Latest neutrino disappearance results from MINOS

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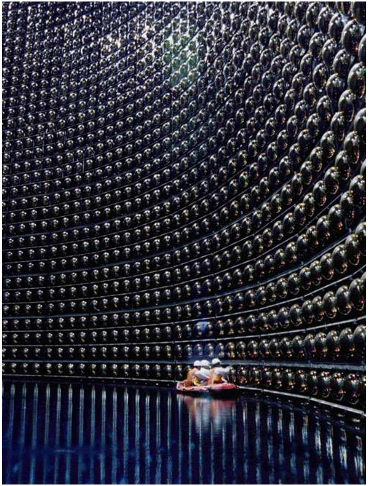
November 23, 2010

Introduction

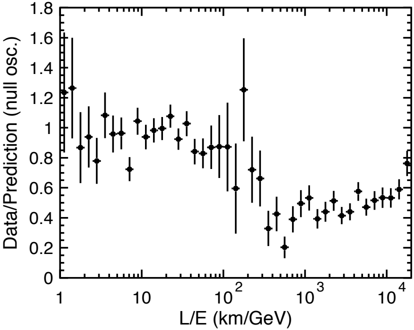
- Focusing on disappearance measurements
- ν_e analysis presented by Jeff de Jong in April

- Neutrino oscillations
- The MINOS experiment
- The NC analysis
- The ν_μ analysis
- The $\bar{\nu}_\mu$ analysis
- Future

Neutrino oscillations - history



- Atmospheric neutrinos created by cosmic rays striking the atmosphere
- Super-Kamiokande sees deficit versus expected rate of ν_μ
- Angle and energy dependent



Neutrino oscillations - theory

$$|\nu_\alpha\rangle = \sum_i U^\star_{\alpha i}|\nu_i\rangle \qquad i = 1, 2, 3 \qquad \alpha = e, \mu, \tau$$

- PMNS matrix. ∼CKM matrix for neutrinos

$$P_{\alpha\beta} = \left|\sum_i U^\star_{\alpha i} e^{-im_i^2 L/2E} U_{\beta i}\right|^2$$

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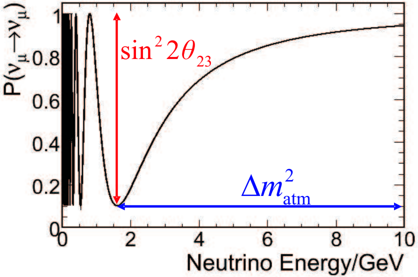

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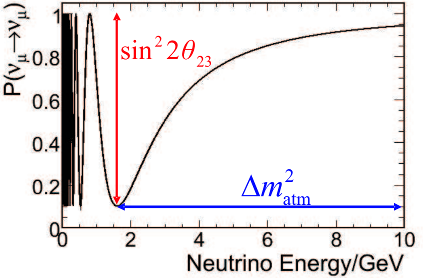

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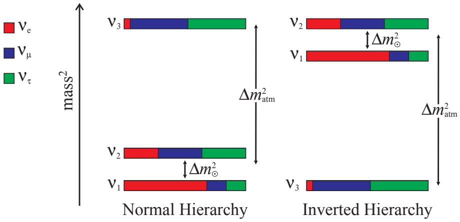

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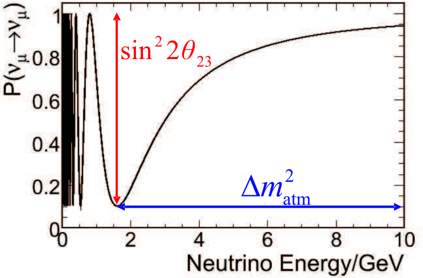

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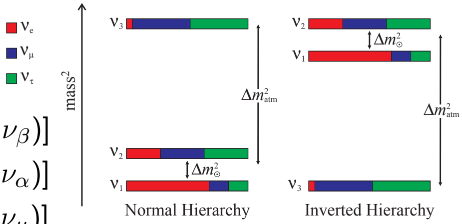

$$\begin{aligned} \text{NB}: P(\bar\nu_\alpha \to \bar\nu_\beta) &= \mathcal{CP}[P(\nu_\alpha \to \nu_\beta)] \\ P(\bar\nu_\alpha \to \bar\nu_\beta) &= \mathcal{CPT}[P(\nu_\beta \to \nu_\alpha)] \\ P(\bar\nu_\mu \to \bar\nu_\mu) &= \mathcal{CPT}[P(\nu_\mu \to \nu_\mu)] \end{aligned}$$

Main Injector Neutrino Oscillation Search

- Long-baseline neutrino oscillation experiment

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- Near detector on-site at Fermilab
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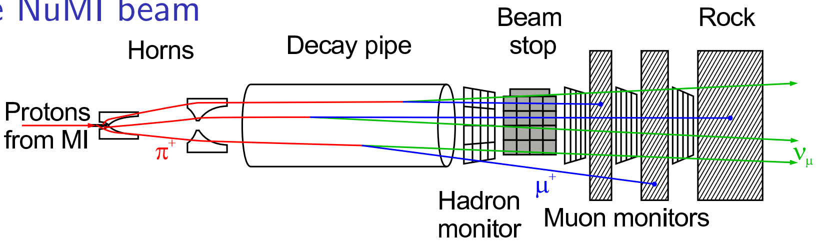
- Far detector 735 km away in Northern Minnesota
- $L/E \sim 500\text{km}/\text{GeV}$
- Measure ν_μ disappearance

Components of a long-baseline neutrino experiment

- A neutrino beam
- A detector technology
  - Neutrino cross-sections are low
  - Low cost/kg
- Two detectors
  - Near detector to measure beam
  - Far detector to detect oscillations
  - Systematics common between the detectors cancel

The NuMI beam

The NuMI beam



- 120 GeV protons from the Main Injector
- Strike graphite target
- Produce hadrons. Primarily $\pi^{\pm}$ and $K^{\pm}$

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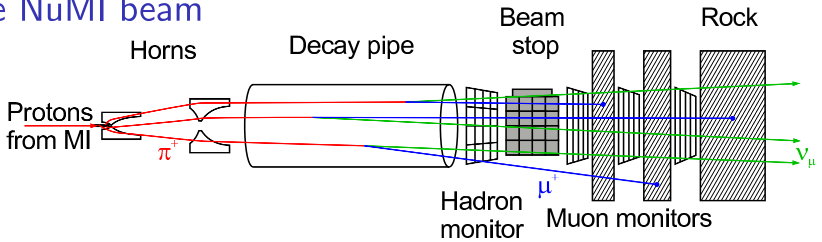

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- Focused by two magnetic horns
- Allow us to select charge sign for a neutrino or antineutrino beam

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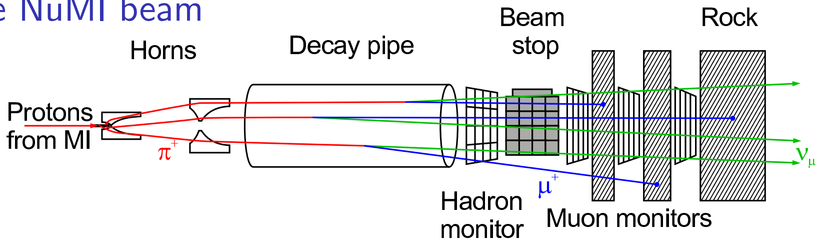

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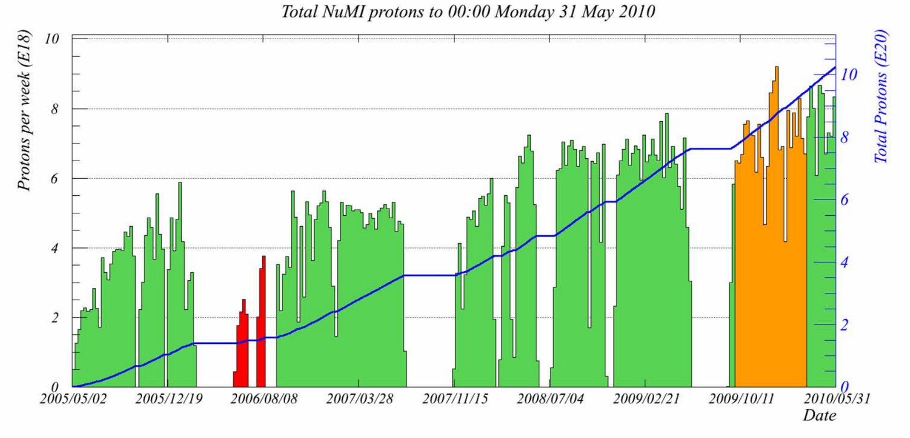
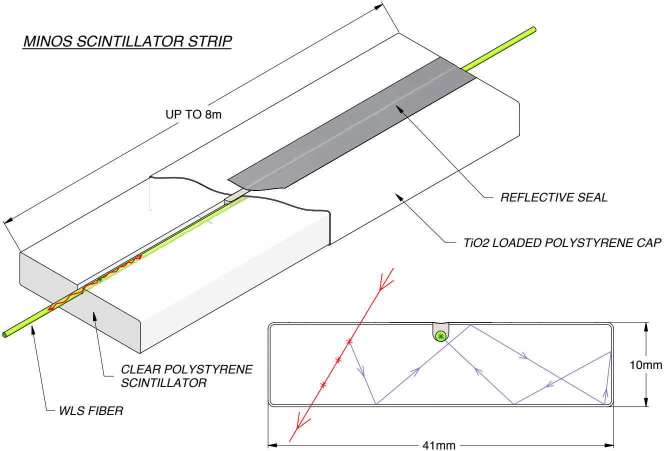
- 675 m decay-pipe: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Muons absorbed by rock

The NuMI beam



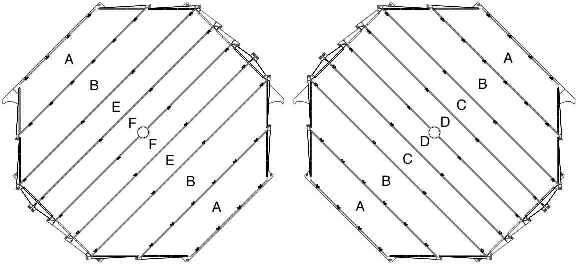
- Taking data since 2005
- Divided into 3 neutrino run periods, and one antineutrino
- ν_μ analysis uses an exposure of 7.2×10^{20} protons-on-target
- $\bar{\nu}_\mu$ analysis uses 1.71×10^{20} POT

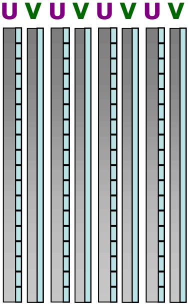
Detecting charged particles



- 4.1 cm × 1 cm plastic scintillator strips
- TiO_2 coating and embedded wavelength-shifting fibre
- Scintillation light detected by multi-anode PMTs

Detector construction



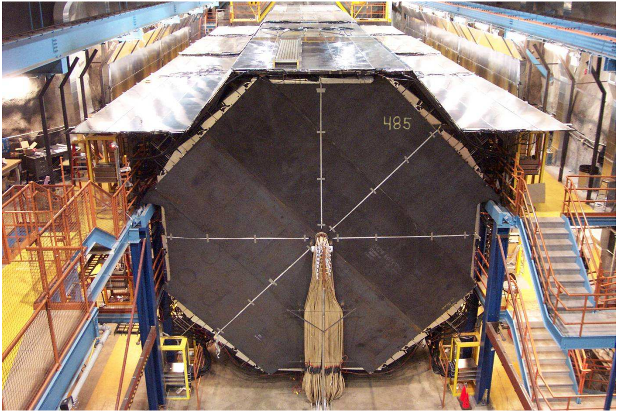


- Magnetized tracking calorimeters
- Scintillator modules mounted on inch-thick steel planes
- Alternate scintillator planes at right angles
- Allows 3D event construction
- $\mathcal{O}(1\mathrm{T})$ magnetic field $\rightarrow$ muon charge sign

Near detector

- 1 kt, 3.8 m×4.5 m×16.7 m
- 1 km from source
- High event rate: $\sim 10^5$ neutrino interactions per day
- Measure beam before oscillations

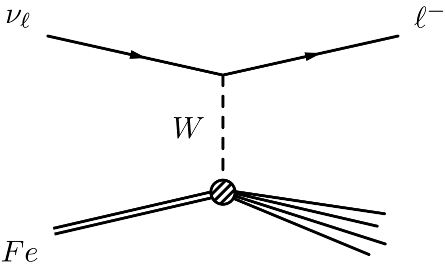
Far detector



- 5.4 kt, 8 m×8 m×30 m
- 735 km from source, 700 m underground
- A few neutrino interactions per day
- Compare spectrum to prediction

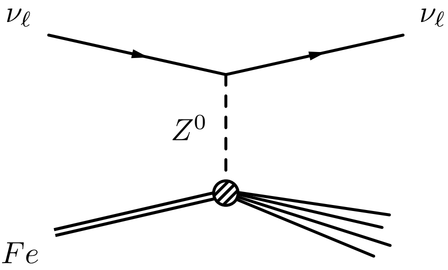
Event classes

Charged current



- Hadronic shower
- Long muon track

Neutral current



- Hadronic shower
- No muon track (possible reconstruction errors)
- Some energy carried away by outgoing neutrino

Event classes

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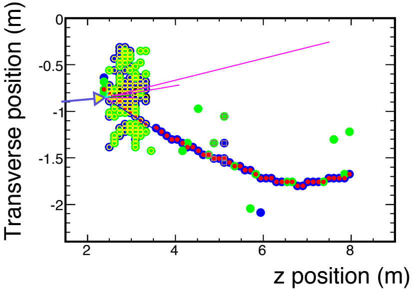

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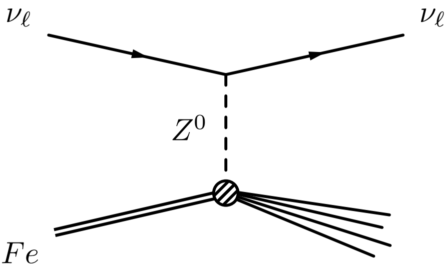

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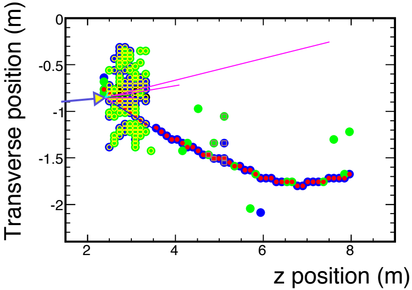

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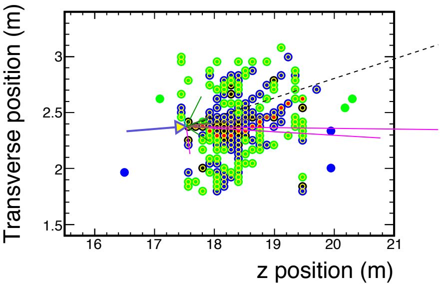

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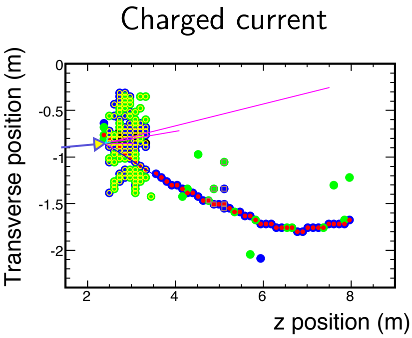
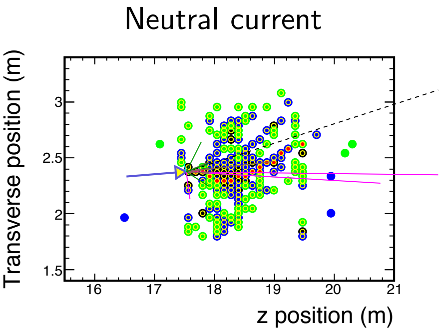


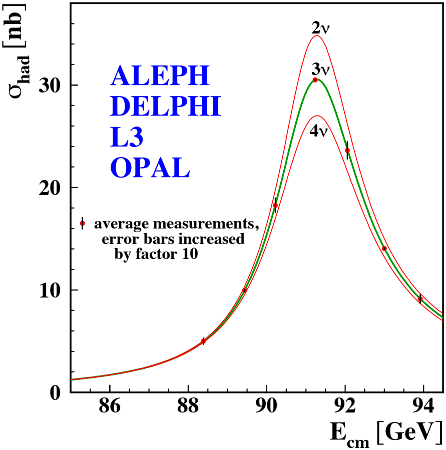


- High energy muons are easy to pick out
- Low energy or high-y event $\longrightarrow$ short muon track
- Likely buried in shower
- To pick out CC or NC events need to determine nature of reconstructed tracks

Neutral current analysis

- LSND experiment saw rare $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- L/E doesn't match $\Delta m^2_\odot$ or $\Delta m^2_{\mathrm{atm}}$
- Requires a fourth mass state

- But measurements of the Z-width at LEP $\rightarrow$ three neutrino flavours
- Would need to not couple to the Z - "sterile"



Neutral current analysis

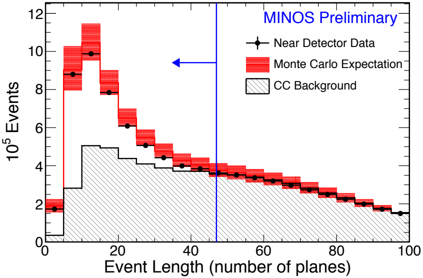
- We assume ν_μ deficit is from oscillations to ν_τ
- What if the oscillations are $\nu_\mu \leftrightarrow \nu_s$ instead?

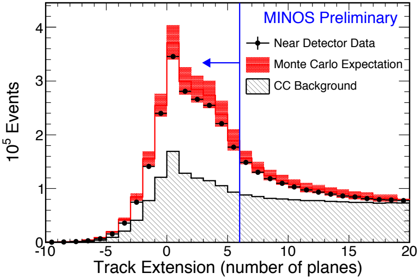
- Rate of neutral current events unaffected by oscillations between active flavours
- But oscillations to sterile neutrinos would give a neutral current deficit

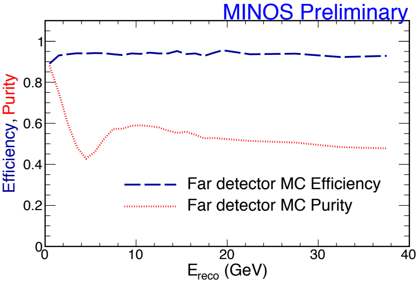
Components of an analysis

- Select the events you want
- "Extrapolate" ND spectrum to FD prediction
- Compare FD data to prediction

Neutral current selection

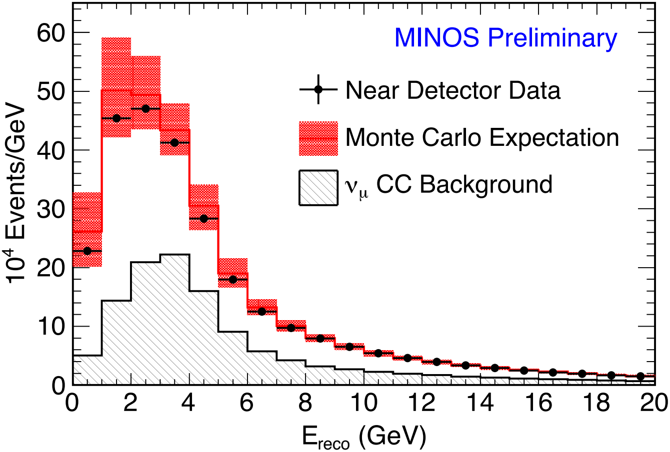






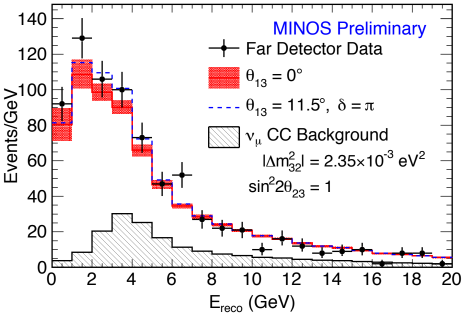
- Select events without a reconstructed track
- Plus events whose track is "short"
- Efficiency is good but lots of charged-current contamination

Neutral current extrapolation



$$F_i^{\text{pred}} = \frac{N_i^{\text{data}}}{N_i^{\text{MC}}} F_i^{\text{MC}}$$

Neutral current results



- Expect 757 events
- Observe 802

$$R \equiv \frac{N_{\text{obs}} - N_{\text{bkg}}}{N_{\text{exp}}}$$

$$R = 1.09 \pm 0.06(\text{stat.}) \pm 0.05(\text{syst.})$$

$$f_s \equiv \frac{P_{\mu s}}{1 - P_{\mu\mu}} < 0.22 \quad (90\%\ \text{C.L.})$$

- Maximum allowed ν_e appearance $\rightarrow f_s < 0.40$

Charged current analysis

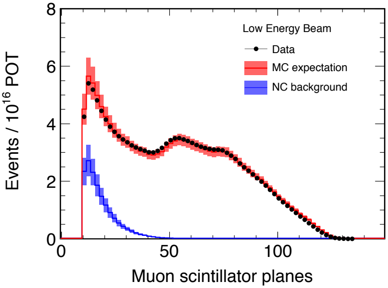
- Neutral current events are insensitive to $\nu_\mu \leftrightarrow \nu_\tau$ oscillations
- Try to get a pure sample of charged current events
- Look for an energy-dependent deficit

Components of an analysis

- Select the events you want
- "Extrapolate" ND spectrum to FD prediction
- Compare FD data to prediction

- Plus some improvements since previous analysis

Charged current selection variables



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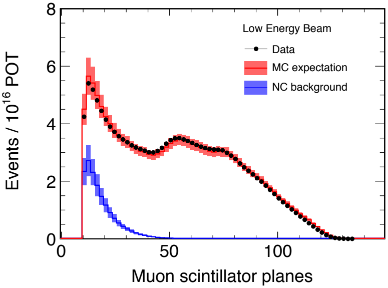

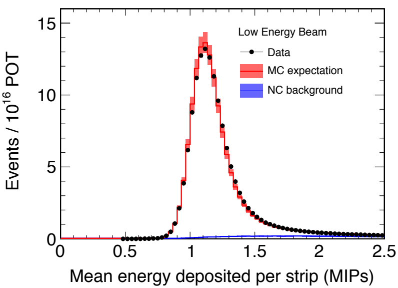

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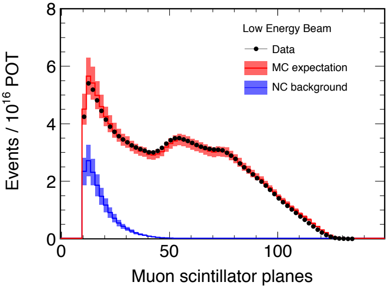

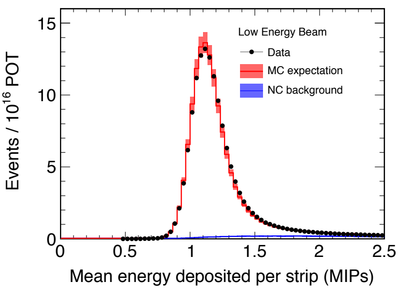

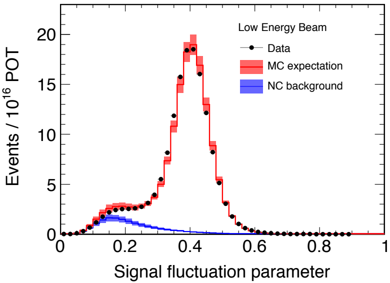

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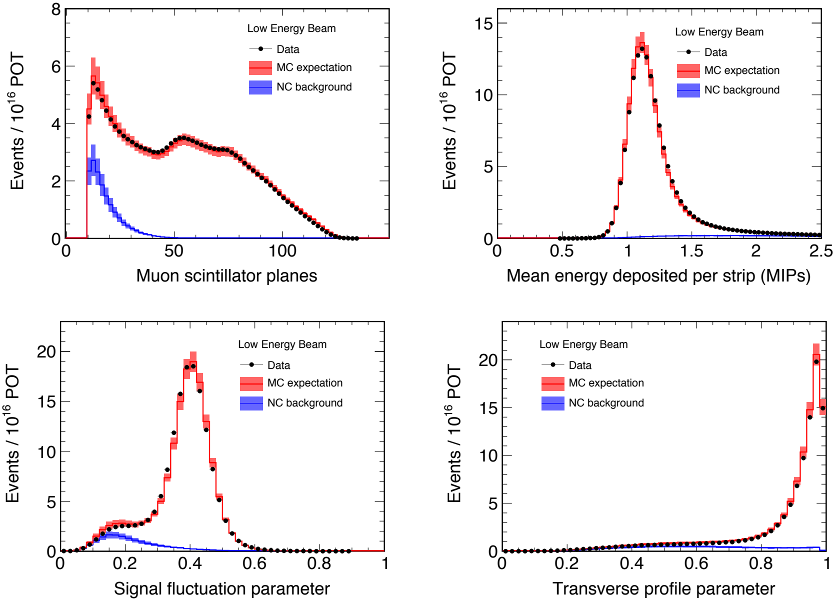
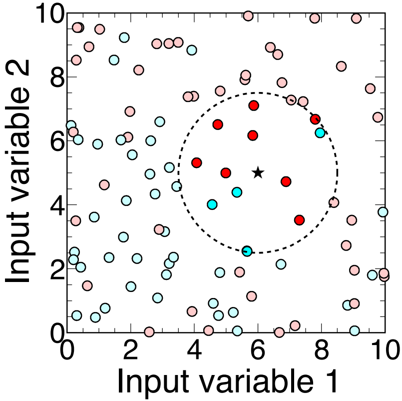


Charged current selector

- Combine information using a k-Nearest-Neighbour algorithm
- For each event to be classified: find 80 closest Monte Carlo events
- PID value is the fraction of these neighbours that are charged current



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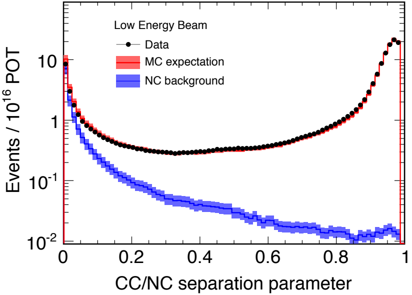
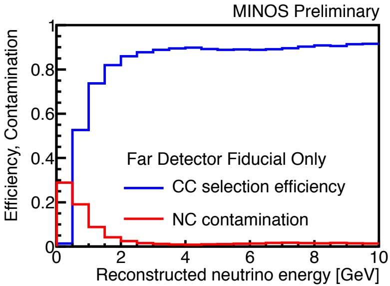


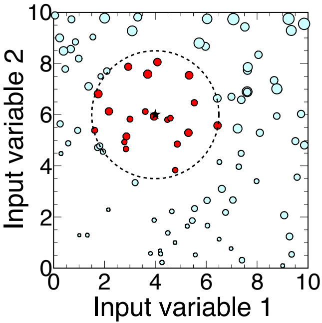


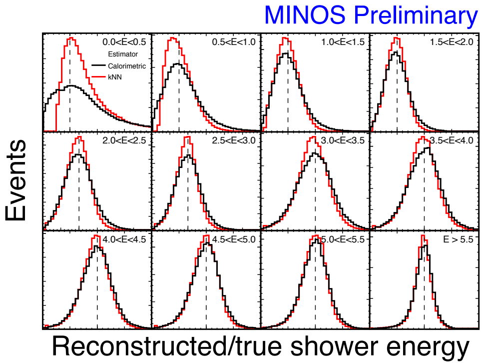
- Cut placed at 0.25 - plus another kNN optimized for low energies
- Above 1 GeV achieve high efficiency with low contamination

Energy estimation

- Better energy resolution $\rightarrow$ better resolved oscillation dip $\rightarrow$ more precise measurement of oscillation parameters
- $E_{\mathrm{tot}} = E_{\mathrm{trk}} + E_{\mathrm{shw}}$
- Energy of muon tracks estimated from range
  - Or curvature if the track exits the detector
- Track resolution is good. Shower resolution dominates
- Previously shower energy estimated calorimetrically
- New for this analysis: kNN shower energy estimator

kNN shower energy

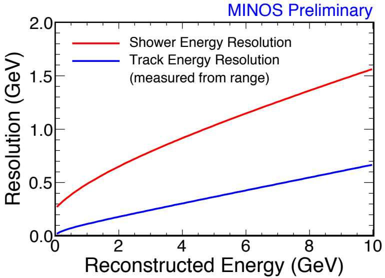




- Three input variables
    - Number of planes in the shower
    - Sum of calorimetric energies of first two showers
    - Total shower energy within 1 m of the track vertex
- Find 400 MC neighbours
- Energy estimate is the average of their true shower energies
- Significant improvement at low energies

Resolution binning

- Another improvement for this analysis
- Parameterize energy resolution as a function of track and shower energies

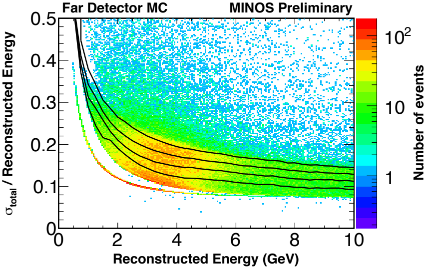


$$\frac{\sigma_{\text{trk}}}{E} = \frac{5.1\%}{\sqrt{E}} \oplus 6.9\%$$

$$\frac{\sigma_{\text{shw}}}{E} = \frac{40.4\%}{\sqrt{E}} \oplus 8.6\% \oplus \frac{275\text{MeV}}{E}$$

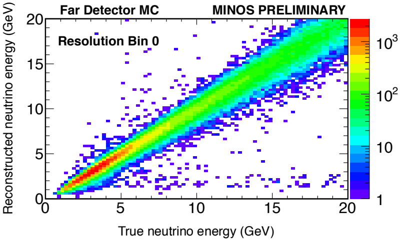
$$\sigma_{\text{evt}} = \sigma_{\text{trk}} \oplus \sigma_{\text{shw}}$$

Resolution binning

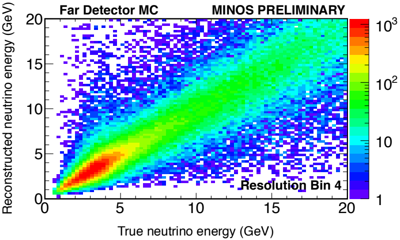


- Divide events into 5 resolution quantiles
- Best resolved events give most information about oscillation dip
- Statistical power of worst events still included

Best 20%

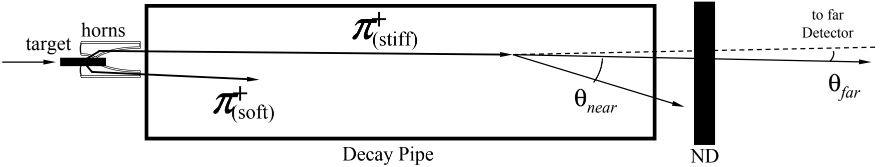


Worst 20%



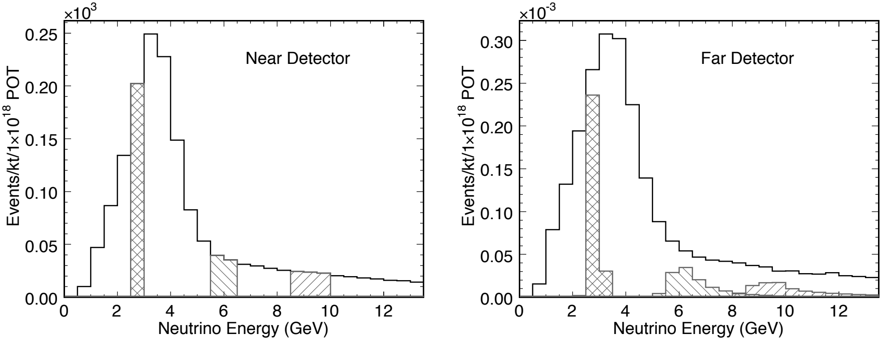
Extrapolation

- Use near detector to cancel systematics
- Measure beam flux, cross-sections and reconstruction effects
- Need to convert near detector observation into far detector prediction



- Detectors subtend different solid angles at the decay pipe
- Neutrinos intersecting the far detector in general come from lower angle pion decays

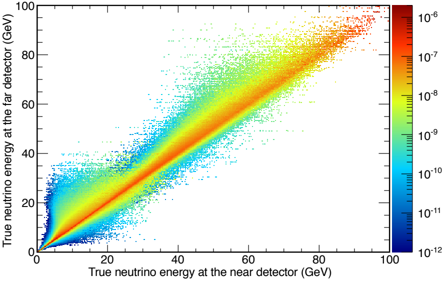
Extrapolation

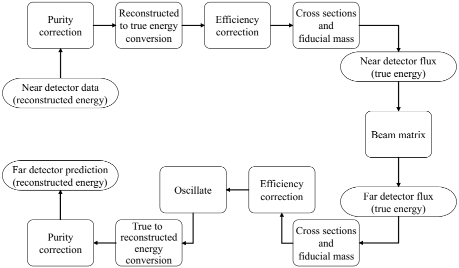


$$\text{Flux} \sim \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 \qquad E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

- The same set of parent hadrons give rise to different energy distributions in the two detectors
- Use Monte Carlo to relate ND neutrinos to their possible parents and thus to the neutrino spectrum at the far detector

Extrapolation

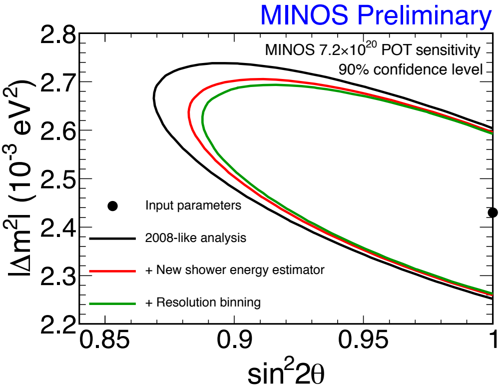




- Apply a series of corrections to convert observed ND spectrum into ND neutrino flux
- Use beam matrix to get an FD flux prediction
- Undo corrections to get an FD spectrum prediction

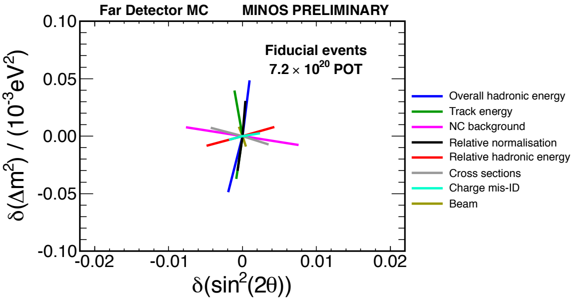
Oscillation sensitivity

- Fit is performed using a binned log-likelihood
- 5 resolution bins fitted seperately
- 90% contour at $\Delta\chi^2 = 4.61$



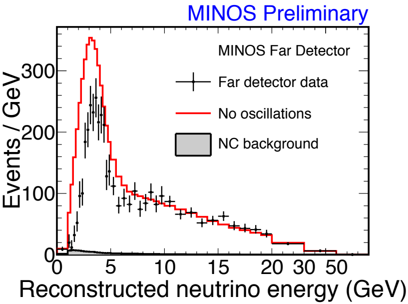
- Fit reweighted Monte Carlo sample $\rightarrow$ sensitivity
- Add energy estimator and resolution binning sequentially to see effect

Systematic errors



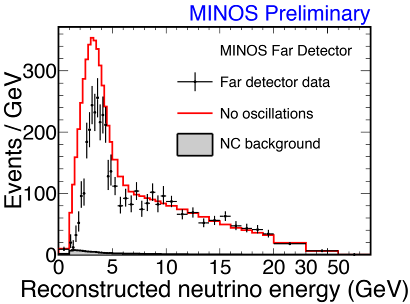
- Calculate the fit bias introduced by various $\pm 1\sigma$ shift
- Top four are
  - Hadronic energy scale
  - Track energy scale
  - NC background
  - Normalization
- We include these parameters in our fit
- The result is still statistics-limited

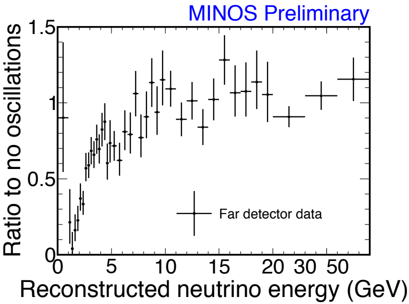
Results - far detector spectrum



- Observe a deficit of events at low energies

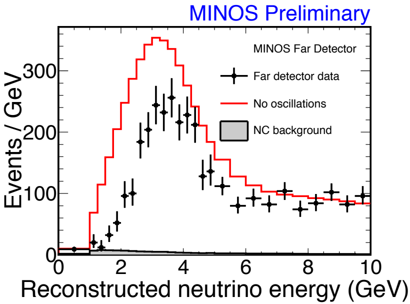
Results - far detector spectrum

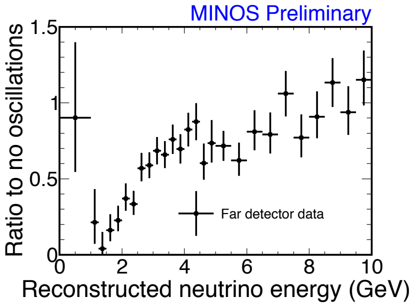




- Observe a deficit of events at low energies
- Has expected oscillation shape

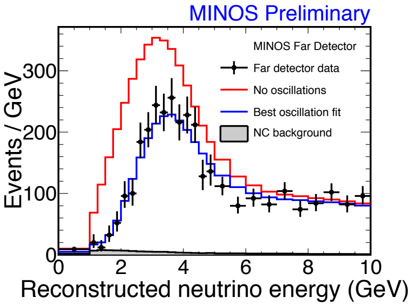
Results - far detector spectrum

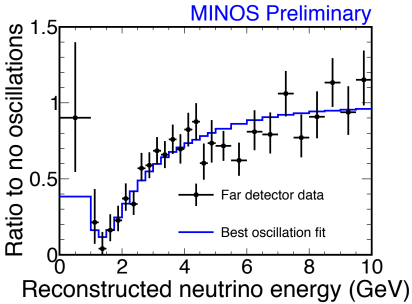




- Observe a deficit of events at low energies
- Has expected oscillation shape

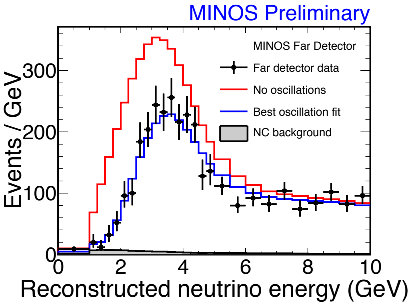
Results - far detector spectrum

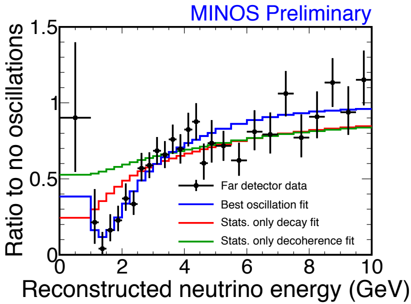




- Observe a deficit of events at low energies
- Has expected oscillation shape
- Good fit to oscillations

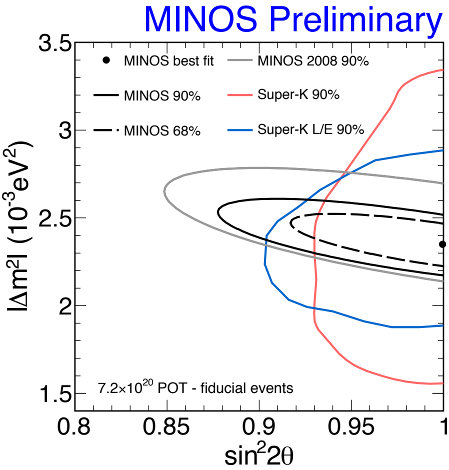
Results - far detector spectrum





- Observe a deficit of events at low energies
- Has expected oscillation shape
- Good fit to oscillations
- Decay and decoherence don't fit well

Results - contour



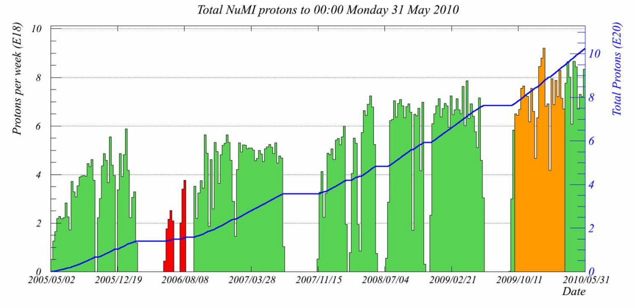
$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\mathrm{eV}^2$$

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

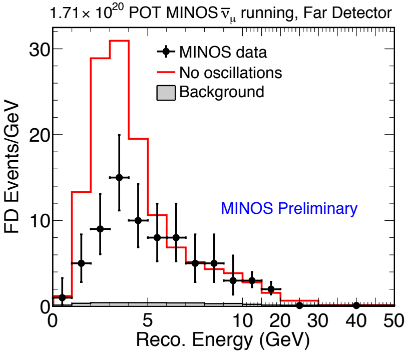
Pure decay disfavoured $> 6\sigma$
Pure decoherence disfavoured $> 8\sigma$

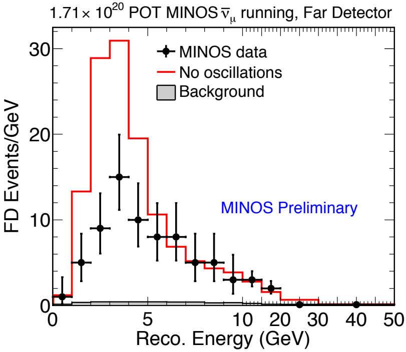
World's best measurement of $\Delta m^2_{\mathrm{atm}}$

Introduction to the antineutrino analysis

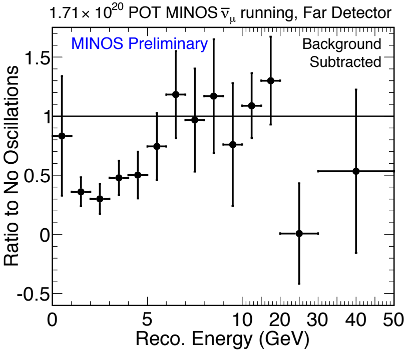


- Reverse horn current to select antineutrinos
- Apply charge-sign cut based on muon curvature
- Calorimetric shower energy, no resolution binning
- 90% C.L. determined by Feldman-Cousins procedure
- Otherwise very similar to neutrino analysis

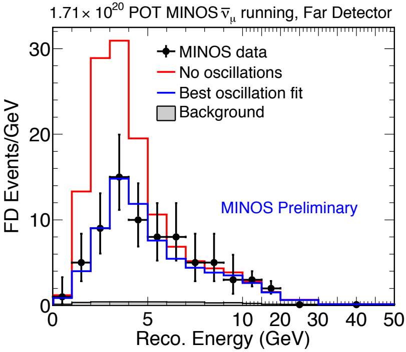

1.71×10^{20} POT MINOS $\overline{\nu}_{\mu}$ running, Far Detector
MINOS data
No oscillations
Background
MINOS Preliminary
FD Events/GeV
Reco. Energy (GeV)
0
10
20
30
0
5
10
20
30
40
50

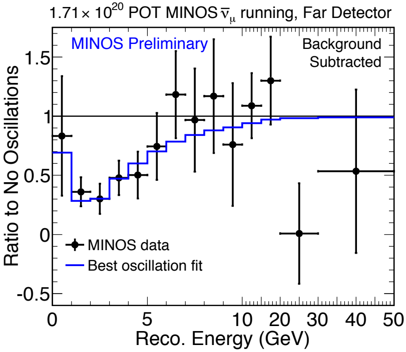


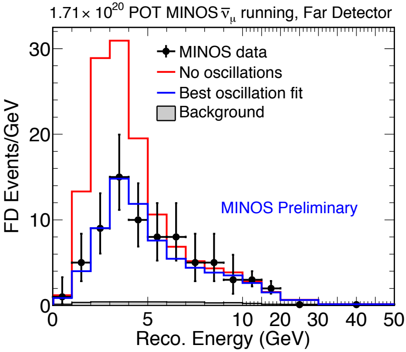
1.71 × 10^20 POT MINOS $\bar{\nu}_\mu$ running, Far Detector
MINOS data
No oscillations
Background
MINOS Preliminary
FD Events/GeV
Reco. Energy (GeV)

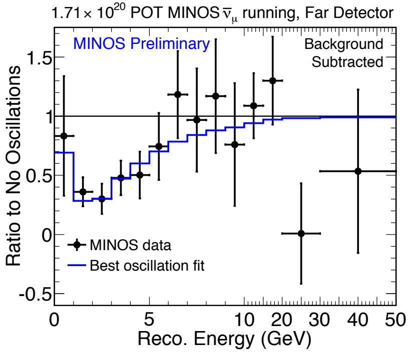


1.71 × 10^20 POT MINOS $\bar{\nu}_\mu$ running, Far Detector
MINOS Preliminary
Background Subtracted
Ratio to No Oscillations
Reco. Energy (GeV)

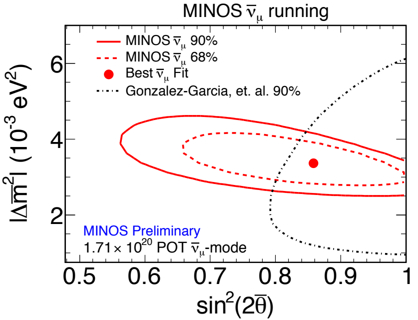

1.71×10^{20} POT MINOS $\bar{\nu}_\mu$ running, Far Detector
MINOS data
No oscillations
Best oscillation fit
Background
MINOS Preliminary
FD Events/GeV
Reco. Energy (GeV)

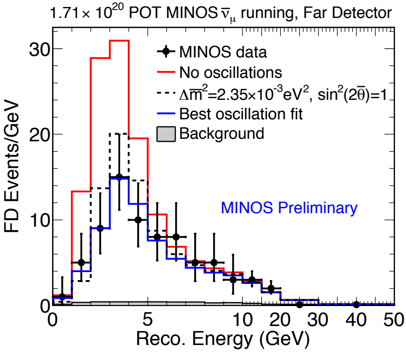

1.71×10^{20} POT MINOS $\bar{\nu}_\mu$ running, Far Detector
MINOS Preliminary
Background
Subtracted
MINOS data
Best oscillation fit
Ratio to No Oscillations
Reco. Energy (GeV)

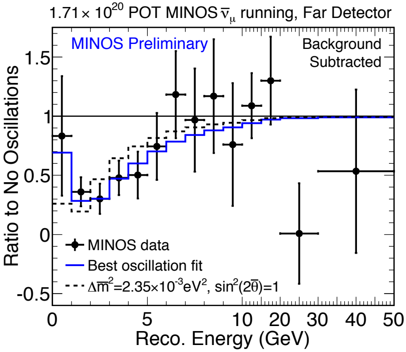




$$|\Delta \bar{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2 2\bar{\theta} = 0.86 \pm 0.11$$







$$|\Delta \bar{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$
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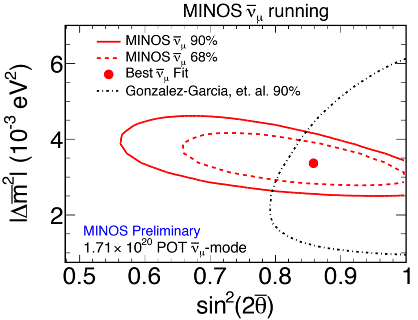
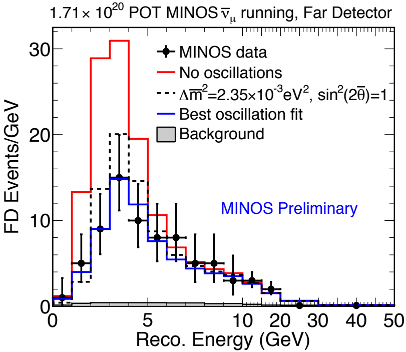
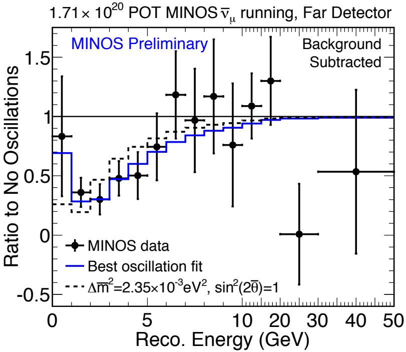
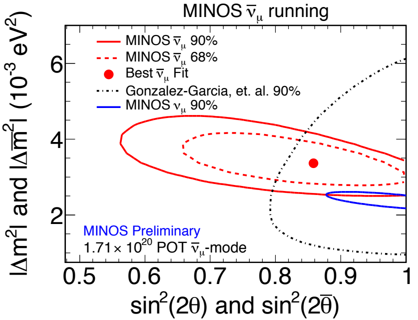




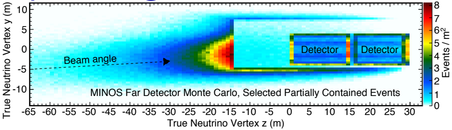


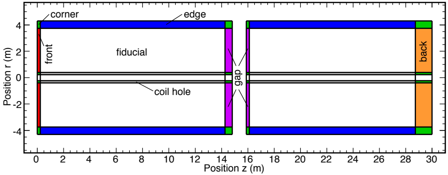
$$|\Delta\bar{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2 2\bar{\theta} = 0.86 \pm 0.11$$

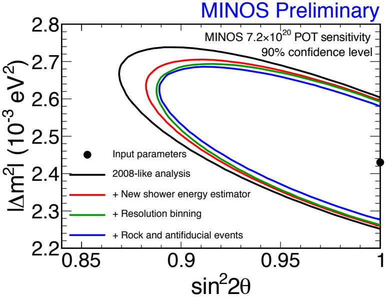
$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2 2\theta > 0.91 \quad (90\%\ \mathrm{C.L.})$$



Upcoming - rock and antifiducial sample



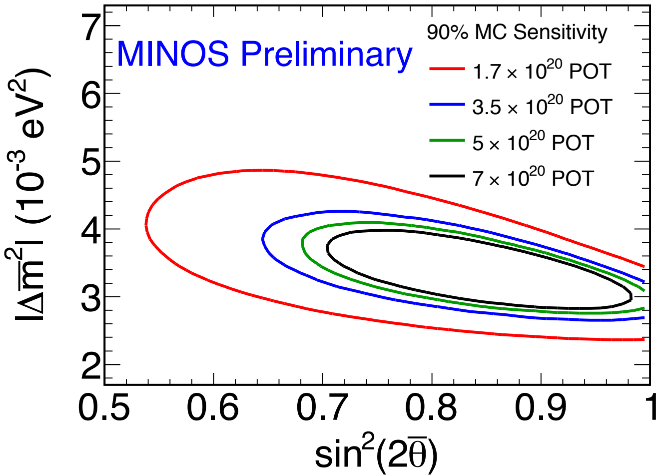




- There is a huge amount of mass in the rock around the MINOS cavern
- And a lot of the detector mass outside the fiducial volume
- Large number of neutrino interactions

- Equivalent statistics to fiducial dataset
- Energy resolution is bad because we only see part of the event
- Still a valuable sample and sensitivity improvement

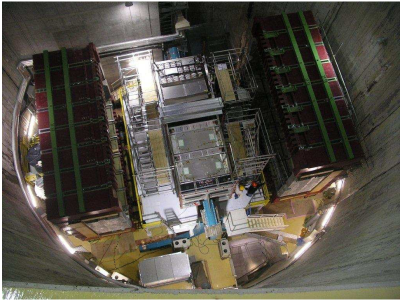
Upcoming - more antineutrino running



- Currently taking additional data in antineutrino mode
- $\sim$doubling current dataset $\rightarrow$ significant sensitivity increase

T2K and NOνA

- Long baseline neutrino experiments
- Primarily searching for $\nu_\mu \rightarrow \nu_e$
- Can also probe ν_μ disappearance



- T2K - JPARC beam + near detector + SuperKamiokande
- Started taking data

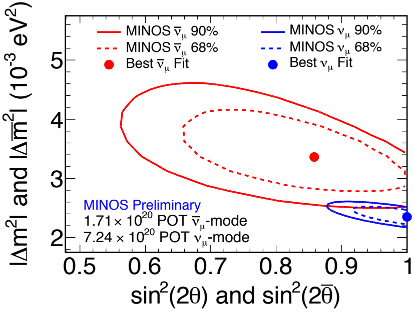
- NOνA - Upgraded NuMI beam
- Far detector construction started

Conclusion

$$f_s < 22\% \ (40\%)$$

$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\text{eV}^2$$
$$\sin^2 2\theta > 0.91 \quad (90\% \text{ C.L.})$$

$$|\Delta \bar{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\text{eV}^2$$
$$\sin^2 2\bar{\theta} = 0.86 \pm 0.11$$

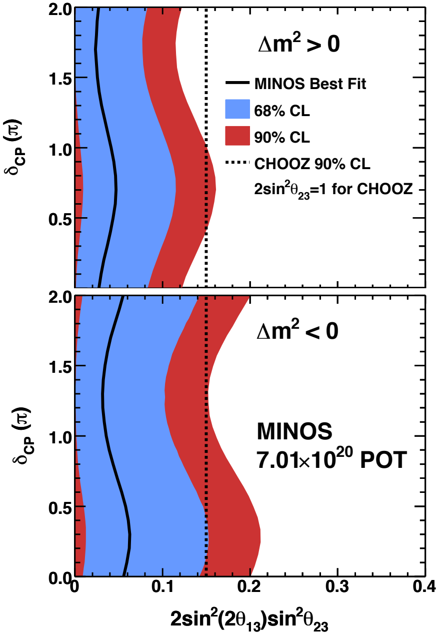


- MINOS has the most precise measurements of Δm^2_{atm} and $\Delta \bar{m}^2_{\text{atm}}$

- Taking additional antineutrino data now
- Watch this space...

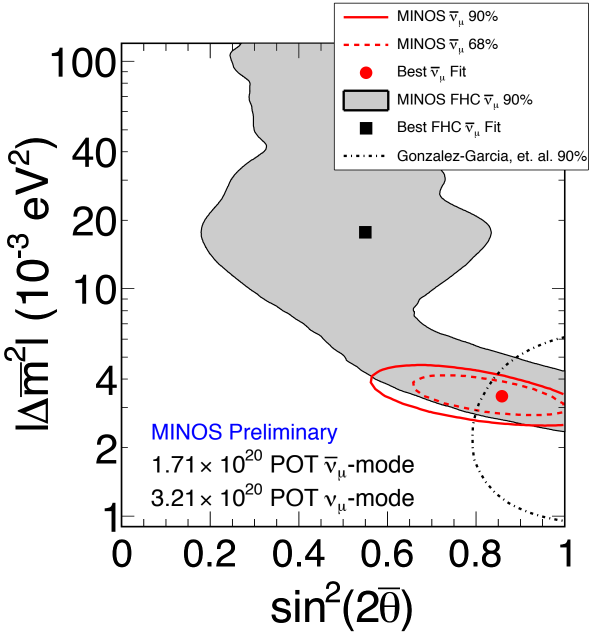
Backup

ν_e results

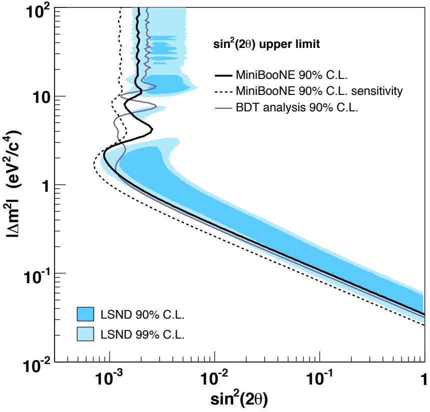


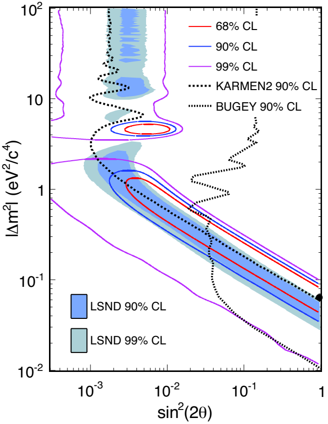
$\Delta m^2 > 0$
MINOS Best Fit
68% CL
90% CL
CHOOZ 90% CL
$2\sin^2\theta_{23}$=1 for CHOOZ
$\Delta m^2 < 0$
MINOS
7.01×10^{20} POT
δ_{CP} (π)
$2\sin^2(2\theta_{13})\sin^2\theta_{23}$

FHC


MINOS $\bar{\nu}_\mu$ 90%
MINOS $\bar{\nu}_\mu$ 68%
Best $\bar{\nu}_\mu$ Fit
MINOS FHC $\bar{\nu}_\mu$ 90%
Best FHC $\bar{\nu}_\mu$ Fit
Gonzalez-Garcia, et. al. 90%
MINOS Preliminary
1.71×10^{20} POT $\bar{\nu}_\mu$-mode
3.21×10^{20} POT ν_μ-mode
$|\Delta\bar{m}^2|$ (10^{-3} eV^2)
100
40
20
10
4
2
1
0
0.2
0.4
0.6
0.8
1
$\sin^2(2\bar{\theta})$

MiniBooNE


sin^2(2θ) upper limit
MiniBooNE 90% C.L.
MiniBooNE 90% C.L. sensitivity
BDT analysis 90% C.L.
LSND 90% C.L.
LSND 99% C.L.
lΔm^{2}l (eV^2/c^4)
sin^2(2θ)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1


68% CL
90% CL
99% CL
KARMEN2 90% CL
BUGEY 90% CL
LSND 90% CL
LSND 99% CL
lΔm^{2}l (eV^2/c^4)
sin^2(2θ)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1