Recent Results from the MINOS Experiment

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for the MINOS Collaboration

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UCL

The MINOS Experiment

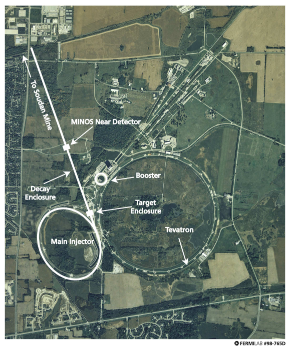
Send the intense NuMI ν_μ beam 735 km
- From Fermilab to Soudan, MN

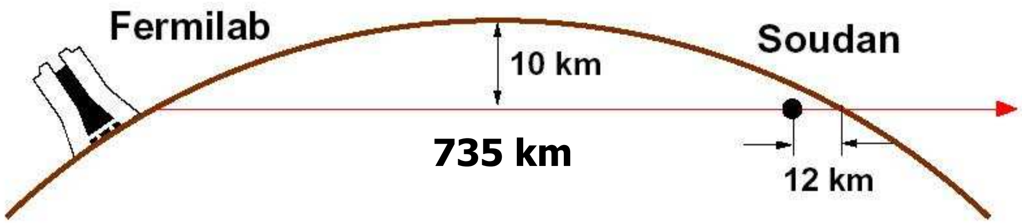
Observe energy-dependent ν_μ disappearance
- World's most precise measurement of Δm^2_{atm}

Look for ν_e appearance
- Search for θ_{13}

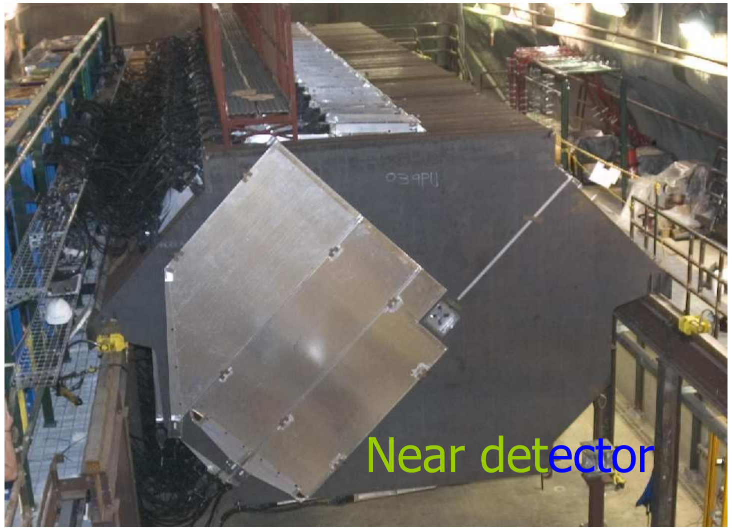
Measure the NC interaction rate
- Set limits on sterile neutrinos

Look at the 7% beam $\overline{\nu}_\mu$ component
- Test of CPT conservation





The MINOS Detectors



Near detector, 1.0 ktonne, 1km from source

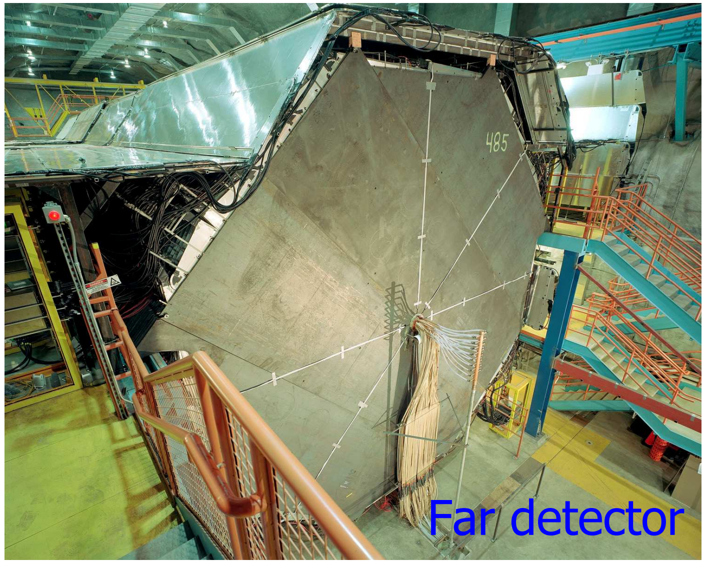
Far detector, 5.4 ktonne, 735 km from source

Tracking, sampling calorimeters

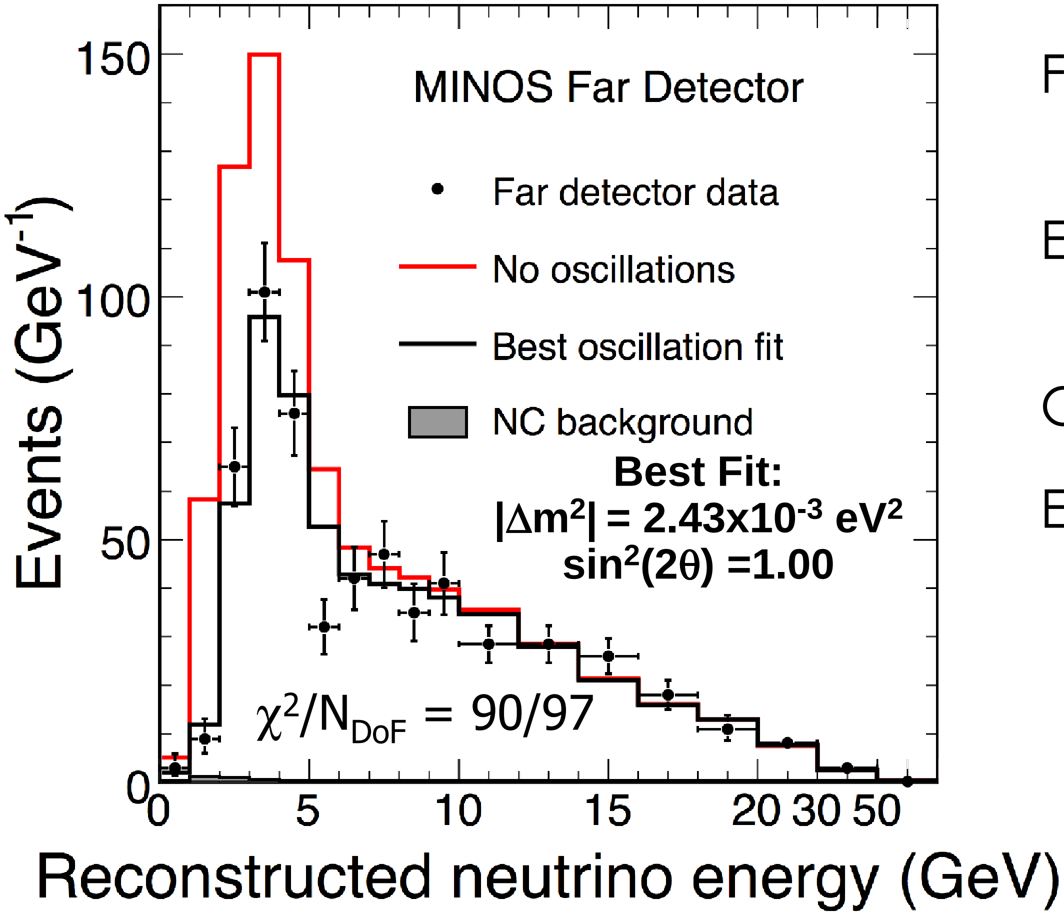
- Alternate steel and scintillator planes
- Functionally identical
- Magnetised to 1.3 T

Two detectors to mitigate systematics

- e.g. neutrino flux or cross section mismodelings
- Use measured near detector data to predict what should be observed at the far detector
- An observed ν_μ deficit at the far detector tells us about the oscillation parameters



Far Detector ν_μ Data



FD data not looked at until the analysis was finalised

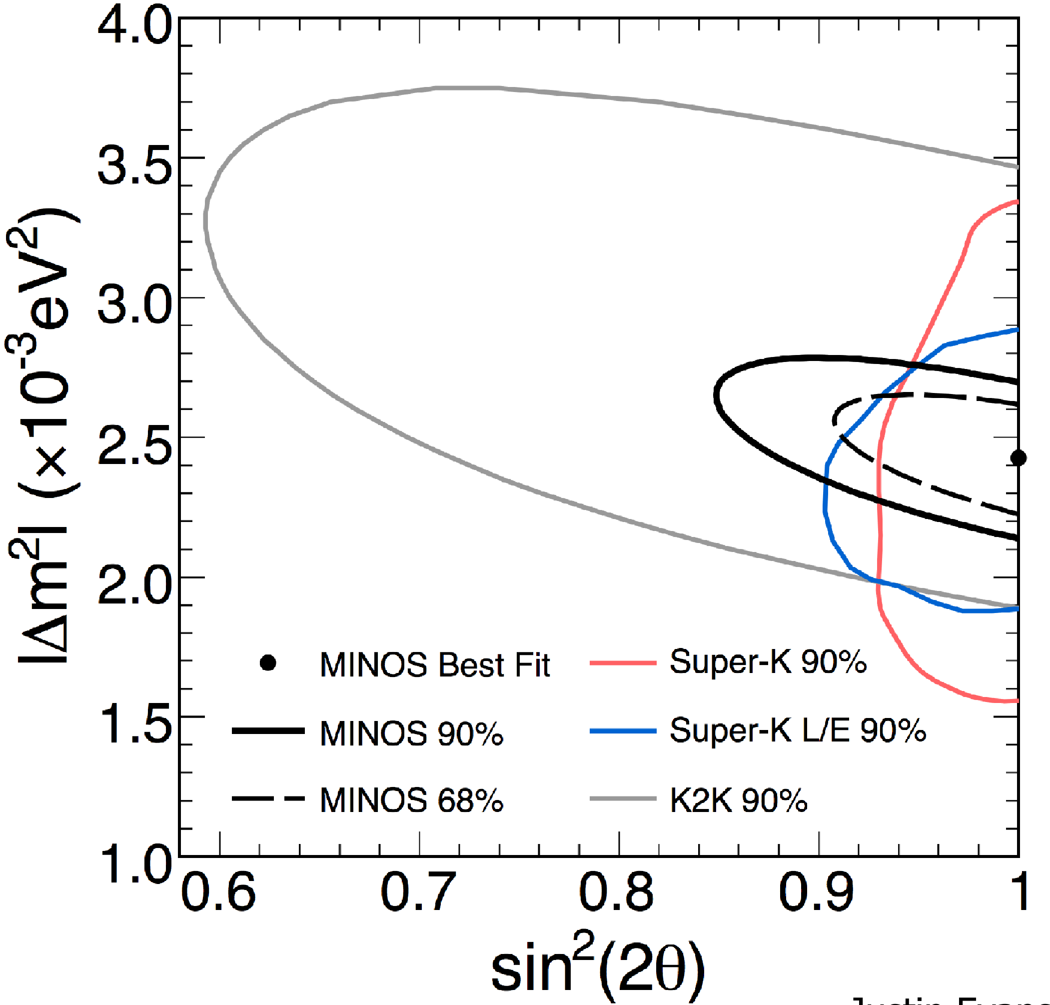
Expected 1065 ± 60 with no oscillations

Observed 848 events

Energy spectrum fit with the oscillation hypothesis

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Allowed Region



Constrained fit

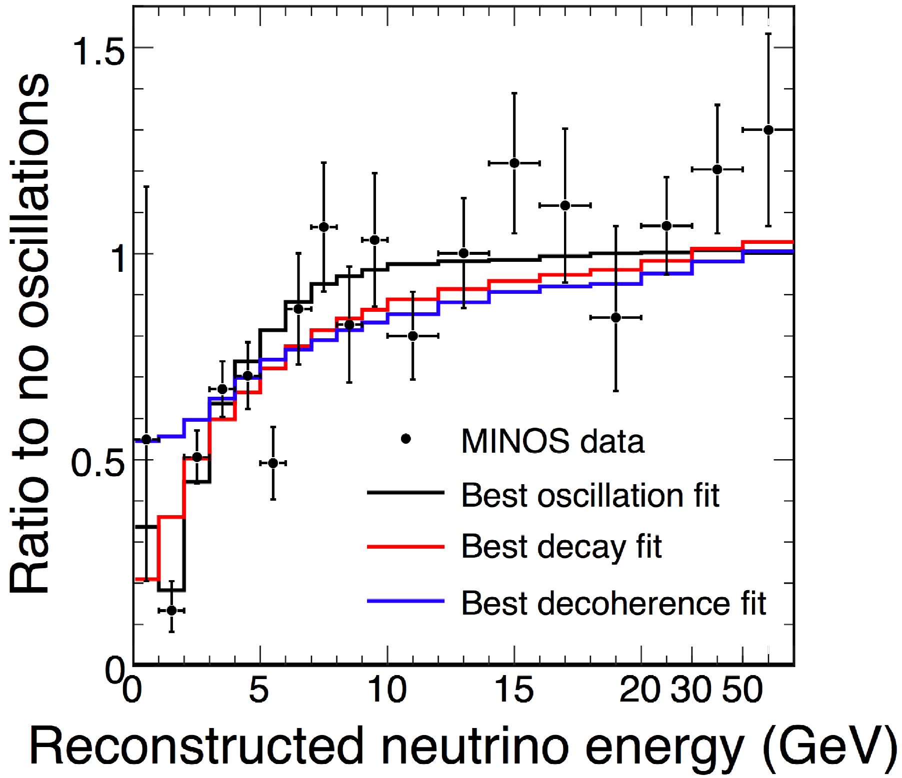
- $|\Delta m^2|$ =(2.43±0.13)x10^{-3} eV^2 (68% C.L.)
- $\sin^2(2\theta_{23})$ > 0.90 (90% C.L.)
- χ^2/N_{DoF} = 90/97

Unconstrained fit

- $|\Delta m^2|$ = 2.33 x 10^{-3} eV^2
- $\sin^2(2\theta_{23})$ = 1.07
- $\Delta\chi^2$ = -0.6

Alternative Models

Two alternative disappearance models are disfavoured



Decay:

$$P_{\mu\mu} = \left(\sin^2(\theta) + \cos^2(\theta)\exp(-\alpha L/2E)\right)^2$$

V. Barger *et al.*, PRL82:2640(1999)

χ^2/ndof = 104/97

$\Delta\chi^2 = 14$

disfavored at 3.7σ

Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006 (2003)

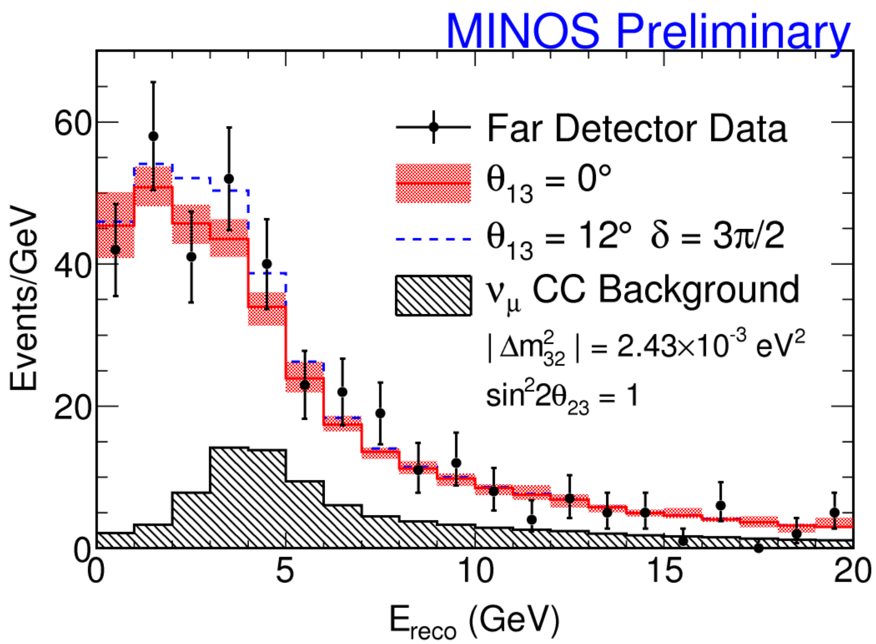
χ^2/ndof = 123/97

$\Delta\chi^2 = 33$

disfavored at 5.7σ

NC Event Rate

- Neutral current interaction rate is unaffected by oscillations between active neutrino flavours
- Oscillations to a sterile state would cause a deficit in the observed rate at the FD
  - For oscillations driven by Δm^2_{atm}, the deficit would be most pronounced below 3 GeV
- Event selection looks for showers with no muon track
- Graph shows the data, and predictions in the case of no sterile neutrinos
- Data are consistent with no mixing to sterile neutrinos



$$R = \frac{N_{data} - (CC\,background)}{(NC\,signal)}$$

$E_{\rm reco}$ (GeV)	$N_{\rm Data}$	$S_{\rm NC}$	$B^{\nu_\mu}_{\rm CC}$	$B^{\nu_\tau}_{\rm CC}$	$B^{\nu_e}_{\rm CCn}$
0 – 3	141	125.1	13.3	1.4	2.3 (12.4)
3 – 120	247	130.4	84.0	4.9	16.0 (32.8)
0 – 3	$R = 0.99 \pm 0.09 \pm 0.07 - 0.08(\nu_e)$				
3 – 120	$R = 1.09 \pm 0.12 \pm 0.10 - 0.13(\nu_e)$				
0 – 120	$R = 1.04 \pm 0.08 \pm 0.07 - 0.10(\nu_e)$				

Electron Neutrinos

ν_e selected by looking for events with a compact shower

- MINOS is optimized for muon tracking: EM shower resolution is limited

Near detector data & MC disagree by 20%

Data is made up of a number of background components

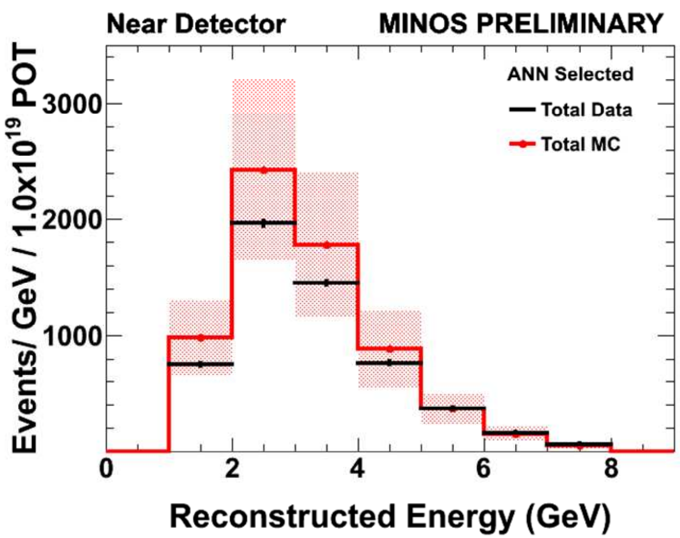
- Turning off the focusing horns changes the relative contribution
- Allows the individual components to be measured

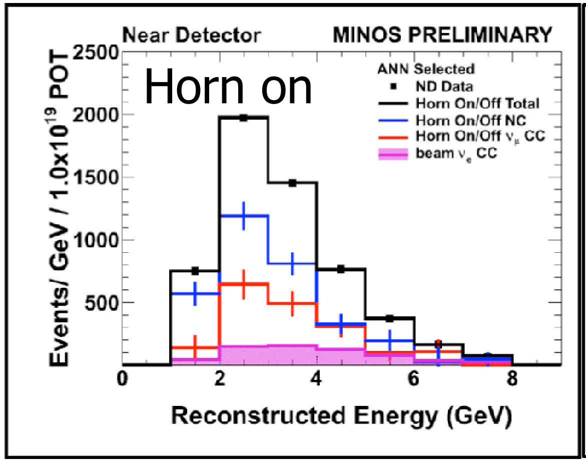
An independent method provides consistent results

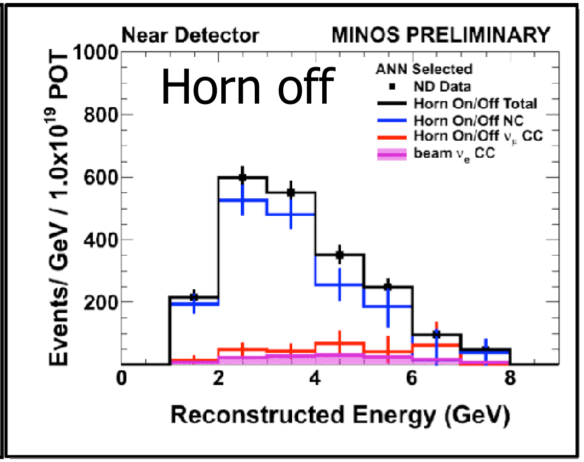
- Looking at muon-removed CC events

Systematic uncertainty on FD prediction is 7.3%

- Compare with statistical uncertainty of 19%







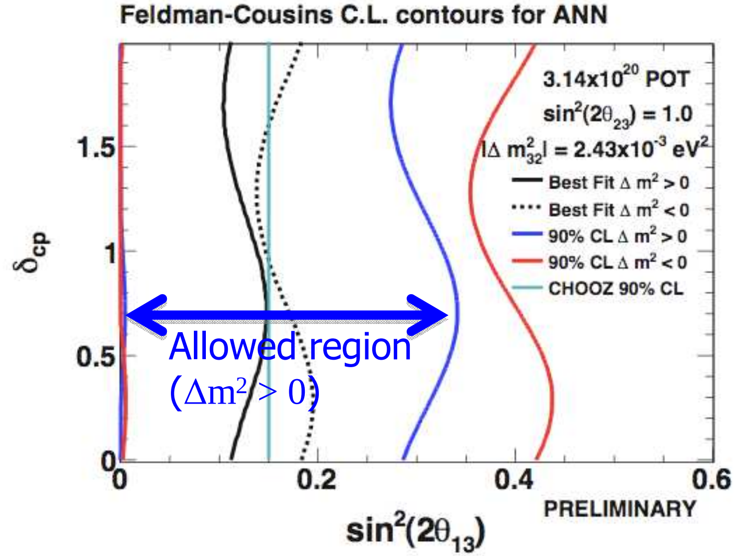
Far Detector ν_e Data

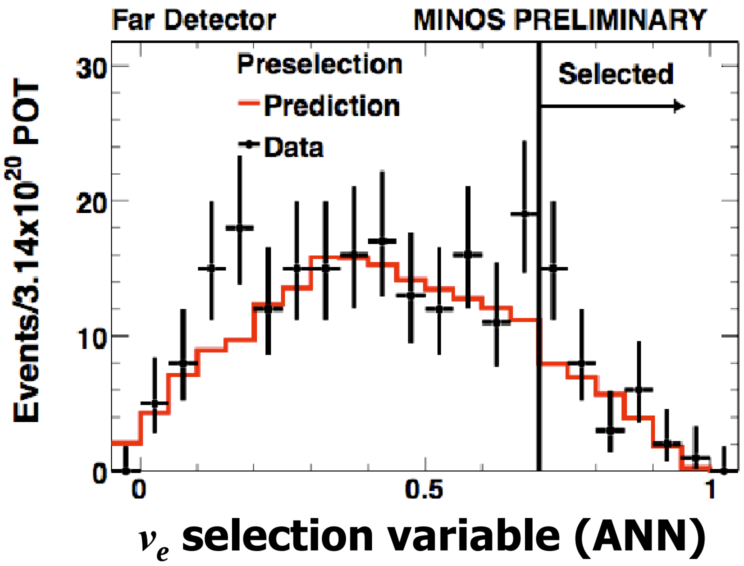
35 ν_e selected events seen

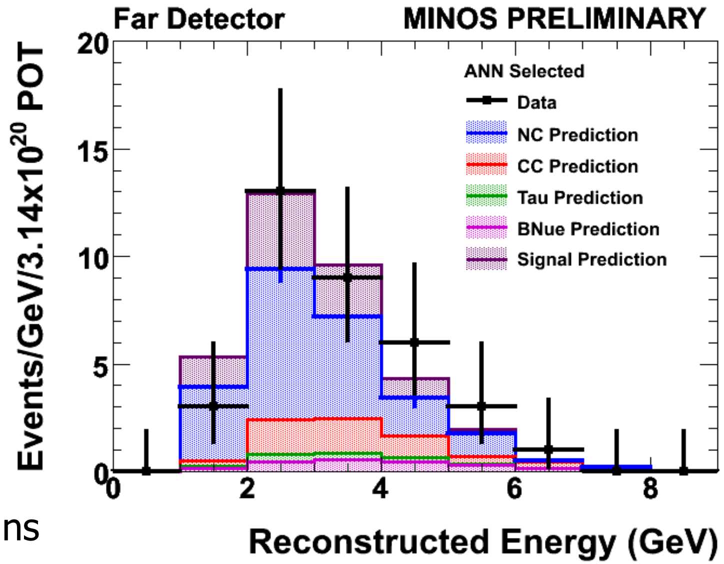
- Expected background: $27 \pm 5_{stat} \pm 2_{syst}$
- Excess is 1.5σ

Fit to the oscillation hypothesis using Feldman-Cousins method

- Best fit is at the Chooz limit
- $\sin^2(2\theta_{13}) < 0.29$ (90% c.l.); $\Delta m^2 > 0$ $\delta_{CP}=0$
- $\sin^2(2\theta_{13}) < 0.42$ (90% c.l.); $\Delta m^2 < 0$ $\delta_{CP}=0$





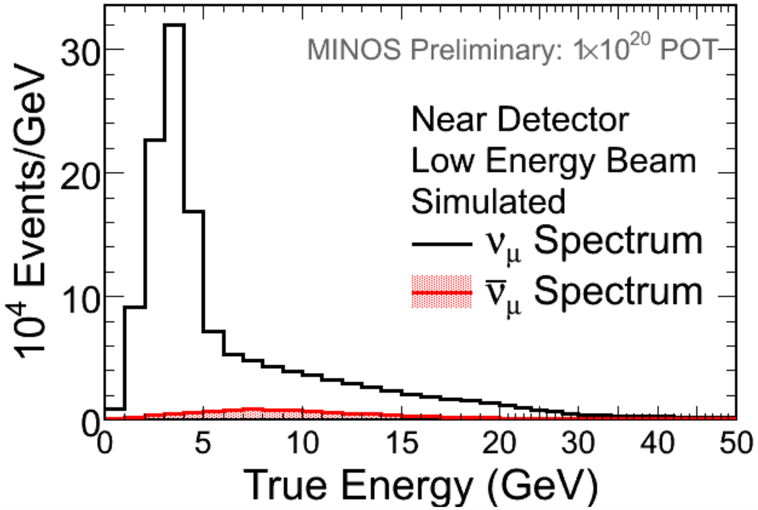


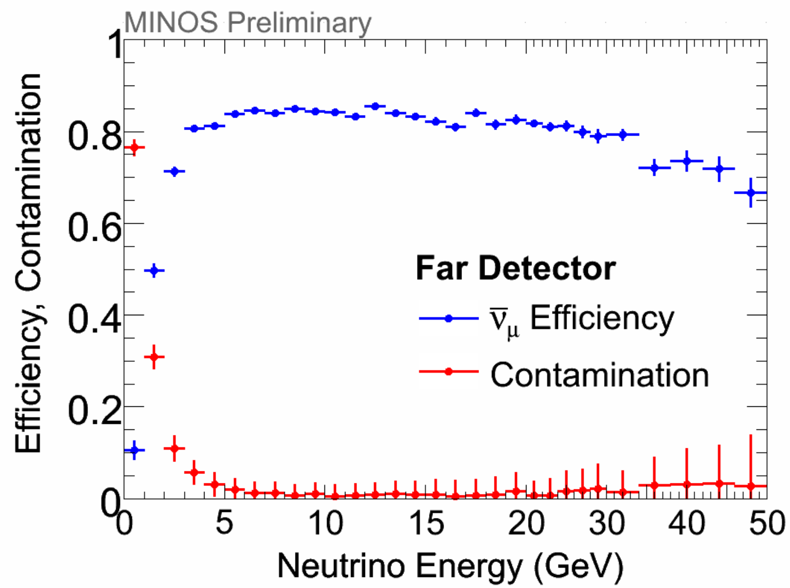
Muon Antineutrinos

- NuMI beam contains a 7% background of antineutrinos
- Magnetised detectors allow these to be separated from neutrinos
  - From the sign of the muon produced in CC interactions
- Can perform the same disappearance measurement as for neutrinos
  - But with a lower event rate and higher average energy, sensitivity is lower
  - Peak energy is 8 GeV; oscillation maximum expected at ~2 GeV

- A differing $\Delta\overline{m}^2$ could be evidence for CPT violation
- Are any of the disappearing ν_μ turning into $\overline{\nu_\mu}$?

$$P(\nu_\mu \rightarrow \bar{\nu}_\mu) = \alpha \sin^2(2\theta_{23}) \sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$





Antineutrino Results

42 events observed

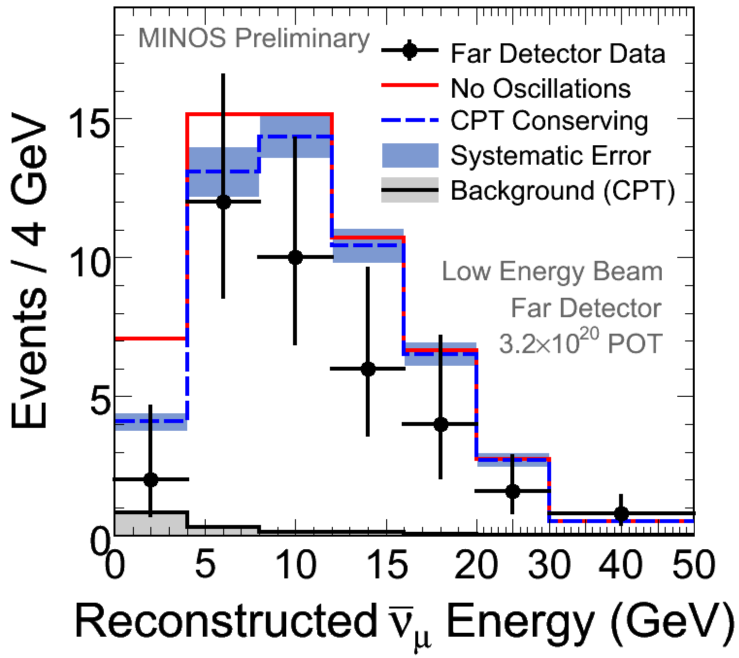
- No oscillations, $64.6 \pm 8.0_{stat} \pm 3.9_{syst}$
- CPT conserving, $58.3 \pm 7.6_{stat} \pm 3.6_{syst}$

Deficit is 1.9σ

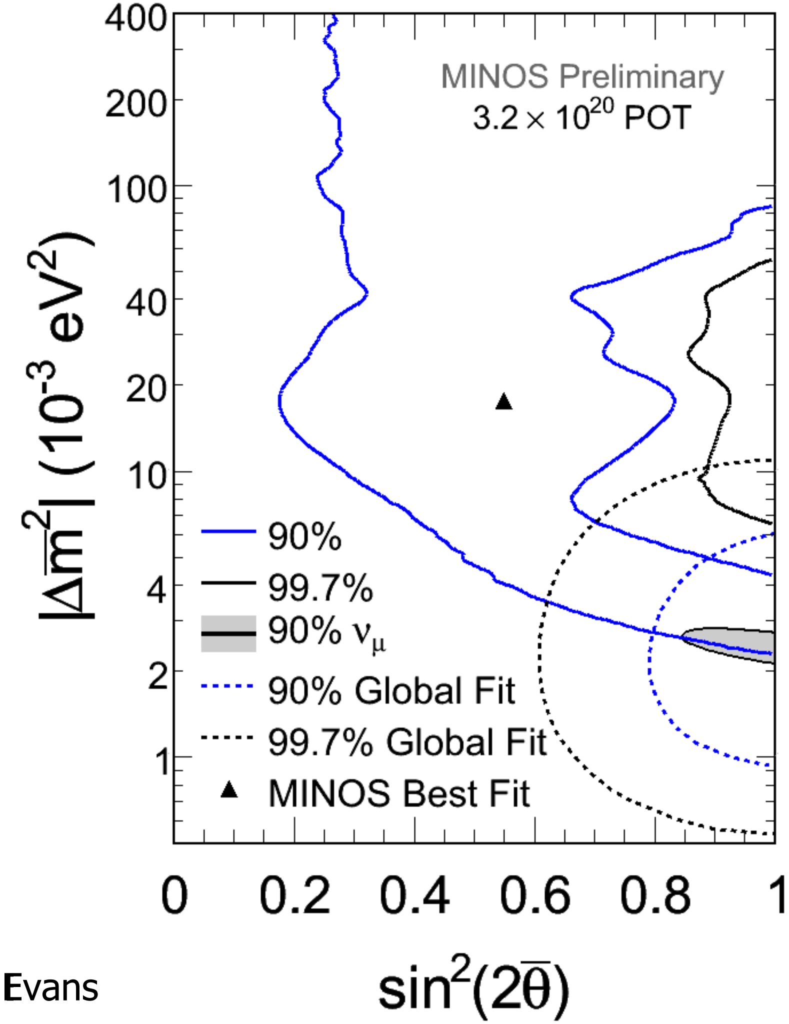
Consistent with the ν_μ oscillation parameters at 90% c.l.

No $\overline{\nu}_\mu$ appearance seen

- Fraction $\nu_\mu \rightarrow \overline{\nu}_\mu$, $\alpha <$ 0.026 (90% c.l.)



Global fit from Gonzalez-Garcia & Maltoni, *Phys. Rept.* 460 (2008), SK data dominates



The Future

All these analyses have used 3×10^{20} of the 7×10^{20} protons-on-target that have been recorded

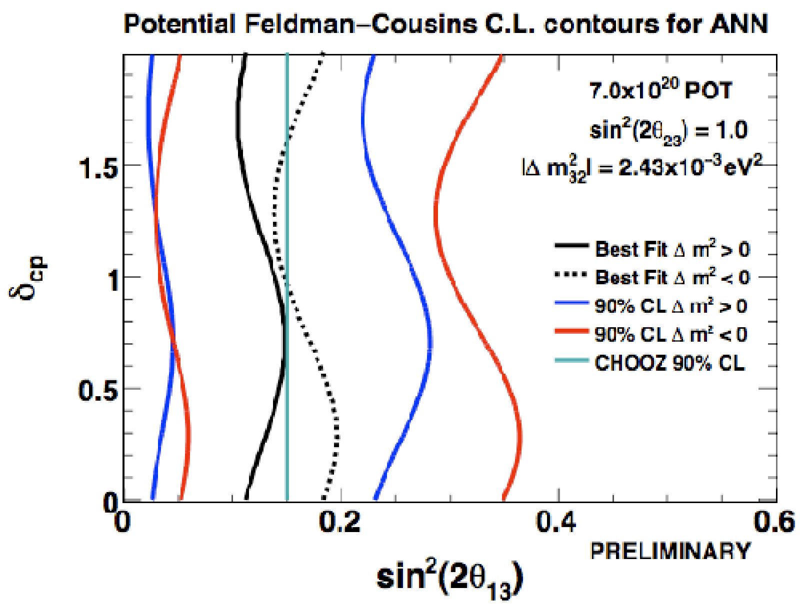
- As of this June's summer shutdown

Over the next year, the analyses will be updated with the increased dataset

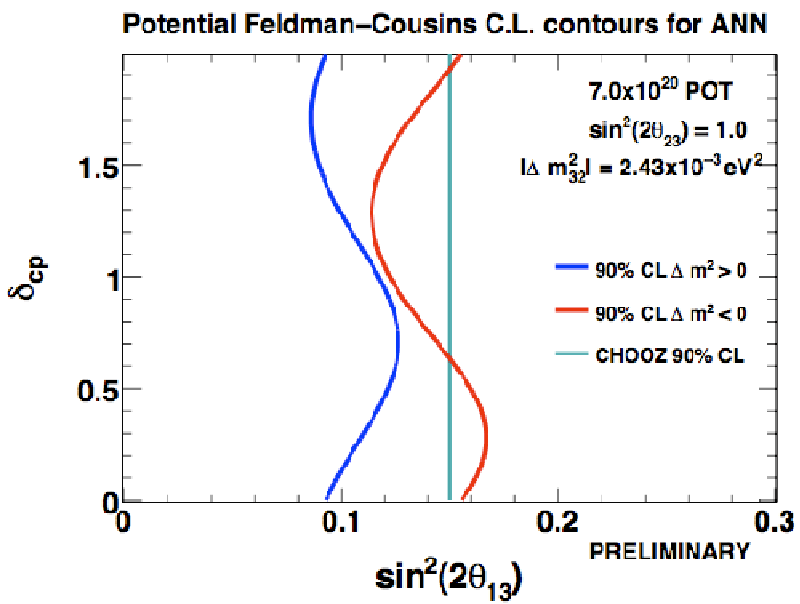
- Using the blind analysis policy on the new data

Graphs below show the θ_{13} sensitivity for 7×10^{20} PoT

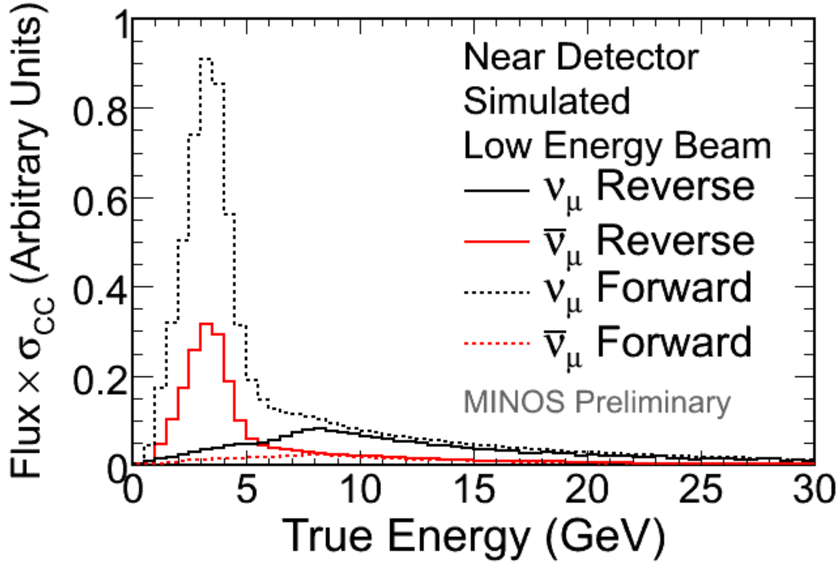
If the excess persists



If the excess goes away



Dedicated $\bar{\nu}_\mu$ Running



By reversing the current in the NuMI focusing horns MINOS can run with a dedicated antineutrino beam

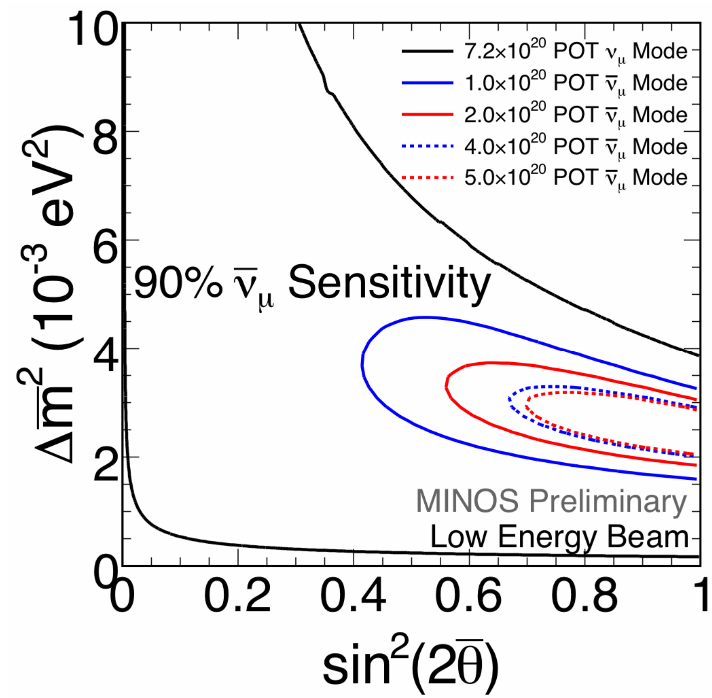
- Obtain a greatly enhanced $\bar{\nu}_\mu$ sample around the oscillation maximum

Data-taking will begin in September 2009

Will allow us to make the first ever precision measurement of the atmospheric-regime $\bar{\nu}_\mu$ oscillation parameters

After one year of running

- Can make a 5σ observation of antineutrino oscillations



Summary and Outlook

MINOS has made the world's most accurate measurement of the atmospheric neutrino mass splitting

- $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% c.l.)
- $\sin^2(2\theta_{23}) > 0.90$ (90% c.l.)

Alternative models disfavoured

- Decay at 3.7σ, decoherence at 5.7σ

Set a new limit on θ_{13}

- $\sin^2(2\theta_{13}) < 0.29$ (90% c.l.); $\Delta m^2 > 0$ $\delta_{CP} = 0$
- $\sin^2(2\theta_{13}) < 0.49$ (90% c.l.); $\Delta m^2 < 0$ $\delta_{CP} = 0$

Measurement of the NC event spectrum consistent with no mixing to sterile flavours

Antineutrino oscillation parameters consistent with the neutrino parameters at 90% c.l.

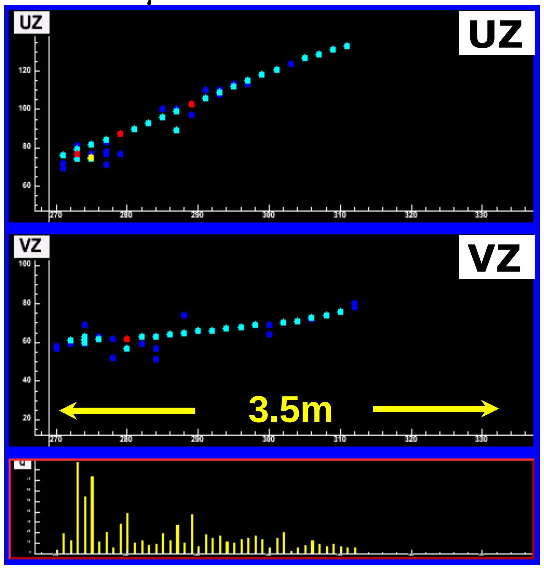
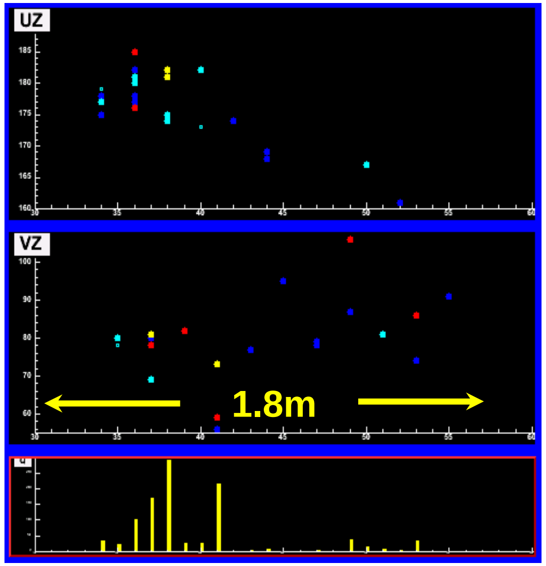
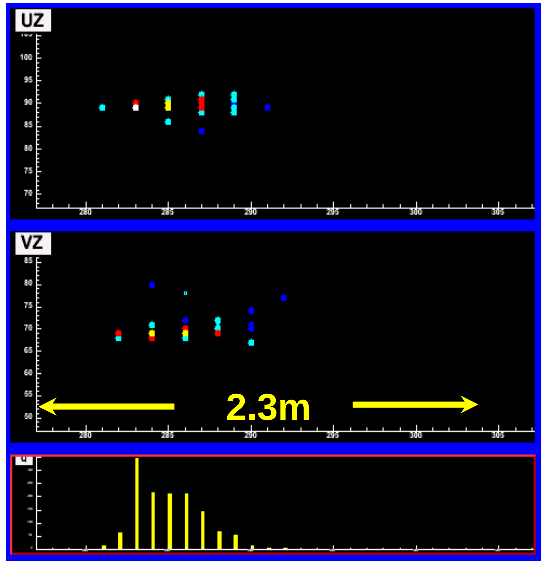
All the analyses will be repeated with double the dataset

Dedicated antineutrino running begins in September

- The first precision measurement of the atmospheric-regime antineutrino oscillation parameters

Backup Slides

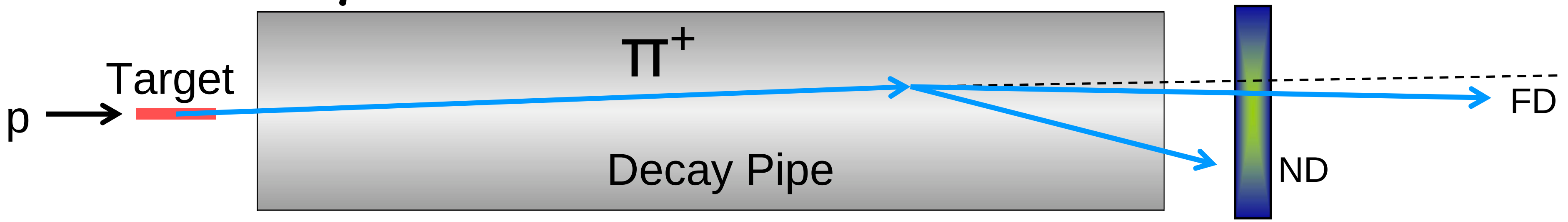
Event Topologies

ν_μ CC Event	NC Event	ν_e CC Event
		
long μ track & hadronic activity at vertex	short event, often diffuse	short, with typical EM shower profile

$$E_\nu = E_{\text{shower}} + p_\mu$$

Monte Carlo

CC ν_μ Beam Extrapolation



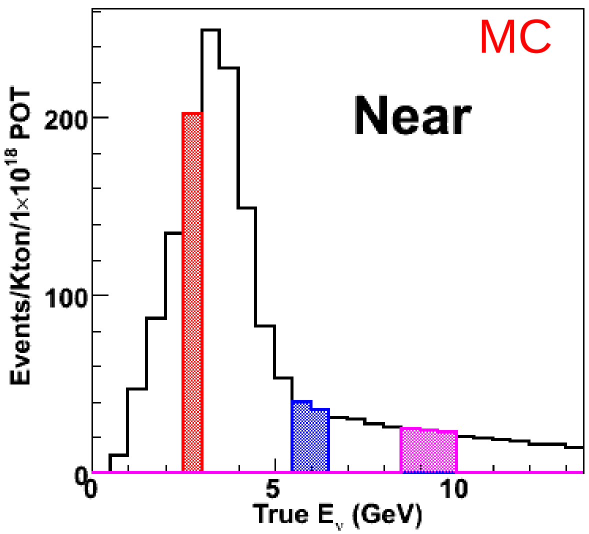
Use the measured ND energy spectrum to predict the FD spectrum:

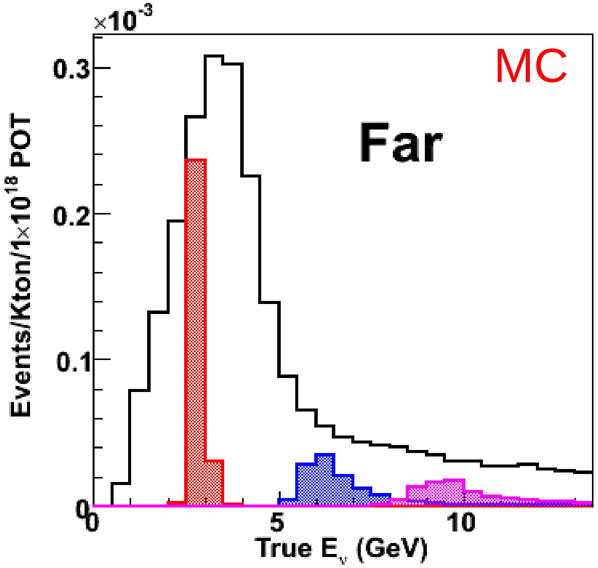
Spread of pion decay directions smears neutrino energies

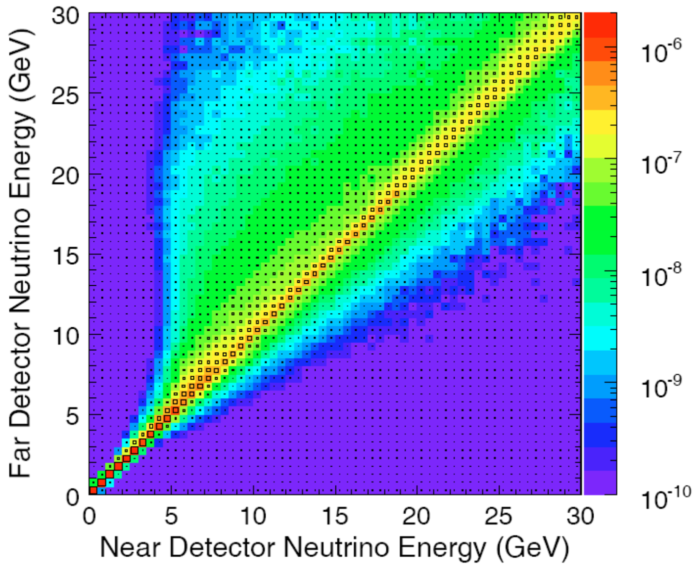
- Different energy spectra at the two detectors

Encode the pion decay kinematics into a beam transfer matrix

- Convert ND to FD spectrum





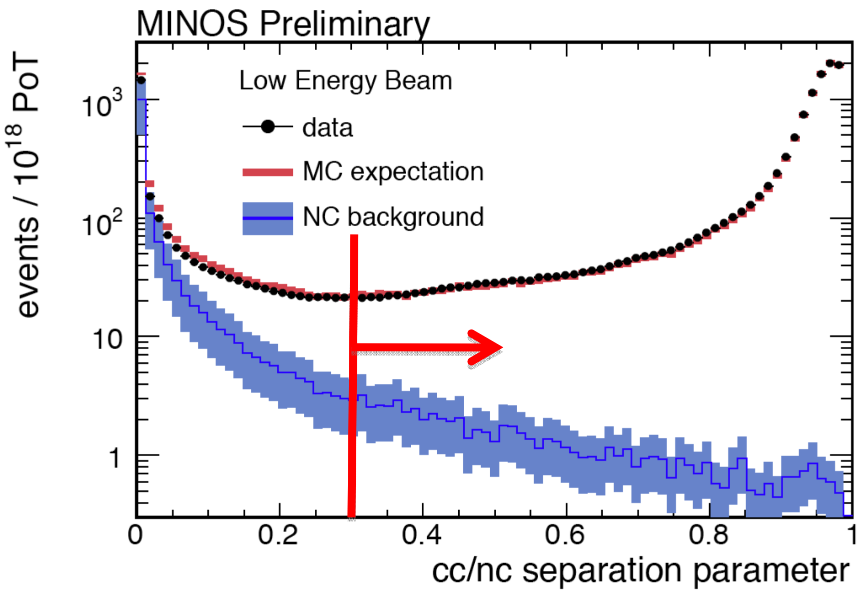


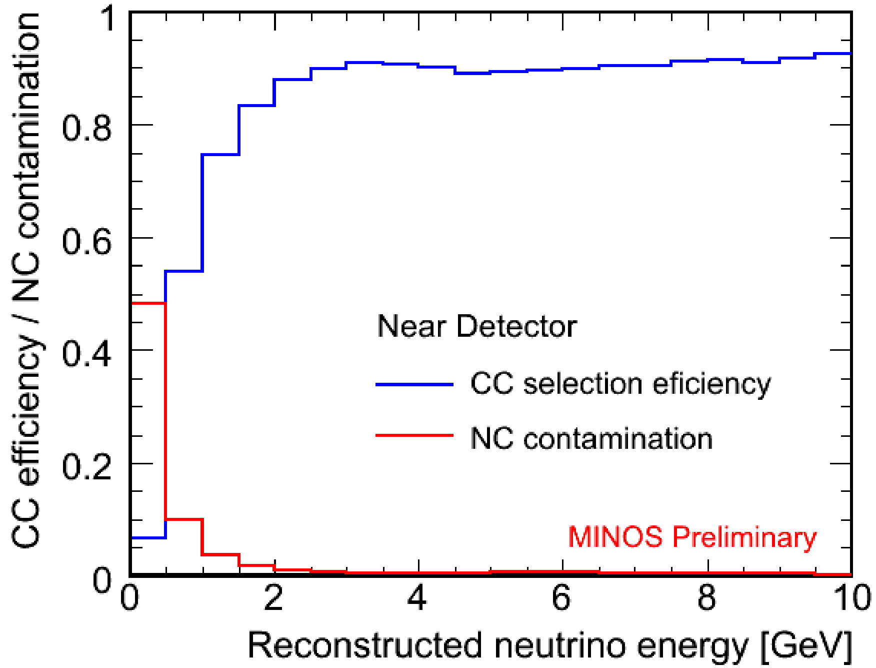
CC ν_μ Event Selection

Aim to separate charged and neutral current ν_μ interactions

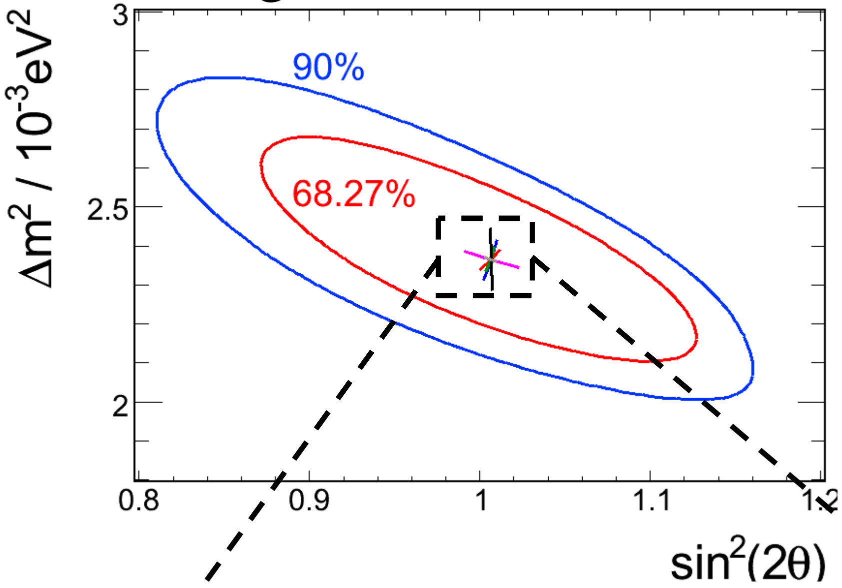
Four variables combined using a k-nearest-neighbour algorithm

- Track length
- Mean signal in track planes
- Transverse track profile
- Signal fluctuation along the track

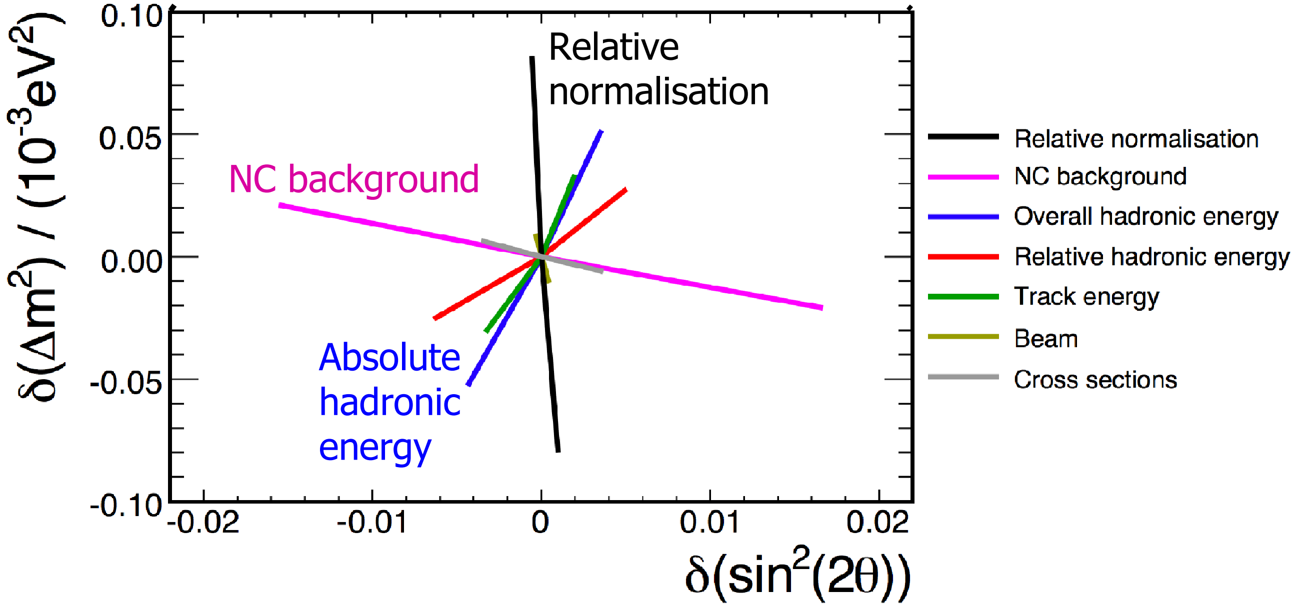




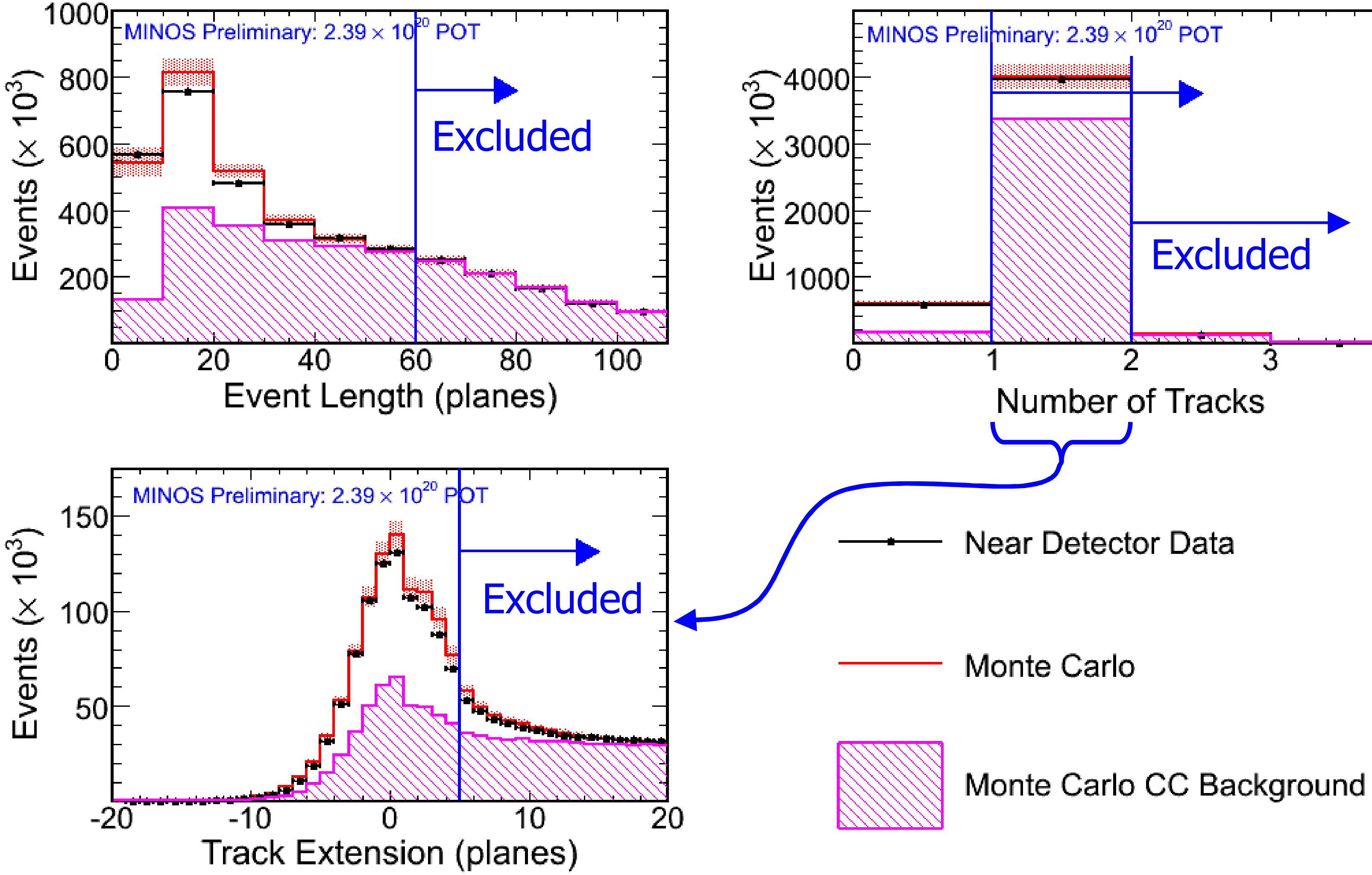
Systematic Uncertainties



- Effect of uncertainties estimated by fitting systematically shifted MC in place of data
- Analysis is still statistically limited
- Three largest uncertainties included as penalty terms in fit to data
  - Relative (ND to FD) normalisation (4%)
  - Absolute hadronic energy scale (10%)
  - NC background (50%)



NC Event Selection



Sterile Neutrino Models

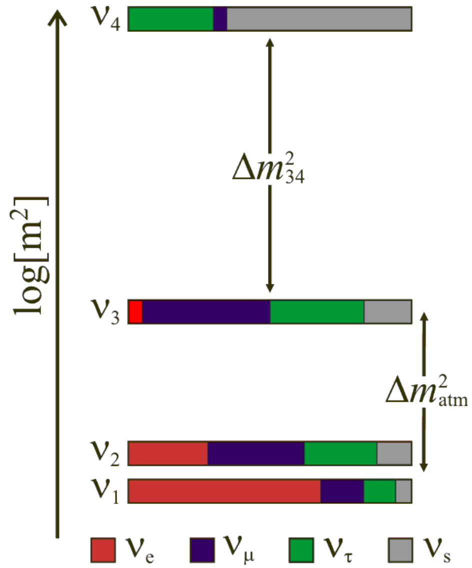
Fit to a model with one sterile neutrinos

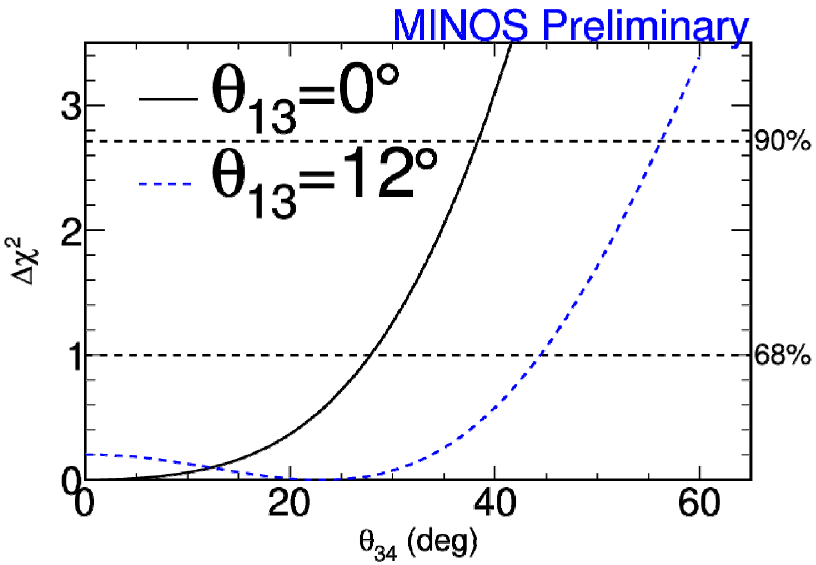
Look at the two cases

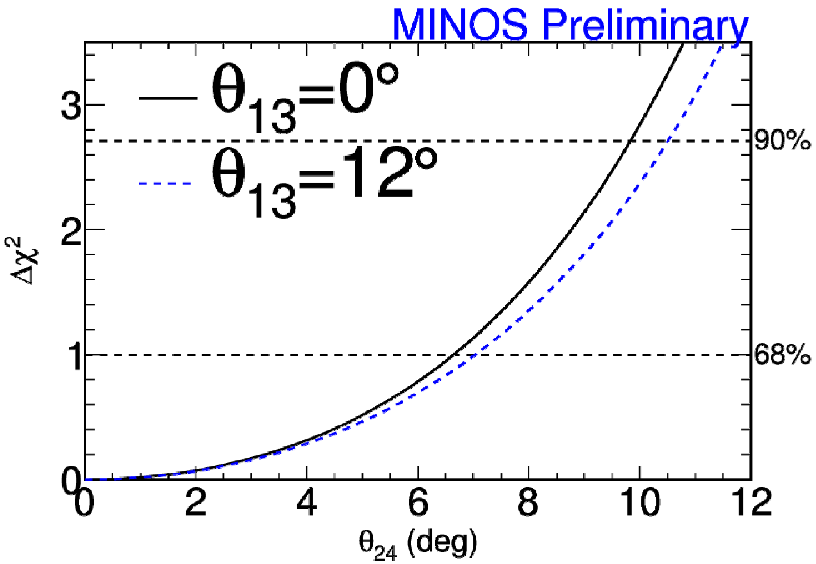
- $|\Delta m^2_{41}| >> |\Delta m^2_{31}|$
- $|\Delta m^2_{41}| << |\Delta m^2_{31}|$

θ_{34}<38° (56° ν_e) (90% C.L.) (Both models)

θ_{24}<10° (10.6° ν_e) (90% C.L.) (Δ_{41}>> Δ_{31})







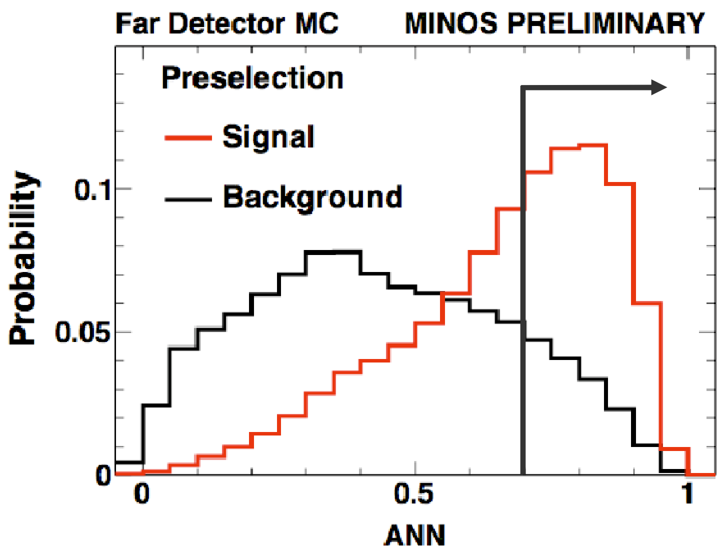
ν_e Selection

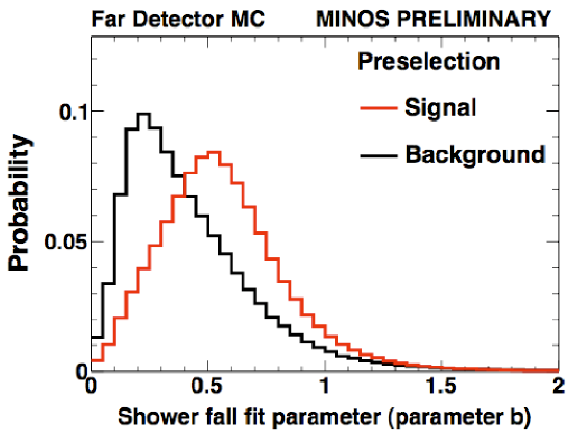
Events characterised by a compact shower

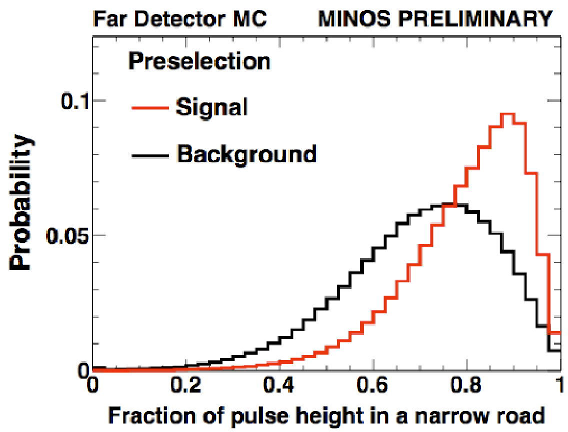
Form 11 variables characterising shower shape, length and width

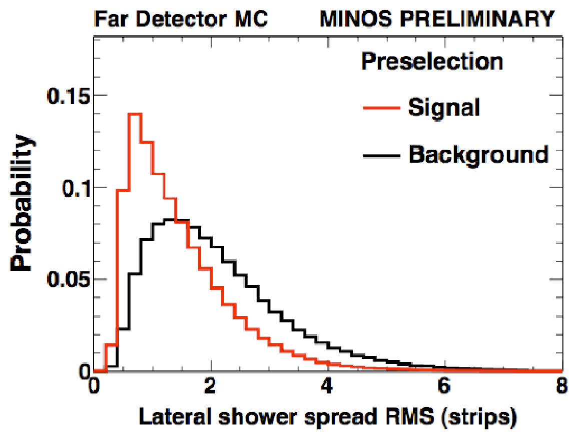
Put these together in a neural net

- Signal efficiency – 41%
- NC rejection – 92.7%
- ν_μ CC rejection – 99.4%

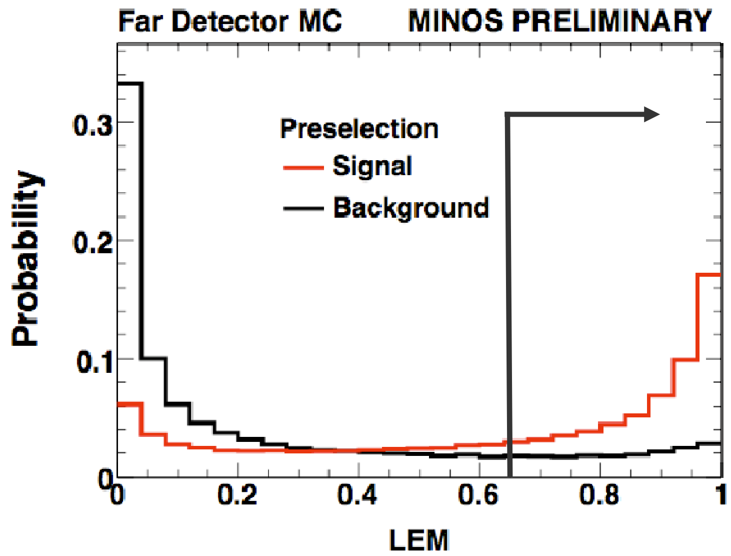








Alternative ν_e Selection



Alternative method: Library Event Matching

- Compare each event to an MC library of NC and ν_e CC
- Look for the 50 best matches according to hit pattern in position and energy deposition
- Construct discriminant variables from three properties of these best matches
- Combine the discriminant variables in a likelihood