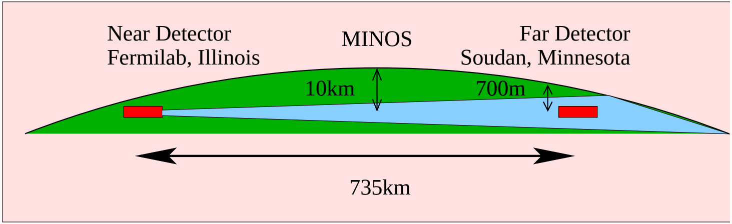
Neutrino oscillations in the MINOS experiment

Katarzyna Grzelak, University of Warsaw
for the MINOS Collaboration

Alushta,Crimea
6.09.2011

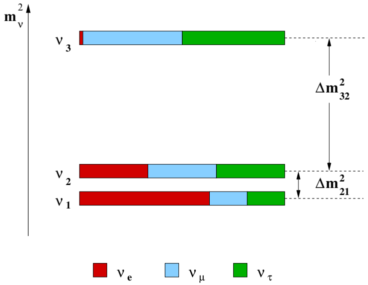
Introduction



- MINOS experiment: two magnetized (1.3 T), underground detectors located on NuMI beam axis
- NuMI: ν_μ or $\overline{\nu}_\mu$ enhanced beam
- Near Detector (ND) (1kt) at Fermilab, 1km from target, $\sim$ 100m underground: study of neutrino interactions with absence of oscillations
- Far Detector (FD) (5.4 kt), 735km away, at Soudan (Minnesota), 730m underground: study/search for neutrino oscillations
- Latest results based on data from 2005-2011

MINOS Oscillation Measurements

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



MINOS is sensitive to the larger Δm^2_{ij} $(= m_i^2 - m_j^2)$

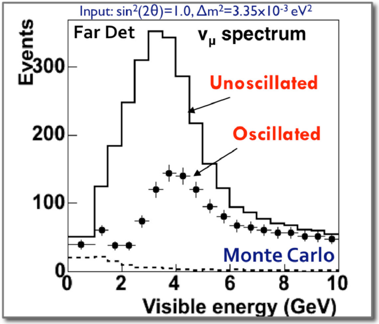
$$\mathbf{U} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric,accelerator}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{reactor,accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar,reactor}}$$

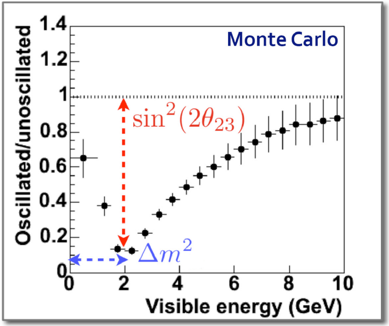
$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, $\delta \equiv CP$ violation phase.

MINOS Oscillation Measurements

Measurement of energy-dependent ν_μ disappearance

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





In this talk latest (2010) results for statistics: 7.25×10^{20} pot

MINOS Oscillation Measurements

Measurement of energy-dependent $\overline{\nu}_\mu$ disappearance

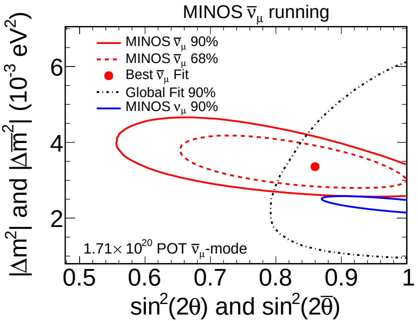
$$P(\overline{\nu}_\mu \to \overline{\nu}_\mu) \simeq 1 - \sin^2 2\overline{\theta}_{23} \sin^2 \frac{1.27 \Delta \overline{m}^2 L}{E_{\overline{\nu}}}$$

- Antineutrino analysis very similar to the neutrino analysis.
- MINOS is unique: magnetic field allows for the event-by-event separation of ν_μ and $\overline{\nu}_\mu$ charged-current interactions.
- Difference between neutrinos and antineutrinos ?
- Two possible sources of $\overline{\nu}_\mu$:
  - 7% antineutrino component of neutrino beam
  - By reversing the horn current, NuMI can create $\overline{\nu}_\mu$-enhanced beam

MINOS Oscillation Measurements

Measurement of energy-dependent $\overline{\nu}_\mu$ disappearance

MINOS results in 2010

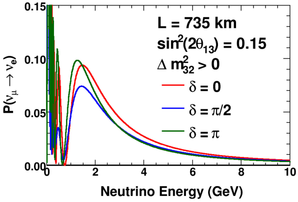


- In 2010, MINOS presented ν_μ and $\overline{\nu}_\mu$ oscillation parameters measurements (for 1.71×10^{20} pot) that are consistent with each other at the 2% level.
- In this talk new 2011 results for increased statistics: 2.95×10^{20} pot

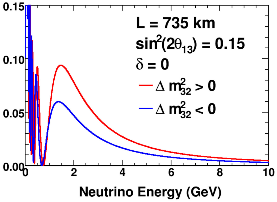
Search for ν_e appearance in the ν_μ beam

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta$$
$$\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta$$
$$+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin^2 \Delta$$
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta$$

δ dependence



mass hierarchy dependence



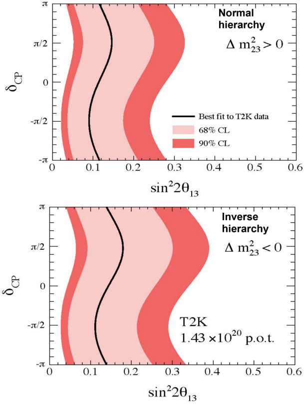
$$\Delta \equiv \frac{\Delta m^2_{atm} L}{4E_\nu},$$
$$\alpha \equiv \frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}$$

For ν_e probabilities are modified by matter effects.

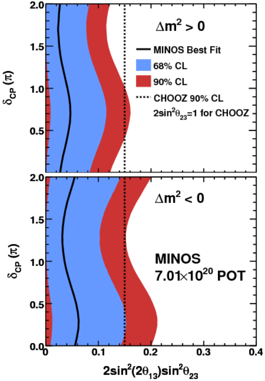
MINOS Oscillation Measurements

Search for ν_e appearance in the ν_μ beam

T2K 2011 result



MINOS 2010 result

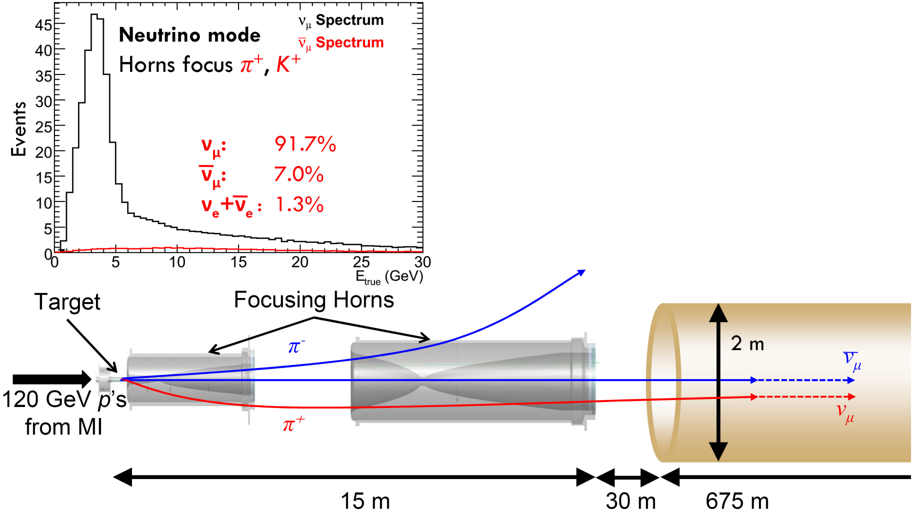


T2K observed 6 events with expected background 1.5 ± 0.3 events for $\theta_{13} = 0$

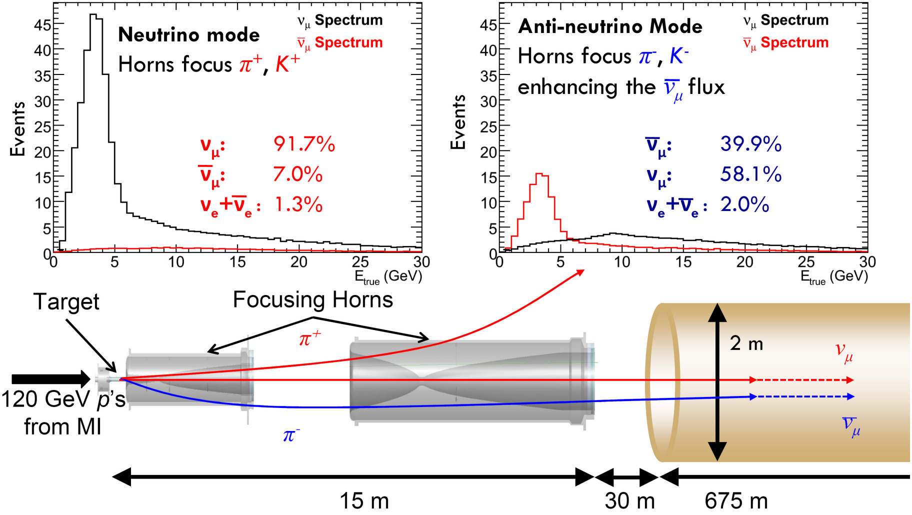
In this talk new 2011 results for increased statistics: 8.2×10^{20} pot

NuMI beam and MINOS detectors

Neutrino Mode



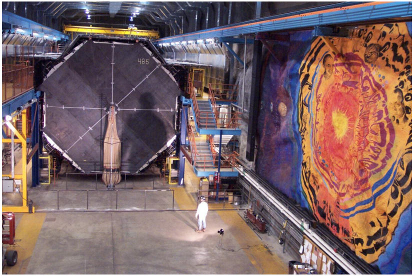
Antineutrino Mode



Minos Detectors

Near Detector (ND)

Far Detector (FD)



scintillator planes segmented into 4.1cm ($\sim$ 1.1 Molière radii) wide strips

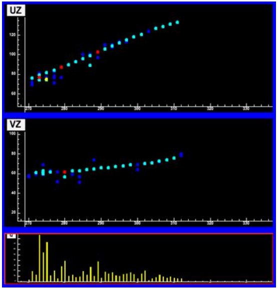
- steel-scintillator sandwich
- each plane is 2.54cm of steel and 1cm of solid scintillator strips ($\sim$ 1.4 radiation length)
- FD: 484 planes; 8m $\times$ 8m $\times$ 30m
- ND: 282 planes; 3.8m $\times$ 4.8m $\times$ 15m
- magnetic field $B = 1.3$ T

Neutrino interactions in the MINOS detectors

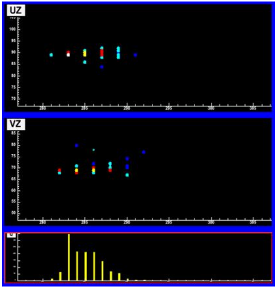
ν_μ ($\overline{\nu}_\mu$) disappearance $\quad$ ν_e appearance

charged current (CC) $\quad$ neutral current (NC)

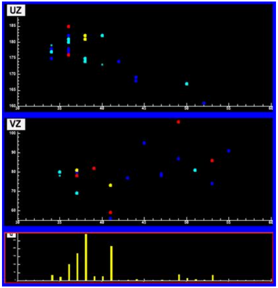
$\nu_\mu + N \rightarrow \mu + X$



$\nu_e + N \rightarrow e + X$



$\nu_x + N \rightarrow \nu_x + X$



ν_μ-CC,$\overline{\nu}_\mu$-CC
long, μ track
$E_\nu = E_{shower} + E_\mu$

ν_e-CC
compact showers,
EM-profile

NC
diffuse showers

Analyses Overview

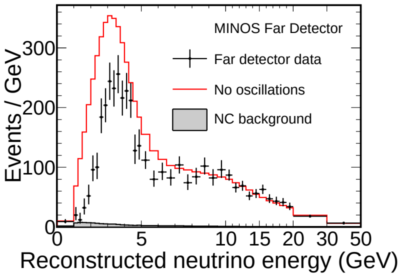
Two detectors (ND and FD) reduce systematics. Methodology:

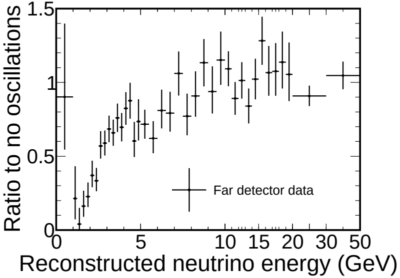
- measure unoscillated energy spectrum at ND
- use Near Detector spectrum to predict FD spectrum
- compare to measured spectrum at FD

Blind to full FD sample until all analysis procedures are frozen.

ν_μ disappearance (7.25 $\times 10^{20}$ pot)

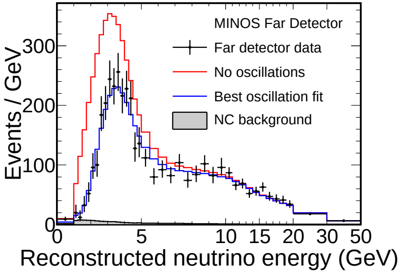
ν_μ disappearance, Far Detector Energy Spectrum

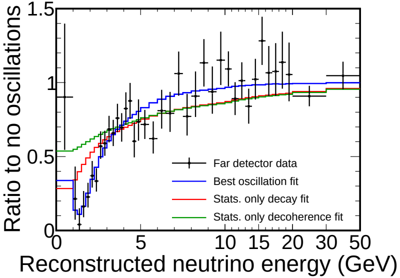




Predicted if no oscillations: 2451 events.
Observed: 1986 events

ν_μ disappearance, Far Detector Energy Spectrum

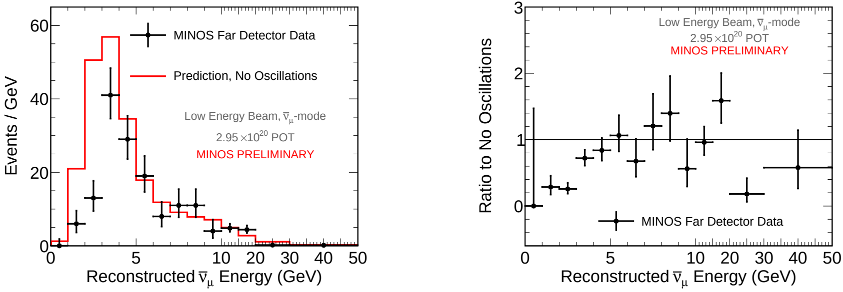




$\Delta m^2 = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\mathrm{eV}^2$

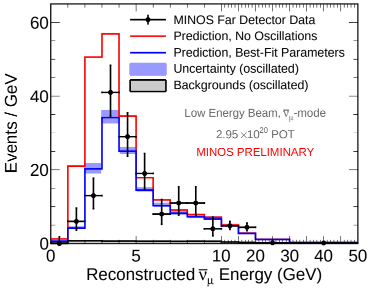
$\sin^2 2\theta_{23} > 0.90$ (90% C.L.)

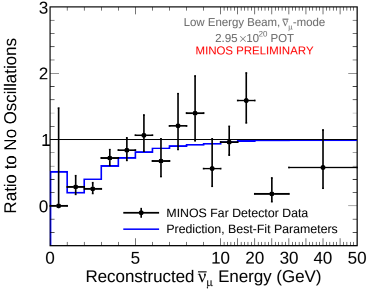
$\overline{\nu}_\mu$ disappearance (2.95 $\times 10^{20}$ pot)



Predicted if no oscillations: 273 events.
Observed: 193 events
Null-oscillations excluded at 7.3σ

$\overline{\nu}_\mu$ disappearance: Far Detector Energy Spectrum





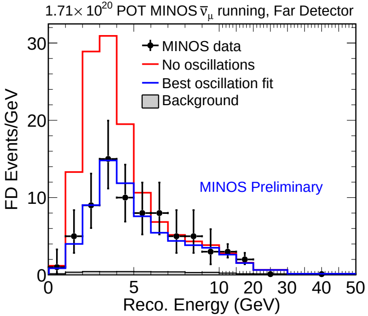
$\overline{\nu}_\mu$ Best Fit Parameters:

$$\Delta\overline{m}^2 = (2.62^{+0.31}_{-0.28}(stat) \pm 0.09(syst)) \times 10^{-3}\mathrm{eV}^2$$

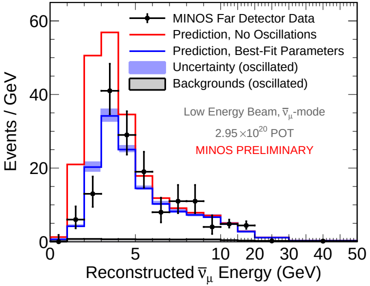
$$\sin^2 2\overline{\theta}_{23} = 0.95^{+0.10}_{-0.11}(stat) \pm 0.01(syst)$$

Comparison with previous result

2010 result



2011 result

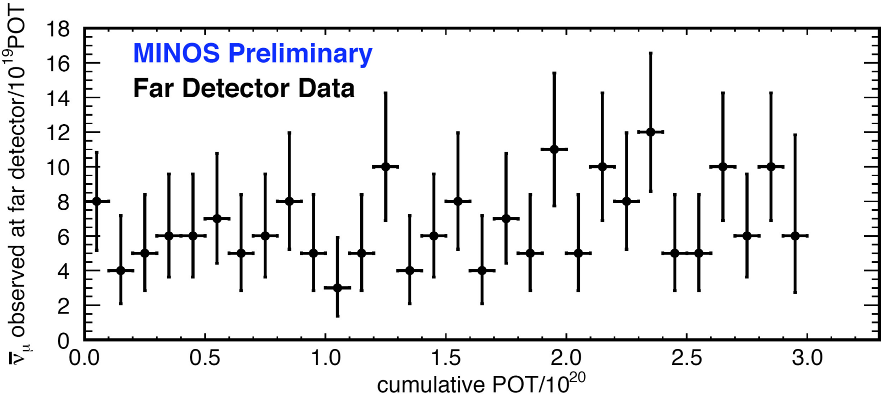


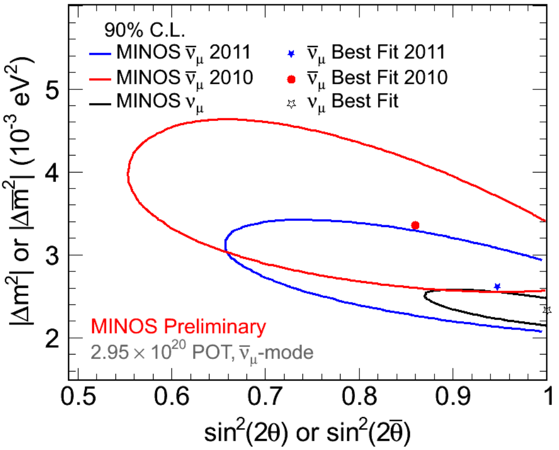
Predicted if no oscillations: 155 events.
Observed: 97 events
$\Delta\overline{m}^2 =$
$(3.36^{+0.46}_{-0.40}(stat) \pm 0.06(syst)) \times 10^{-3}\mathrm{eV}^2$
$\sin^2 2\overline{\theta}_{23} = 0.86^{+0.11}_{-0.12}(stat) \pm 0.01(syst)$

Predicted if no oscillations: 273 events.
Observed: 193 events
$\Delta\overline{m}^2 =$
$(2.62^{+0.31}_{-0.28}(stat) \pm 0.09(syst)) \times 10^{-3}\mathrm{eV}^2$
$\sin^2 2\overline{\theta}_{23} = 0.95^{+0.10}_{-0.11}(stat) \pm 0.01(syst)$

Comparison with previous result

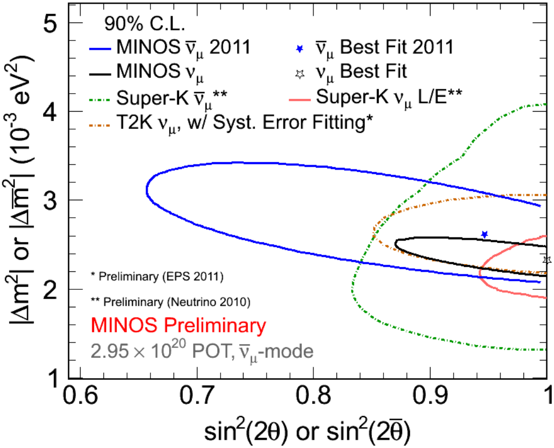
Far Detector Data Rates





ν_μ and $\overline{\nu}_\mu$ oscillation parameters measurements are consistent with each other at the 42% C.L. (was 2% level).

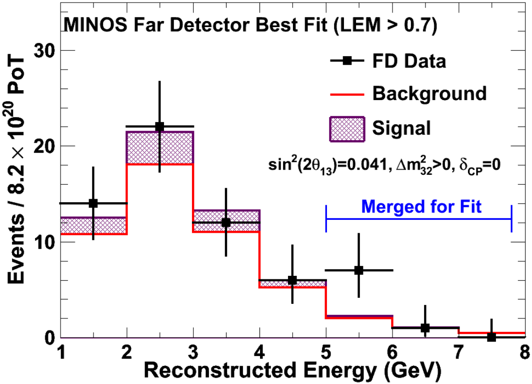
Contour Comparisons



Comparisons with Super-K and T2K results.

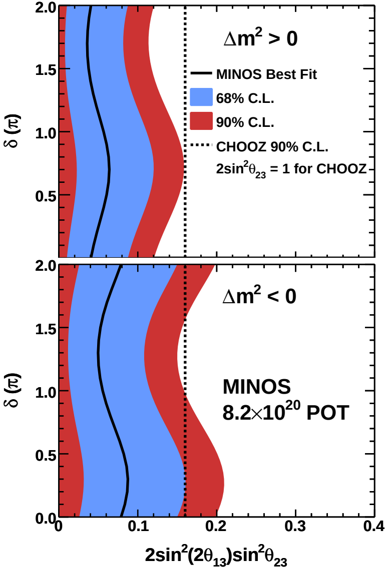
ν_e appearance (8.2 $\times 10^{20}$ pot)

ν_e appearance: Far Detector Energy Spectrum



Predicted if $\theta_{13} = 0$:
$49.6 \pm 7.0(stat.) \pm 2.7(syst.)$ events
In the signal region observed: 62 events.

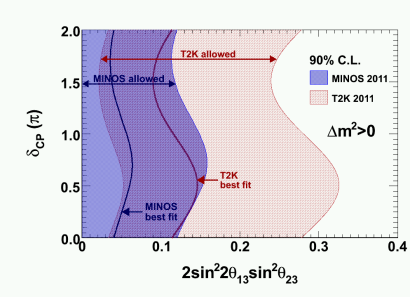
ν_e oscillation parameters

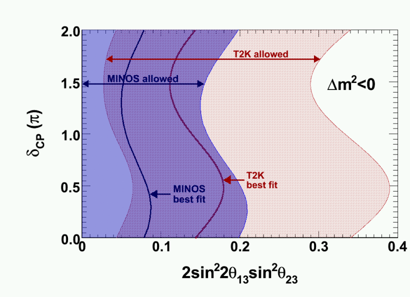


$2\sin^2\theta_{23}\sin^2 2\theta_{13} < 0.12$ at 90% C.L. for normal hierarchy
$2\sin^2\theta_{23}\sin^2 2\theta_{13} < 0.20$ at 90% C.L. for inverted hierarchy

$\theta_{13} = 0$ is disfavoured at 89% C.L.

Comparison to T2K result





MINOS result significantly constrains θ_{13} region allowed by T2K data.

Summary

- ν_e appearance analysis:
  MINOS result significantly constrains θ_{13} region allowed by T2K data.
- ν_μ disappearance analysis:
  The most precise measurement of larger $|\Delta m^2|$ to date
- $\overline{\nu}_\mu$ disappearance analysis:
  The most precise, direct measurement of larger $|\Delta \overline{m}^2|$.
  ν_μ and $\overline{\nu}_\mu$ oscillation parameters measurements are consistent with each other at the 42% C.L.
- Future: MINOS+ = MINOS at NOvA beam from 2013