The MINOS Experiment and MINOS+

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UCL

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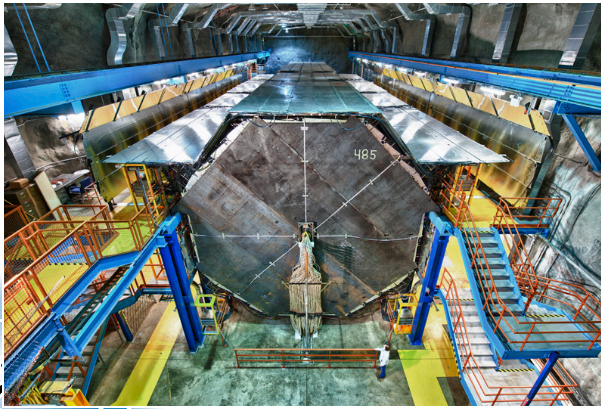
NNN13

The MINOS Experiment

- Long-baseline neutrino oscillation experiment
  - L/E ~500 km / GeV
- Exposed by the NuMI beam
  - Runs off the Main Injector at Fermilab, USA
  - ν_μ or $\bar{\nu}_\mu$ beam mode
- Two detector system used to minimise systematics:
  - Beam flux
  - Neutrino interaction cross-sections
- Look for:
  - ν_μ disappearance
  - ν_e appearance
  - Neutral current events

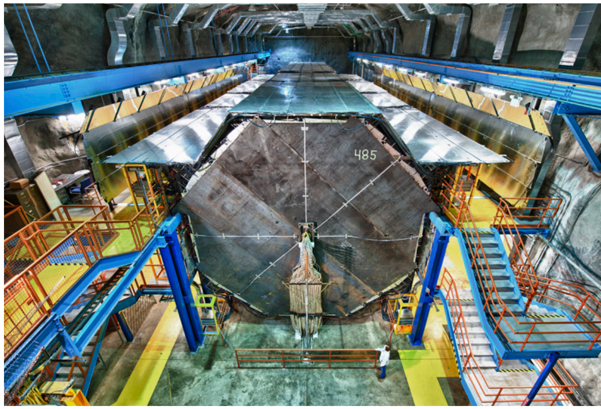


Far Detector (FD)

Near Detector (ND)

The MINOS Detectors

- Magnetised steel/scintillator sampling tracking calorimeters
  - Consecutive steel / scintillator planes
  - Average 1.3T field for charge selection
  - Functionally equivalent between ND and FD



Far Detector (FD)

Detector	Baseline / km	Mass / kton	Start up
Far	735	5.4	2003
Near	1	1.0	2005

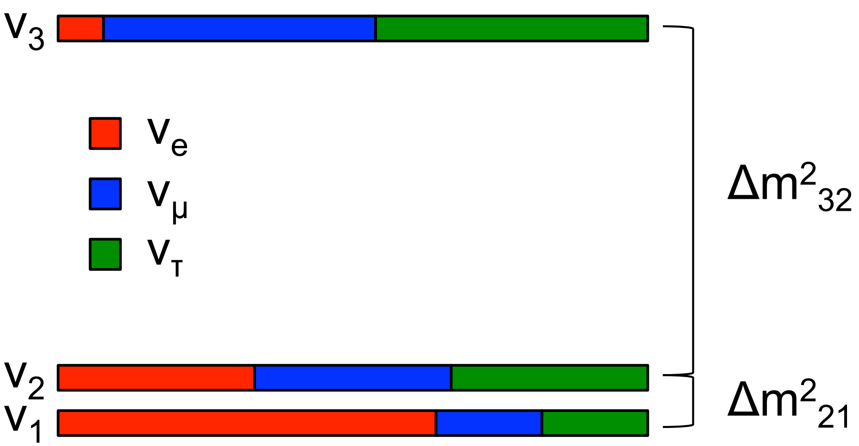
Near Detector (ND)

- ND measures beam before oscillations
- FD looks for changes in the beam relative to the ND

What do we want to measure?

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

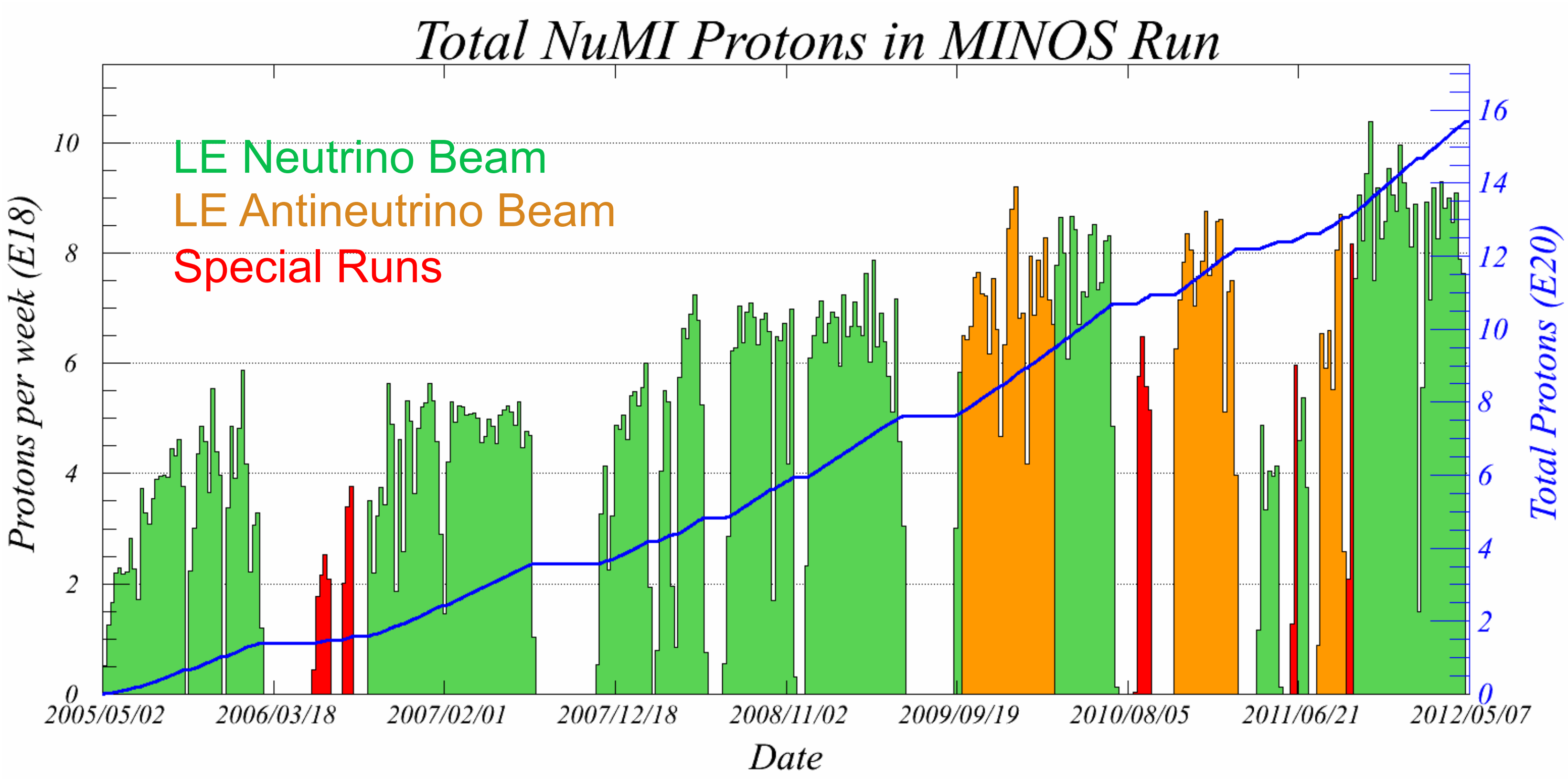
- MINOS can measure:
  - θ_{23} from ν_μ disappearance
  - $|\Delta m^2_{32}|$ from ν_μ disappearance
  - θ_{13} from ν_e appearance



- Current unknowns:
  - Octant of θ_{23}
    - Is it maximal?
  - Sign of Δm^2_{32}
    - Normal or inverted hierarchy?
  - Value of δ_{CP}
- Studying three flavour oscillations will provide the answers!

Data Samples

- Use the full MINOS data set.



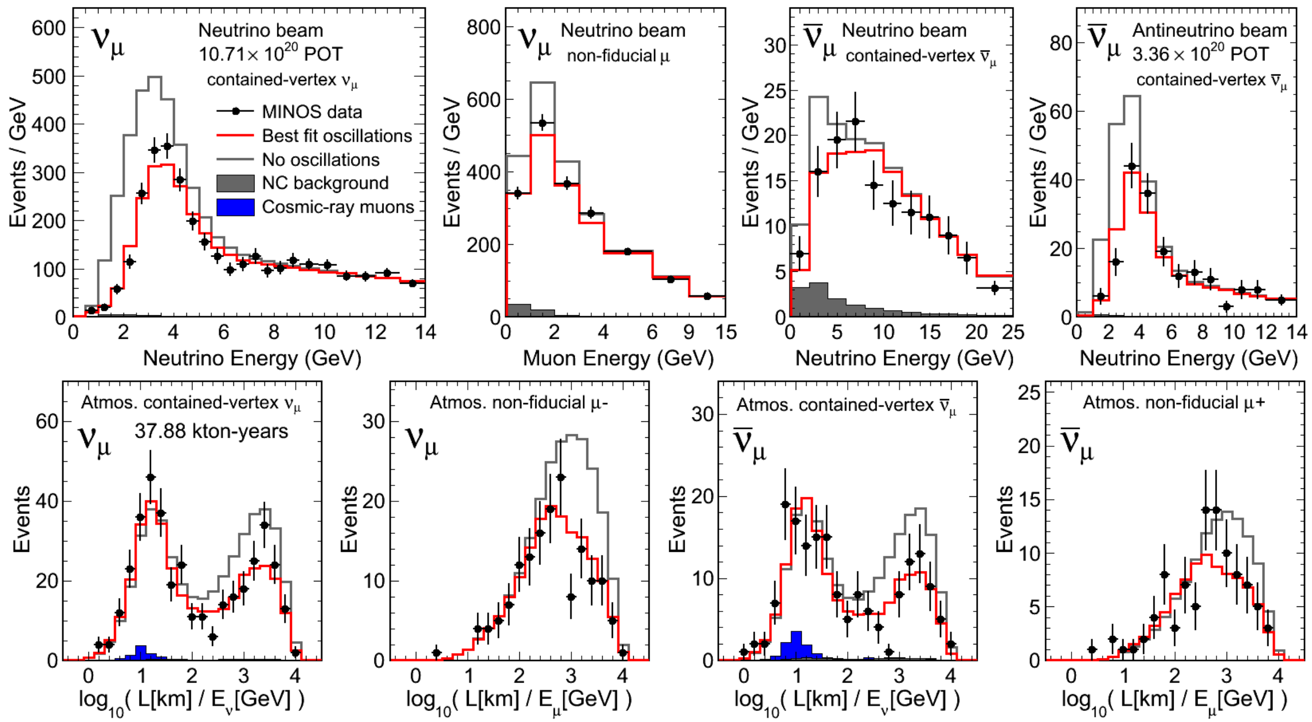
- 10.71 x 10^{20} POT neutrino mode
- 3.36 x 10^{20} POT antineutrino mode
- 37.88 kton years FD atmospheric neutrinos

Disappearance Measurements

- Predict the FD un-oscillated spectrum
  - Compare FD data to the prediction.

Beam Neutrinos

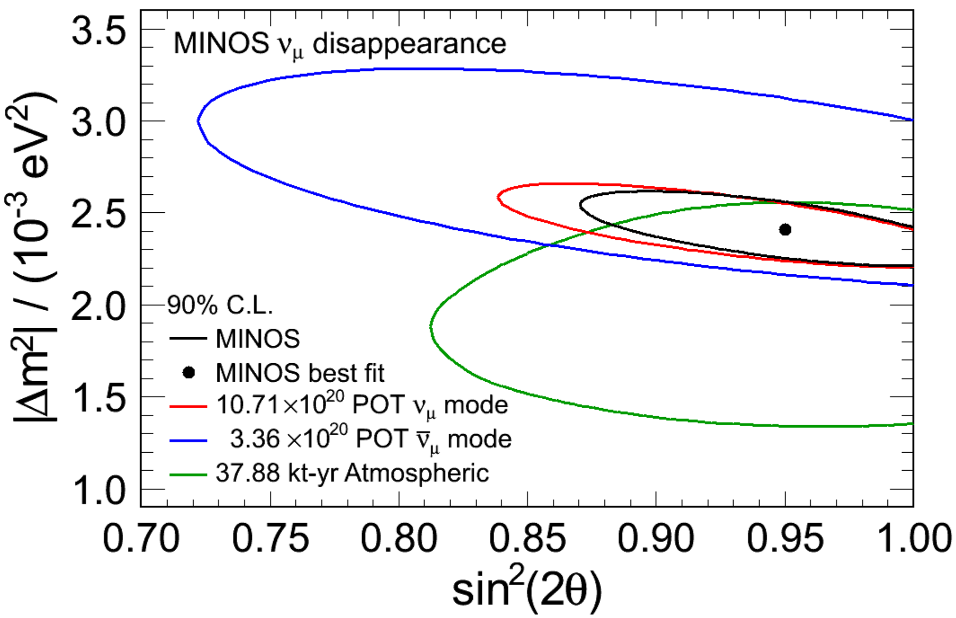
Atmospheric Neutrinos



- Fit the FD under the hypothesis of neutrino oscillations.
  - Two flavour approximation, or full three flavour
- Include 15 systematic parameters as nuisance terms

Two Flavour Muon Neutrino Disappearance

- Two flavour approximation: $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$



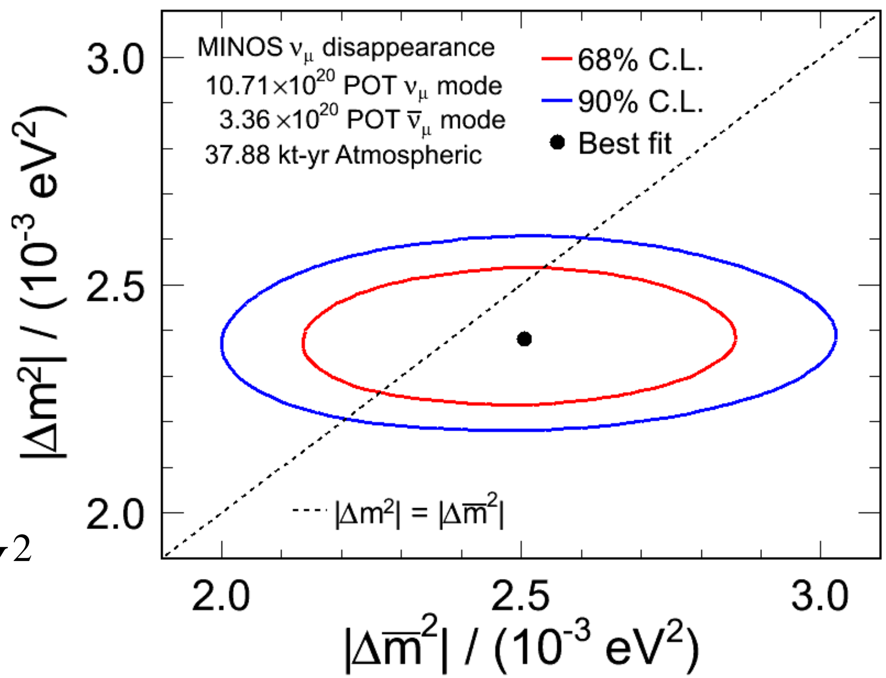
- Two parameter fit:

$$\Delta m^2 = 2.41^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2 2\theta = 0.950^{+0.035}_{-0.036}$$

- Four parameter fit:

$$\left|\Delta \bar{m}^2\right| - \left|\Delta m^2\right| = \left(0.12^{+0.24}_{-0.26}\right) \times 10^{-3} eV^2$$



Phys. Rev. Lett. 110, 251801 (2013)

Three Flavour Muon Neutrino Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{1.27\Delta m^2_{\mu\mu}L}{E}\right) + \mathcal{O}\left(\Delta m^2_\odot \frac{L}{E}\right)^2$$

$$\sin^2\theta_{\mu\mu} = \sin^2\theta_{23}\cos^2\theta_{13}$$

$$\Delta m^2_{\mu\mu} = \Delta m^2_{32} + \frac{1-|U_{\mu 1}|^2}{|U_{\mu 3}|^2}\Delta m^2_{21}$$

- Disappearance depends on:
  - Solar oscillation parameters
  - Mass hierarchy
  - θ_{13}
- Matter effects important for multi-GeV up-going atmospherics
- Make a 4D fit to the FD data in $\left(\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta_{CP}\right)$
  - Constrain θ_{13} from the reactor experiment average:

    $$\sin^2\theta_{13} = 0.0242 \pm 0.0025$$
- Solar parameters fixed at the global average†

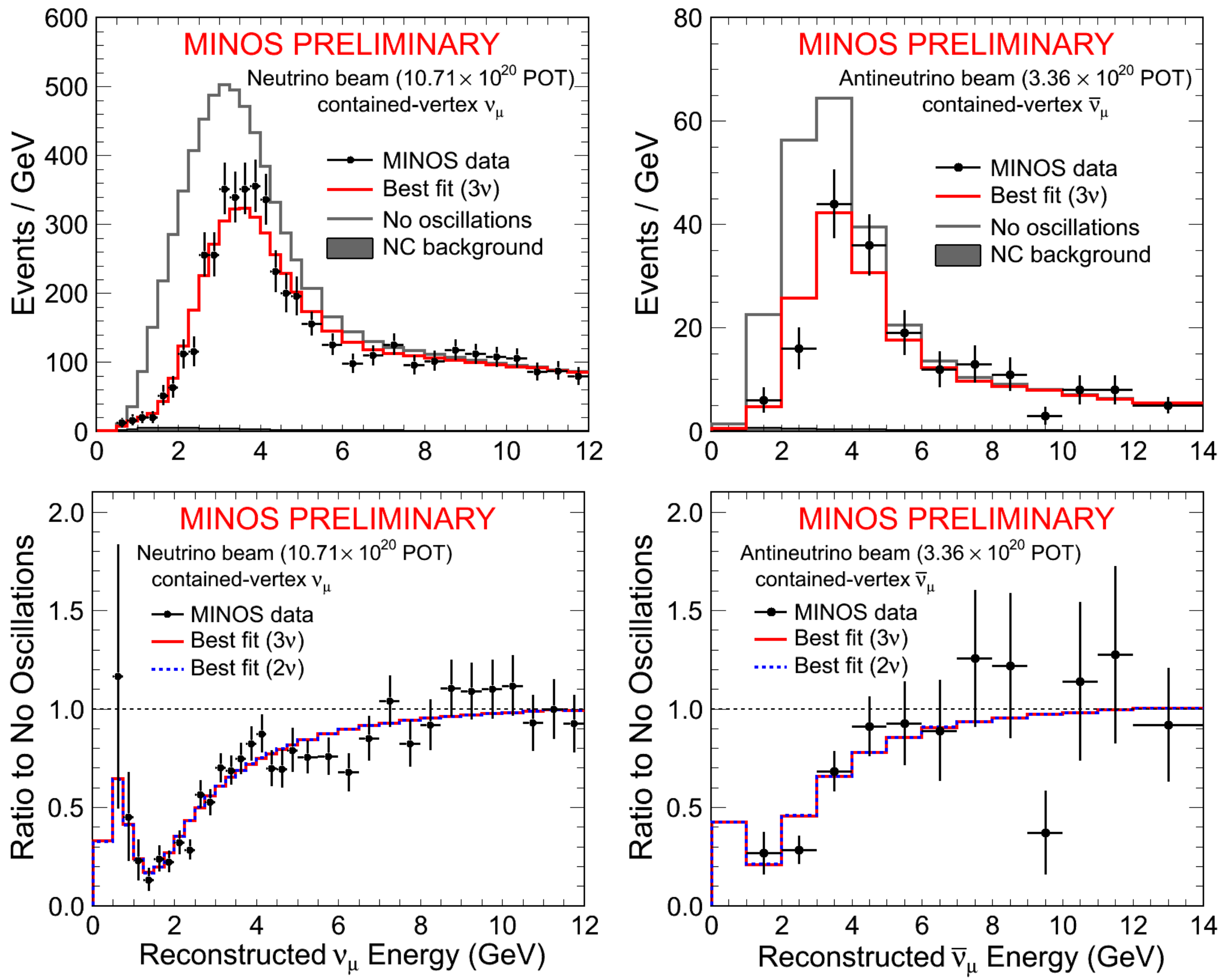
  $$\Delta m^2_{21} = 7.54 \times 10^{-5}\, eV^2$$

  $$\sin^2\theta_{12} = 0.307$$

† Fogli et al. Phys. Rev. D 86, 013012 (2012)

Fitted Far Detector Beam Samples

- Best fit shown for the ν_μ and $\bar{\nu}_\mu$ samples.
- Two and three flavour fits almost indistinguishable.
- Fit also includes $\bar{\nu}_\mu$ in the neutrino beam and the non-fiducial muons.

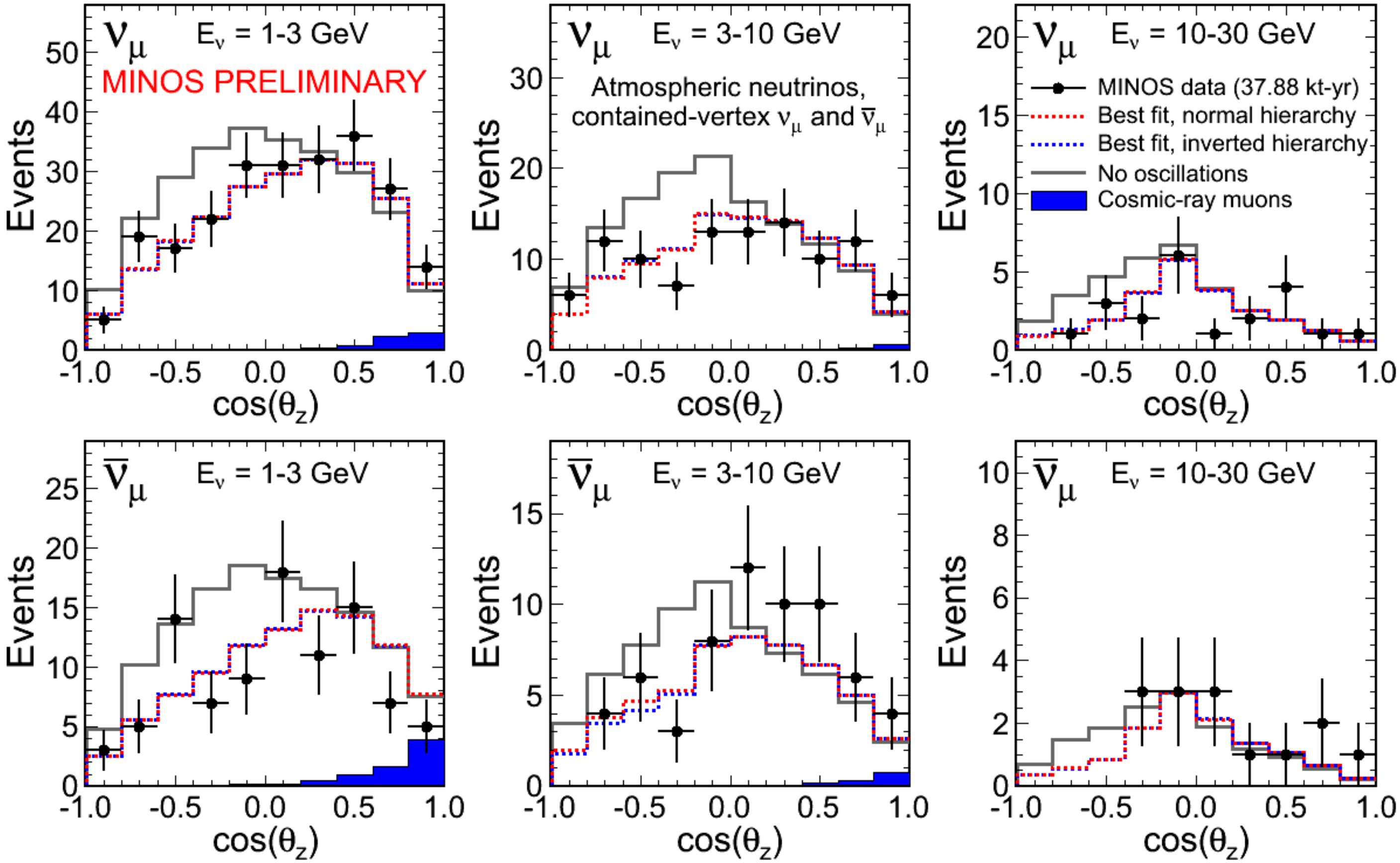


Fitted Far Detector Atmospheric Samples

- Best fit shown contained ν_μ and $\overline{\nu}_\mu$ samples.

Neutrinos

Antineutrinos



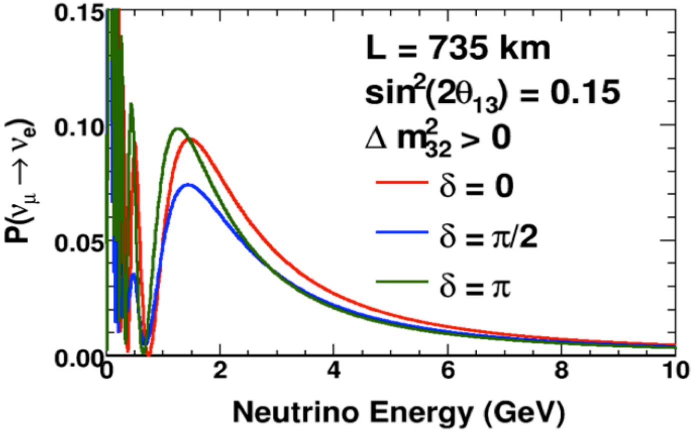
- Fit also includes non-contained μ^- / μ^+ and shower-like events.

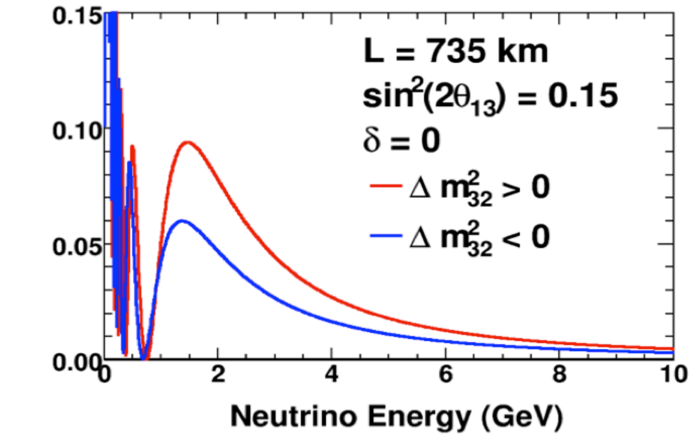
Three Flavour Electron Neutrino Appearance

- In the three flavour fit, we can also include the ν_e appearance
  - Helps to probe the three flavour oscillation effects
  - To first order, neglecting matter effects:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{31}L}{E}\right)$$

- Sensitive to the value of δ_{cp}
- Matter effects play a large role
  - Modifies oscillation probability by ~30%
  - Term is dependent on the sign of the mass splitting
    - Provides potential to probe the mass hierarchy
- Sensitive to θ_{23} octant



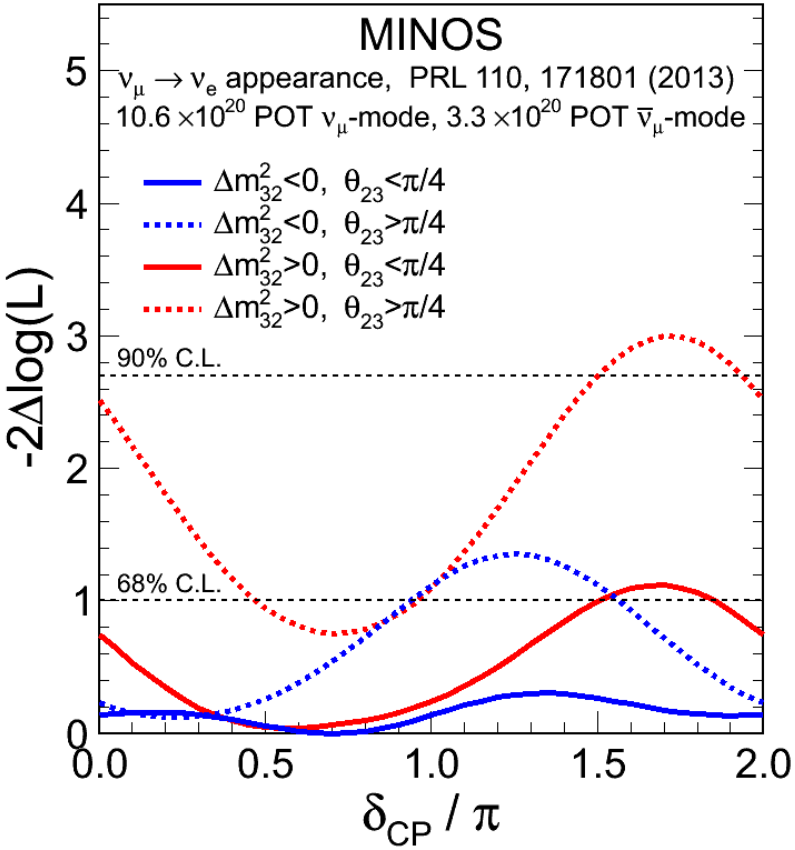


Three Flavour Electron Neutrino Appearance

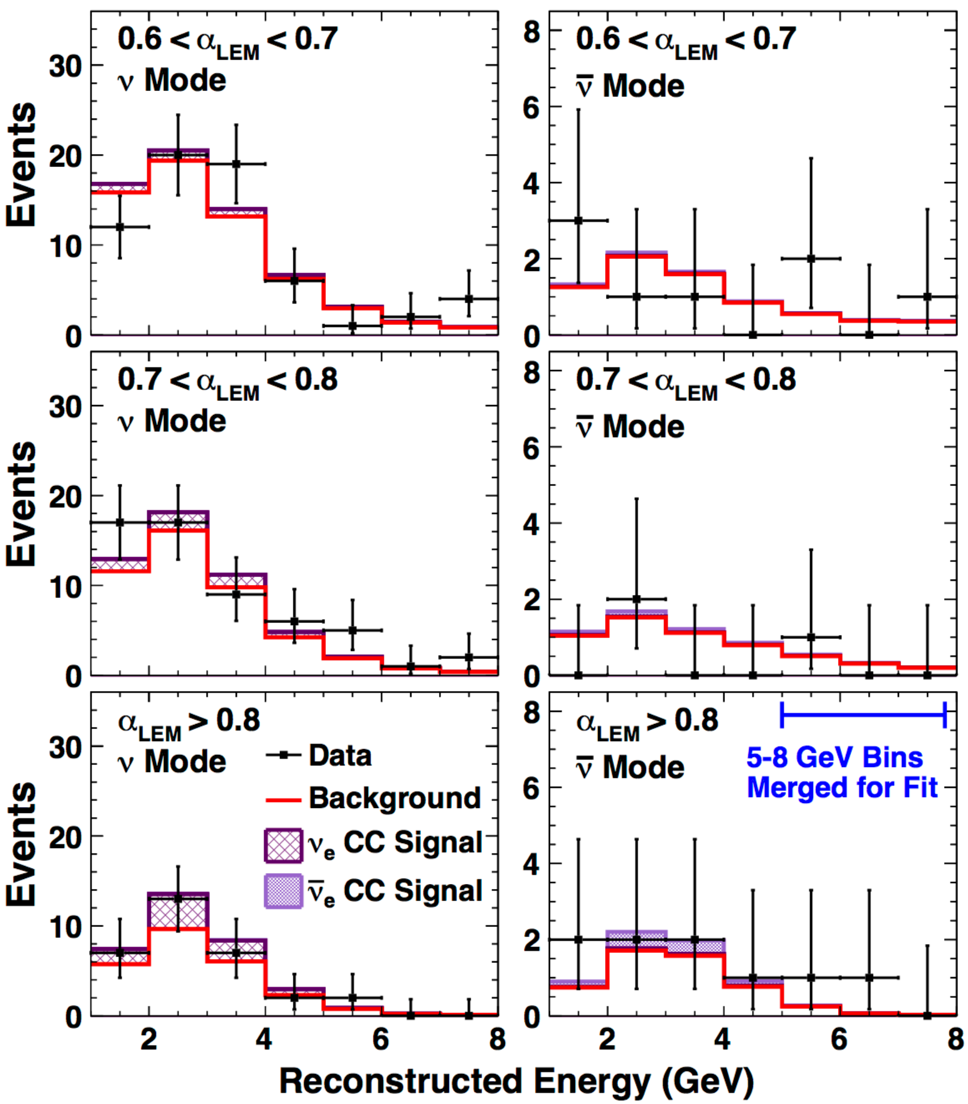
- Fit both ν_e and $\bar{\nu}_e$

$$\sin^2(2\theta_{13}) = 0.053\ (0.094)$$

$$\sin^2(2\theta_{13}) > 0 (96\%)$$



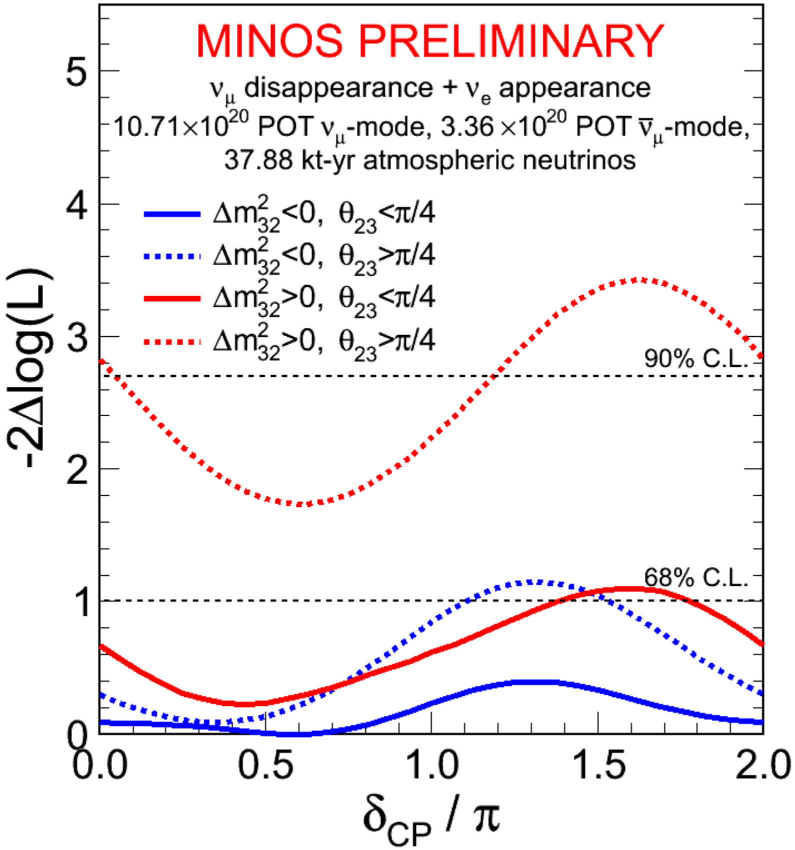
MINOS Far Detector Data



Phys. Rev. Lett. 110, 171801 (2013)

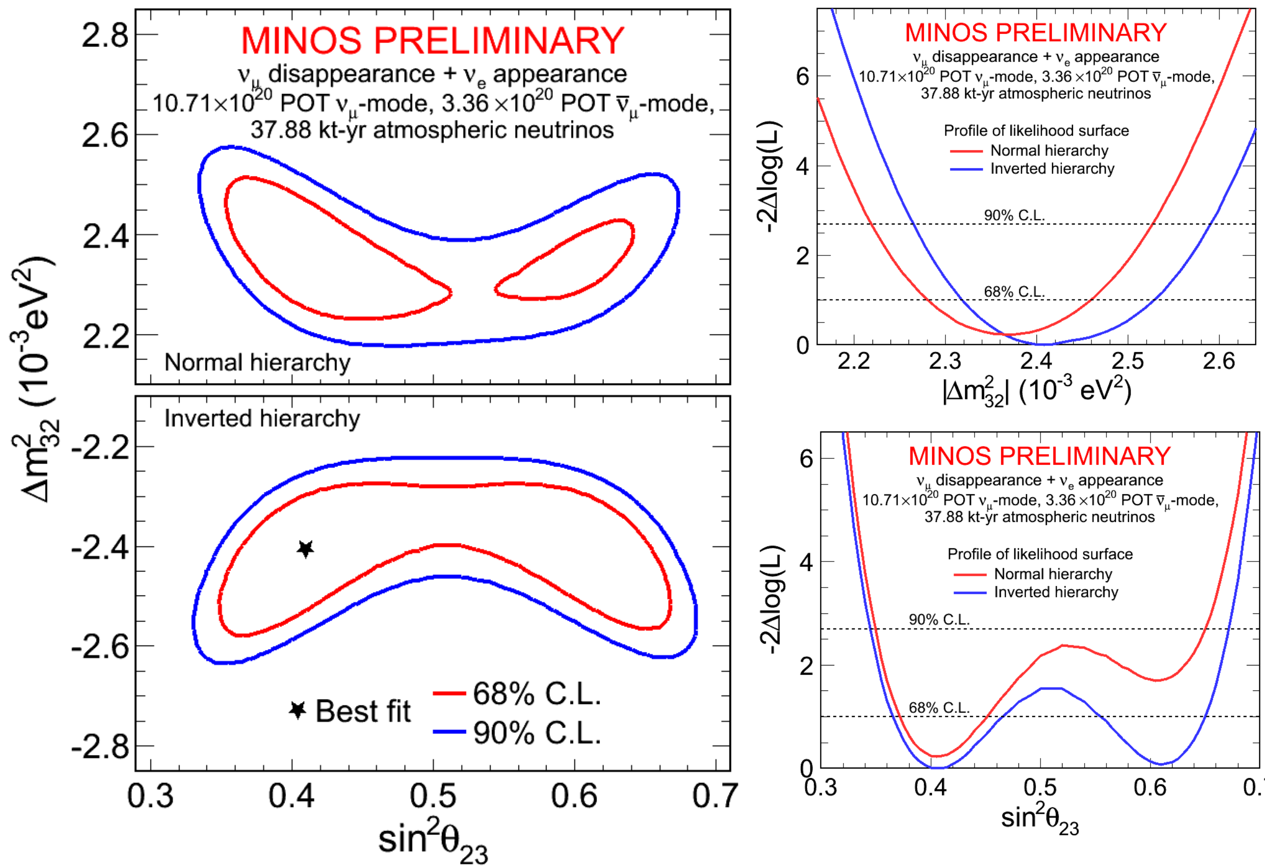
Three Flavour Disappearance and Appearance

- Combine the information from both fits
  - Each provides a 4D likelihood surface in Δm^2_{32}, $\sin^2\theta_{23}$ $\sin^2\theta_{13}$ and δ_{cp}
- Systematics assumed to be uncorrelated



- Normal hierarchy, upper octant case is now further disfavoured
  - At least 90% C.L for half δ_{cp} range

Three Flavour Disappearance and Appearance



- Slight preference for the inverted hierarchy
- Normal hierarchy, higher octant disfavoured

Three Flavour Disappearance and Appearance

- The four local best fit points:

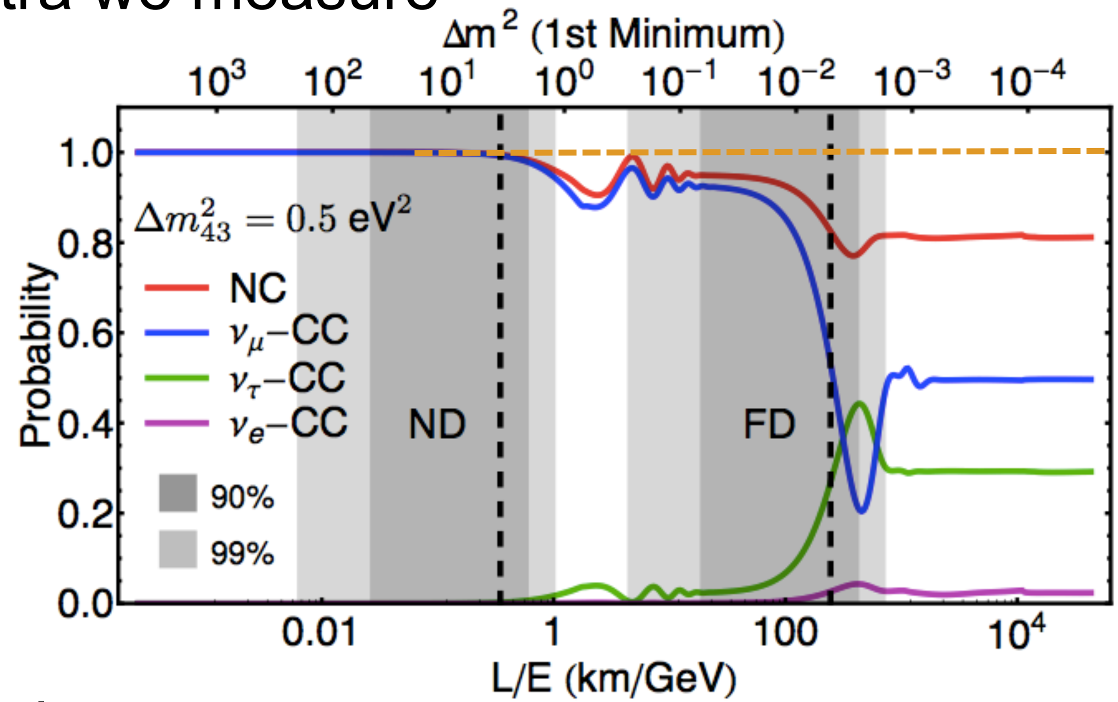
Hierarchy	Octant	Best fit parameters				$-2\Delta\log(L)$
		Δm^2_{32} /10^{-3}eV^2	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP} / π	
Normal	Lower	2.37	0.41	0.0242	0.44	0.23
Normal	Higher	2.35	0.61	0.0238	0.62	1.74
Inverted	Lower	-2.41	0.41	0.0243	0.62	-
Inverted	Higher	-2.41	0.61	0.0241	0.37	0.09

Hierarchy	Δm^2_{32} / 10^{-3} eV^2	$\sin^2\theta_{23}$ (90% C.L.)
Normal	$2.37^{+0.09}_{-0.09}$	$0.35 < \sin^2\theta_{23} < 0.65$
Inverted	$-2.41^{+0.12}_{-0.09}$	$0.34 < \sin^2\theta_{23} < 0.67$

- Prefer non-maximal mixing at 79% C.L.

Four Flavour Oscillations

- Oscillations to a fourth sterile neutrino will change the energy spectra we measure



NC reduction.
Not seen in 3 flavour.

- 3 Regimes:
  - Small Δm^2_{43}: Wide oscillations at the FD. Coming soon!
  - Medium Δm^2_{43}: Rapid oscillations that average out at the FD. Done!
  - Large Δm^2_{43}: Oscillations in the ND. Coming soon!

Neutral Current

- All neutrino flavours undergo neutral current (NC) interactions
  - Any deficit in the number of NC events can probe sterile neutrinos

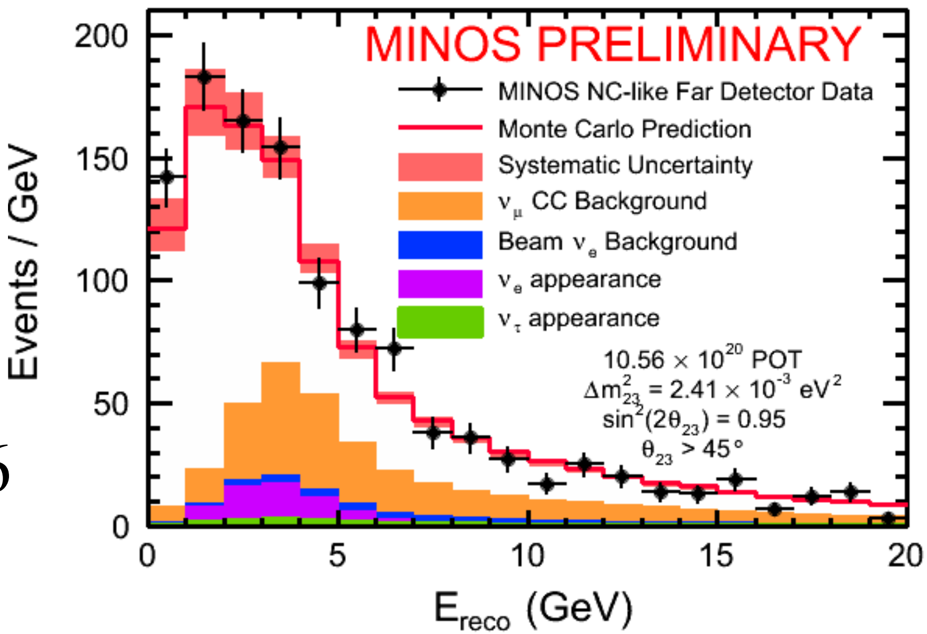
- Combined fit of the CC and NC spectra
  - No evidence found for sterile neutrinos with $\Delta m^2_{43} = 0.5 eV^2$

Predicted background

- Define $R = \frac{N_{data} - N_{bkg}}{S_{NC}}$

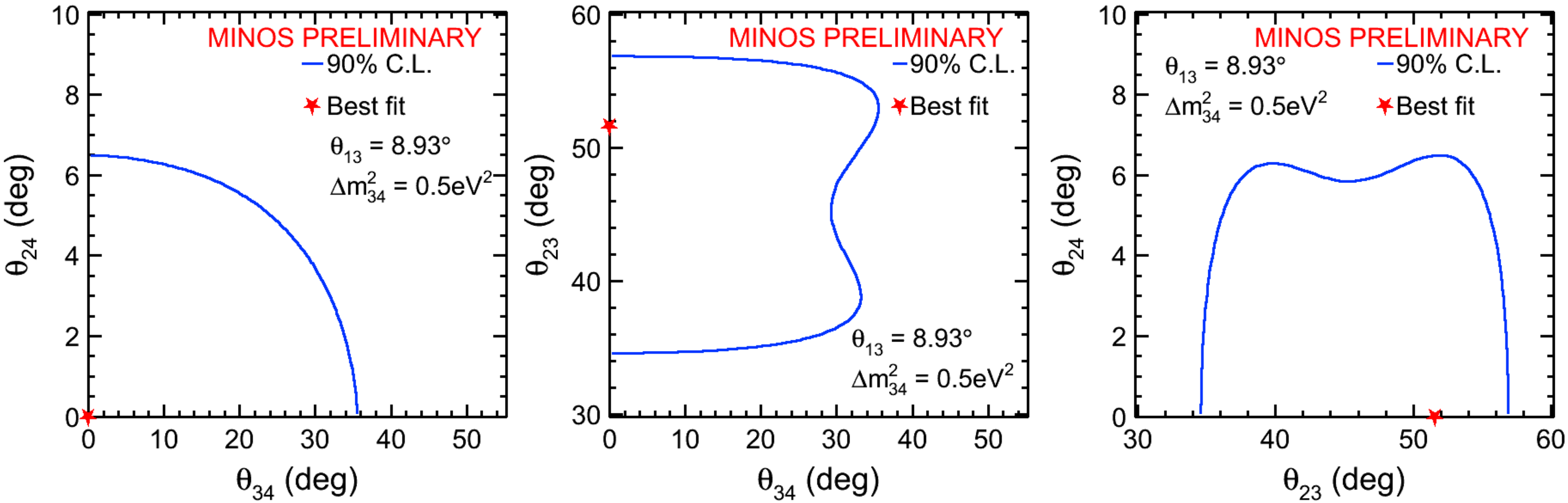
Predicted signal

- 0 – 200 GeV: $R = 1.049 \pm 0.076$
  - 0 – 3 GeV: $R = 1.093 \pm 0.097$
  - 3 – 200 GeV: $R = 1.009 \pm 0.095$



Neutral Current – Mixing Angle Limits

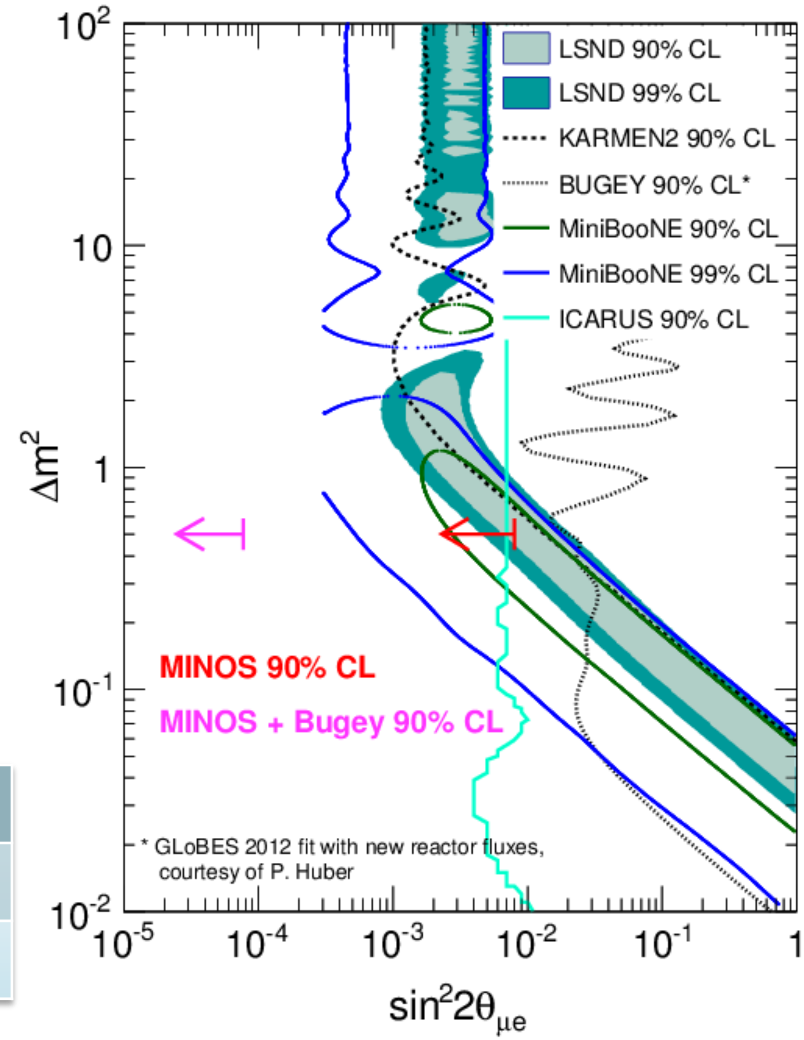
- We can now place limits on the values of the mixing angles



- 90% C.L: $\theta_{24} < 5^o$
- 90% C.L: $\theta_{34} < 24^o$
- Very slight preference to upper octant of θ_{23}

Neutral Current – Combined with BUGEY

- To compare to short-baseline appearance experiments, combine with BUGEY:
  - $\sin^2 2\theta_{\mu e} \sim \sin^2 2\theta_{14} \sin^2 \theta_{24}$
  - MINOS sensitive to θ_{24} and θ_{34}
  - BUGEY sensitive to θ_{14}



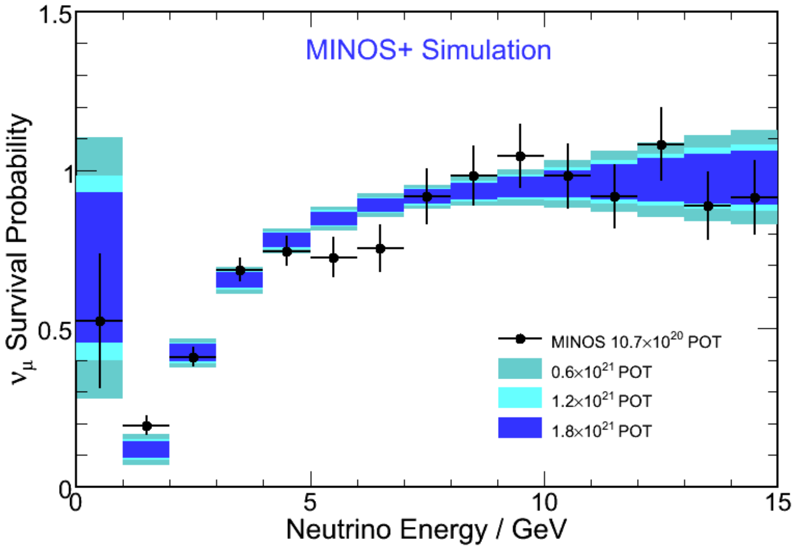
- Coming soon:
  - Full contour over range of Δm^2

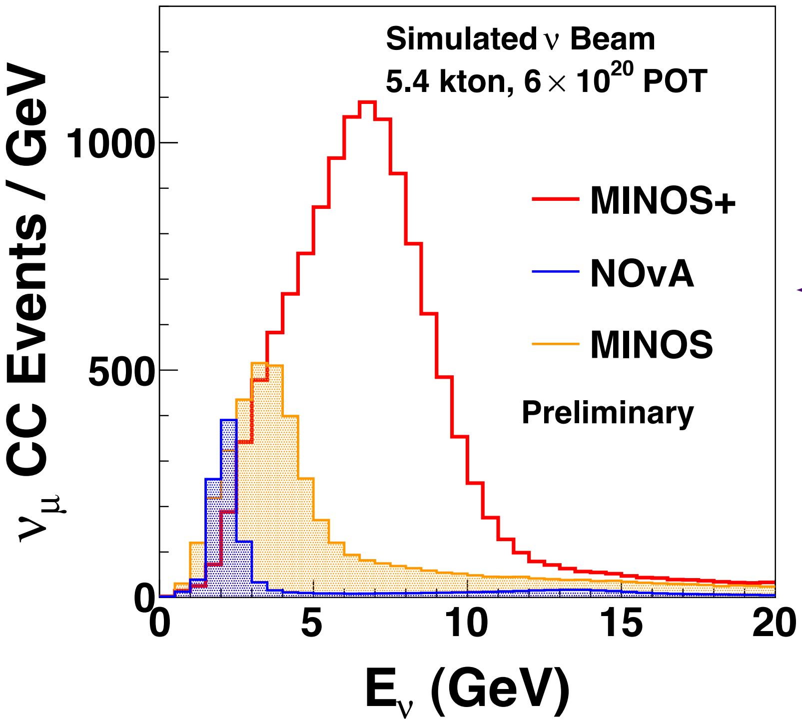
- At $\Delta m^2_{43} = 0.5 eV^2$

Sample	$\sin^2 2\theta_{\mu e}$ (90% C.L.)
MINOS	$< 7.1\times10^{-3}$
MINOS + BUGEY	$< 7.7\times10^{-5}$

MINOS+

- MINOS+ is a continuation of the MINOS experiment into the NOvA era.
  - Beam now runs in ME mode.
  - ME spectrum peaks above oscillation dip.

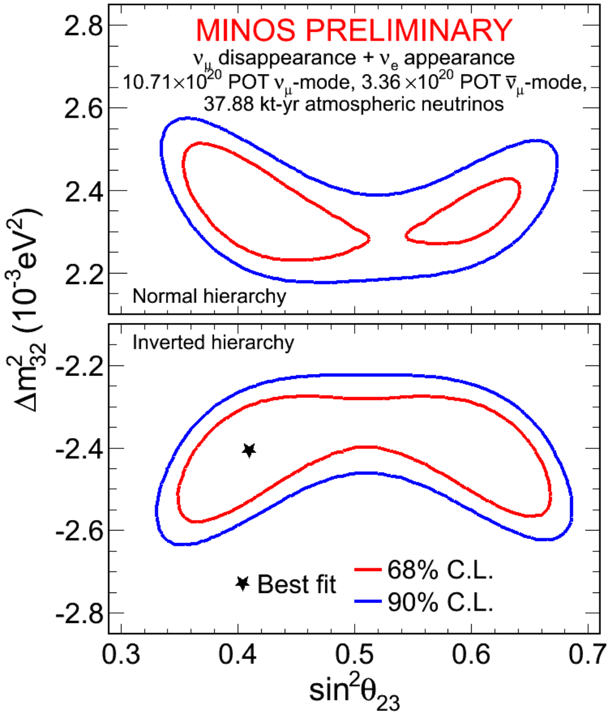




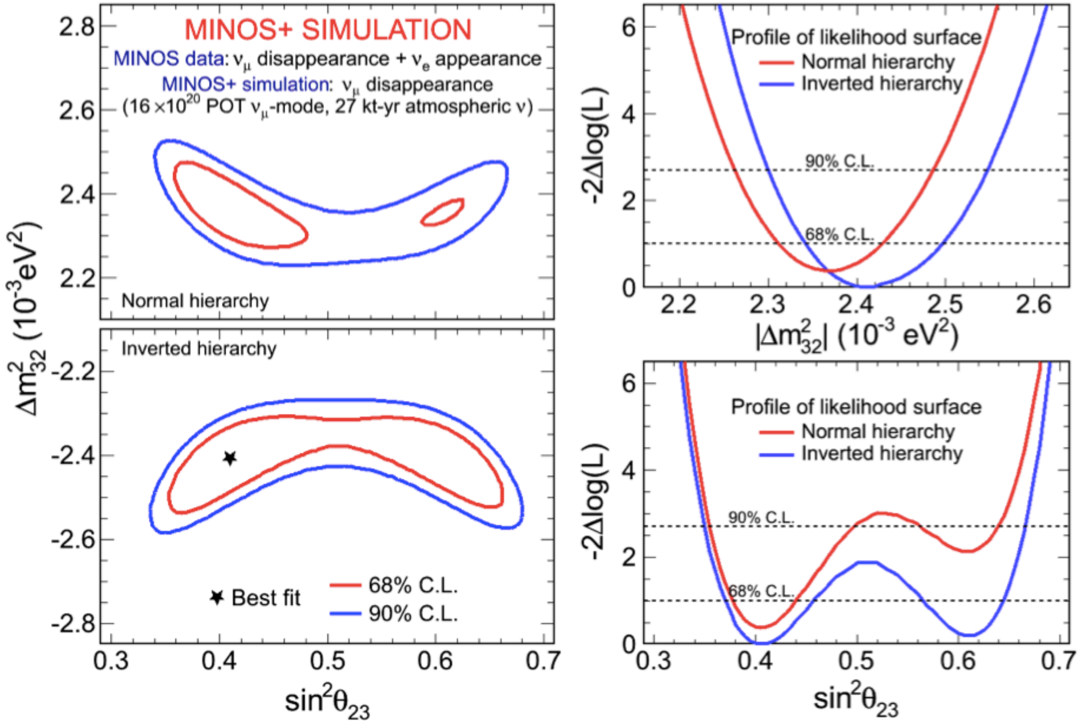
- Expect ~4000 events per year.
  - Precision test of the oscillation hypothesis in the tail.
  - Search for sterile neutrinos (using both CC and NC), extra dimensions etc.

MINOS+ Three Flavour Sensitivity

- Sensitivity of MINOS & MINOS+



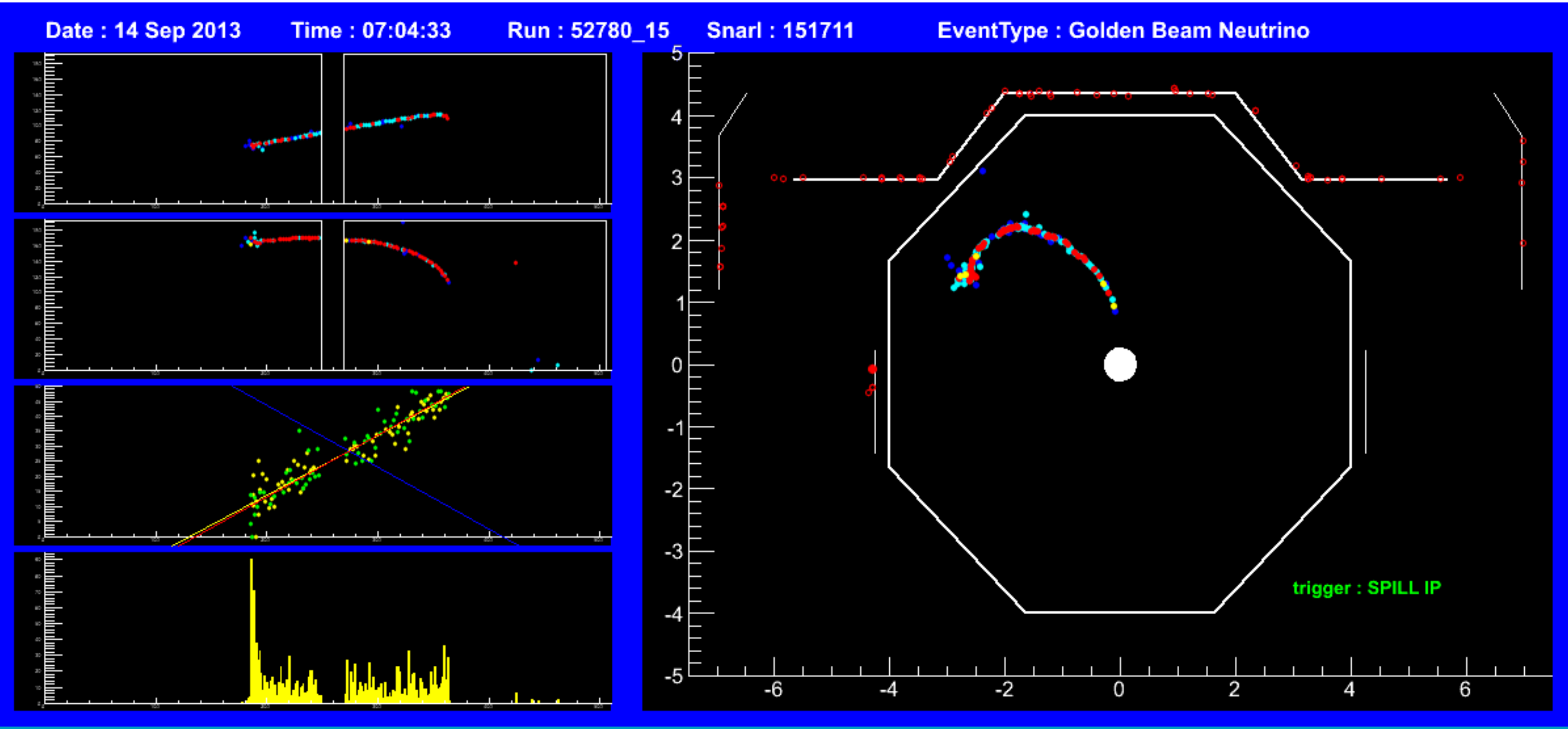
MINOS combined disappearance and appearance.



MINOS combined disappearance and appearance plus MINOS+ disappearance

MINOS+: Up and running!

- As of the start of September
  - NuMI running well at ~350kW
  - We have FD events!
- NuMI expected to run at ~700kW once all upgrades are completed



Conclusions

- The final word from MINOS:
  - First combined disappearance and appearance result from a long-baseline experiment

Hierarchy	Δm^2_{32} / 10^{-3} eV^2	$\sin^2\theta_{23}$ (90% C.L.)
Normal	$2.37^{+0.09}_{-0.09}$	$0.35 < \sin^2\theta_{23} < 0.65$
Inverted	$-2.41^{+0.12}_{-0.09}$	$0.34 < \sin^2\theta_{23} < 0.67$

  - See no tension between neutrino and antineutrino oscillation parameters
  - No evidence of sterile neutrinos at $\Delta m^2_{43} = 0.5 eV^2$
  - Look out for updates to the sterile neutrino analysis

- MINOS+ will continue where MINOS left off, providing exciting physics results in the coming years

Thank You

Backup Slides

Neutrino Oscillations

- The neutrino weak flavour states are not the same as the neutrino mass states.
  - Creation and detection governed by flavour states
  - Propagation governed by mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^{\dagger}_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^{*}_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- Matrix U governs the oscillation of a neutrino of one flavour into a different flavour.

The PMNS Matrix and Mass Hierarchy

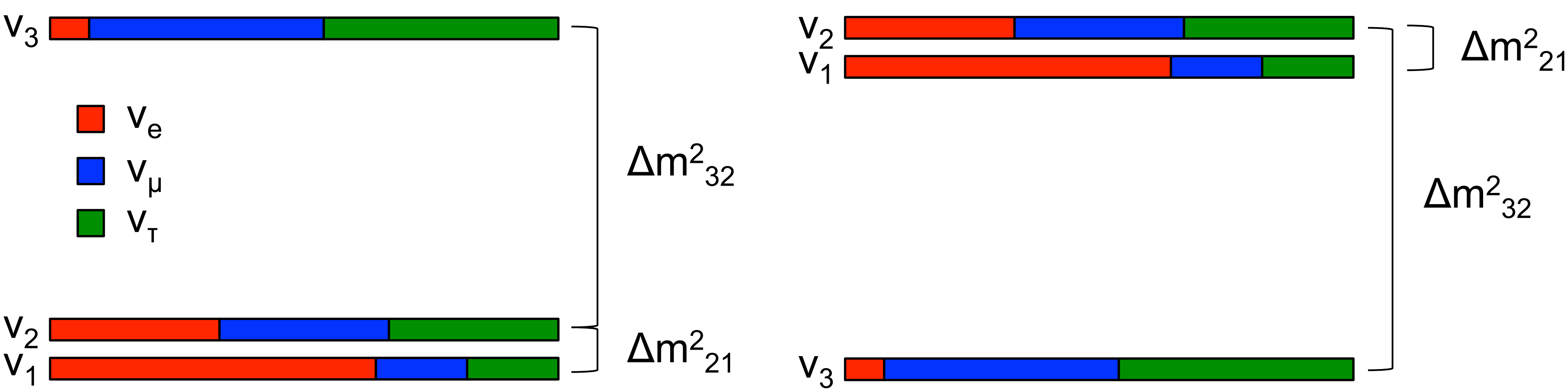
- Can be written as a product of three matrices

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric and LBL beam experiments

SBL reactor and LBL beam experiments

LBL reactor and solar experiments

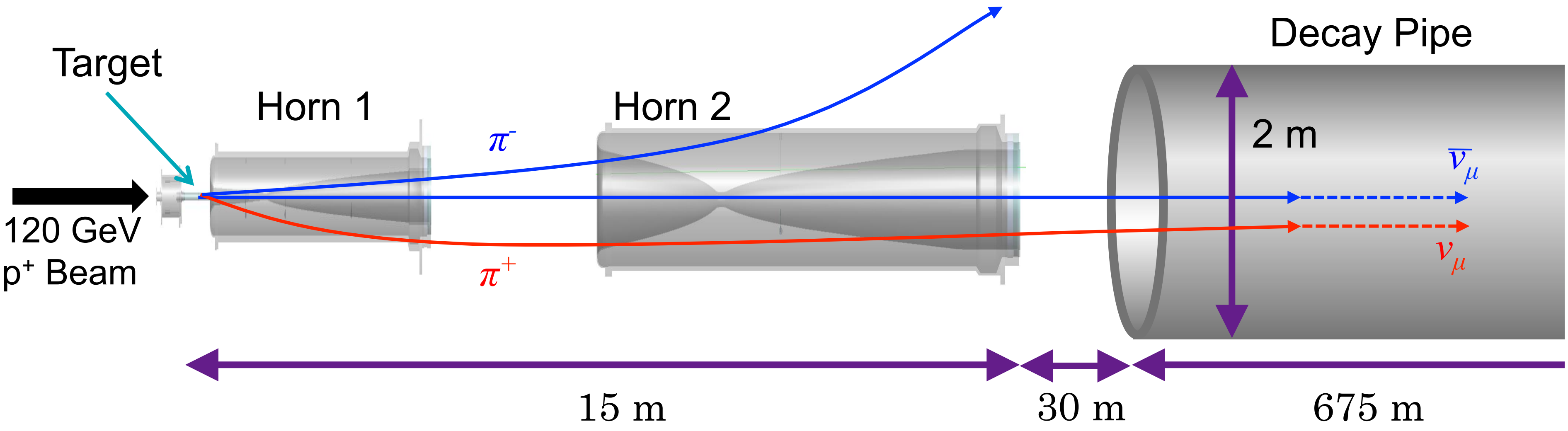


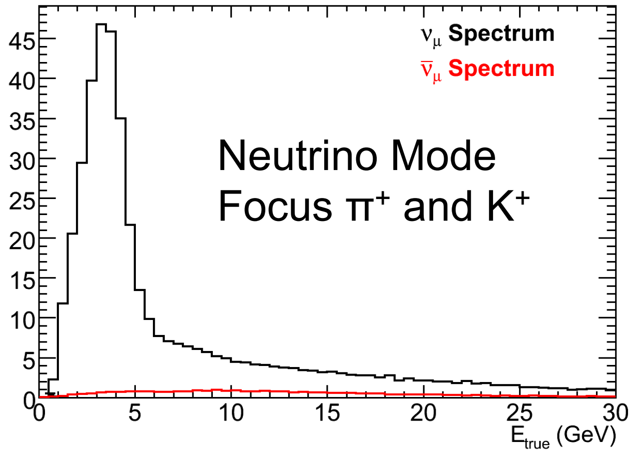
Open Questions

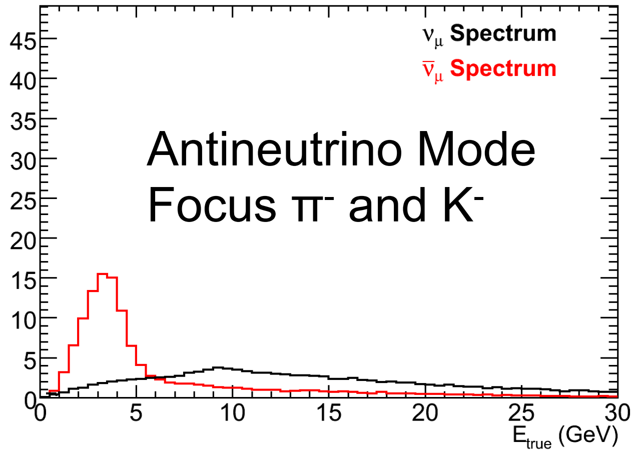
- There are still lots of unknowns in neutrino physics!
  - Is $\theta_{23} = 45^o$?
    - If not, is it higher or lower octant?
  - Is the mass hierarchy normal or inverted?
  - What is the absolute scale of neutrino mass?
  - Are neutrinos Dirac or Majorana?
    - Majorana neutrinos would open the door to the seesaw mechanism
  - Do neutrinos violate CP?
    - Is it enough to explain the matter – antimatter asymmetry of the universe?
  - Why does the PMNS matrix have the form it does?
    - Is there an underlying symmetry?
  - Why is the PMNS matrix different to the CKM matrix?
  - Are there any sterile neutrinos?

The NuMI Beam

- Beam starts with 120 GeV protons from the Main Injector.



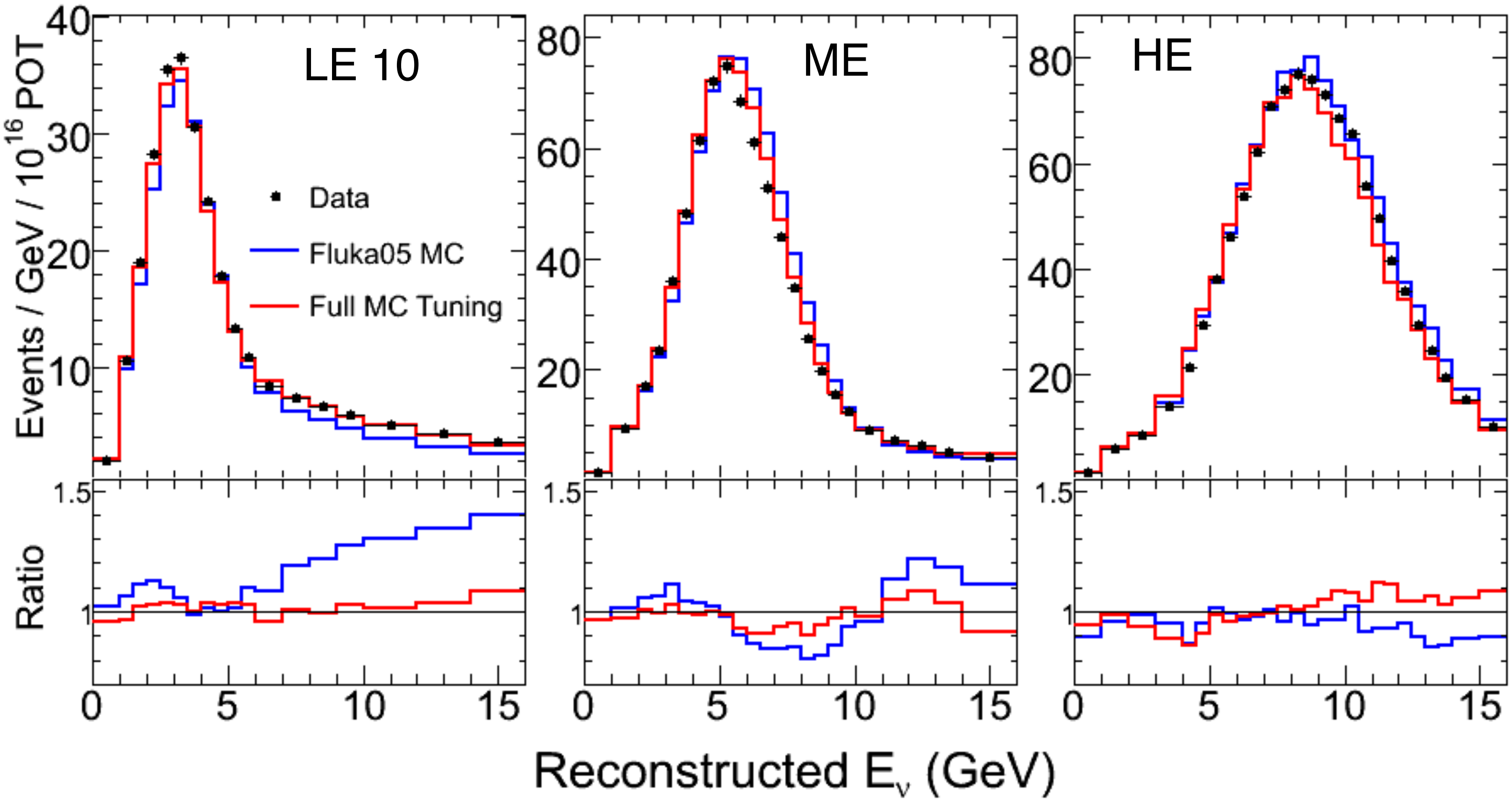




- Wrong sign high energy mesons give "wrong sign" neutrinos

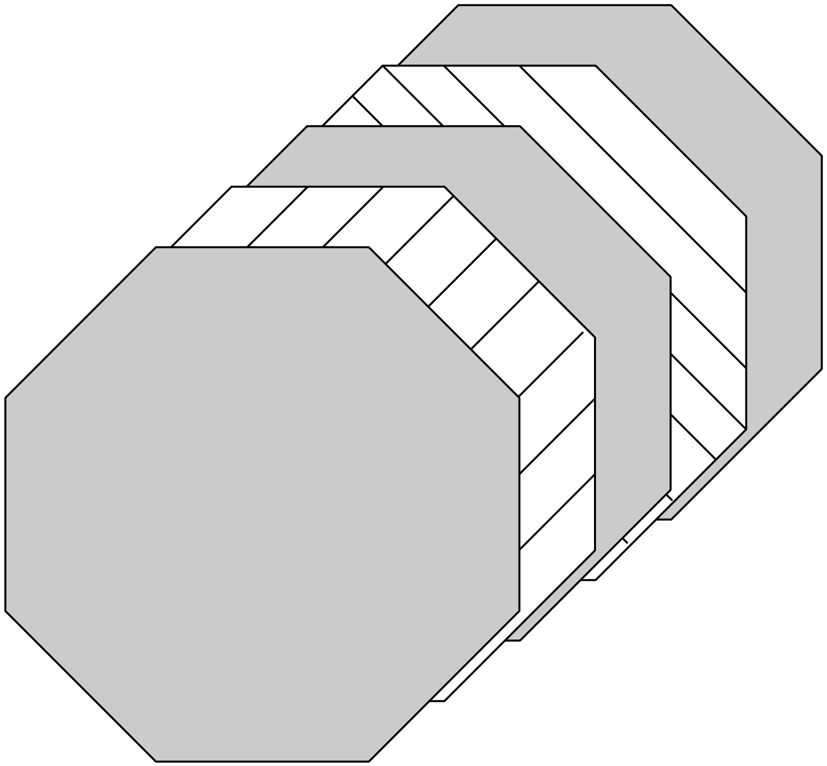
Beam Simulation

- The beam simulation is tuned using data from the ND
  - Take advantage of the different run types to constrain the simulation



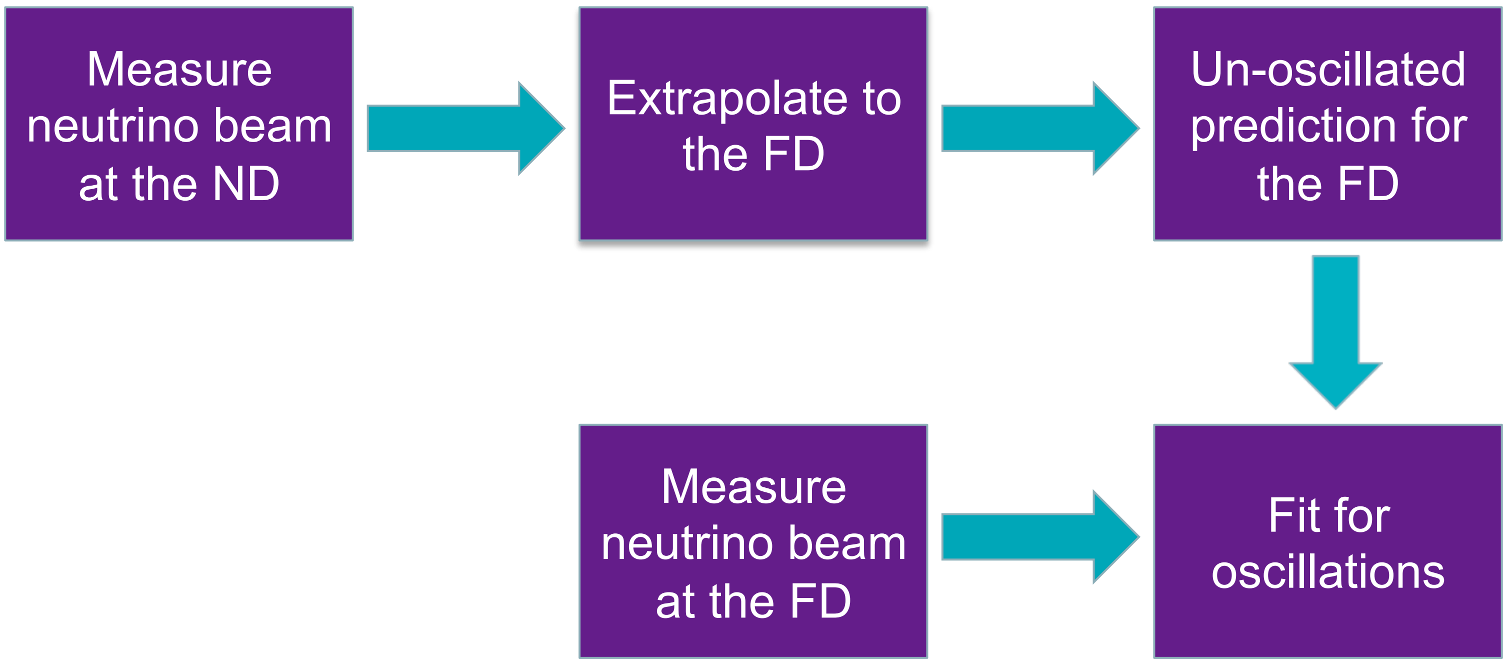
Detector Technology

- Detectors built from alternating planes:
  - 2.54cm steel absorber ~1.4 X_0
  - 1cm thick scintillator.
- Scintillator planes:
  - Made from plastic scintillator bars, each 4.1cm wide.
  - Read out by multi-anode PMTs via WLS fibres.
  - Alternating layers have bars in orthogonal directions views, U and V
- Magnetic field allows for charge separation.
  - Both detectors have average field of 1.3T



Measurement Strategy: Overview

- Use the ND to predict the FD un-oscillated spectrum

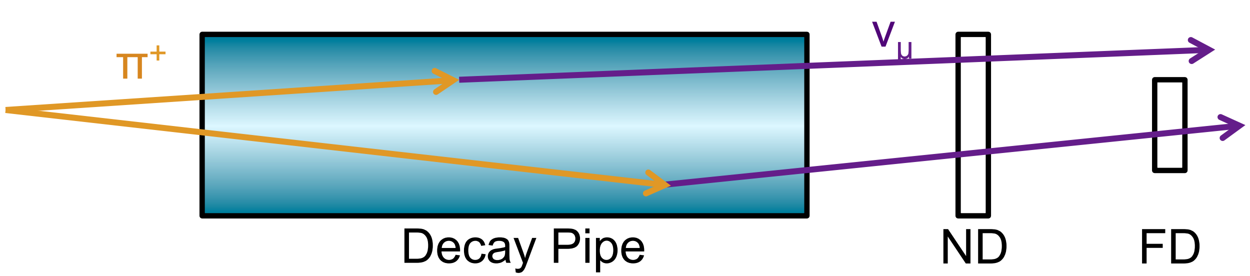


- The extrapolation to the FD requires a few steps…

Measurement Strategy: Extrapolation I

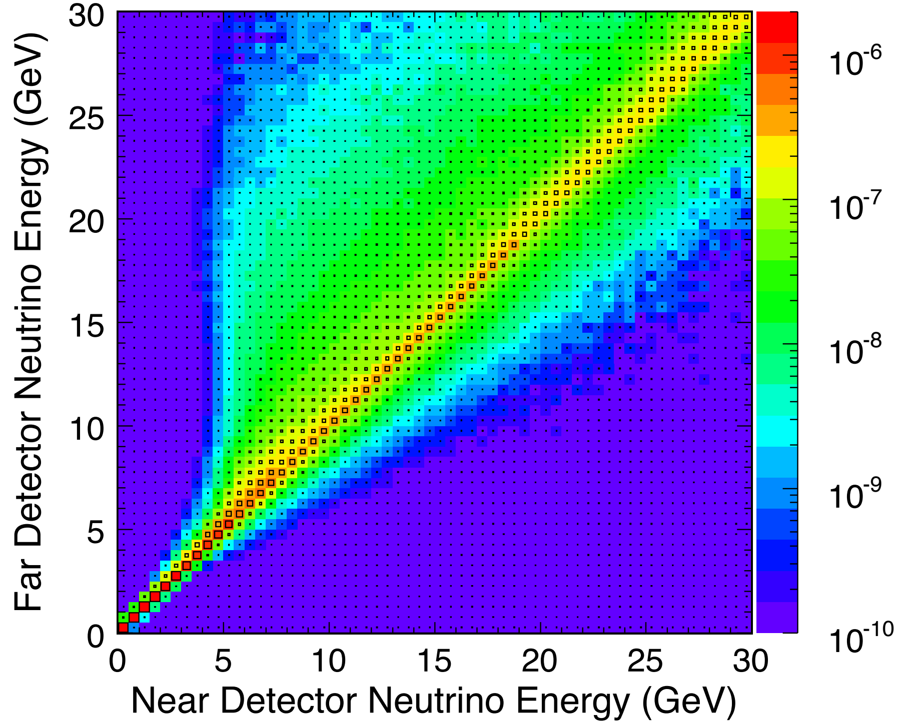
- Starting with the ND data:
  - Correct for ND purity and efficiency and apply reco-true matrix
  - Account for cross-sections, PoT and ND mass

- Need to account for beam differences now
  - The energy spectrum differs between the two detectors
    - Different angular acceptances
    - Low energy pions decay upstream in the decay pipe.
  - FD sees a point source
  - ND sees an extended source



Measurement Strategy: Extrapolation II

- Apply the beam matrix to extrapolate to the FD.

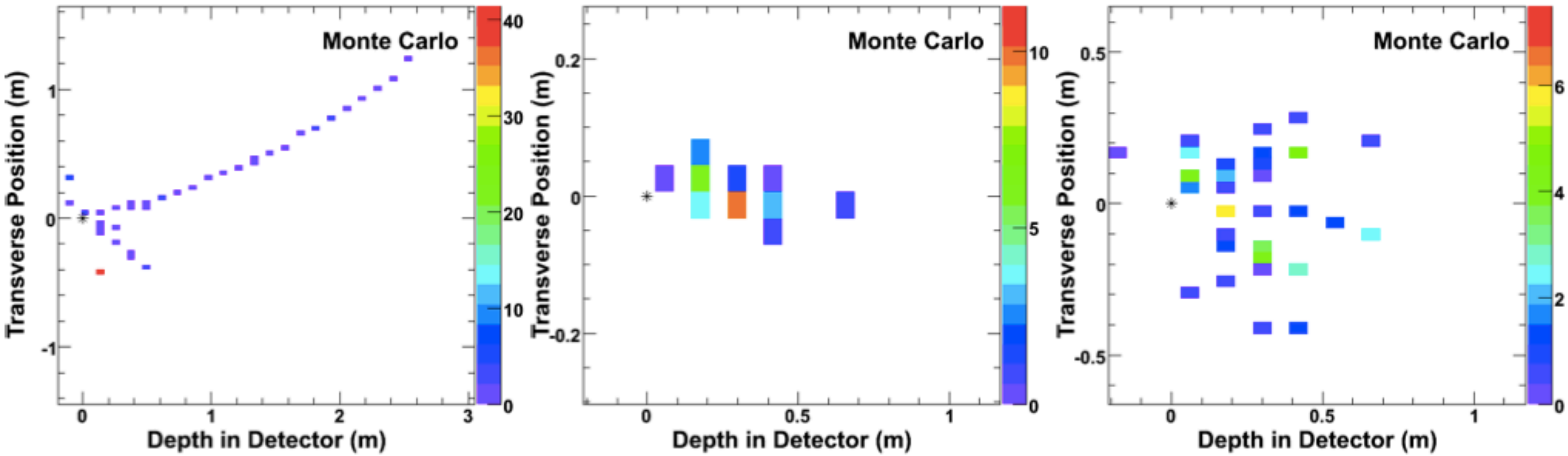


- Then apply the FD specific corrections.
  - These are the analogues to those shown previously for the ND

- Provides the un-oscillated prediction at the FD

Event Topologies in MINOS

- Expect to see three classes of event.



CC ν_μ

Identify muon track and use curvature to measure the sign.

Momentum comes from range or curvature (if not contained).

CC ν_e

Compact electro-magnetic shower.

NC ν_x

Disperse hadronic shower energy deposits.

Three Flavour Muon Neutrino Disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \cos^2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{\mu\mu} L}{E}\right) + \mathcal{O}\left(\Delta m^2_\odot \frac{L}{E}\right)^2$$

$$\Delta m^2_{\mu\mu} = \Delta m^2_{32} + \frac{1-\left|U_{\mu 1}\right|^2}{\left|U_{\mu 3}\right|^2} \Delta m^2_{21}$$

- Disappearance depends on:
  - Solar oscillation parameters
  - θ_{13}
  - Mass hierarchy
  - θ_{23} octant (very weakly)
- Matter effects important for multi-GeV up-going atmospherics
- Make a 4D fit to the FD data in $\left(\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta_{CP}\right)$
  - Constrain θ_{13} from the reactor experiment average:

$$\sin^2\theta_{13} = 0.0242 \pm 0.0025$$

- Solar parameters fixed at the global average†

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Disappearance Analysis Event Counts

- Predicted numbers with oscillations made assuming:

$$\Delta m^2 = 2.41 \times 10^{-3} eV^2$$

$$\sin^2 2\theta = 0.95$$

Sample	No Osc	Osc	Measured
ν_μ from ν_μ beam	3201	2543	2579
$\bar{\nu}_\mu$ from ν_μ beam	363	324	312
Non-fiducial μ^- from ν_μ beam	3197	2862	2911
$\bar{\nu}_\mu$ from $\bar{\nu}_\mu$ beam	313	227	226
Atm. contained $\nu_\mu + \bar{\nu}_\mu$	1100	881	905
Atm. Non-fiducial $\mu^- + \mu^+$	570	467	466
Atm. showers	727	724	701

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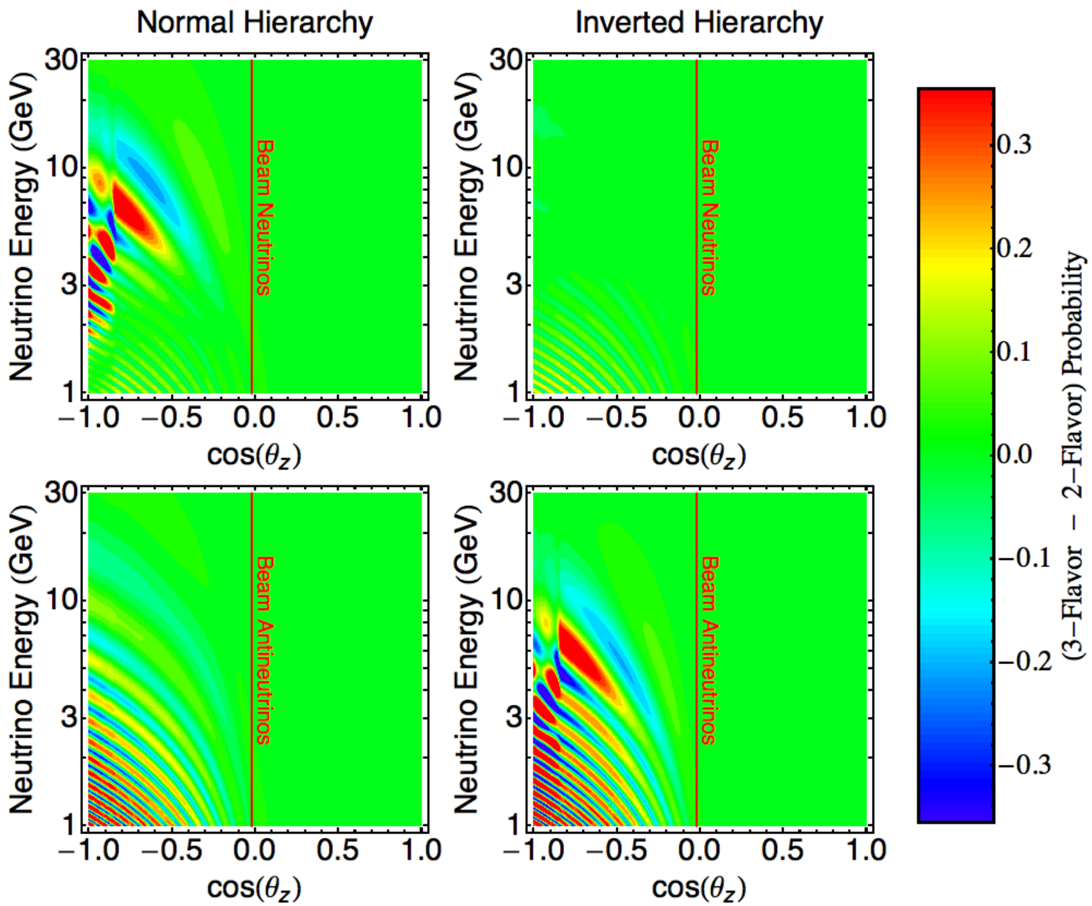
Matter Effects (MSW)

- Interactions with matter modify the standard oscillations
  - Comparing between 2 and 3 flavour oscillations, see fairly large variation for ~few GeV atmospheric neutrinos

- Changes the probability by up to 30%

- Gives sensitivity to the mass hierarchy

- Very small effect for the beam neutrinos



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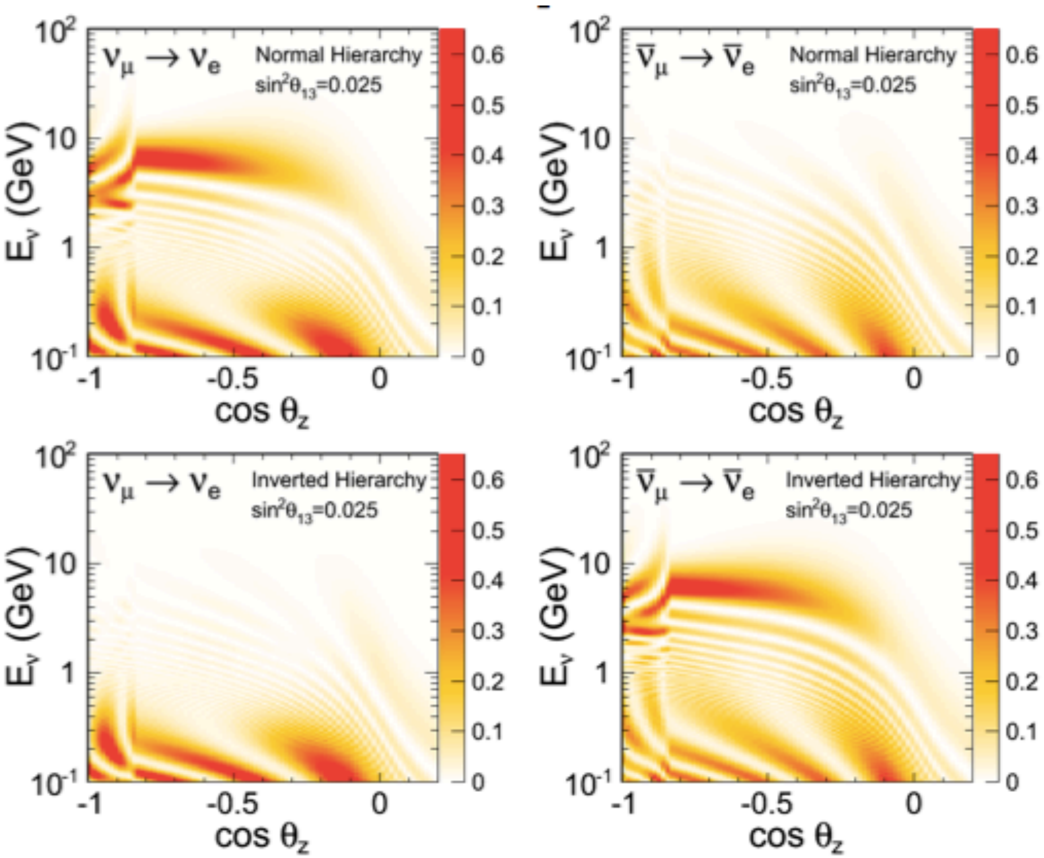
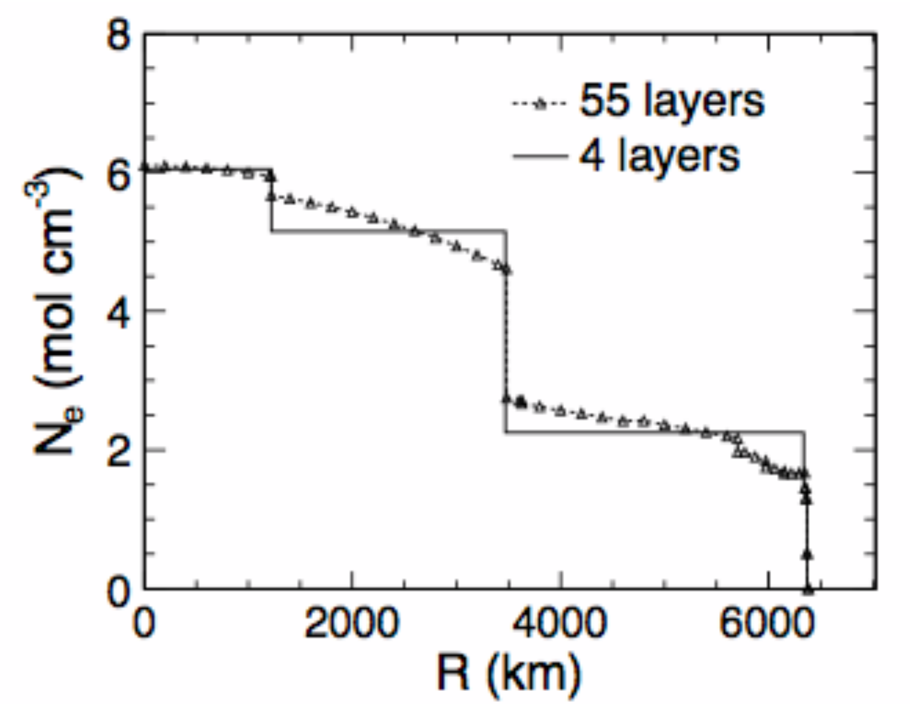


Earth Matter Model

- Beam: Use fixed electron density of 1.36 mol cm^{-3}

- Atmospherics: Use a 4 layer model

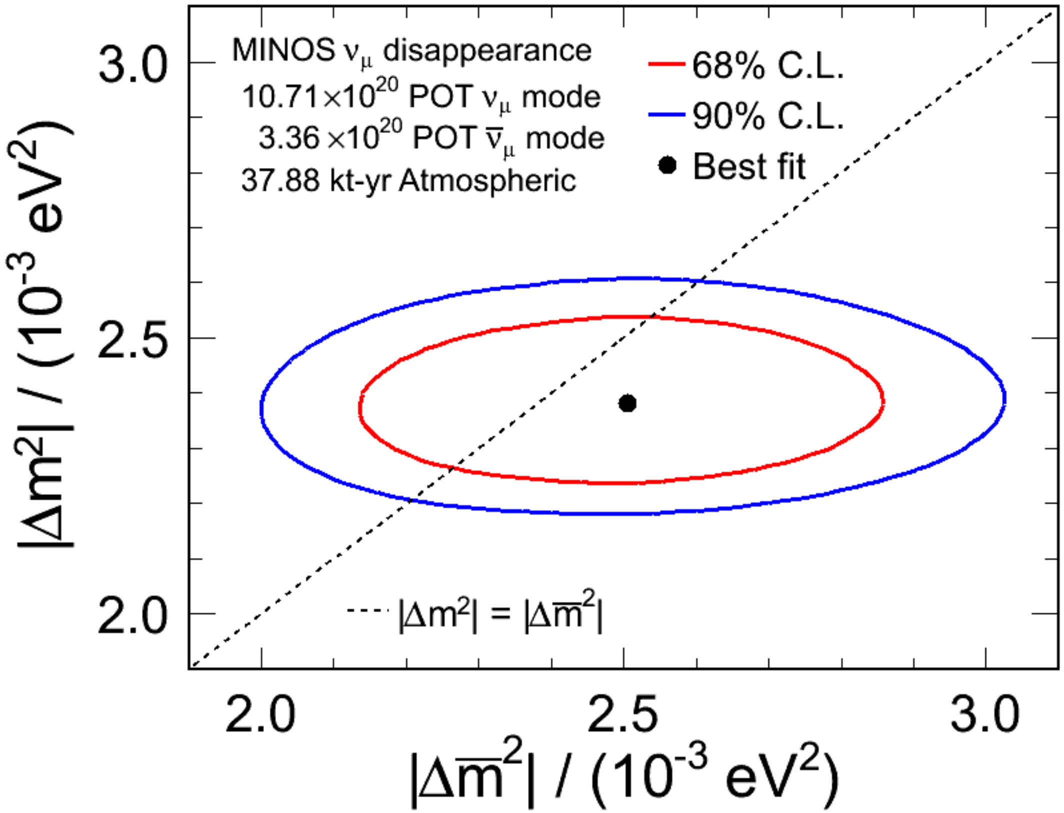


Region	Radius (km)	Earth density (mol cm^{-3})
Crust	> 6336	1.45
Mantle	3470 – 6336	2.25
Outer Core	1220 – 3470	5.15
Inner Core	< 1220	6.05

- Negligible effect on the result between using 4 and 55 layers

Two Flavour Disappearance: CPT

- Fitted with neutrino and antineutrino parameters separate and free to float
- The old tension between the results has vanished
  - CPT conserved



$$\left|\Delta\bar{m}^2\right| - \left|\Delta m^2\right| = \left(0.12^{+0.24}_{-0.26}\right)\times10^{-3}eV^2$$

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Two Flavour Disappearance: Comparisons

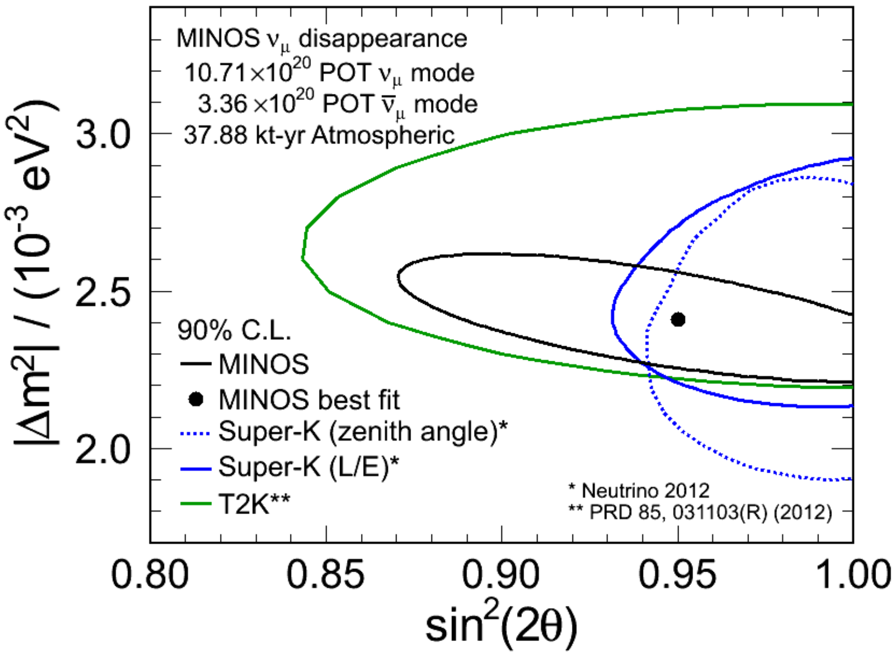
- Combined MINOS two-flavour contour with same oscillation parameters for neutrinos and antineutrinos.

- Best fit at:

$$\Delta m^2 = 2.41^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2 2\theta = 0.950^{+0.035}_{-0.036}$$

- Hints that mixing may not be maximal



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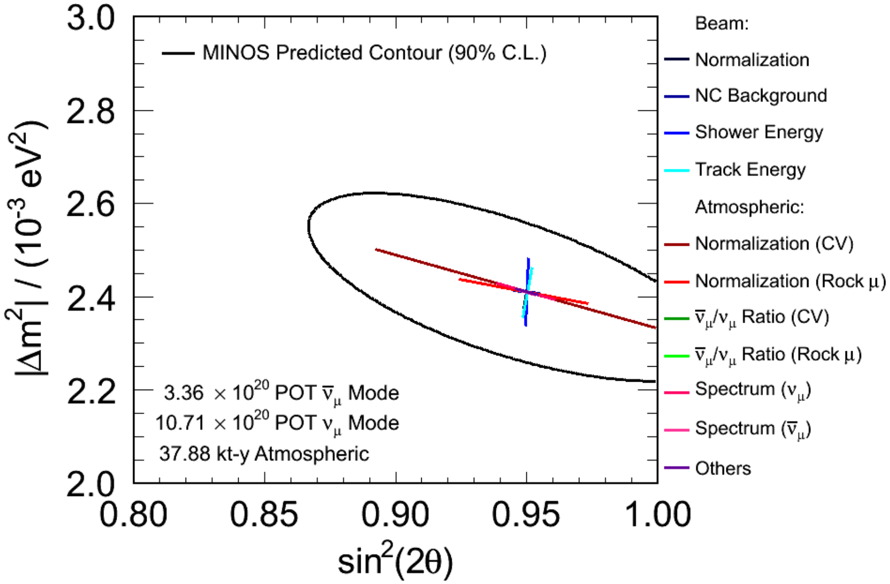
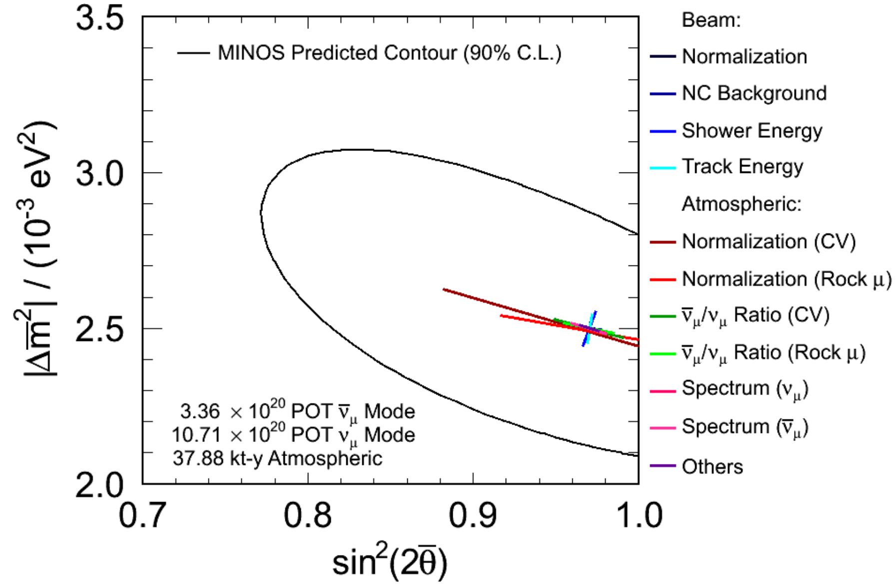
Disappearance: Systematic Uncertainties

- Star plots show the relative size of statistical and systematic uncertainties
  - They are fitted as nuisance parameters in the fit

Neutrinos



Antineutrinos



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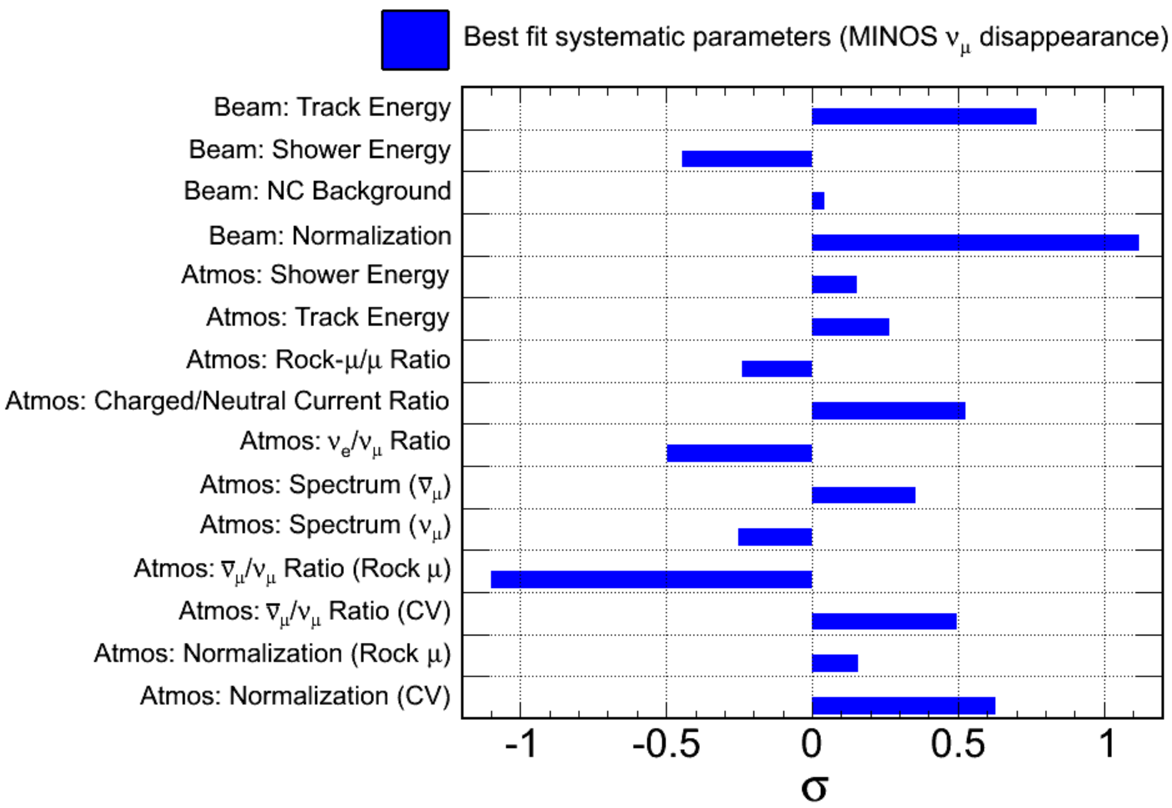
Disappearance: Systematic Uncertainties

- Plot shows how the systematics are pulled in the fit



- The majority of these pulled by less than one sigma.

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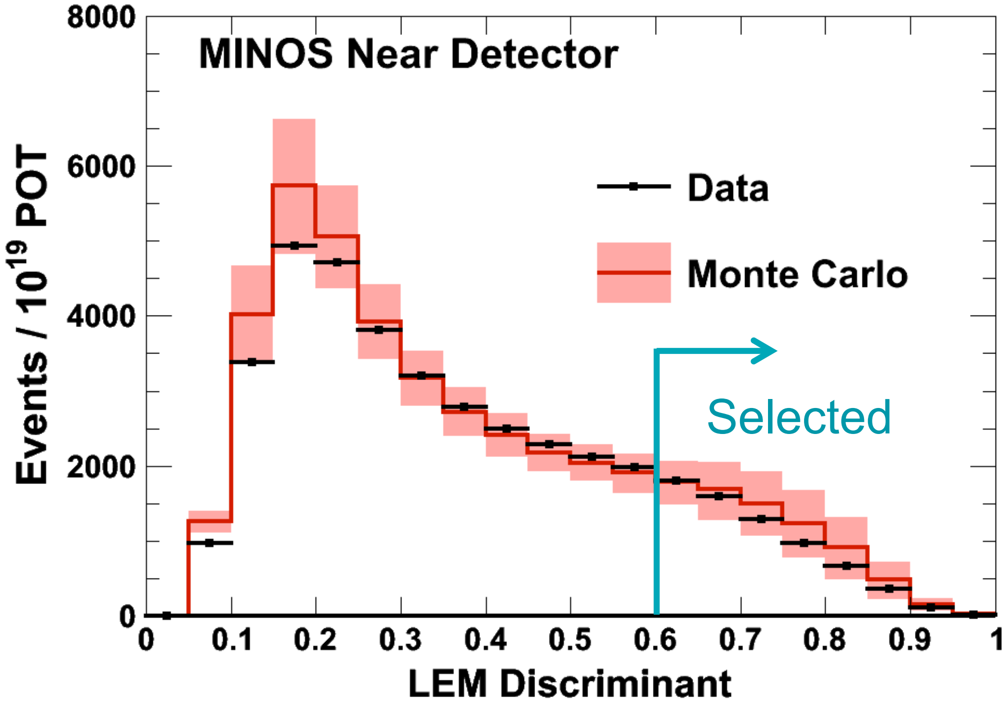
Electron Neutrino Selection

- Very challenging given the coarse nature of the calorimeters!
- Electron neutrinos are selected using the Library Event Matching algorithm
- Candidates compared to a library of simulated signal and background events.
- The 50 best matches are used to form variables to discriminate signal and background.



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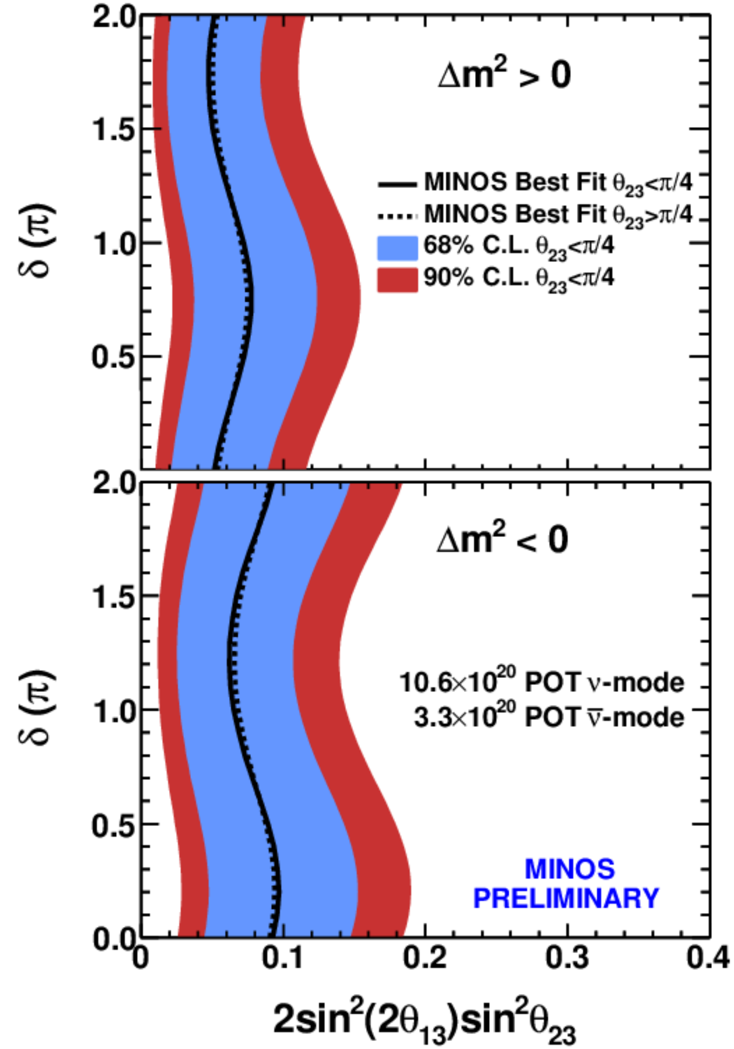
Electron Neutrino Results

- Combined neutrino and antineutrino fit.
- Best fit, assuming $\sin^2(2\theta_{23})=1, \delta=0$ and normal (inverted) hierarchy:

$$\sin^2(2\theta_{13})=0.053\ (0.094)$$

$$\sin^2(2\theta_{13})=0$$ excluded at 96%



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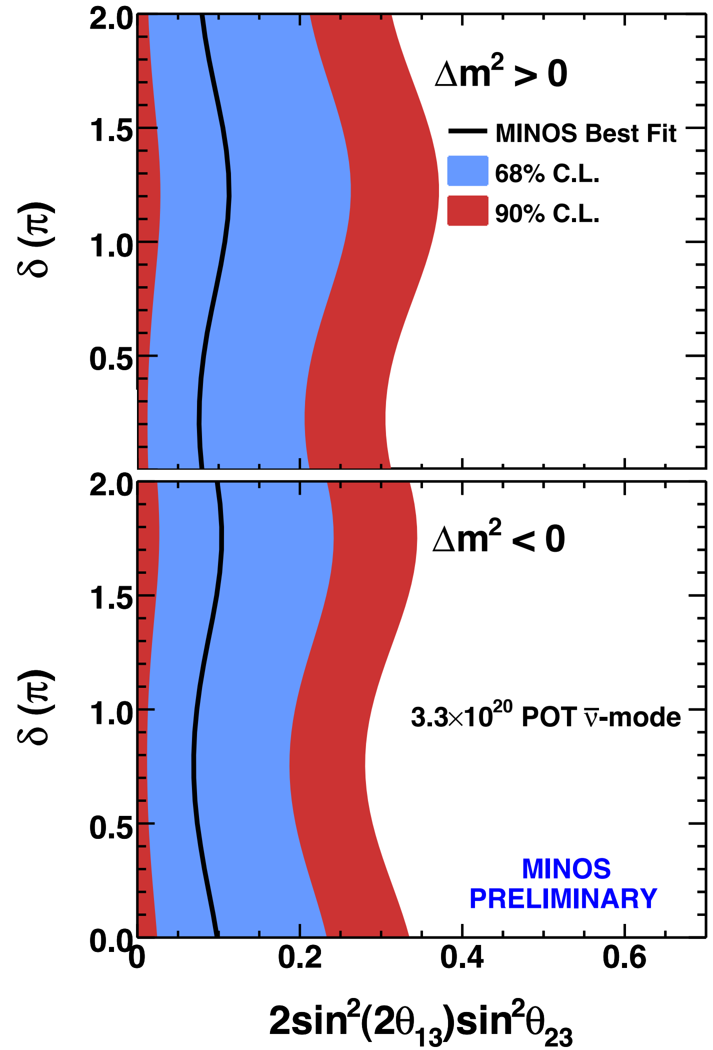
Electron Antineutrino Results

- Fit to just the antineutrino events

- Best fit, assuming $\sin^2(2\theta_{23})=1, \delta=0$ and normal (inverted) hierarchy:

$$\sin^2(2\theta_{13})=0.079\,(0.098)$$

$\sin^2(2\theta_{13})=0$ excluded at 80%



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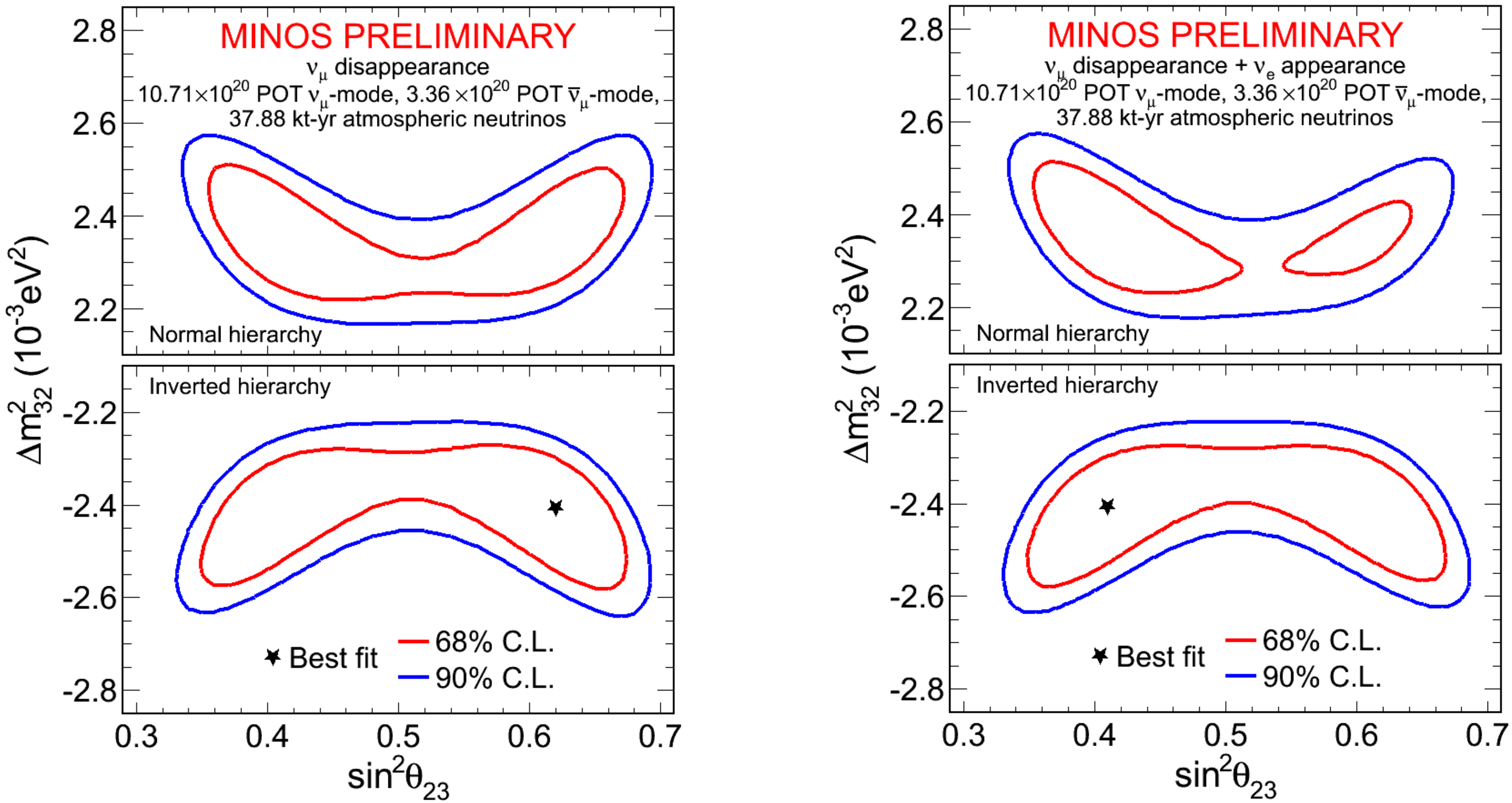
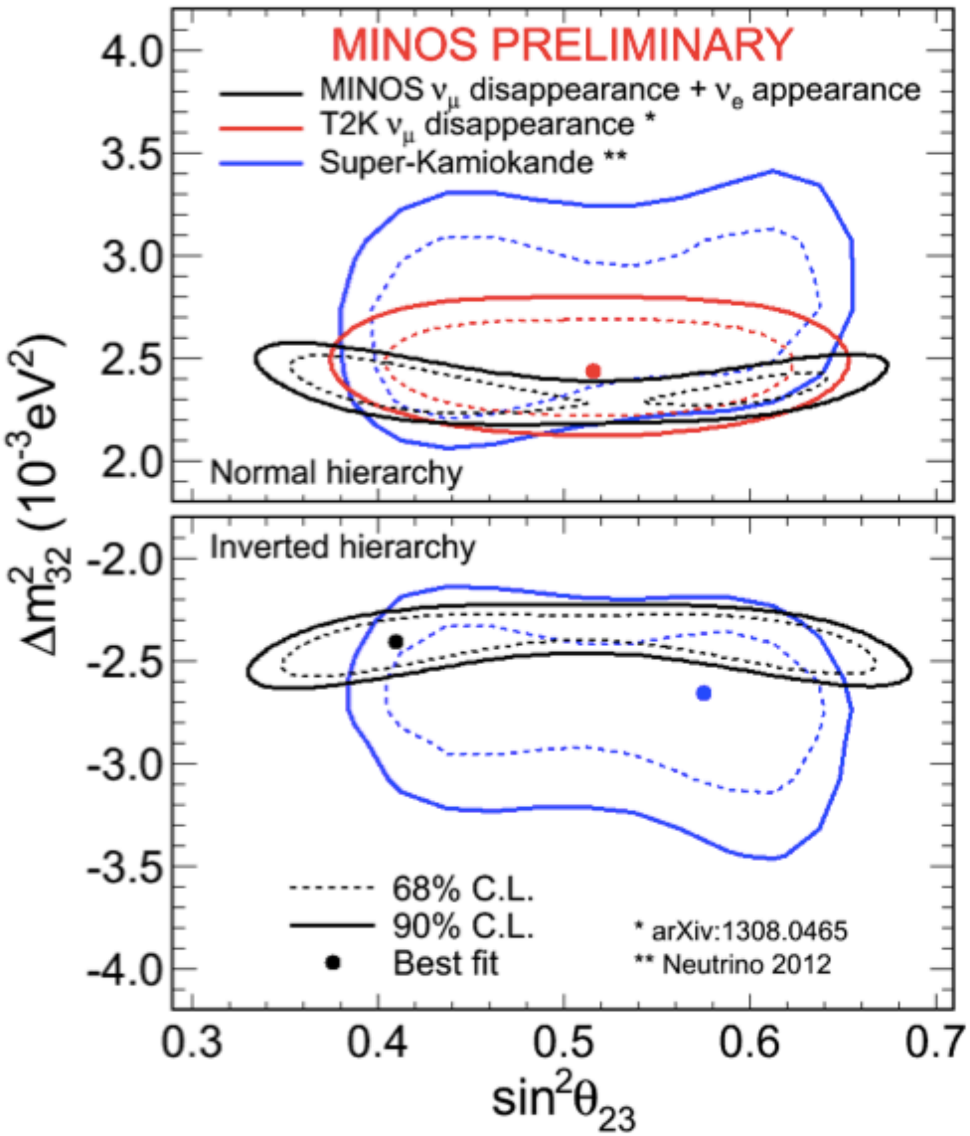
Disappearance + Appearance



MINOS, T2K and SK

- Comparison of the MINOS combined result with SK and T2K
  - Note: T2K result converted from $\sin^2 2\theta$ to $\sin^2\theta_{23}$



Four Flavour Oscillations

- A fourth neutrino state adds:
  - 3 mixing angles: $\theta_{14}, \theta_{24}, \theta_{34}$
  - 3 mass splittings: $\Delta m^2_{43}, \Delta m^2_{42}, \Delta m^2_{41}$
  - 2 additional complex phases

$$U_4 = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- LSND/MiniBooNE measured $\sin^2 2\theta_{\mu e} \sim \sin^2 2\theta_{14} \sin^2 \theta_{24}$
- MINOS NC measures $\sin^2 2\theta_{\mu s} \sim \sin^2 2\theta_{24} \cos^2 \theta_{34}$
- Reactor experiments measure $\sin^2 2\theta_{ee} \sim \sin^2 2\theta_{14}$
- Therefore it makes sense to combine MINOS with a reactor experiment such as BUGEY to set a limit on $\sin^2 2\theta_{\mu e}$

TOF Analysis

TOF Overview

- Measure the time of flight between the ND and FD.
  - Distance of 734,286.8m

- To perform the time of flight measurement, need to know very precisely:
  - The distance between the ND and the FD.
  - All time delays:
    - Cables, GPS offsets, etc etc

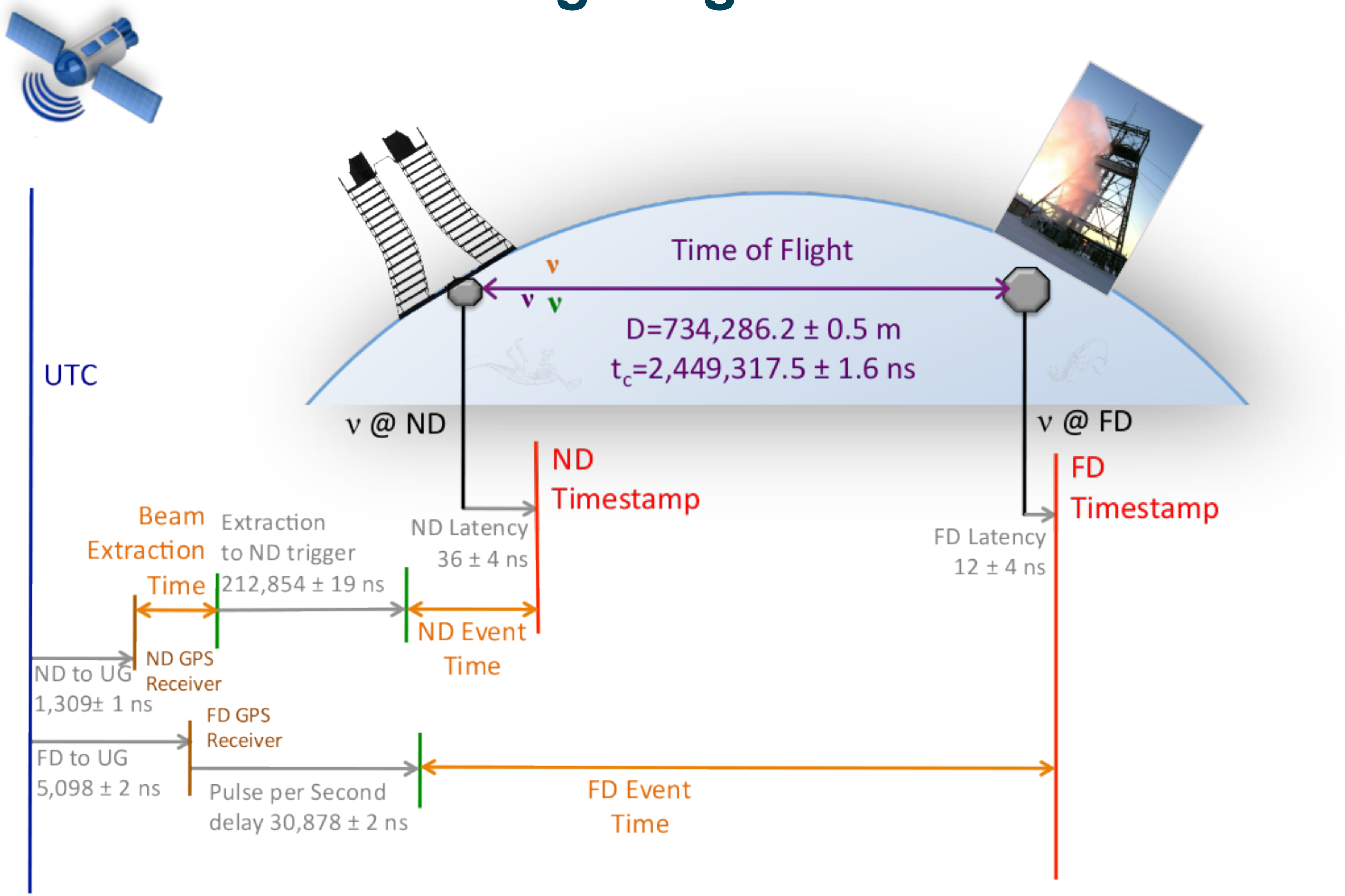
- Worked with:
  - NIST Time and Frequency Division
  - USNO Time Service Department

- Perform a likelihood fit on the FD data to the time of flight

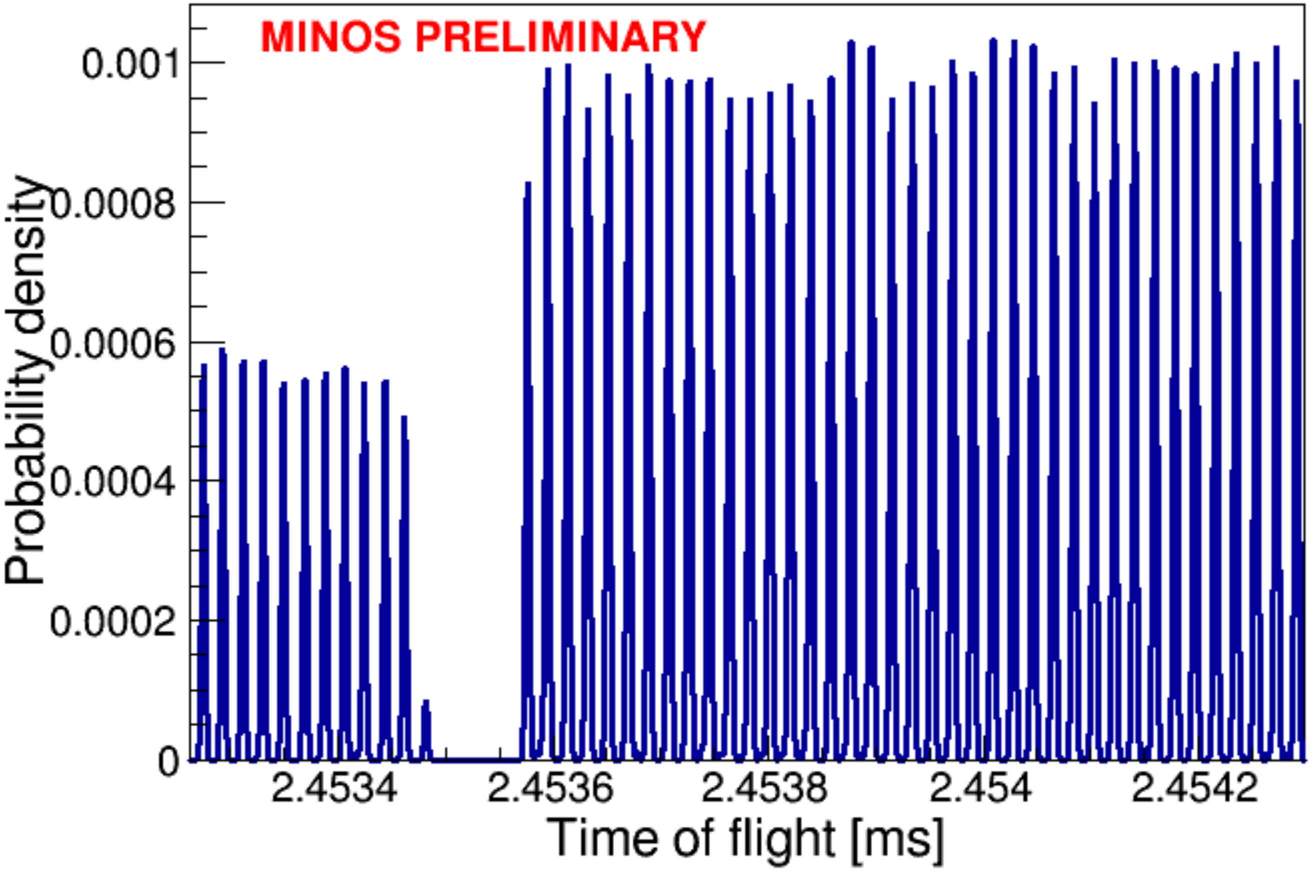
Measuring Distances

- Three components to measure:
  - Surface distance between ND and FD
  - Distance from surface to underground at ND
  - Distance from surface to underground at FD
- The last point is the most challenging
  - FD is 2341 feet down a single mineshaft
  - No line of sight from the surface to the FD
- Don't forget that the Earth rotates!

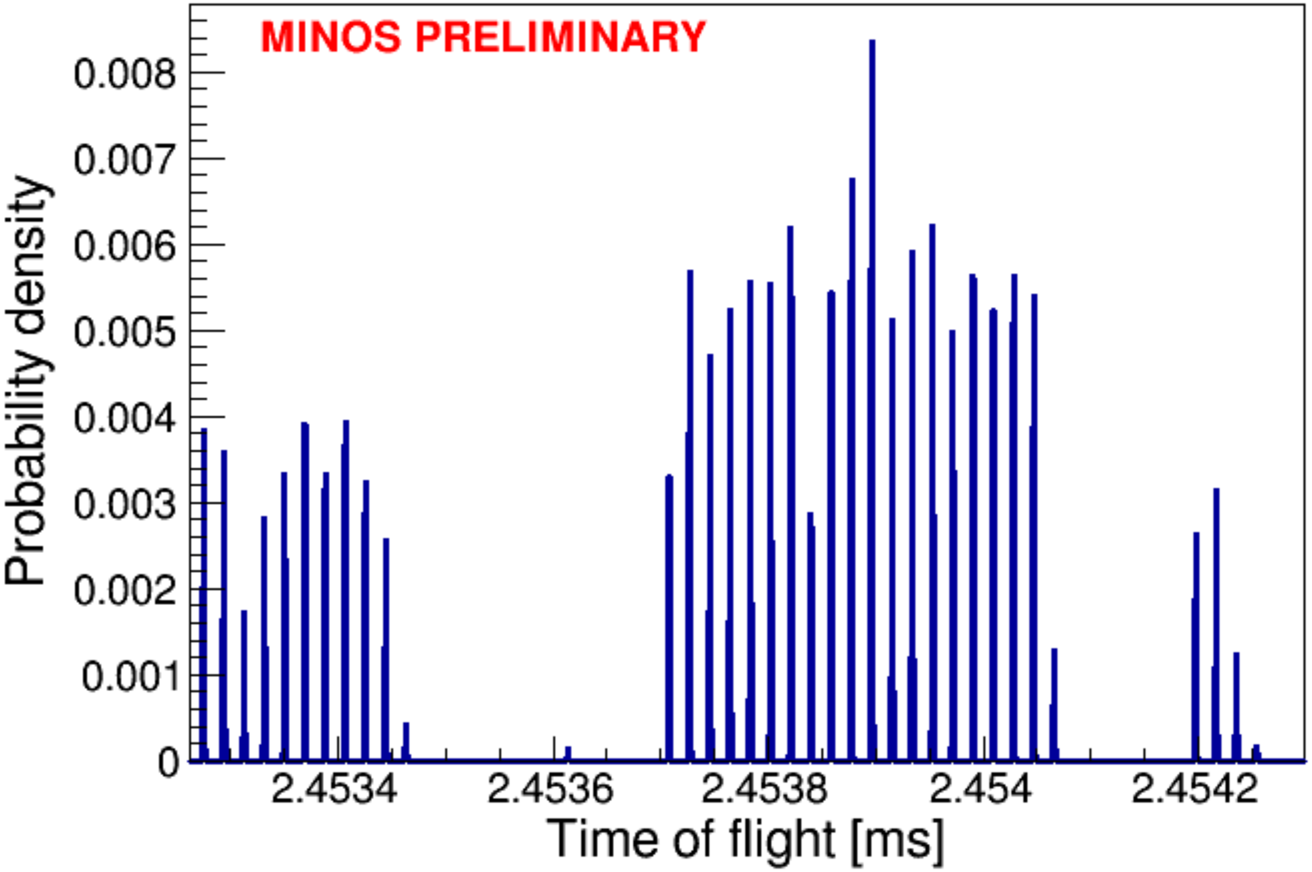
Timing Diagram



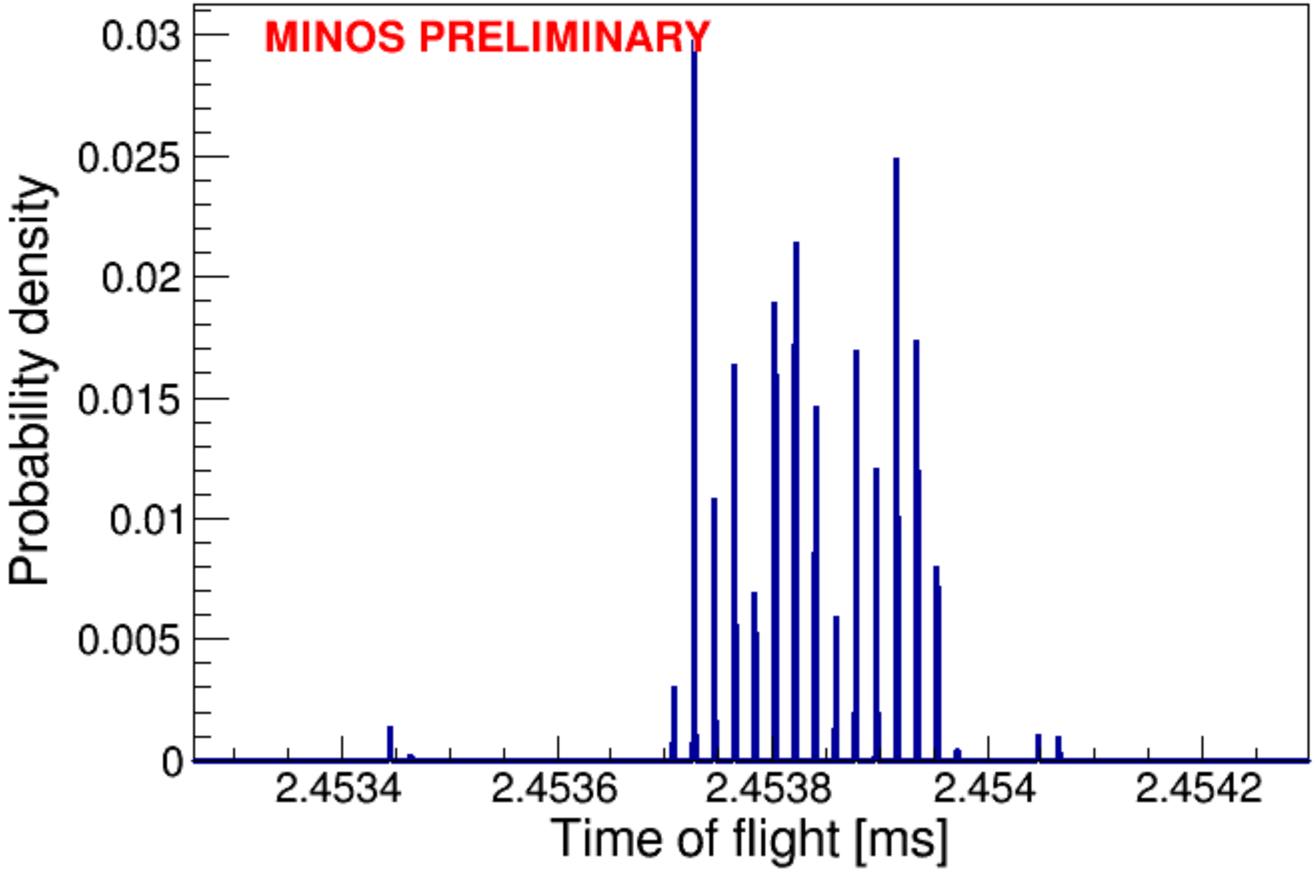
TOF Likelihood: 1 event



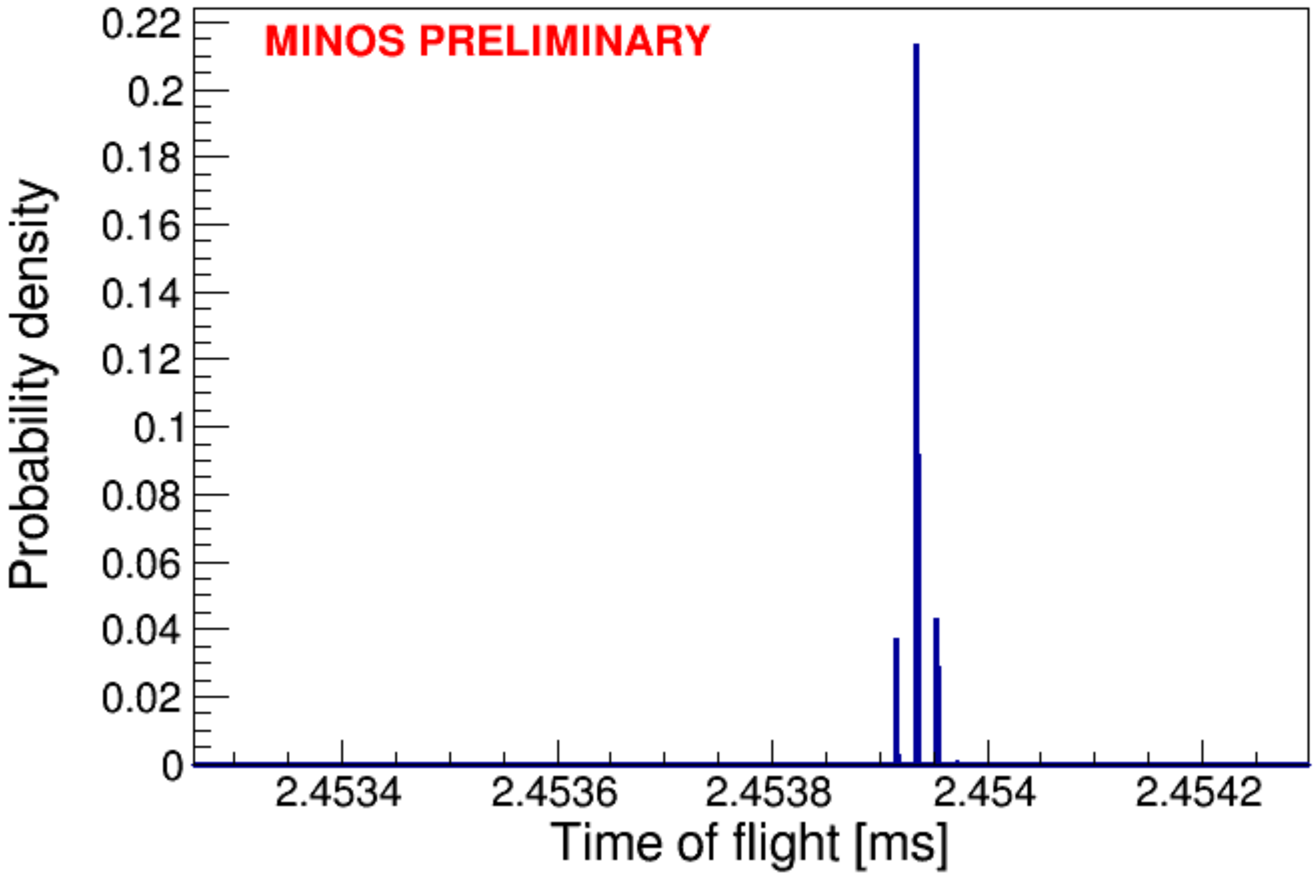
TOF Likelihood: 10 events



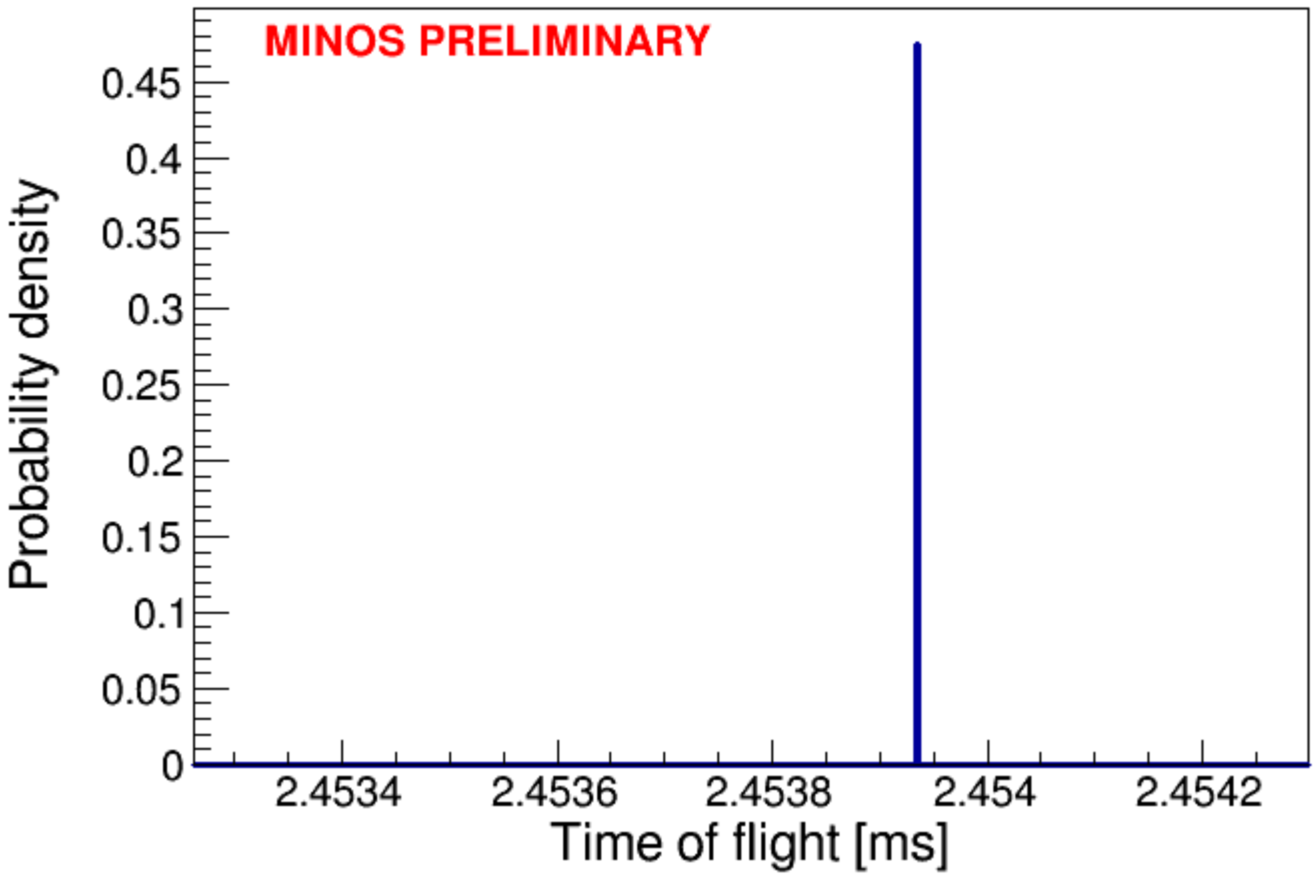
TOF Likelihood: 30 events



TOF Likelihood: 60 events

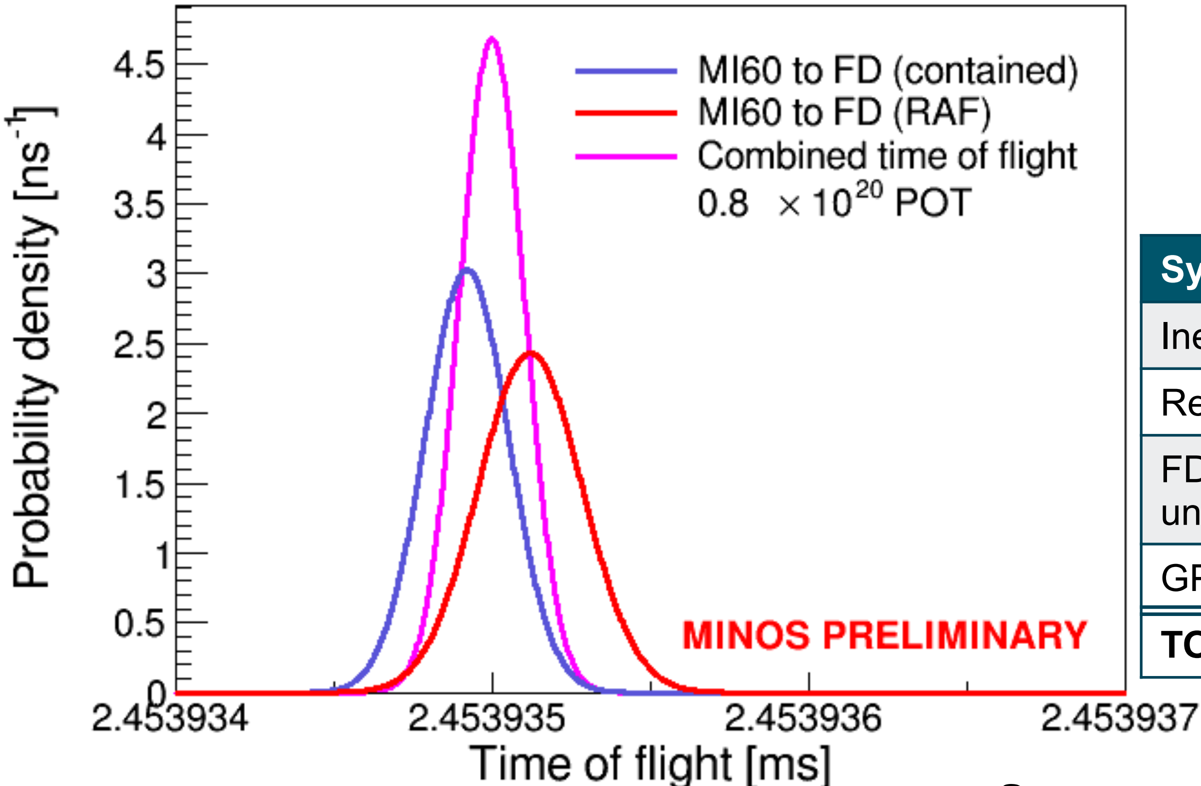


TOF Likelihood: 195 events



TOF Result

- Separate fits to the contained and RAF events.



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 (quadrature sum)	**2.6 ns**

- Difference from speed of light: $\delta = -2.4 \pm 0.1(stat) \pm 2.6(syst)ns$

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