-K $\bar{\nu}_\mu$ disappearance

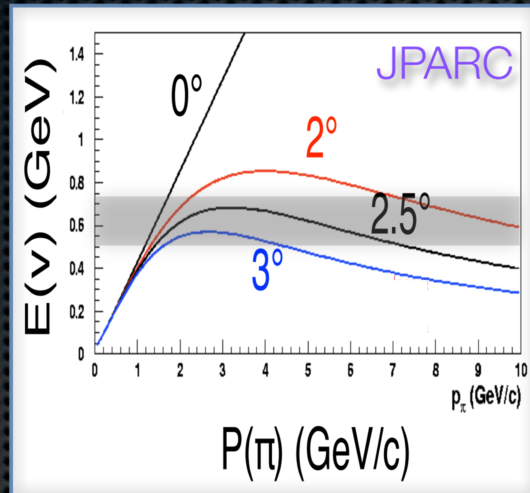
- Because Super-K observes maximal oscillations for the atmospheric neutrino/anti-neutrino mix, it strongly constrains the level of anti-neutrinos allowed.
- Fitting the composite distributions and permitting the neutrinos and anti-neutrinos to oscillate separately, it explores the combined parameter space.

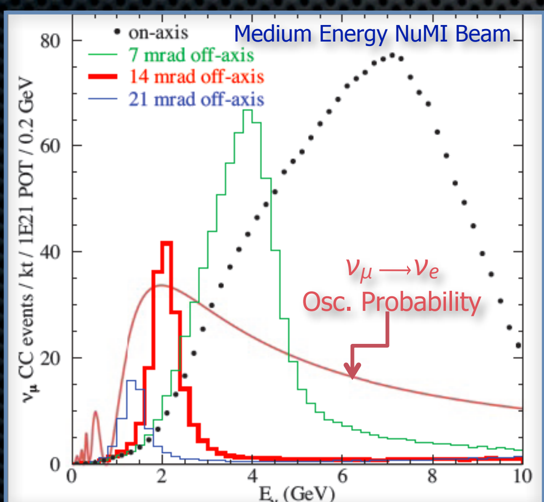
ν	Best Fit
Δm^2	2.1×10^{-3} eV^2
$\sin^2 2\theta$	1.0
$\bar{\nu}$	**Best Fit**
$\Delta \bar{m}^2$	2.0×10^{-3} eV^2
$\sin^2 2\bar{\theta}$	1.0

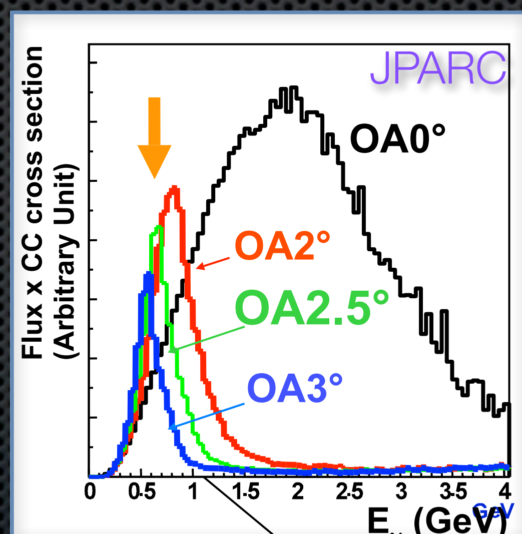


Off-axis ν_μ beam neutrinos





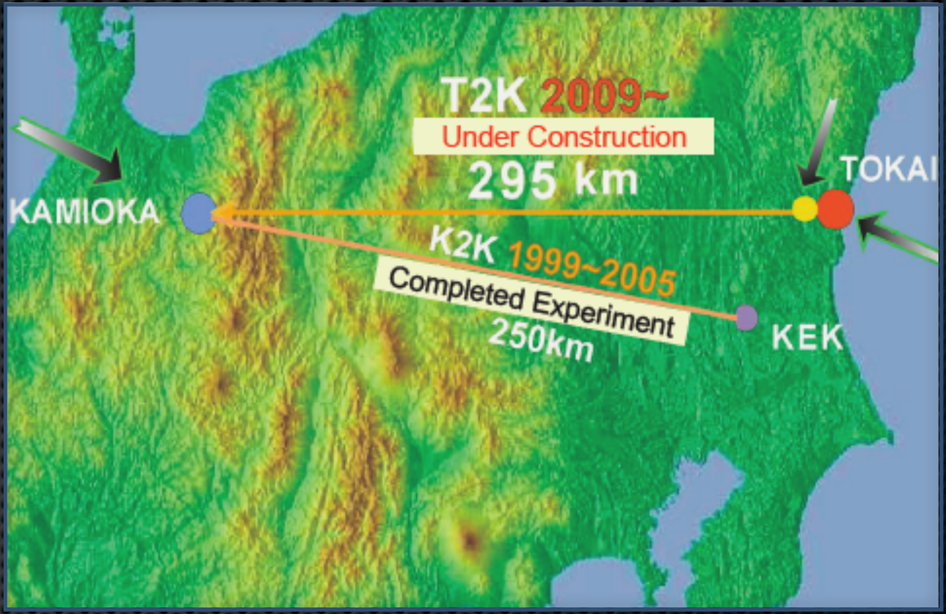




- Next generation of long baseline experiments focuses on electron neutrino appearance searches.
- To reduce neutral current contamination from interactions with high energy neutrinos, the detectors can be placed off-axis.
- The peak is tuned to the first oscillation maximum.
- **For muon neutrino disappearance measurement, this provides a perfect canvas to observe the oscillation pattern.**

T2K in a nutshell

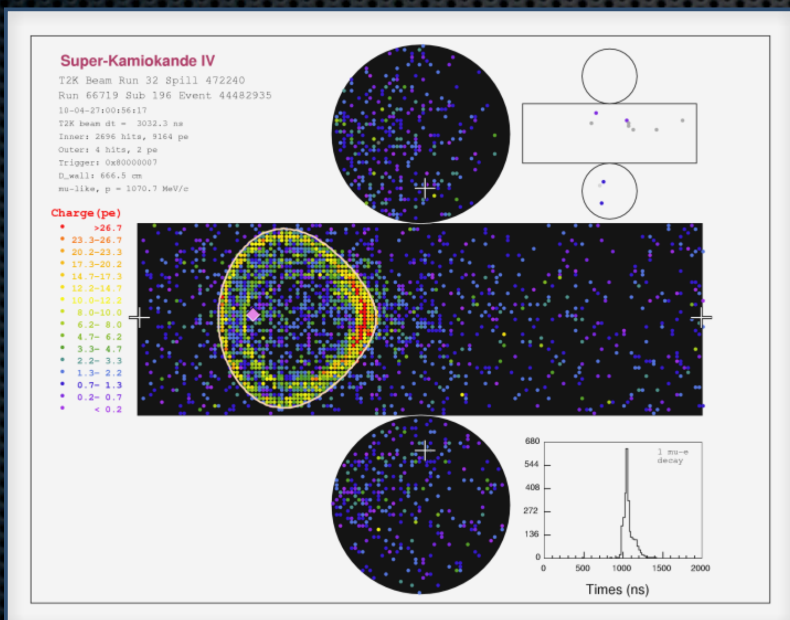
- Build a high intensity off-axis beam of muon neutrinos at JPARC (2.5° away from SuperK).
- Use existing large Water Cherenkov detector SuperK
- Build a near detector complex to understand beam, cross-sections, etc.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector at Kamioka.

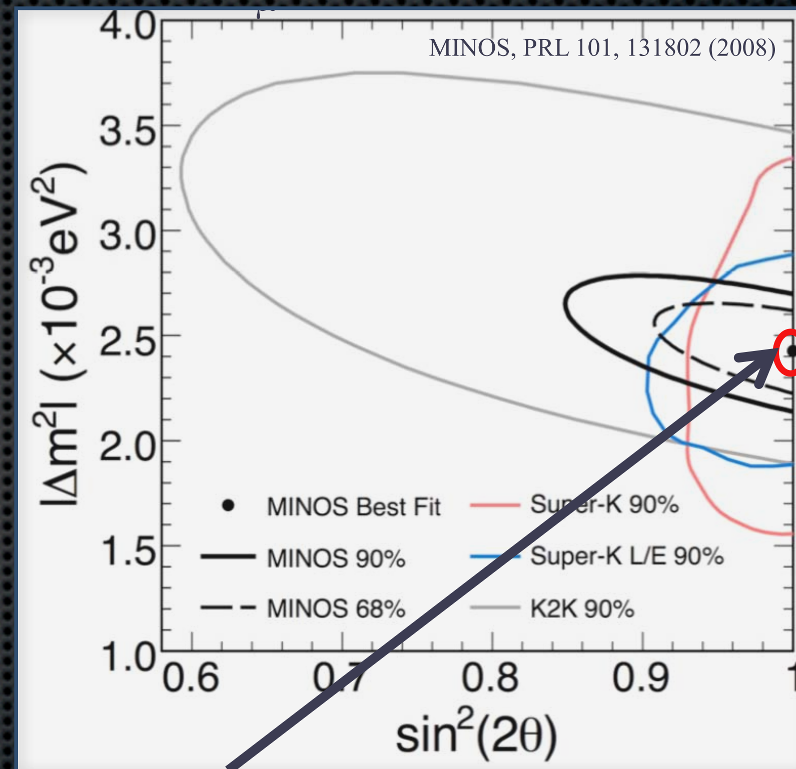


2nd generation long baseline

T2K Status

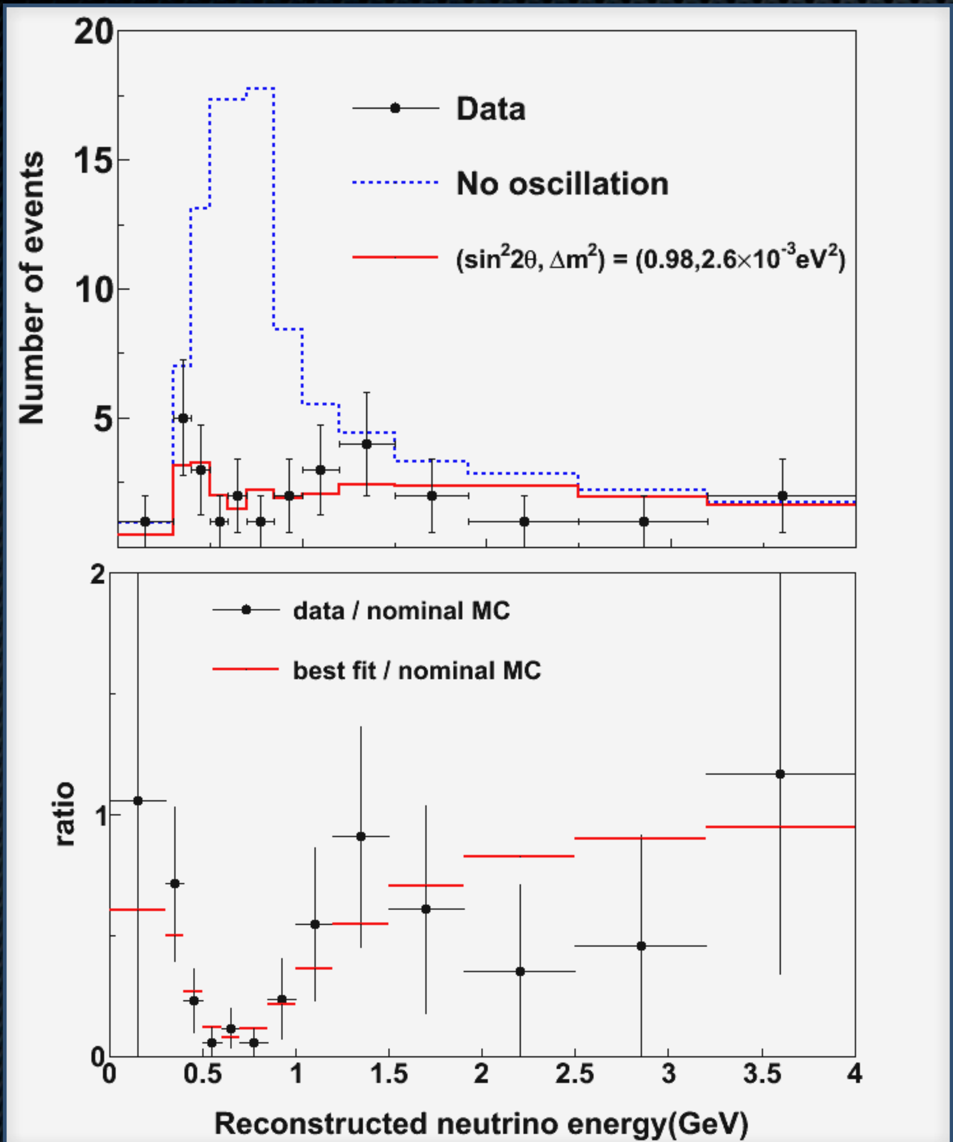
- Expects $\Delta(\Delta m^2_{32})\sim10^{-4}$ and error in $\Delta(\sin^2 2\theta_{23})\sim1\%$ at 90% CL for full data set.
- Roughly a year of data taking. Currently on hold because of earthquake damage. Work in progress to restart Dec 2011.



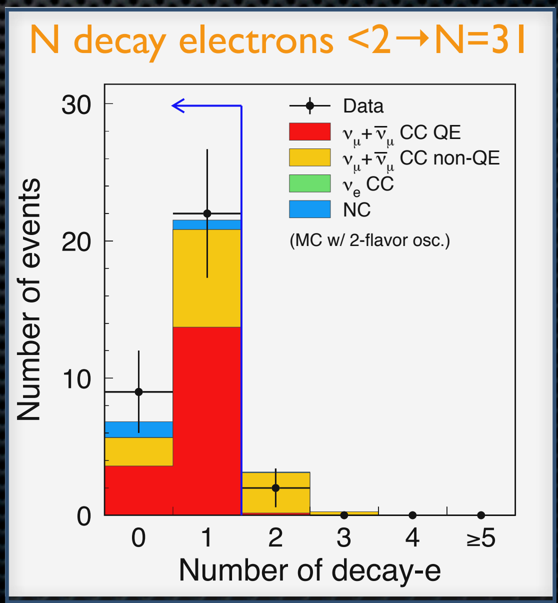


See next talk for more details on T2K including electron neutrino appearance analysis

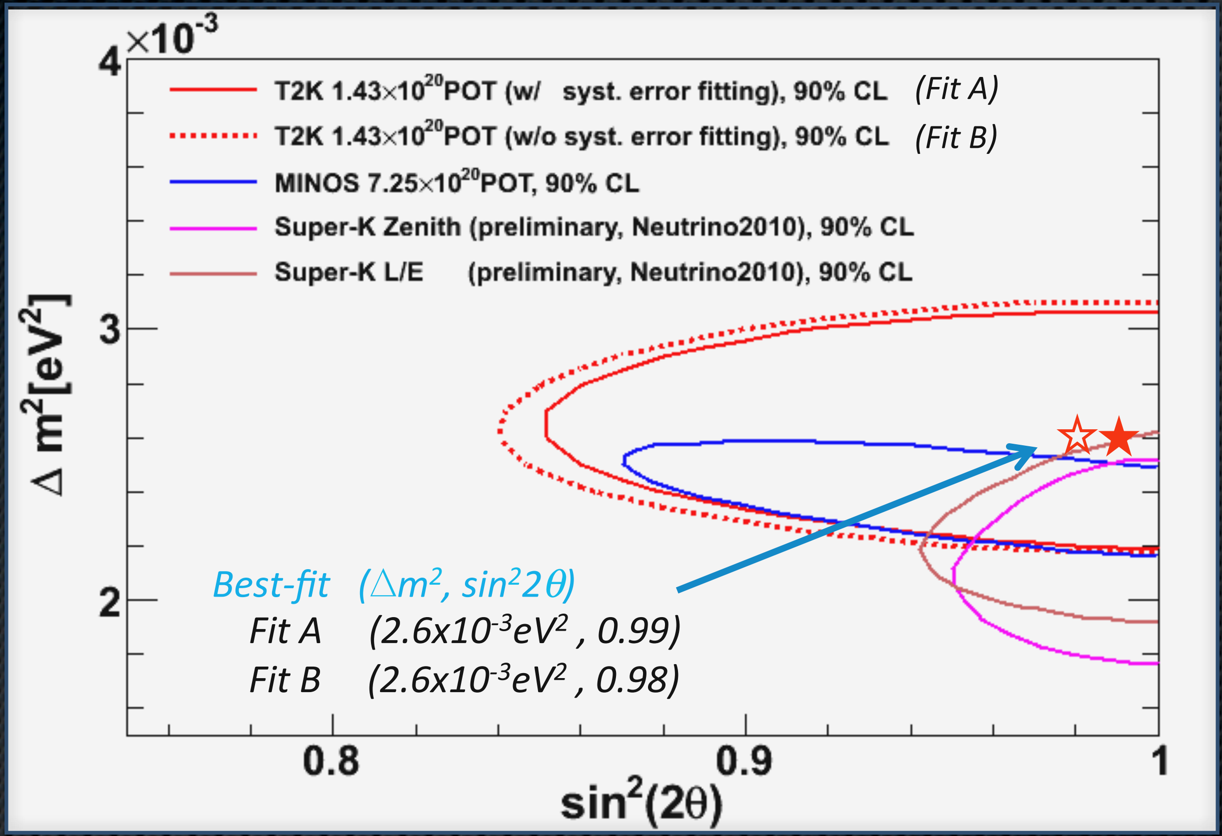
T2K ν_μ disappearance



- Selection for muon neutrinos:
  - 1 single-ring mu-like (33 evt).
  - Less than 2 decay electrons.
  - Reconstructed muon momentum larger than 200 MeV.
- Total of **31 events** pass all selections.



T2K ν_μ disappearance

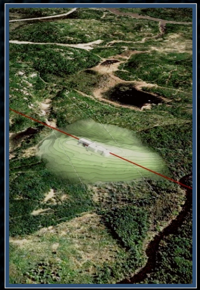


- No oscillation hypothesis excluded at 4.5 σ from event count alone.
- Systematics coming from Far and Near detectors efficiencies, cross sections and beam flux simulations are ~15%.
- Two analyses where one fits for systematic errors.

NOvA in a nutshell

- Use existing high intensity beam of muon neutrinos at Fermilab.
- Construct a totally active liquid scintillator detector off the main axis of the beam.
  - Detector is 14 mrad off-axis.
  - Location reduces background for the search.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Ash River, 810 km away.

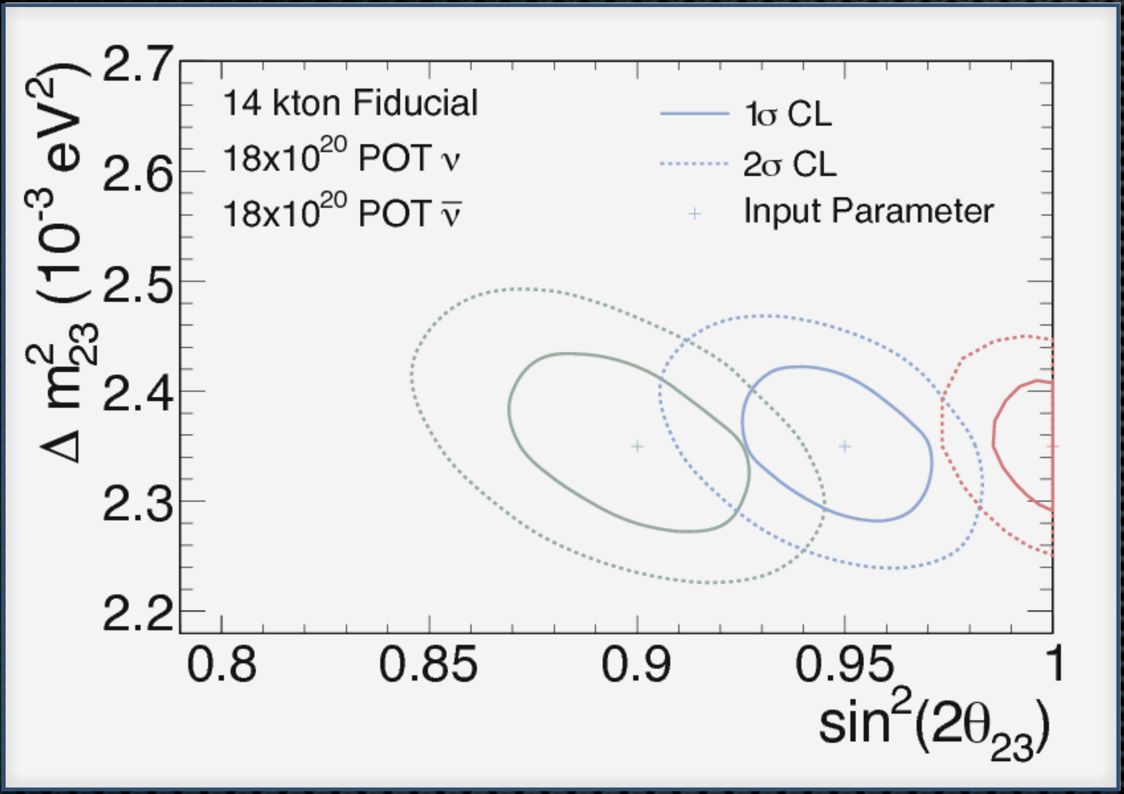
2nd generation
← long baseline →



NOvA status

- Far Detector site construction is now complete.
- Upgrade NuMI beam from 320 kW to 700kW starting March 2012 (shutdown).
- Assembly of Far Detector to start January 2012, expect 50% operational by end of shutdown. Full Far Detector operational early 2014.
- Near Detector cavern excavation during shutdown.
- Currently running Near Detector prototype on the surface.

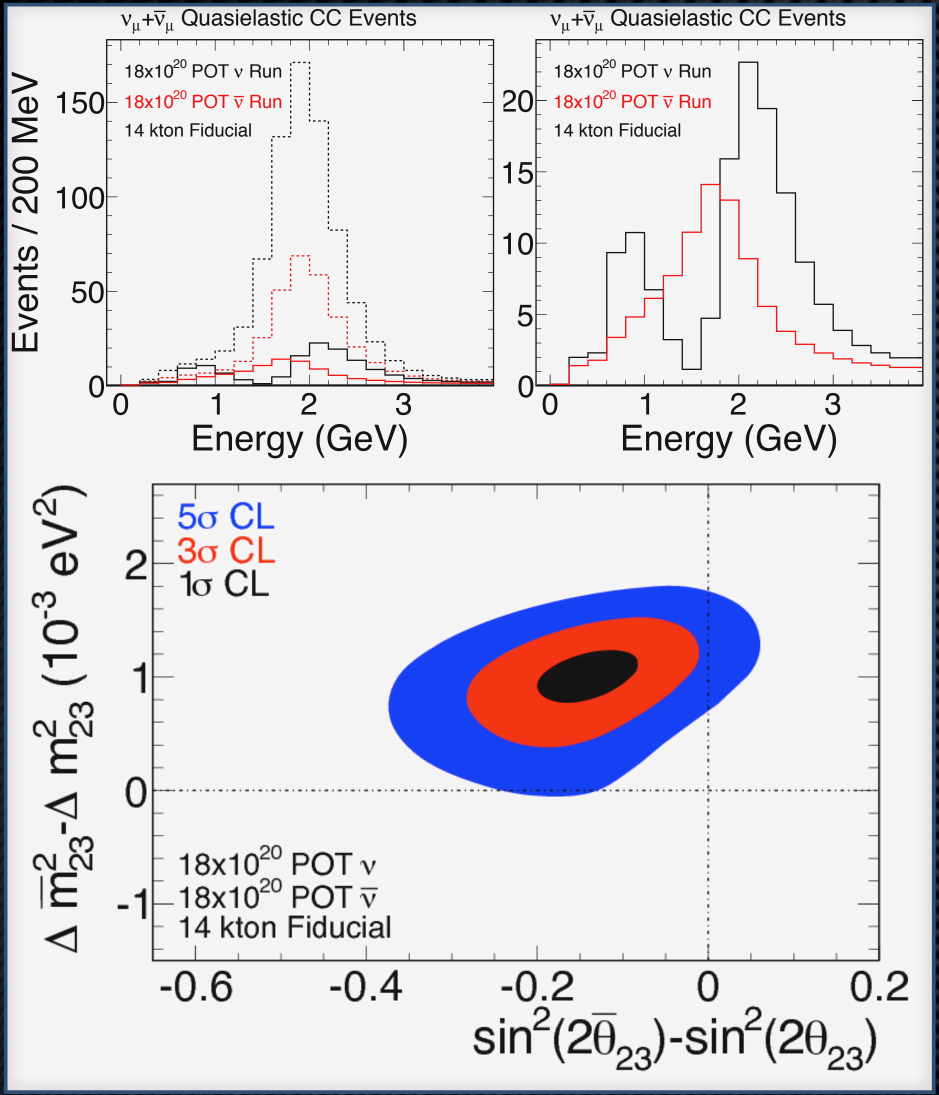
NOvA ν_μ disappearance



- NOvA's narrow band beam centered at the peak of the oscillation, allows for a few % measurement in Δm^2_{32} and $\sin^2 2\theta_{23}$.
- Improvement of one order of magnitude in $\sin^2 2\theta_{23}$.

If combined with Double Chooz/Daya Bay it can break the ambiguity in θ_{23}.

NOvA $\bar{\nu}_\mu$ disappearance

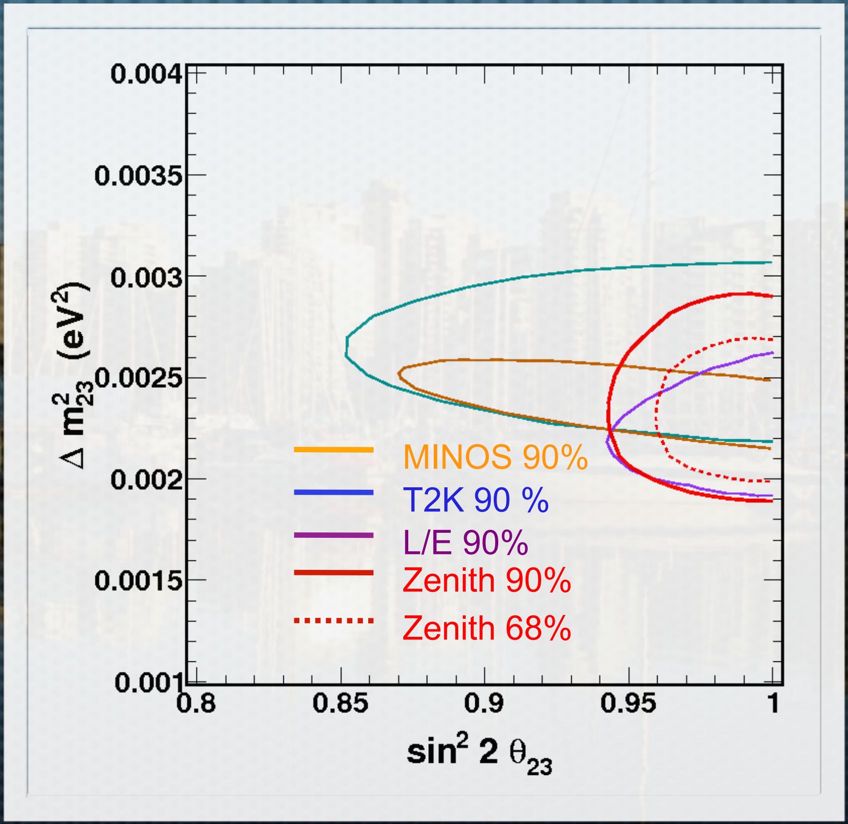


- Left: ν_μ-CC and $\bar{\nu}_\mu$-CC spectra before and after oscillations.
- Right: Zoom of the oscillated ν_μ-CC and $\bar{\nu}_\mu$-CC spectra.
- ν_μ oscillations use (Δm^2, $\sin^2 2\theta$) = (2.35 10^{-3} meV^2, 1.00)
- $\bar{\nu}_\mu$ oscillations use ($\Delta \bar{m}^2$, $\sin^2 2\bar{\theta}$) = (3.36 10^{-3} meV^2, 0.86)
- Bottom: sensitivity 6 years run, 3+3 neutrinos + anti-neutrinos.

Sensitivity to be updated with new MINOS results

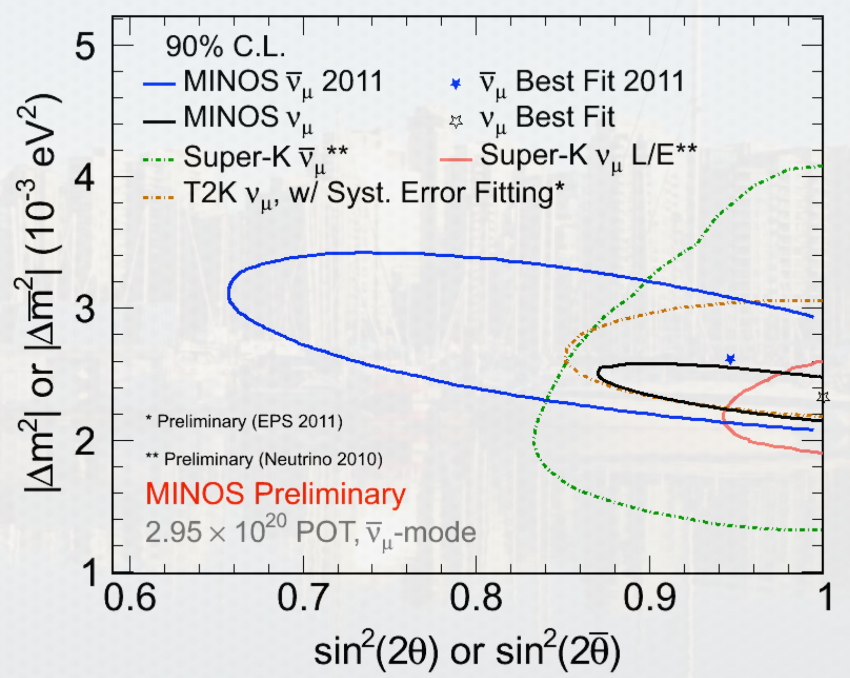
Muon Neutrino Summary

- Consistent picture in the muon-tau neutrino sector from all neutrino data.
- All evidence points to tau neutrino appearance.



Muon Anti-Neutrino Summary

- Muon anti-neutrino sector is converging with the neutrino sector.



Final thoughts

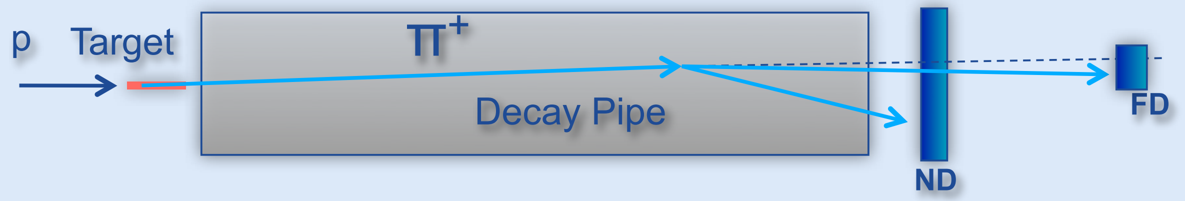
- Uncertainties and degrees of freedom in the muon-tau sector of neutrinos are quickly narrowing. Thanks to both long baseline and atmospheric neutrino experiments.
- Dominant mode of oscillation from muon neutrinos is demonstrated to be to tau neutrinos: one event observed directly in Opera and many more indirectly by SuperK.
- The anti-neutrinos parameter space is aggressively being explored by MINOS and SuperK.
- Off-axis experiments are well under way to making very precise measurements in this sector. Look for future results from T2K and NOvA.

Let's keep looking... Thank you!

Backup

Predicting the FD background

- Use Near Detector data to predict Far Detector spectrum.
- We expect the Far Detector spectrum to be similar to 1/R^2 scaled Near Detector spectrum, but not identical.

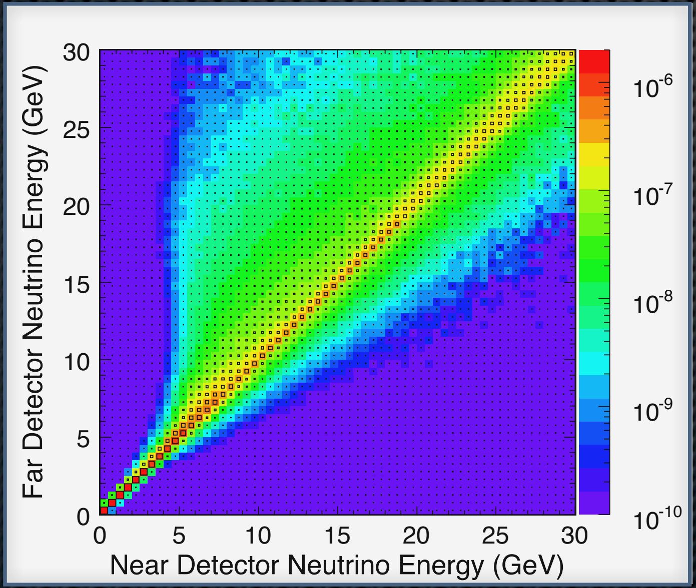


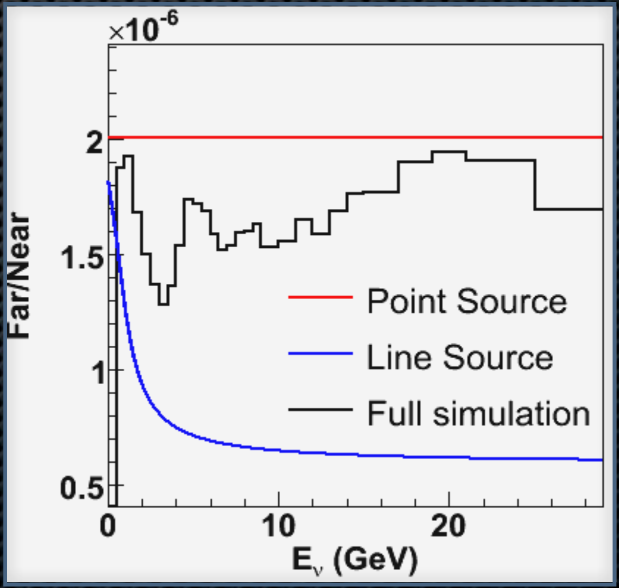
$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

- Neutrino energy depends on angle with respect to the original pion direction and parent energy
  - higher energy pions decay further along the decay pipe
  - angular distributions different between Near and Far: line versus point source.

Predicting the FD background

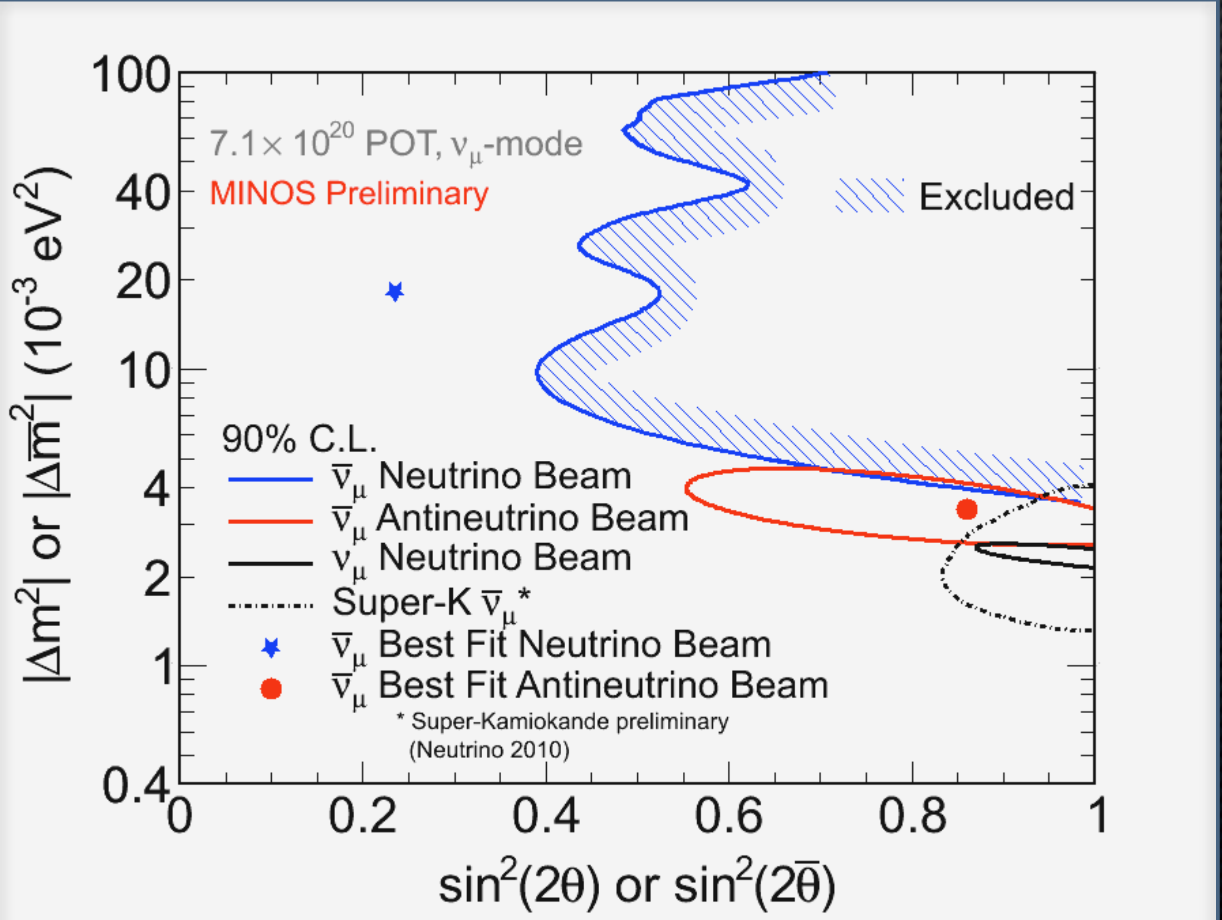
- Predict the event rate at each energy bin by correcting the expected Monte Carlo rate using either a beam matrix (CC analyses) or Far to Near spectrum ratio (Nue/NC) for Far Detector prediction of events.
- The Monte Carlo in each case provides necessary corrections due to energy smearing and acceptance.





MINOS $\bar{\nu}_\mu$ disappearance

- MINOS additionally measures oscillation using the 7% anti-neutrino of the neutrino beam. Peaked at higher energies.

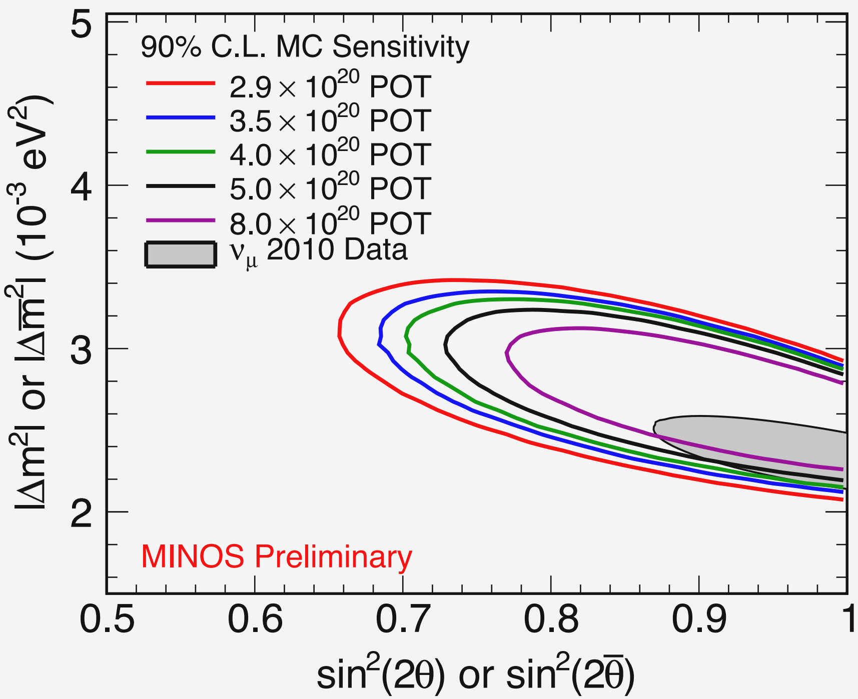


arXiv:hep-ex/1108.1509. Submitted to PRD Rapid Comm.

MINOS $\bar{\nu}_\mu$ disappearance

Future sensitivity

New data at anti-ν_μ best fit



New data at ν_μ best fit