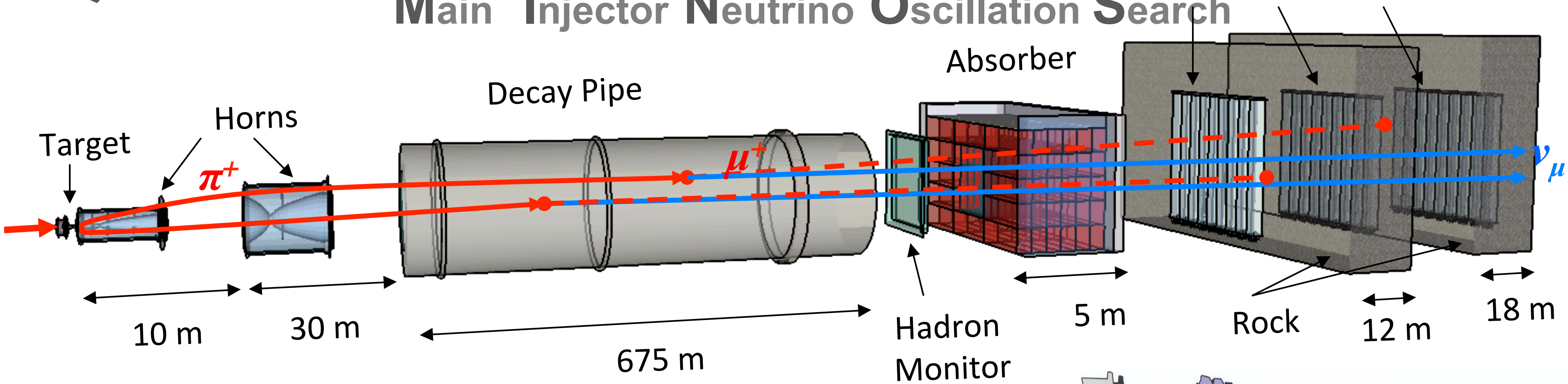
Karol Lang
The University of Texas at Austin

On behalf of the MINOS Collaboration

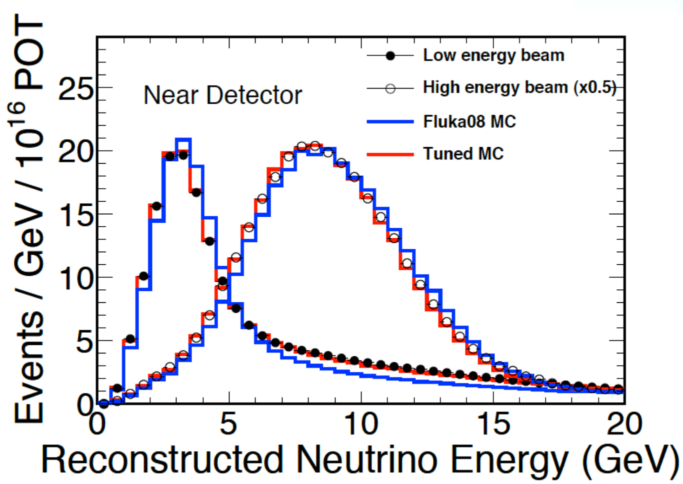
MINOS

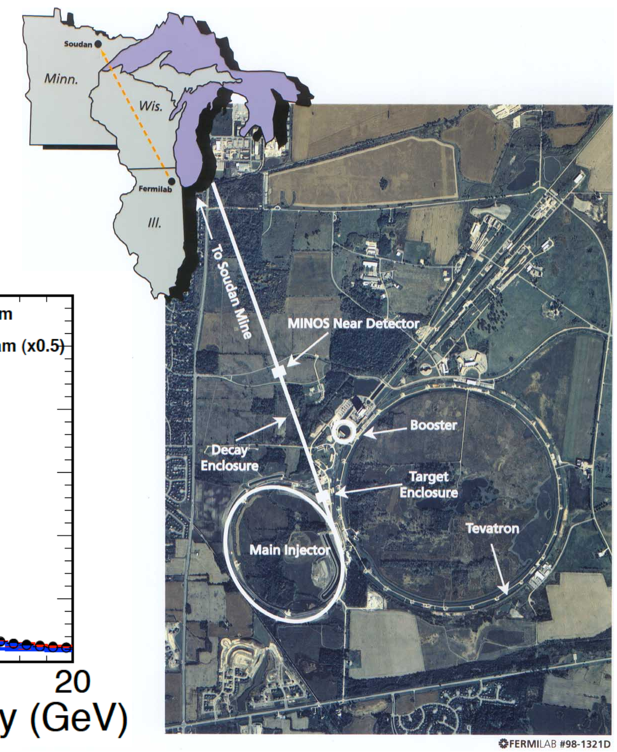
Main Injector Neutrino Oscillation Search



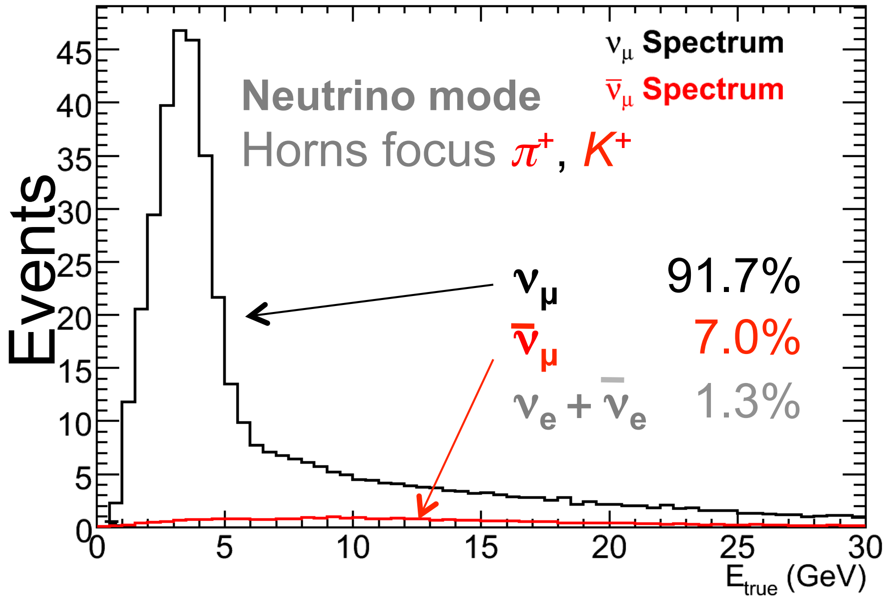
Strategy

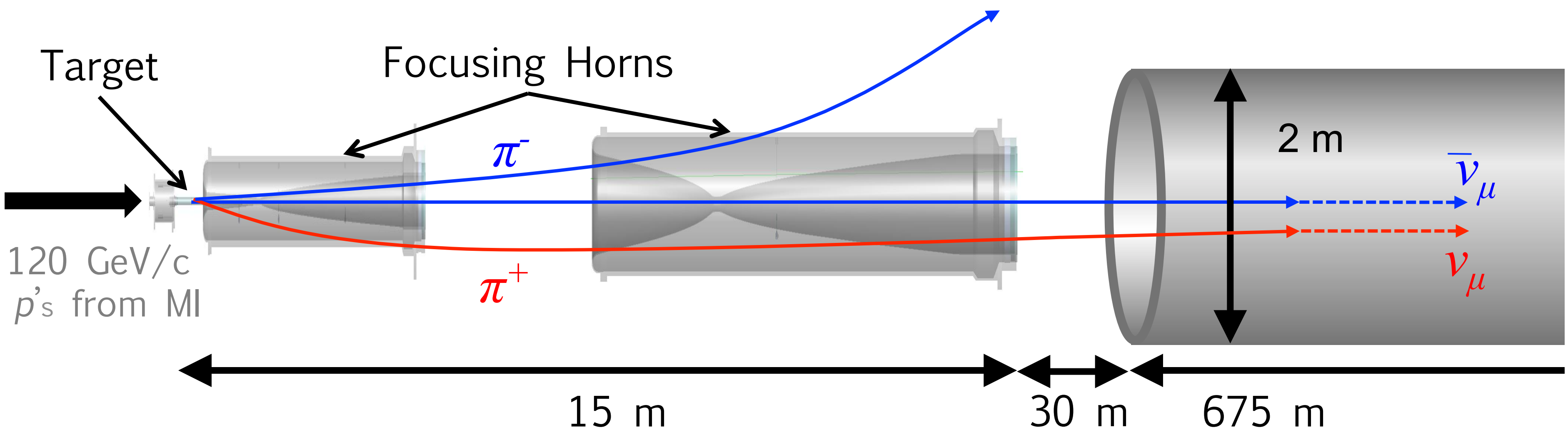
- Two functionally similar magnetized detectors
- High intensity, flexible beam
  - ⇨ 3.5x10^{13} protons/pulse (320 kW beam)
  - ⇨ two magnetic horns
  - ⇨ movable target (→ adjustable energy spectrum)



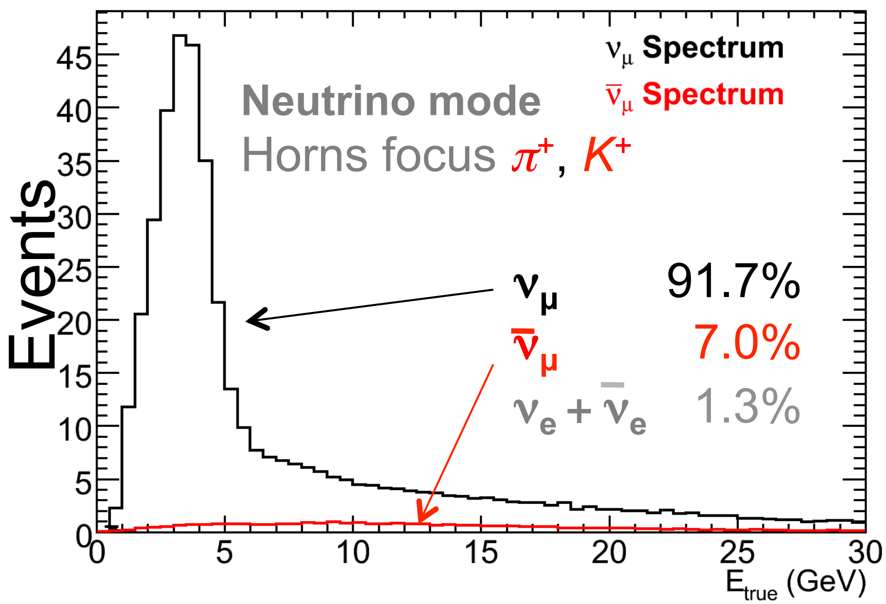


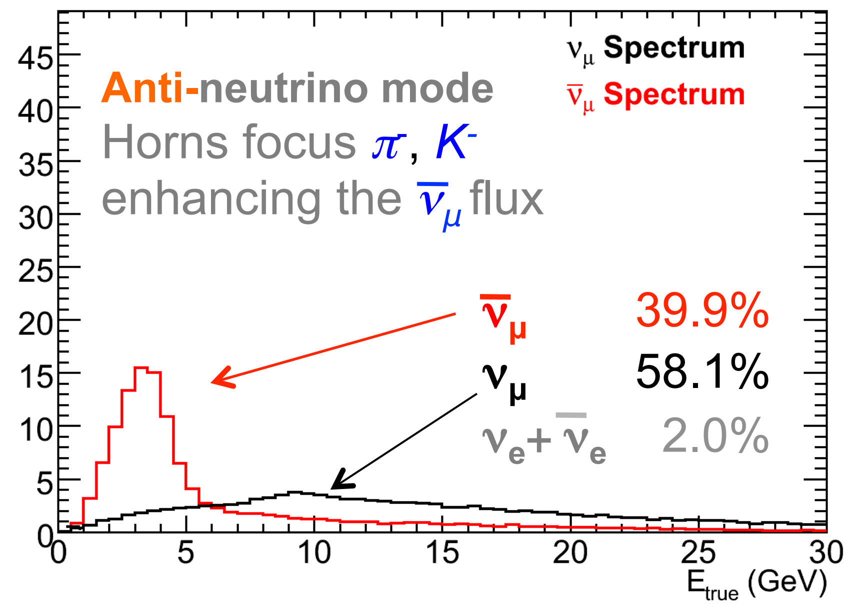
Making a neutrino beam

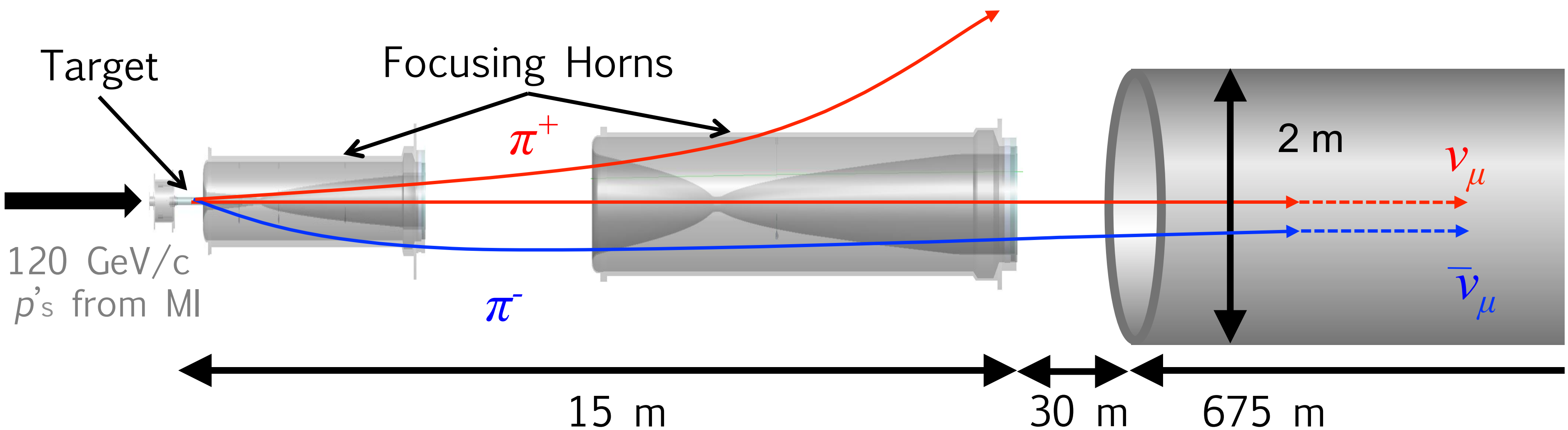




Making an anti-neutrino beam

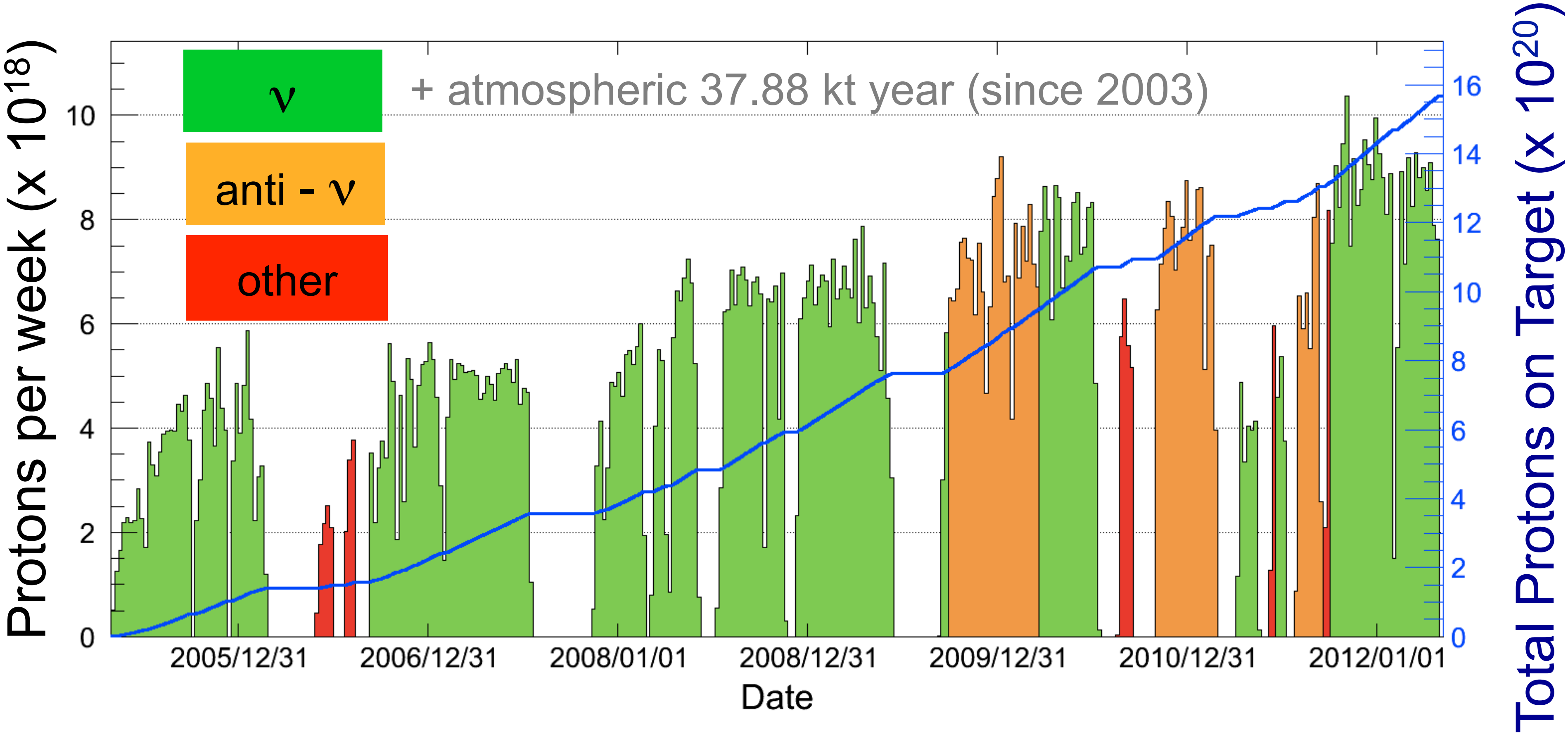






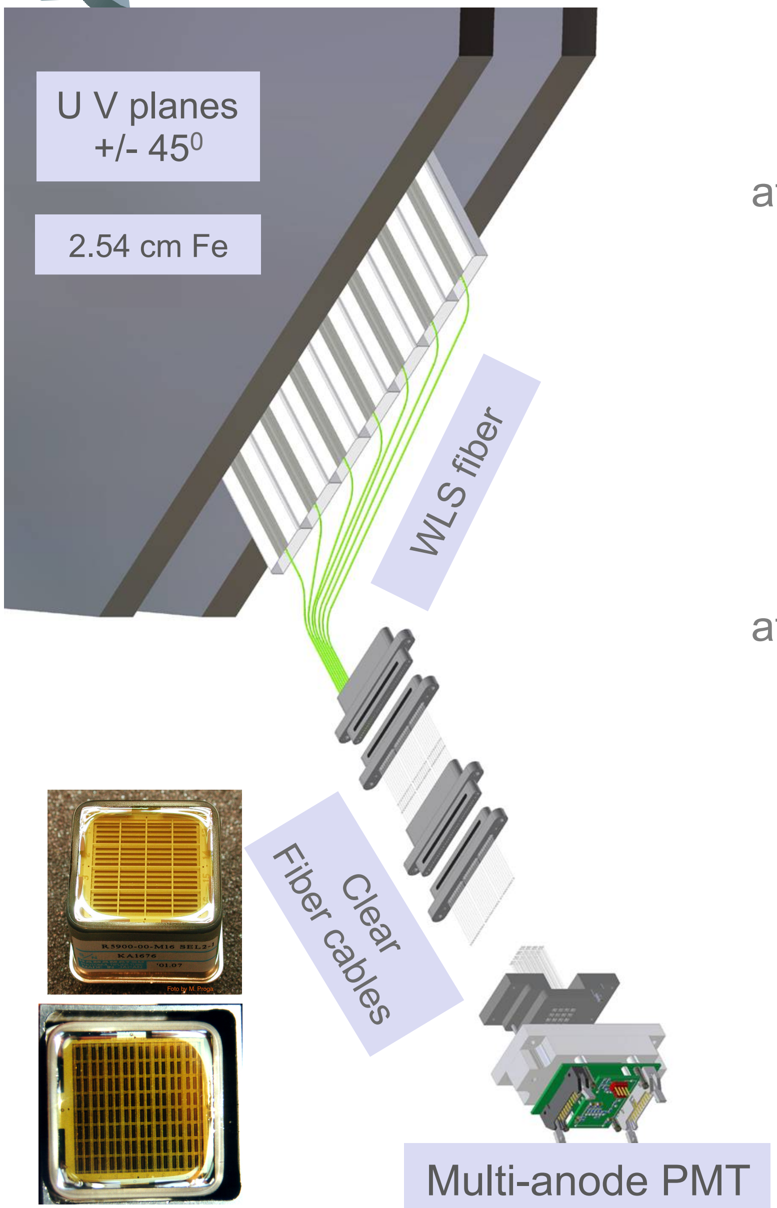
Protons-on-target (POT) history of MINOS

May 1, 2005 → April 30, 2012

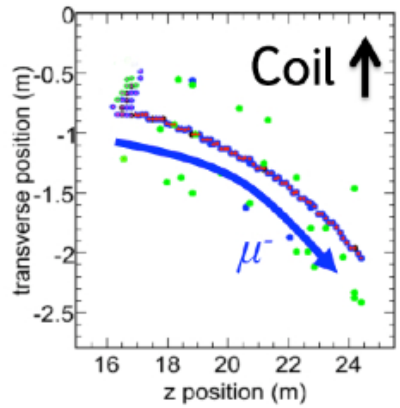


7 years, 7 targets, 2 horns, 15.6×10^{20} POT

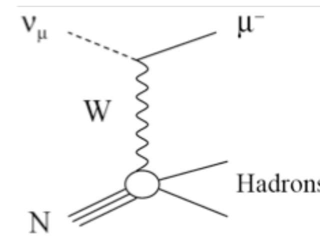
Near and Far Detectors and event classification



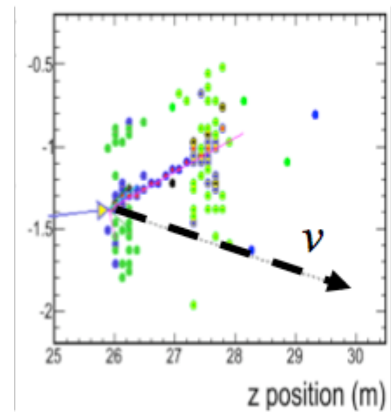
Beam + atmospheric



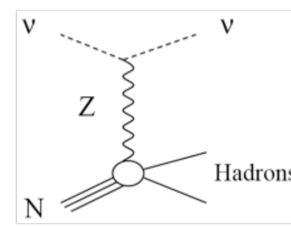
Charged Current neutrino event



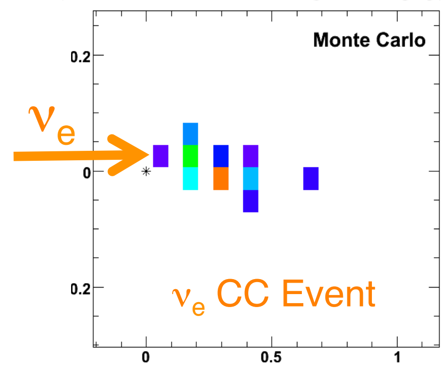
Beam + atmospheric

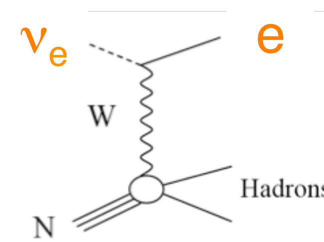


Neutral Current neutrino event



Beam

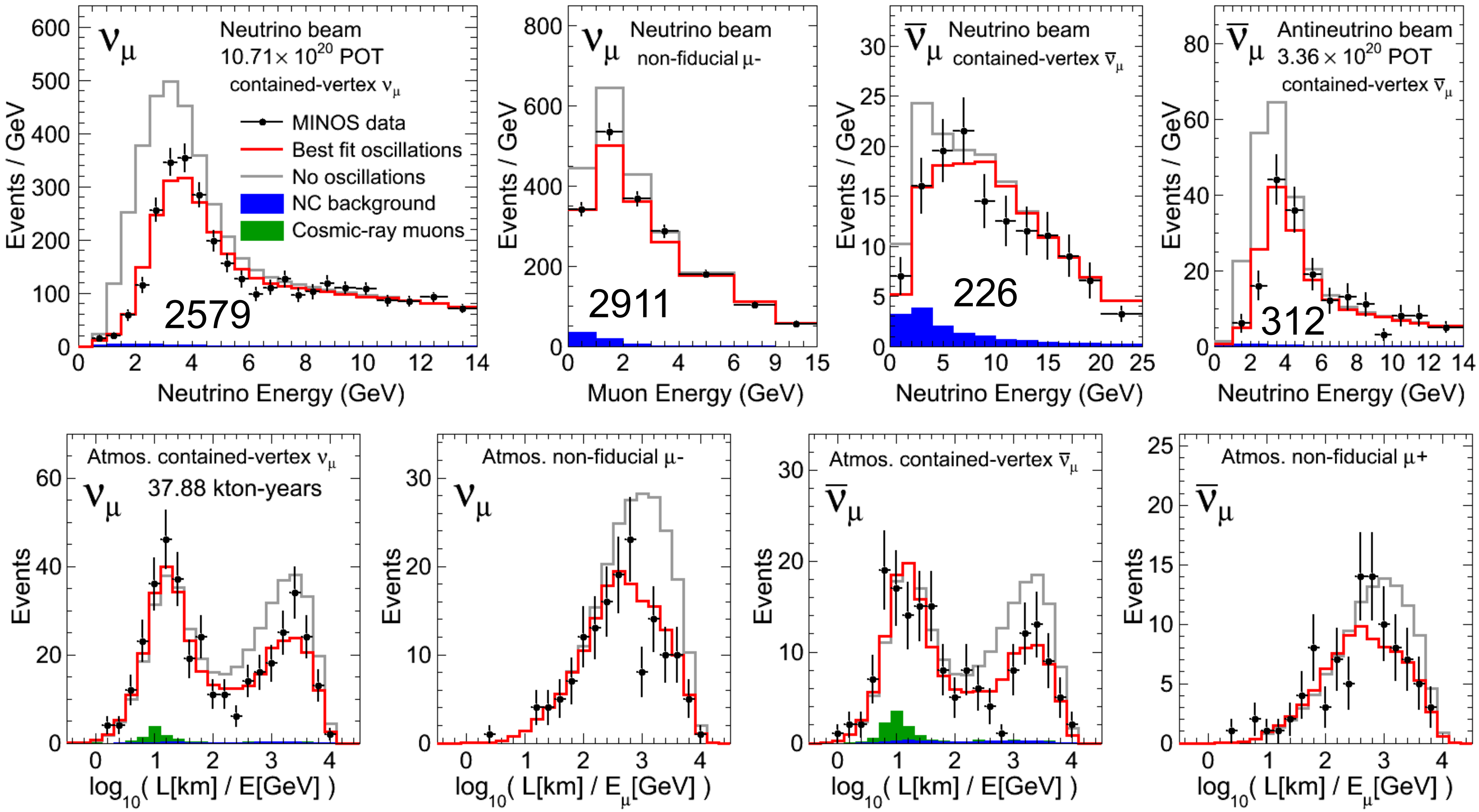




Charged Current electron-neutrino event

MINOS disappearance data sets: beam and atmospheric events

PRELIMINARY



Main stats: 2579 beam nus 312 beam anti-nus 2072 atmospheric

Assume CPT oscillations

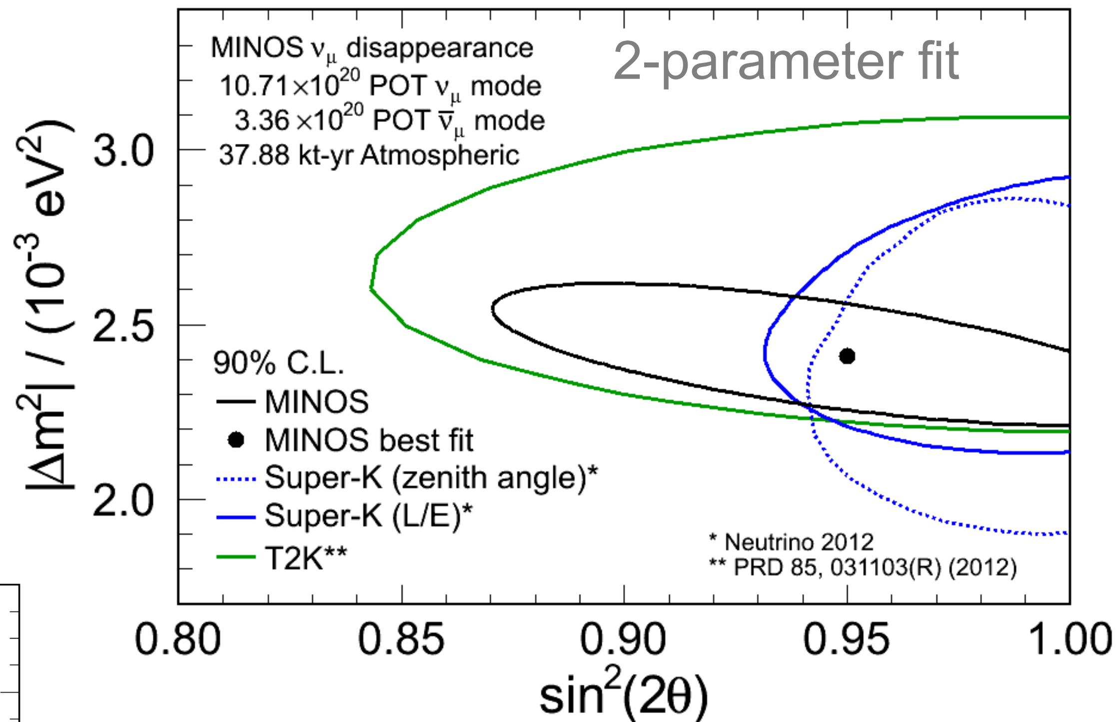
neutrino and antineutrino parameters the same

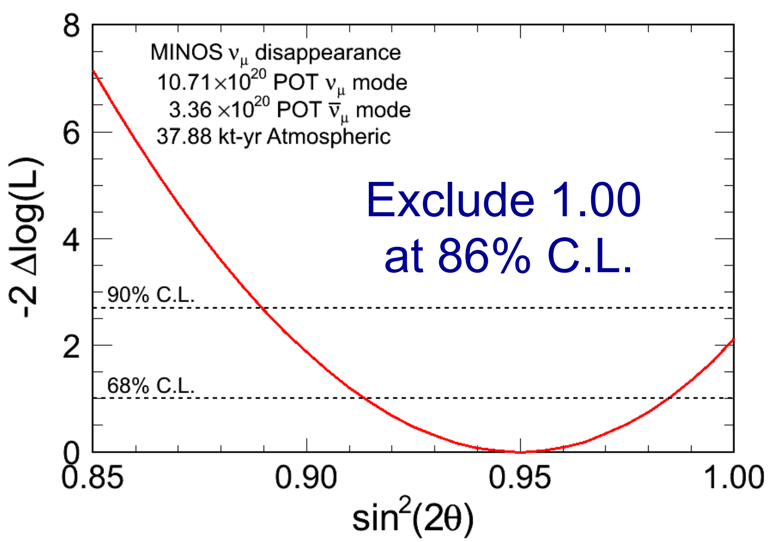
$$\Delta\bar{m}^2 \equiv \Delta m^2$$
$$\bar{\theta} \equiv \theta$$

PRELIMINARY

Beam + atmospheric data

$$\left|\Delta m^2\right| = 2.41^{+0.09}_{-010} \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(2\theta) = 0.950^{+0.035}_{-0.036}$$
$$\sin^2(2\theta) > 0.890 \quad (90\%\ \mathrm{C.L.})$$



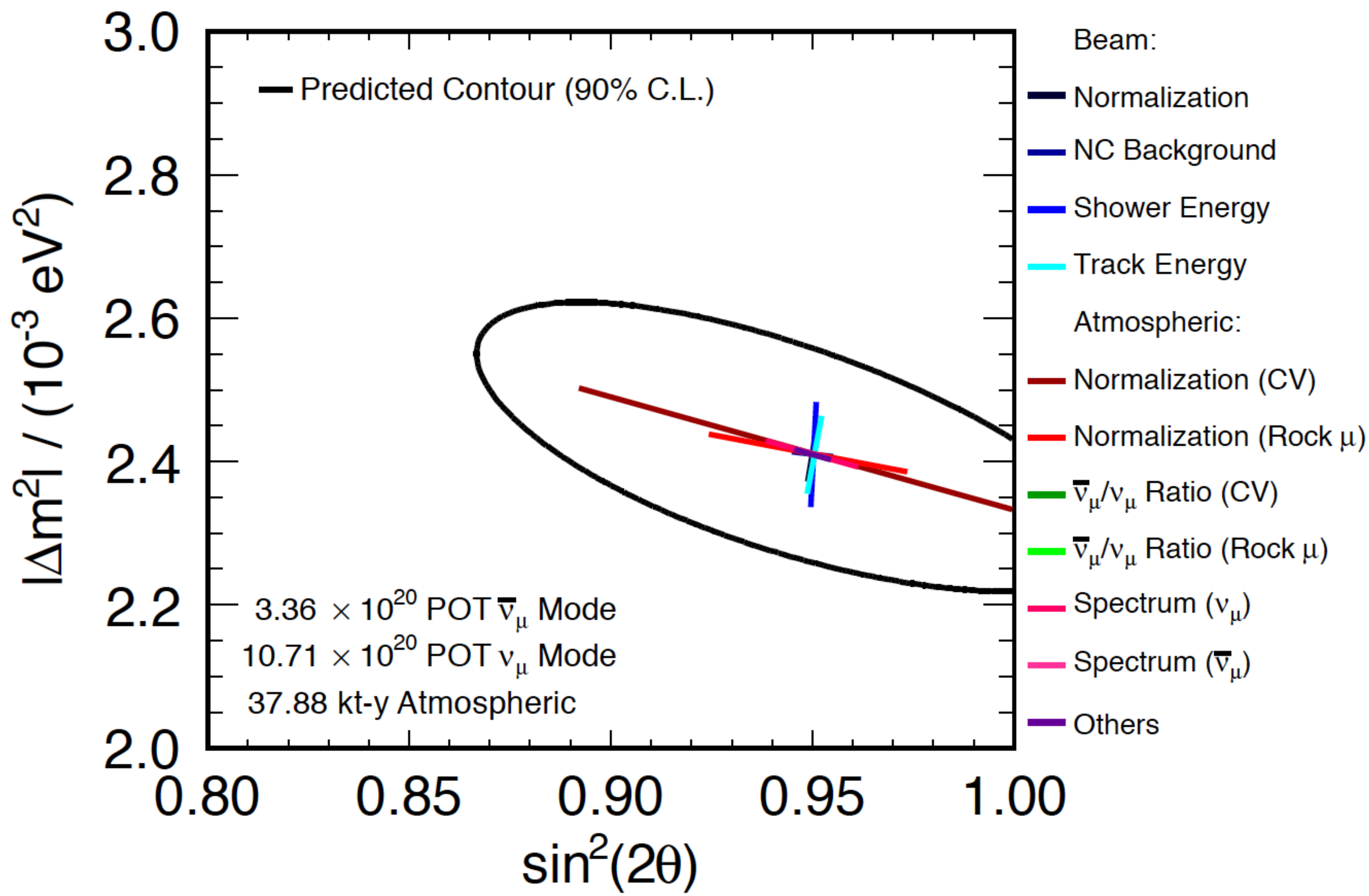


$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \equiv P(\nu_\mu \to \nu_\mu)$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.267\ \ \Delta m^2(\mathrm{eV}^2)\ \ L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Systematics: 2-parameter fit

PRELIMINARY



MINOS – beam + atmospheric data
2-parameter vs. 4-parameter fit

PRELIMINARY

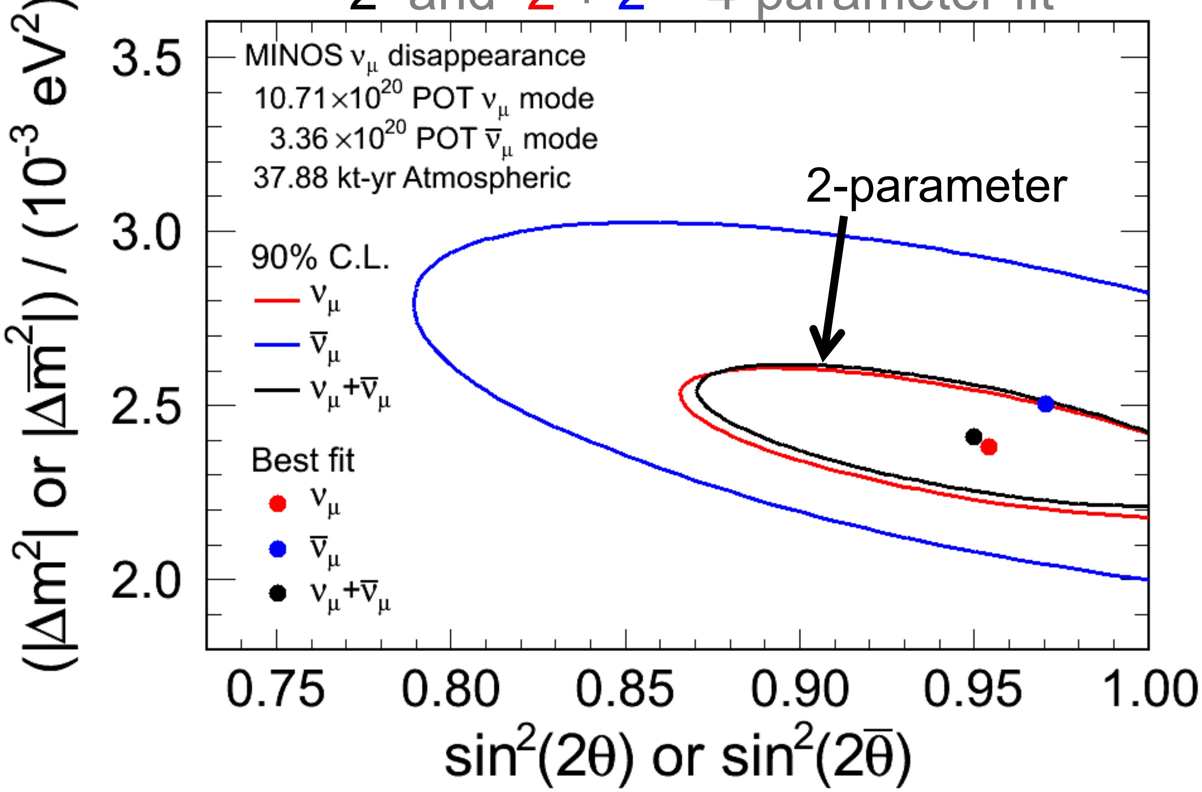
$\Delta\bar{m}^2 \quad \Delta m^2 \quad \bar{\theta} \quad \theta$

$|\Delta\bar{m}^2| = 2.50^{+0.23}_{-0.25} \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2(2\bar{\theta}) = 0.97^{+0.03}_{-0.08}$

$\sin^2(2\bar{\theta}) > 0.83 \quad (90\%\ \mathrm{C.L.})$

2 and 2 + 2 = 4-parameter fit

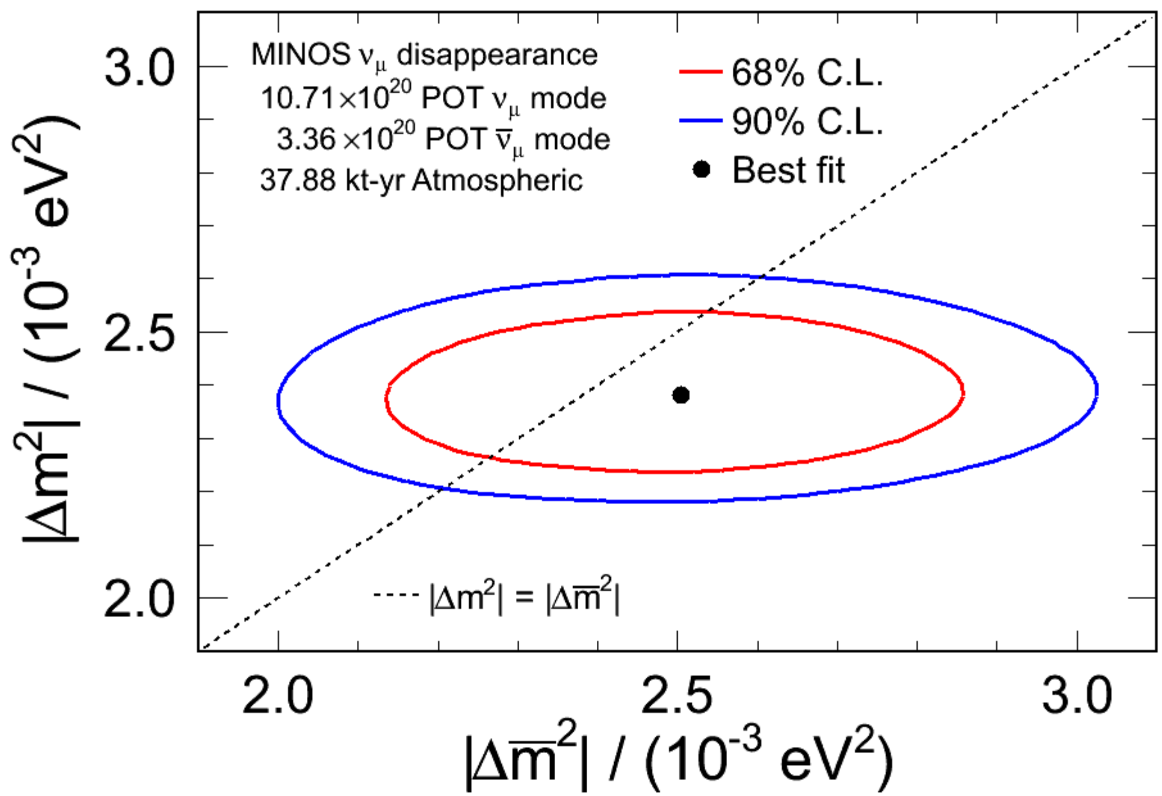


$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.267\ \ \Delta m^2(\mathrm{eV}^2)\ \ L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\bar{\theta})\sin^2\left(\frac{1.267\ \ \Delta\bar{m}^2(\mathrm{eV}^2)\ \ L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

MINOS: beam + atmospheric data

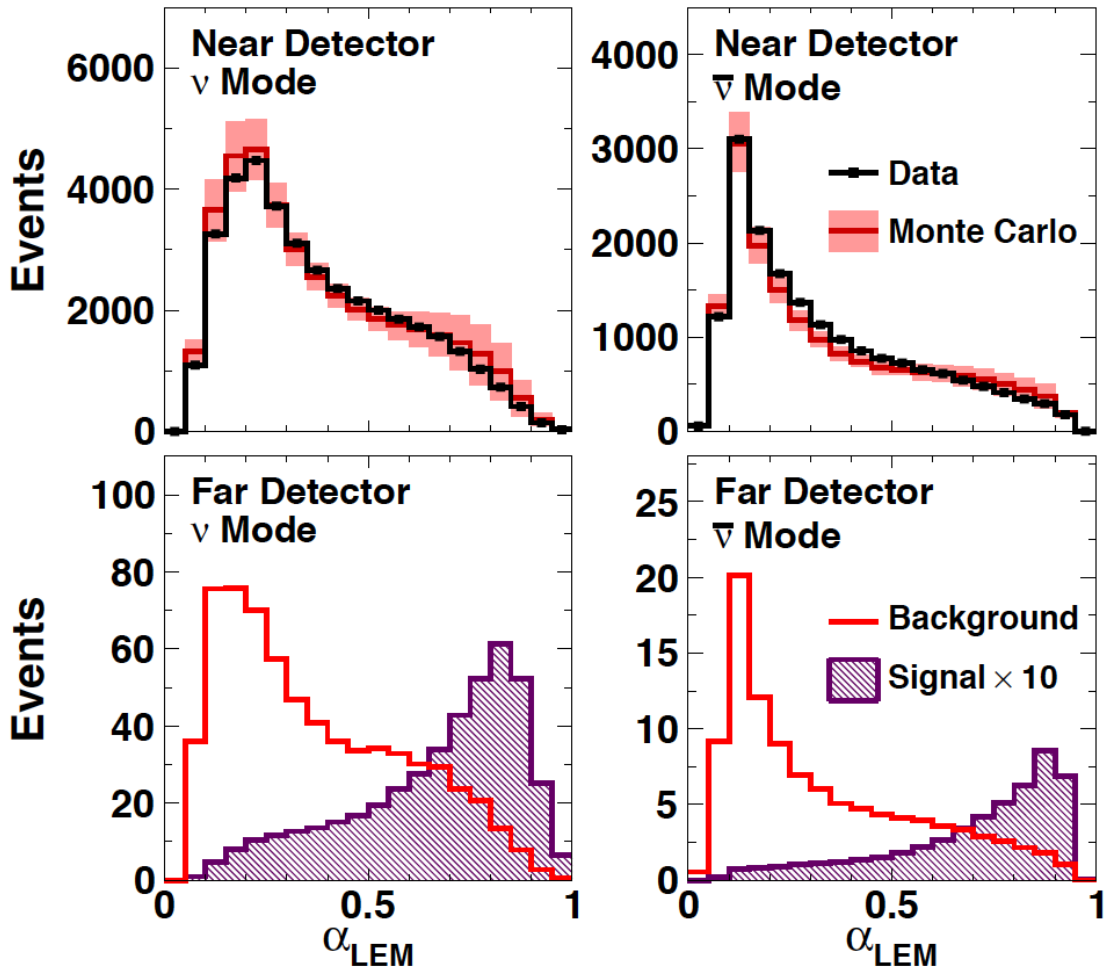
PRELIMINARY



$$\left|\Delta\bar{m}^2\right| - \left|\Delta m^2\right| = 0.12^{+0.24}_{-0.28} \times 10^{-3}\,\mathrm{eV}^2$$

Electron-ν and anti-ν appearance

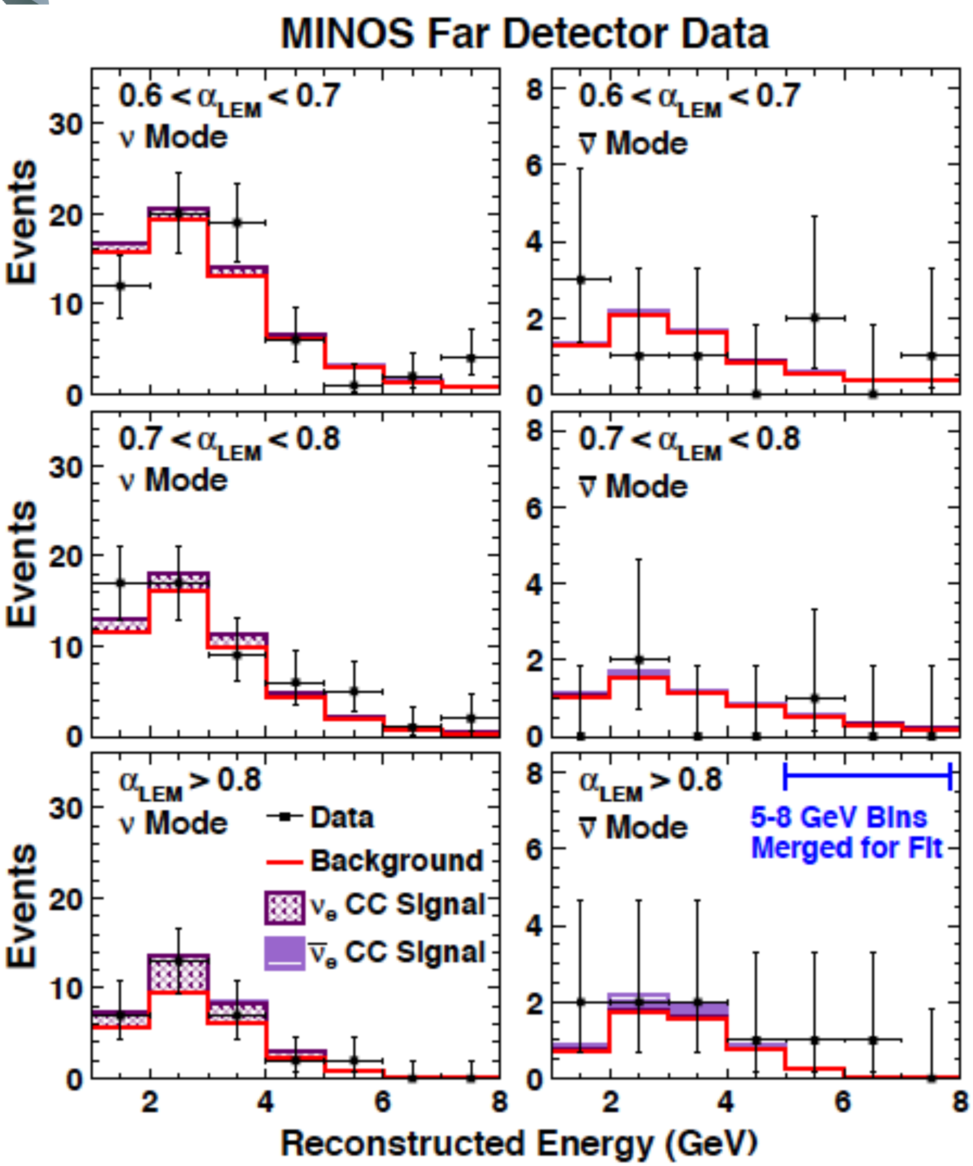
- 10.6 x 10^{20} POT positive-focus + 3.3 x 10^{20} POT negative-focus
- Cannot distinguish → combine $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Library Event Matching (LEM) + ANN

PRELIMINARY

Electron-ν appearance event selection



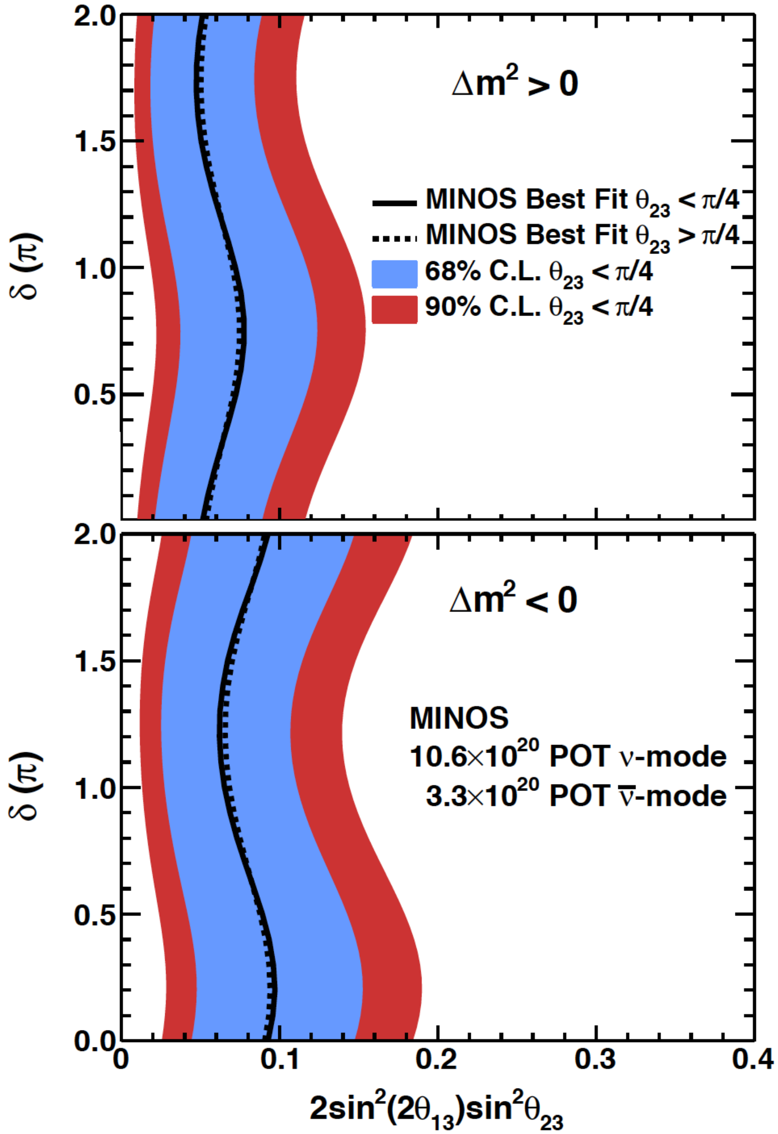
PRELIMINARY

Increasing Signal strength $\alpha_{LEM} \rightarrow 1$

Event Type	ν beam mode	$\bar{\nu}$ beam mode
NC	89.4	13.9
ν_μ-CC and $\bar{\nu}_\mu$-CC	21.6	1.0
Intrinsic ν_e-CC and $\bar{\nu}_e$-CC	11.9	1.8
ν_τ-CC and $\bar{\nu}_\tau$-CC	4.8	0.8
$\nu_\mu \rightarrow \nu_e$-CC	33.0	0.7
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$-CC	0.7	3.2
Total	161.4	21.4
Data	152	20

TABLE II: Expected FD event yields for events with a value of $\alpha_{LEM} > 0.6$, assuming $\sin^2(2\theta_{13}) = 0.1$, $\delta = 0$, $\theta_{23} = \pi/4$, and a normal mass hierarchy.

Electron-ν appearance constraints



PRELIMINARY

Cannot distinguish between ν_e and anti-ν_e events, so we perform a combined analysis:

$$\text{At} \quad \delta_{CP} = 0 \quad \text{and} \quad \theta_{23} < \pi / 4$$

- Assuming normal hierarchy:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$$

$$0.01 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.12 \quad (90\%\ \text{C.L.})$$

- Assuming inverted hierarchy:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$$

$$0.03 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.18 \quad (90\%\ \text{C.L.})$$

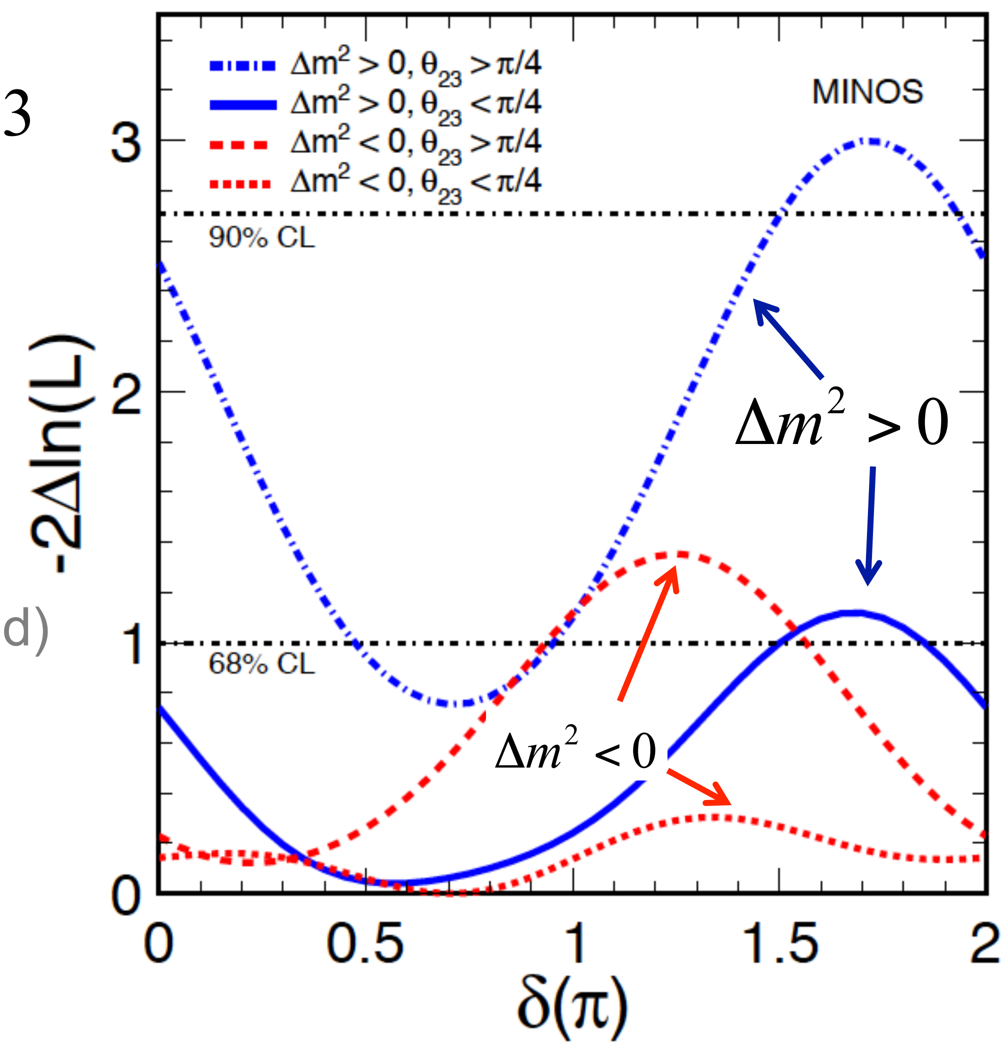
PRELIMINARY

Use reactor results:

$$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$$

Vary
- δ,
- octant of θ_{23},
- mass hierarchy

→ Compare against data (all uncertainties included)



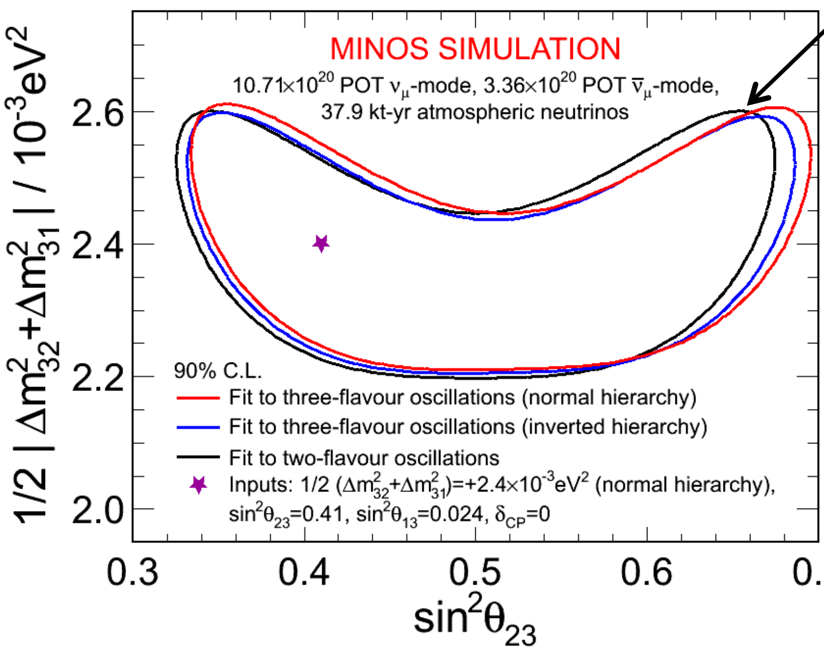
Coming up…

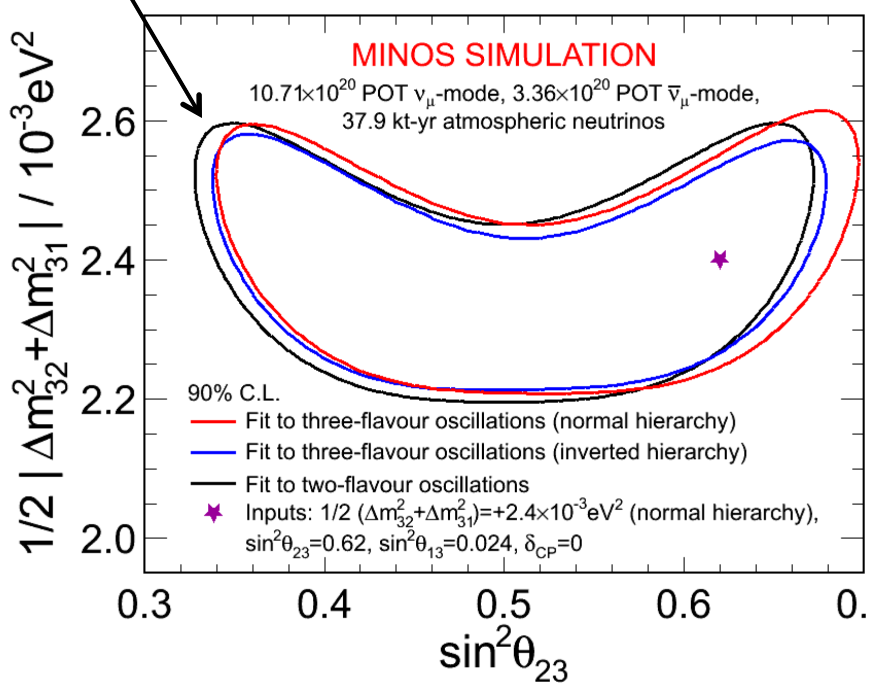
3-flavor mixing framework sensitivities studies

Sensitivities (Lower Octant)

2-flavor framework

Sensitivities (Higher Octant)





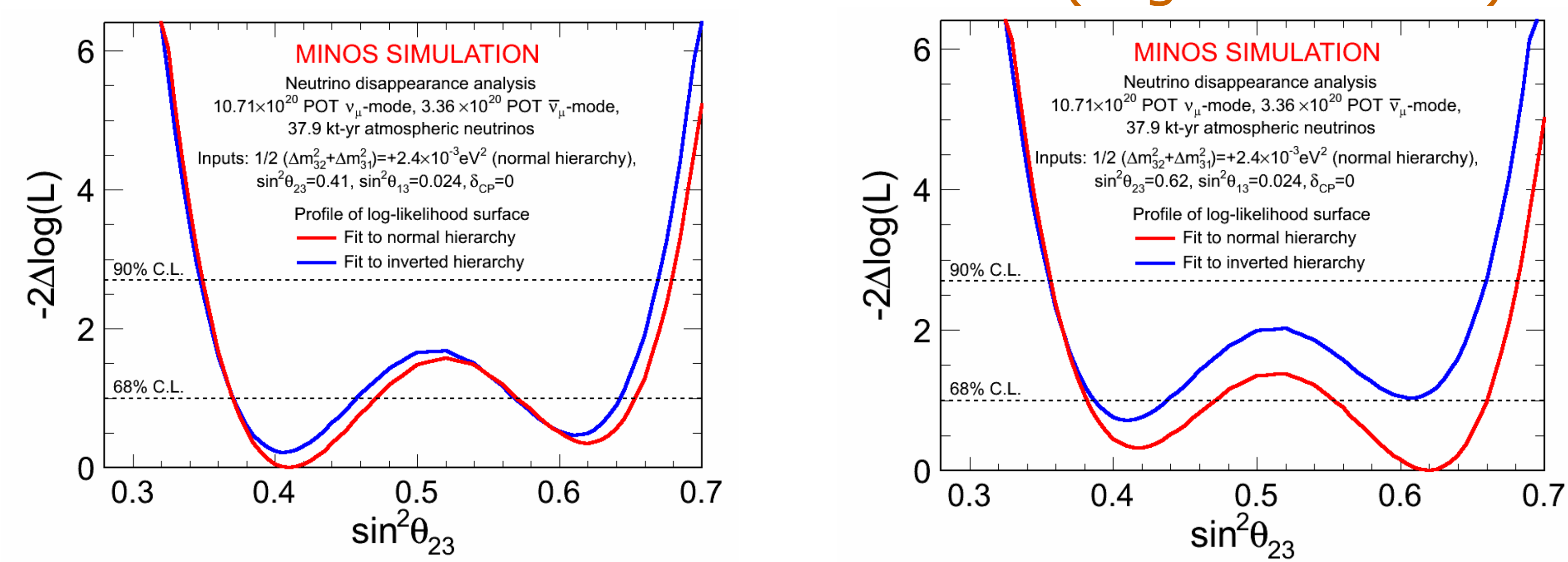
Coming up…

3-flavor mixing framework sensitivities studies

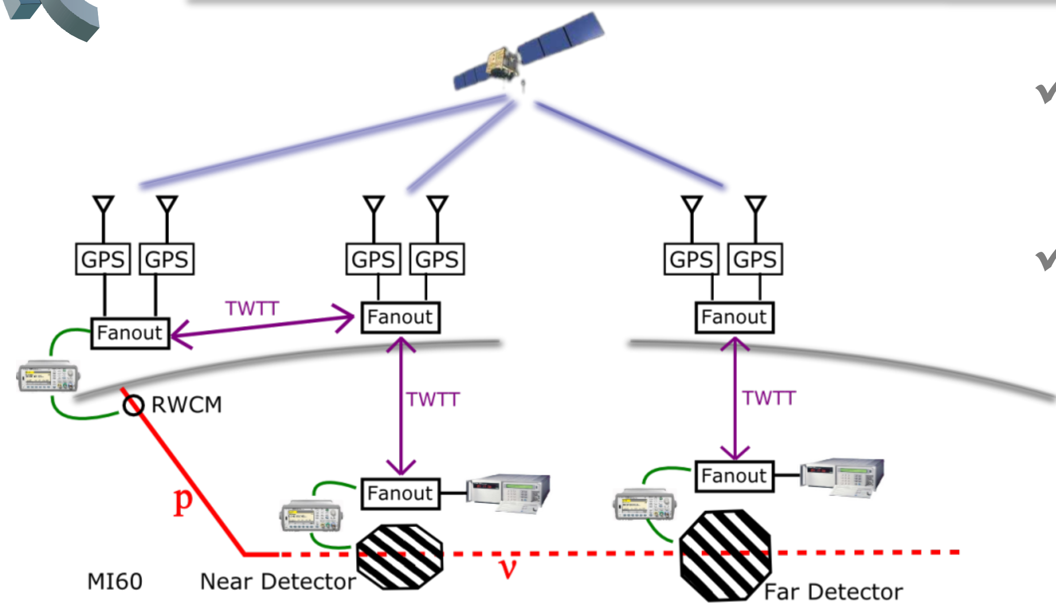
Beam + atmospheric

Sensitivities (Lower Octant)

Sensitivities (Higher Octant)



Neutrino Time of Flight (ND → FD 735 km)



- ✓ Baseline ND – FD = 2,449,316.3 ns
- ✓ Neutrino events:

$$\delta = (-2.4 \pm 0.1_{stat} \pm 2.6_{syst})\ \text{ns}$$

$$\left(\frac{v}{c} - 1\right) = (1.0 \pm 1.1) \times 10^{-6}$$

- ✓ Common view GPS
- ✓ TWTT GPS
- ✓ NIST-NGS-Fermilab
- ✓ Auxiliary Detectors

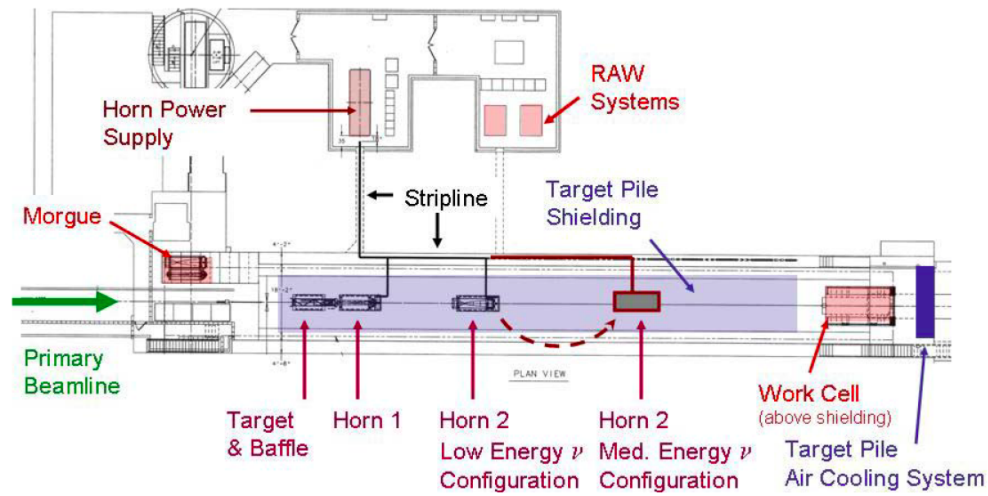
Systematic uncertainty	Value
Inertial survey at FD	2.3 ns
Relative ND-FD latency	1.0 ns
FD TWTT between surface and underground	0.6 ns
GPS time transfer accuracy	0.5 ns
TOTAL	2.6 ns

Near future

MINOS+

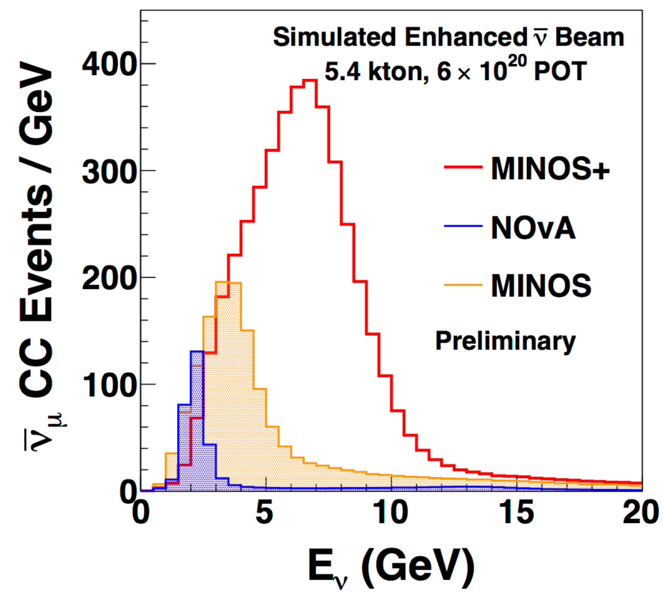
MINOS+

- ME beam (new)
  - ✓ New target
  - ✓ New horn 1
  - ✓ Horn 2 → 10m downstream
  - ✓ 1.33 sec cycle
  - ✓ 700 kW beam power
  - ✓ 6×10^{20} POT/year

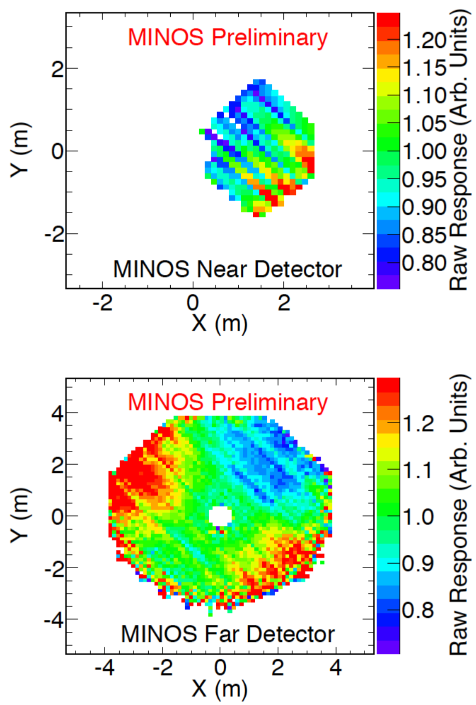


- Physics goals
  - ✓ Precision measurements of atmospheric oscillations
  - ✓ Probes higher energy region
  - ✓ Search for sterile neutrinos
  - ✓ Search for NSI

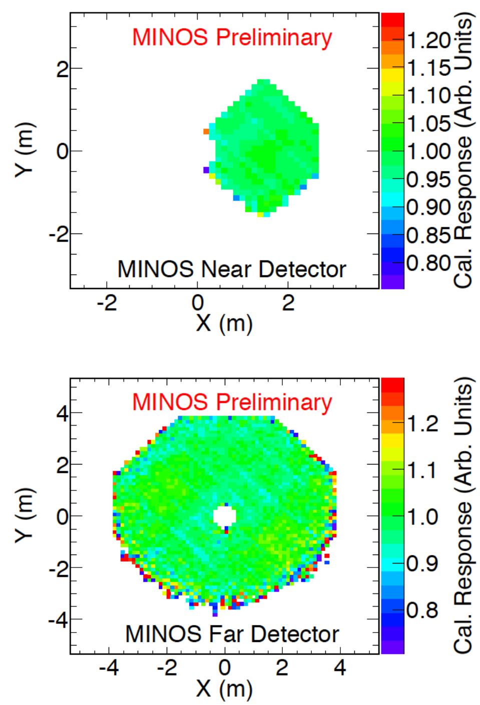
- Corollary:
  - ✓ 3 years of running in 4-10 GeV
  - ✓ Significant reduction in stat. uncertainty
  - ✓ Collect ~3000 numu's CC events/year



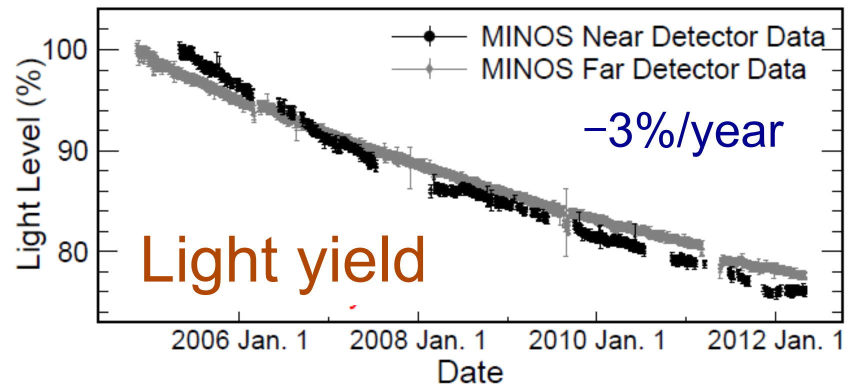
Tools: light injection and stopping muons

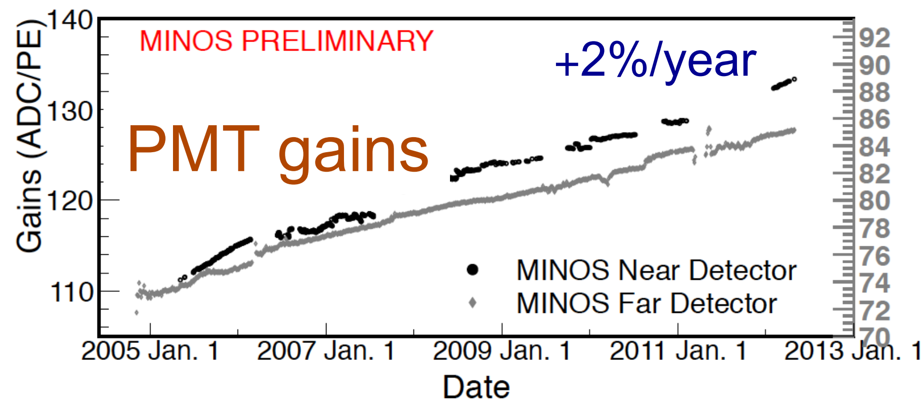


Raw response

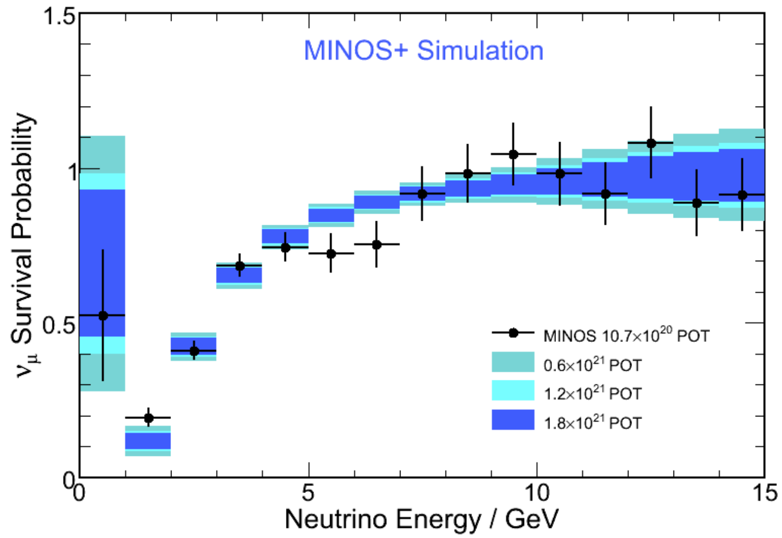


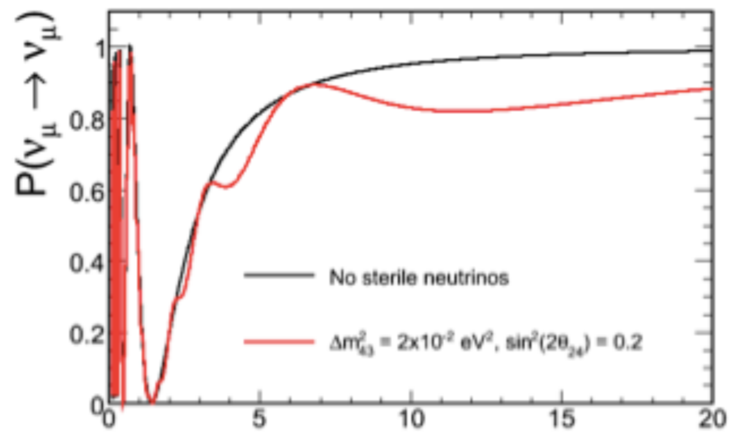
Fully calibrated

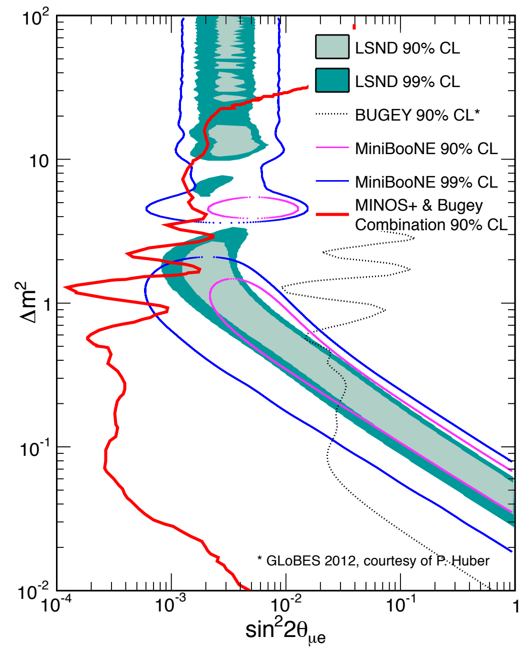




MINOS+

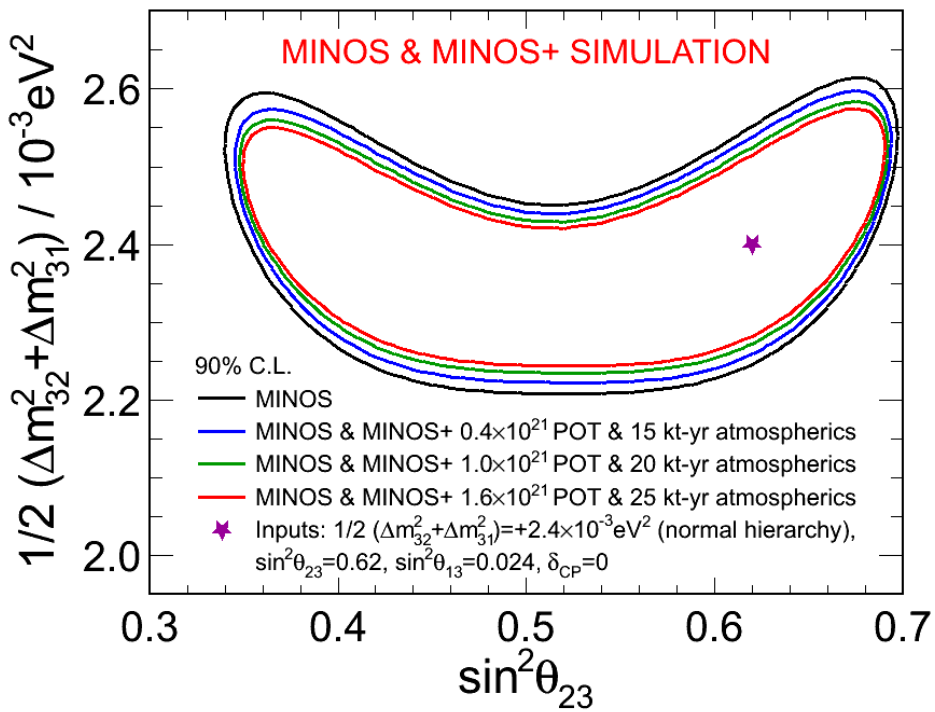




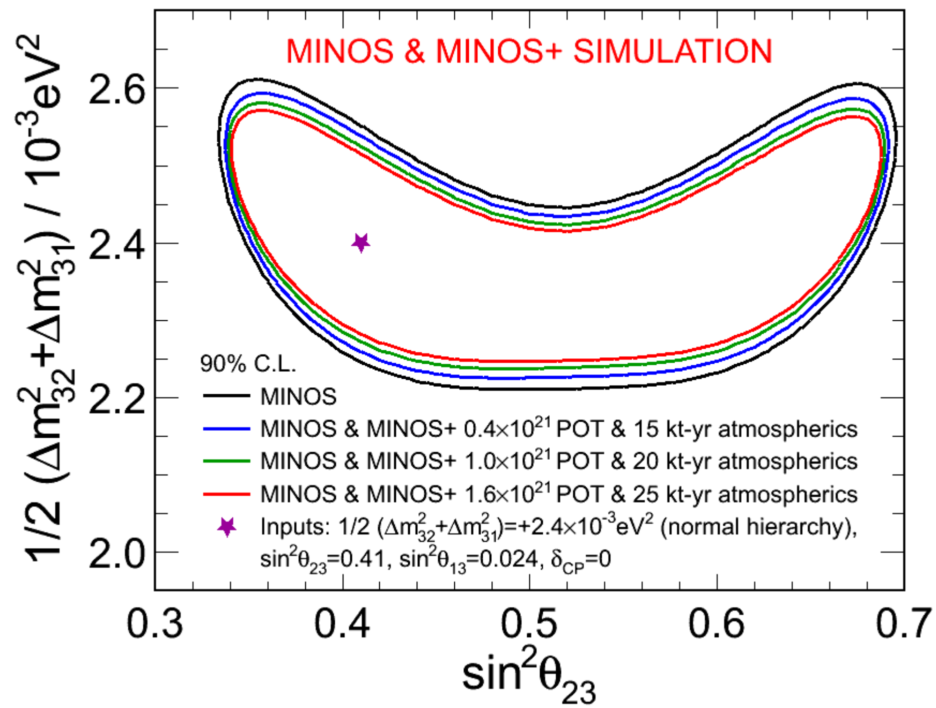


- Significant statistical improvement on the “rising” edge of oscillations
- Using reactor experiments (e.g., Bugey) and high stat. MINOS+ can almost rule out the allowed low mass LSND region

Sensitivities (Higher Octant)



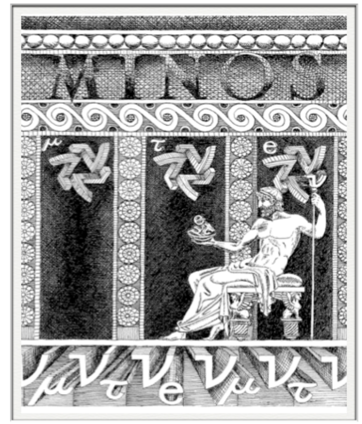
Sensitivities (Lower Octant)



Summary

- **End of MINOS**

  Proposal (1995) → Beam (2005) → End of LE (2012)



- **Set stringent constraints on disappearance**

$$\left|\Delta m^2\right| = 2.41^{+0.09}_{-010} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.950^{+0.035}_{-0.036} \qquad \sin^2(2\theta) > 0.890 \quad (90\%\ \mathrm{C.L.})$$

- **Constraints on long-baseline electron-neutrino appearance**

$$\mathrm{NH:} \quad 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$$

$$\mathrm{I\,H:} \quad 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$$

+ illustration of combined LB & reactors analysis

- **3-flavor analysis coming soon…**
- **MINOS+ → new high statistics data (with medium energy beam)**
- **NuMI – the most powerful beam with 4 experiments w/ 5 detectors**

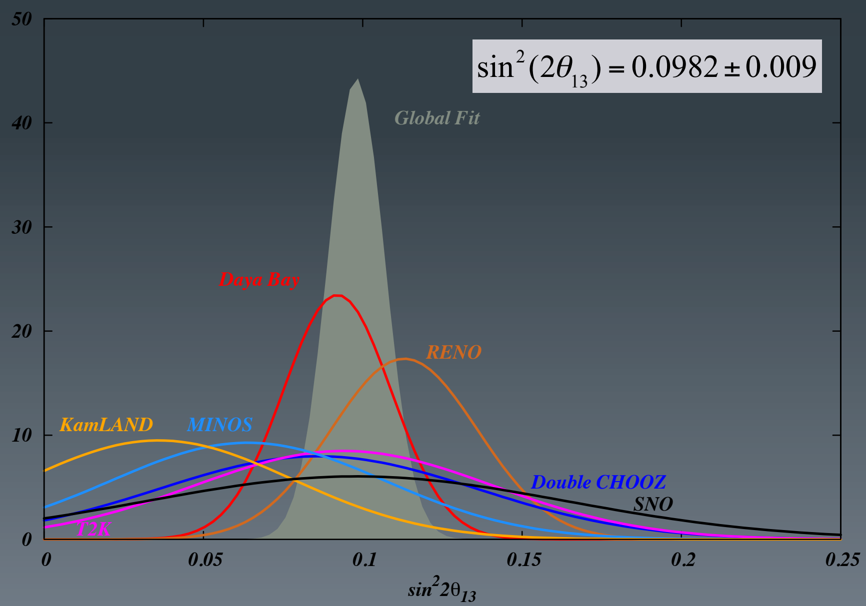
  ⇨ MINOS+ ND, NOvA ND, NOvA NDOS, Minerva, microBooNE

The PMNS Fitter

PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Framework for global fit with deeply involved from all current experiments (not just likelihood surface, but systematic contributions).
- "Bayesian Analysis Toolkit" (BAT based on Bayes' theorem and MCMC) is used as backbone.
- Using MINOS data to test framework (by comparing with MINOS published results)



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Alexandre Sousa
University of Cincinnati

Viet Nus, December 21, 2012

MINOS Collaboration

Argonne · Athens · Benedictine · Brookhaven · Caltech · Cambridge · Campinas · Fermilab · Goias · Harvard · Holy Cross · IIT · Indiana · Iowa State · Lebedev · Livermore · Minnesota-Twin Cities · Minnesota-Duluth· Otterbein · Oxford Pittsburgh · Rutherford · Sao Paulo · South Carolina · Stanford · Sussex · Texas A&M · Texas-Austin · Tufts · UCL · Warsaw · William & Mary