Measuring ν_μ and $\bar{\nu}_\mu$ oscillation parameters with MINOS

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UCL

Introduction

Neutrino oscillations

- Two mass splittings
- Three mixing angles

MINOS can make precision measurements with neutrinos

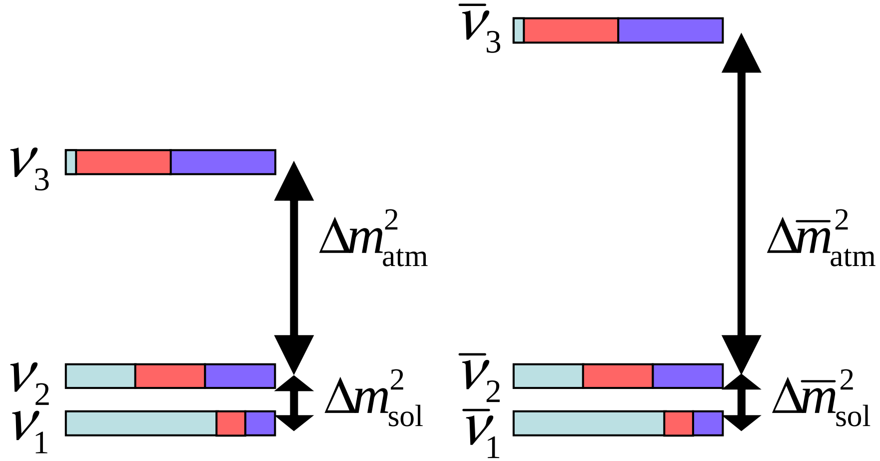
- Largest mass splitting
- Mixing angle θ_{23}

Corresponding antineutrino parameters are much less precisely known

- No direct precision measurements exist
- MINOS will be the first

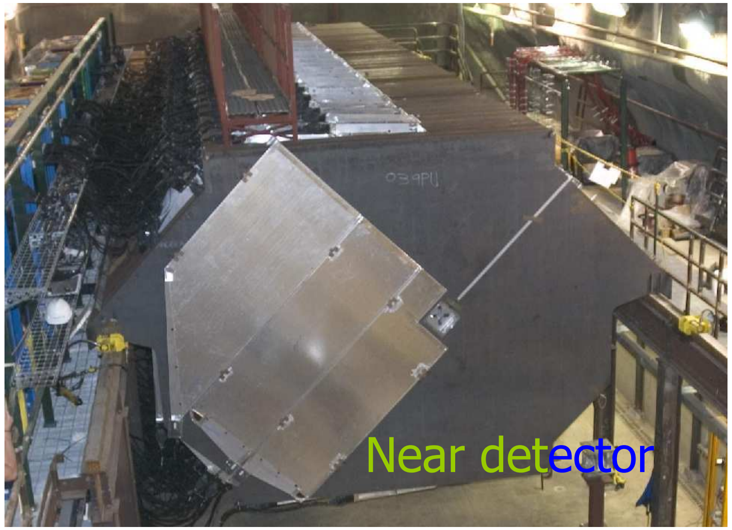
A difference between the two would be very interesting

- Non-standard interactions
- CPT violation



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

The MINOS experiment



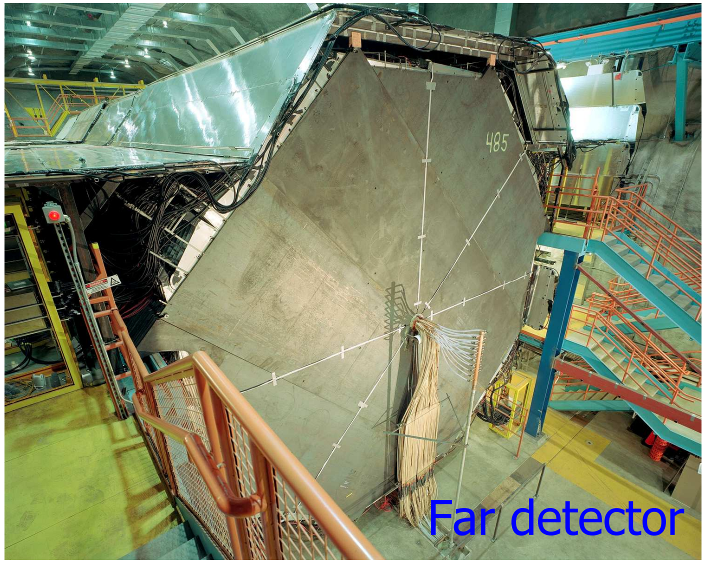
Beam neutrinos pass through two detectors

Detectors are magnetized to 1.3 T

- Allows the measurement of particle charge sign
- Also allows measurement of particle momenta

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 before oscillations
- An observed ν_μ deficit at the far detector tells us about the oscillation parameters



Beam composition

Charged current interactions in the near detector

- 91.7% ν_μ
- 7.1% $\bar{\nu}_\mu$
- 1.3% $\nu_e + \bar{\nu}_e$

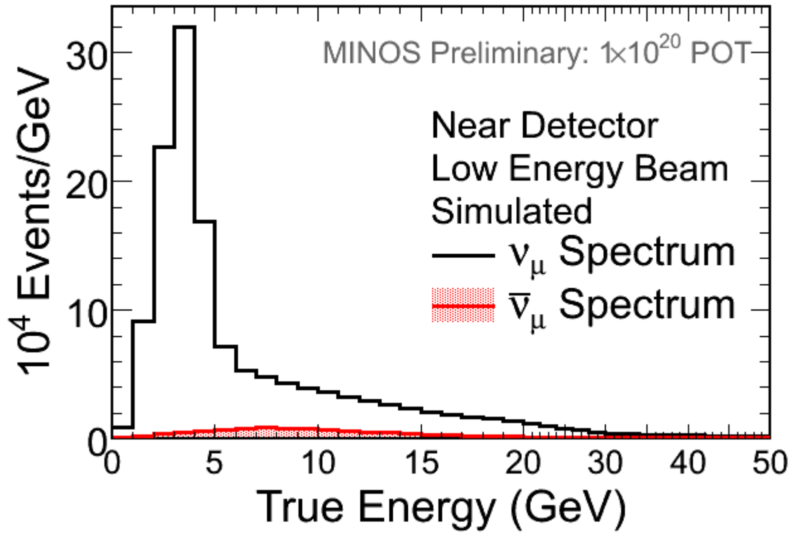
ν_μ and $\bar{\nu}_\mu$ energy spectra are significantly different

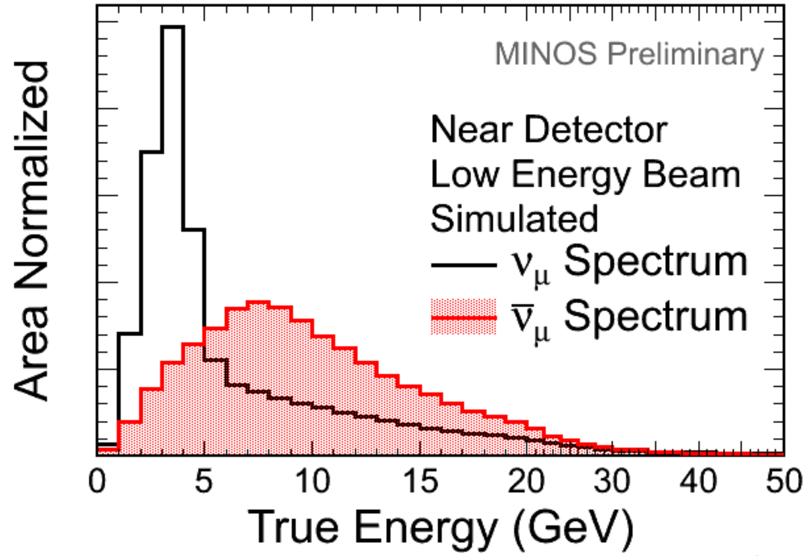
ν_μ spectrum peaks at 3 GeV

- Near the region of most oscillations

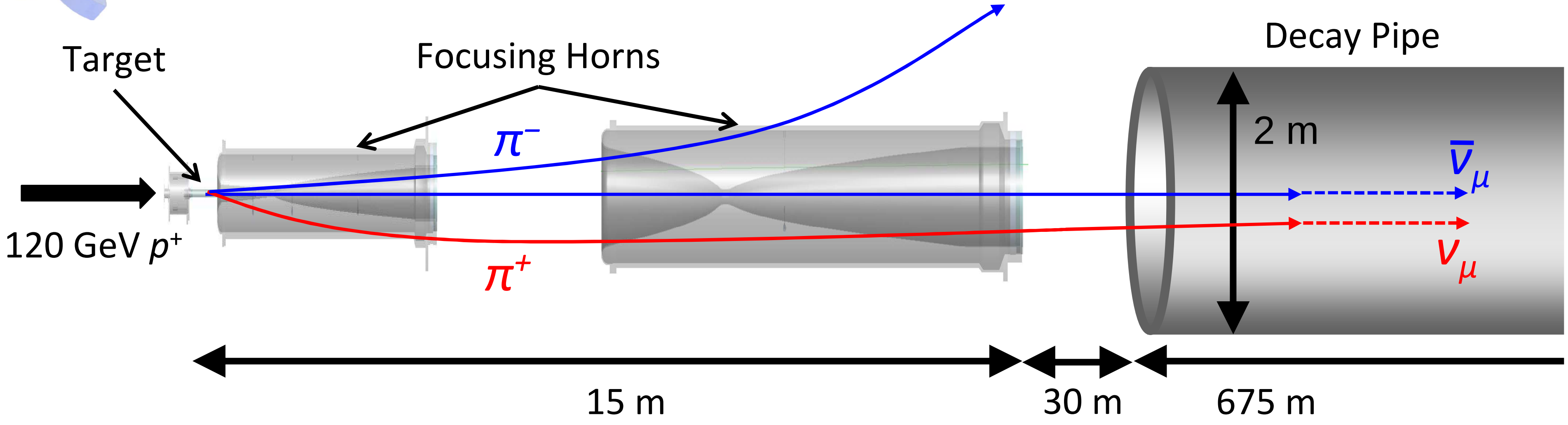
$\bar{\nu}_\mu$ spectrum peaks at 8 GeV

- Away from the oscillation region
- Reducing the sensitivity to oscillations

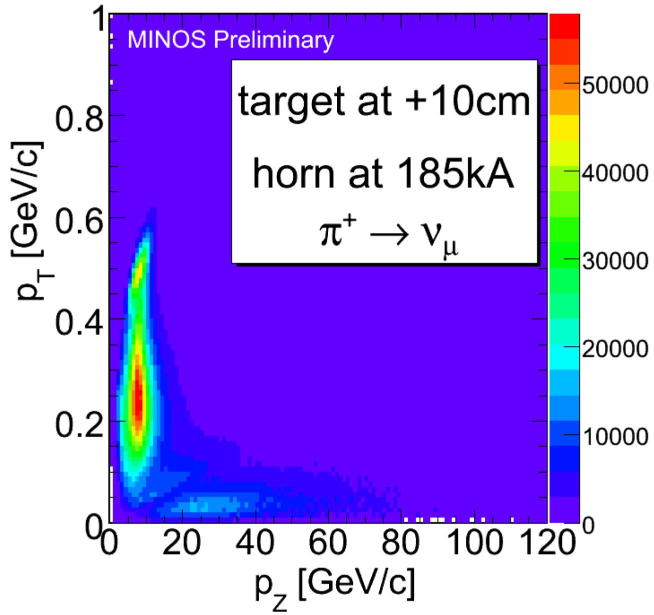


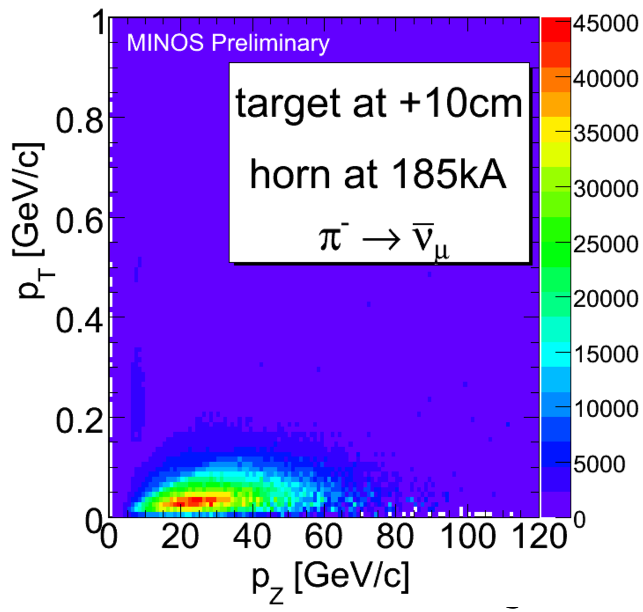


Why are the spectra different?

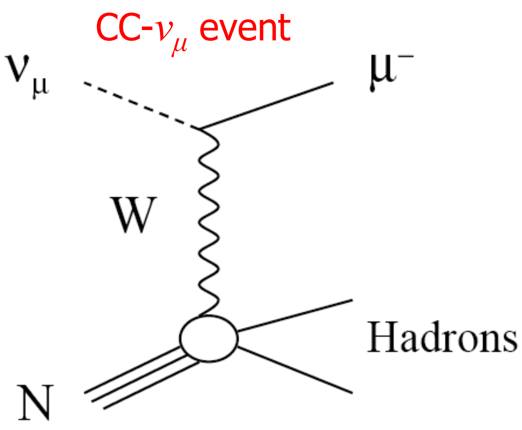


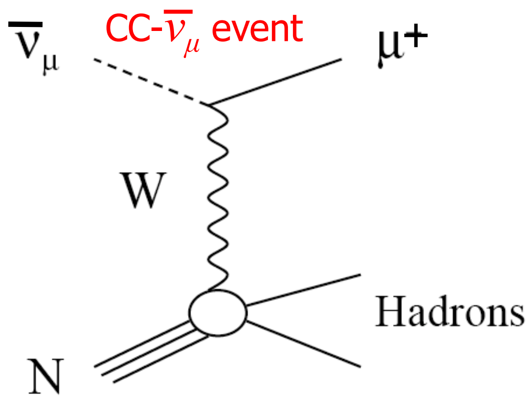
- ν_μ spectrum is dominated by focused high-p_T pions
- Majority of $\bar{\nu}_\mu$ come from low-p_T pions which travel down the centre of the horns where there is no magnetic field

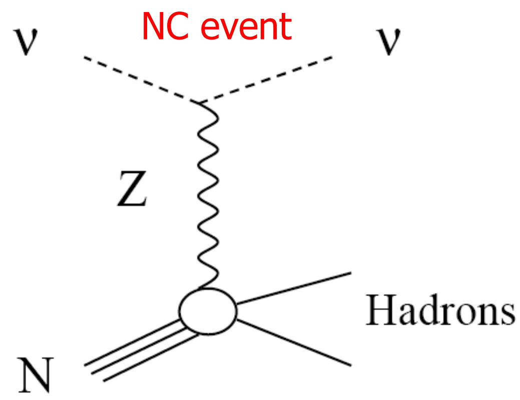


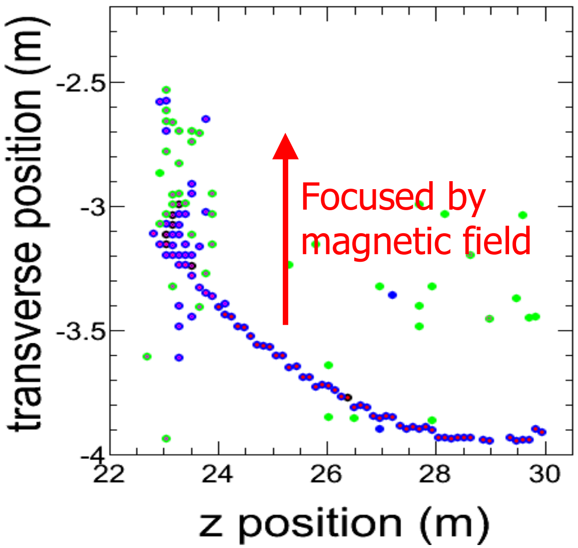


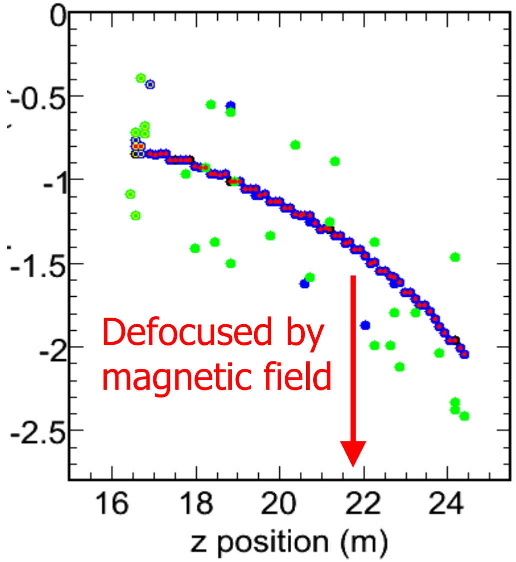
MINOS event topologies

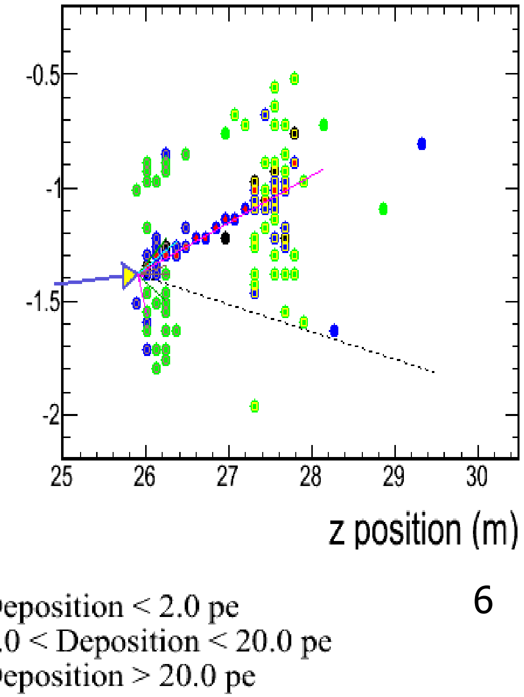










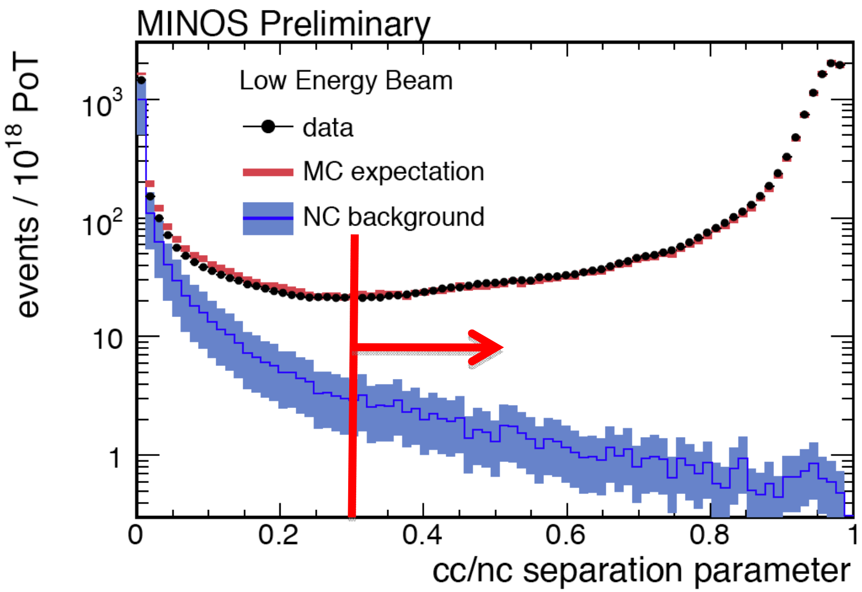


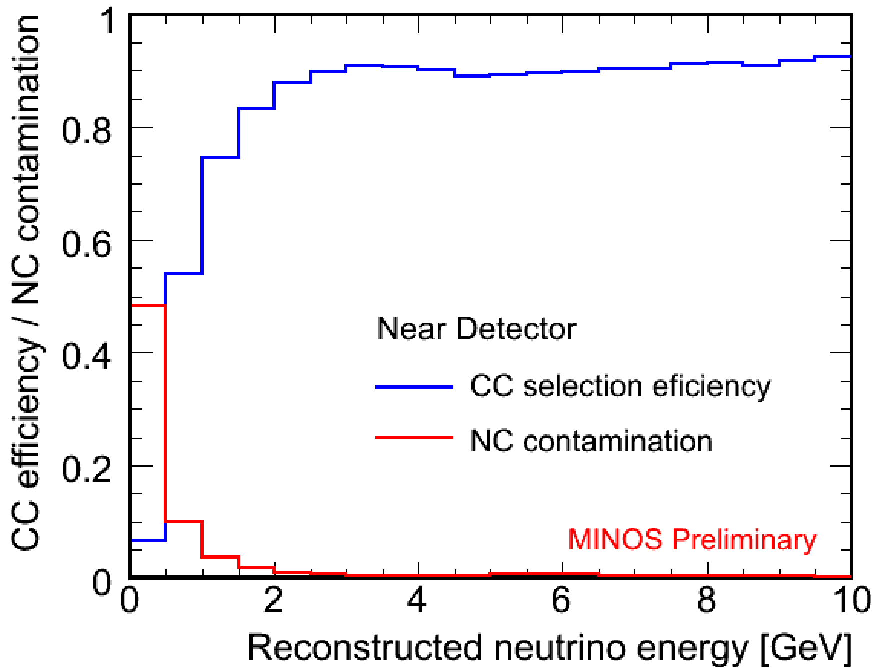
CC ν_μ event selection

Aim to separate charged and neutral current ν_μ interactions

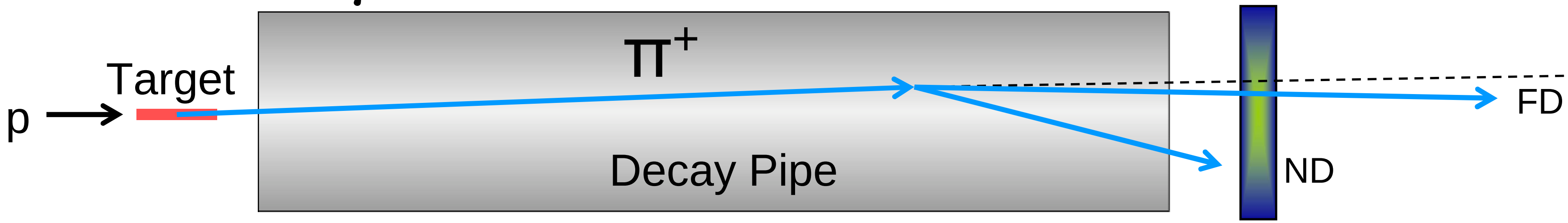
Four variables combined using a k-nearest-neighbour algorithm

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





CC ν_μ beam extrapolation



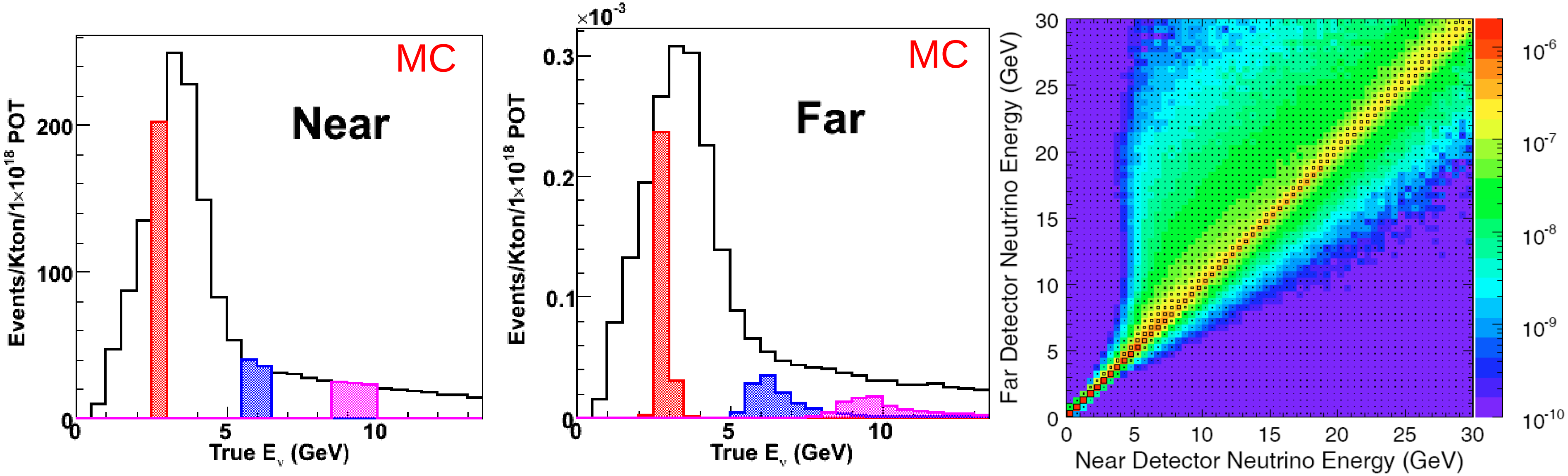
Use the measured ND energy spectrum to predict the FD spectrum:

Spread of pion decay directions smears neutrino energies

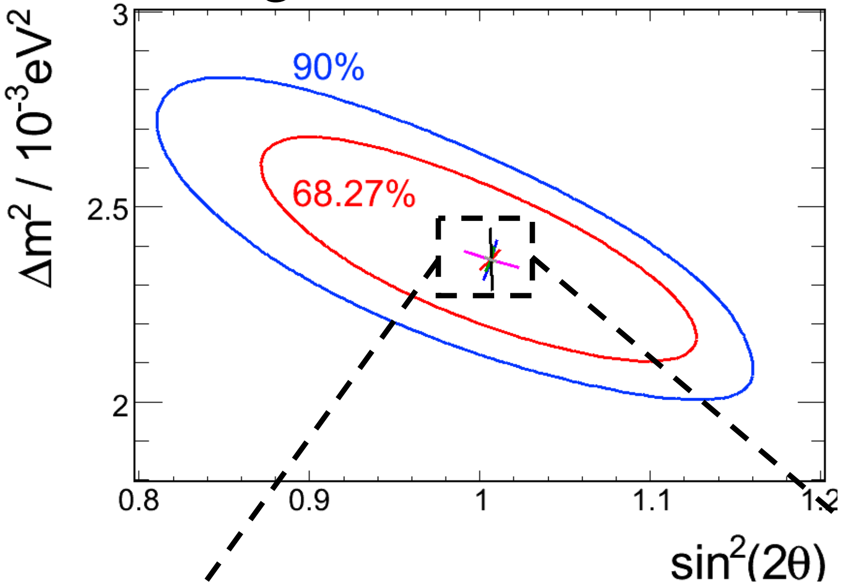
- Different energy spectra at the two detectors

Encode the pion decay kinematics into a beam transfer matrix

- Convert ND to FD spectrum



Systematic uncertainties

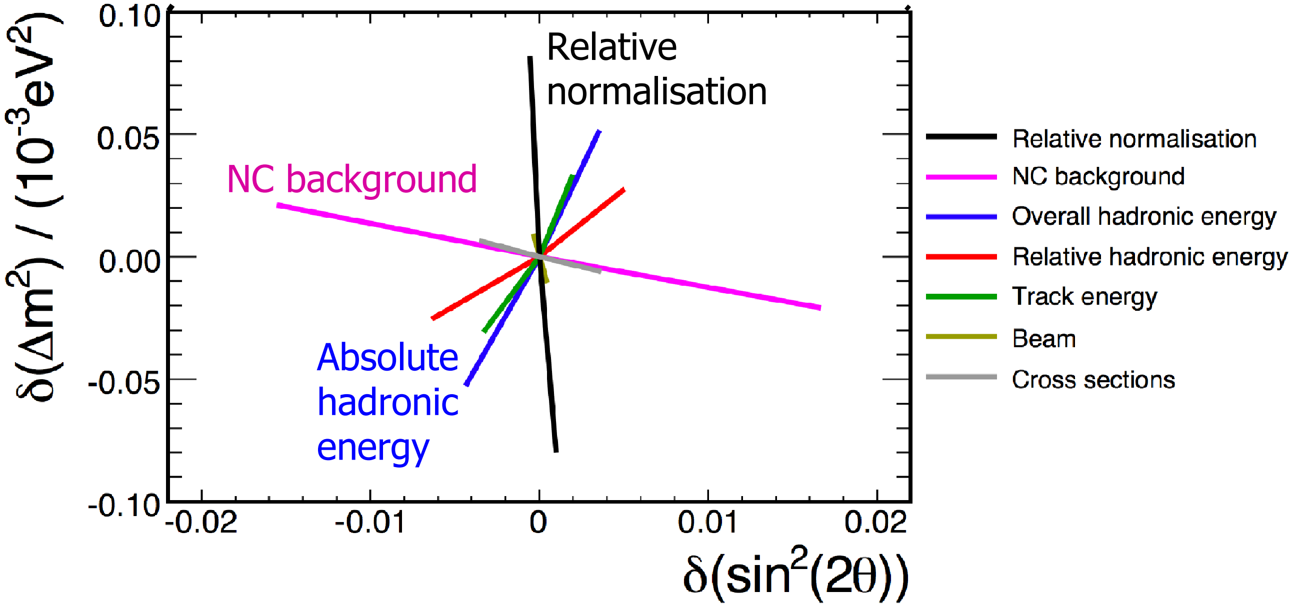


Effect of uncertainties estimated by fitting systematically shifted MC in place of data

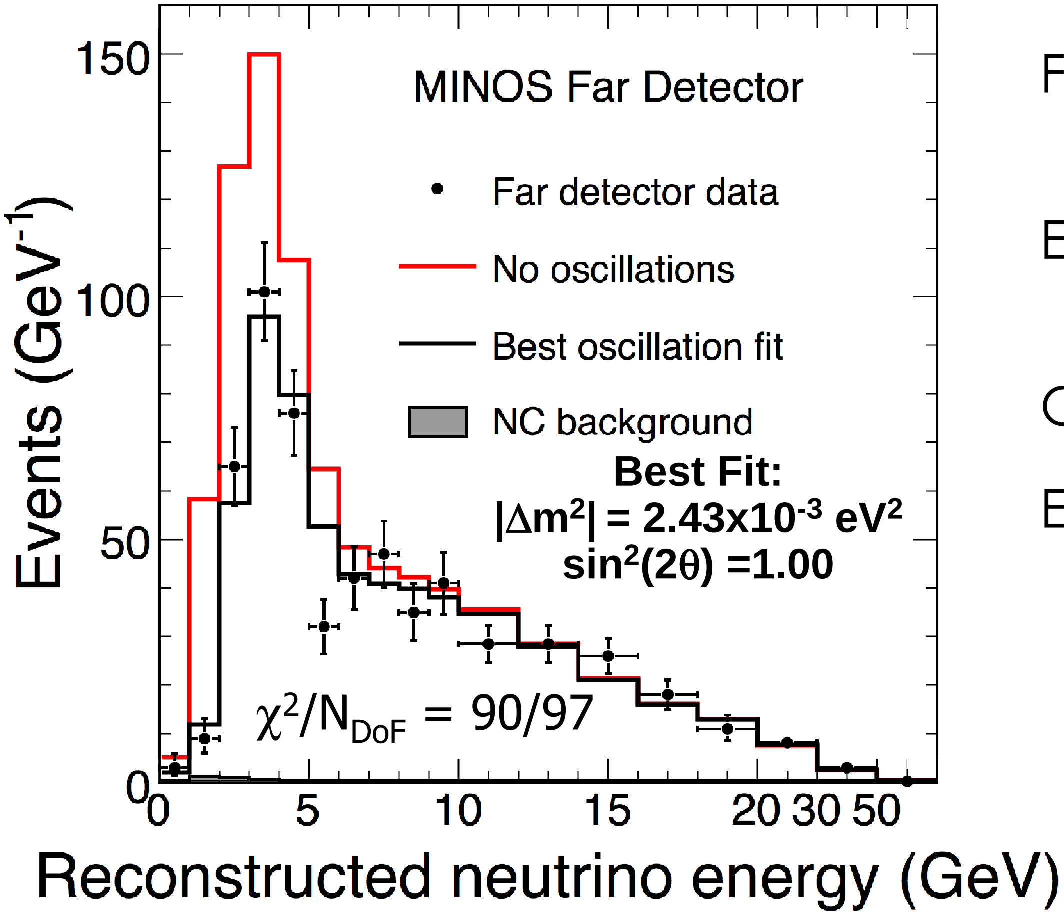
Analysis is still statistically limited

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%)



Far detector data



FD data not looked at until the analysis was finalised

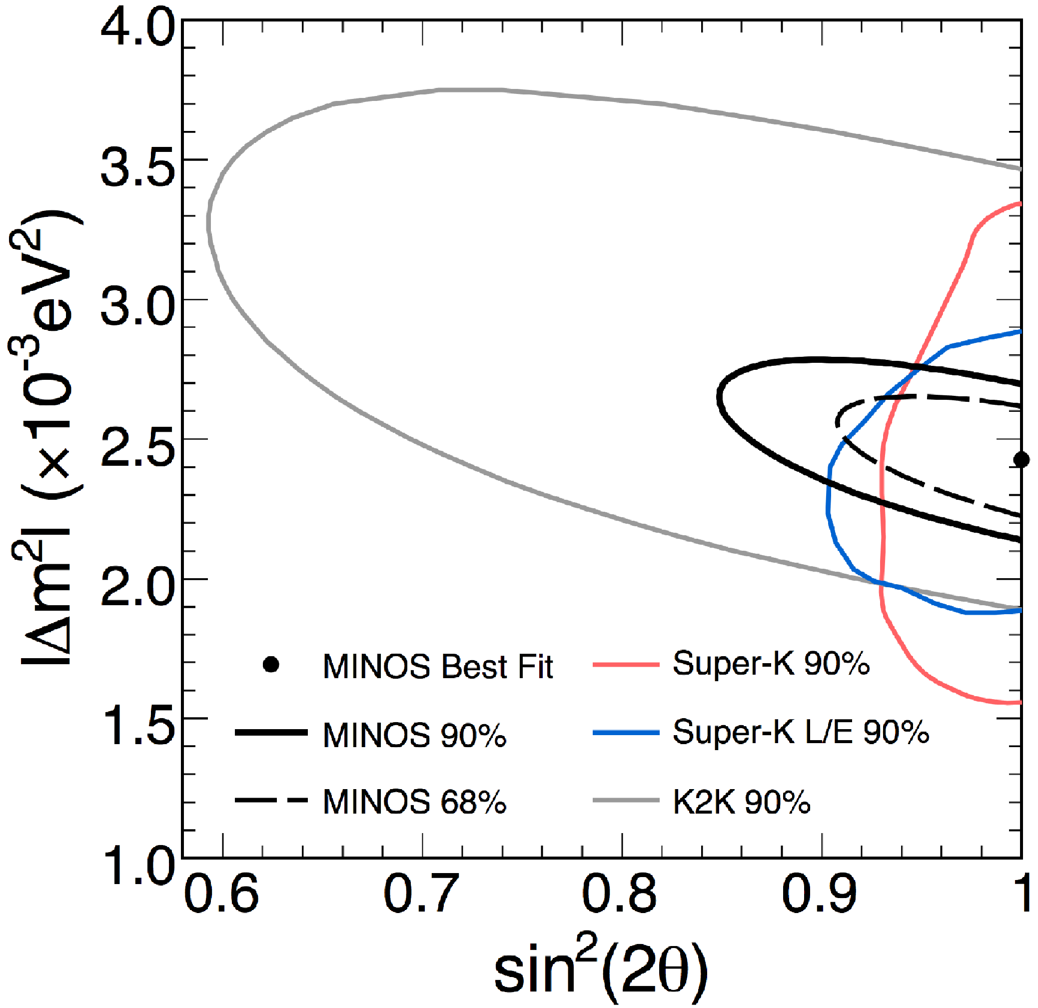
Expected 1065 ± 60 with no oscillations

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

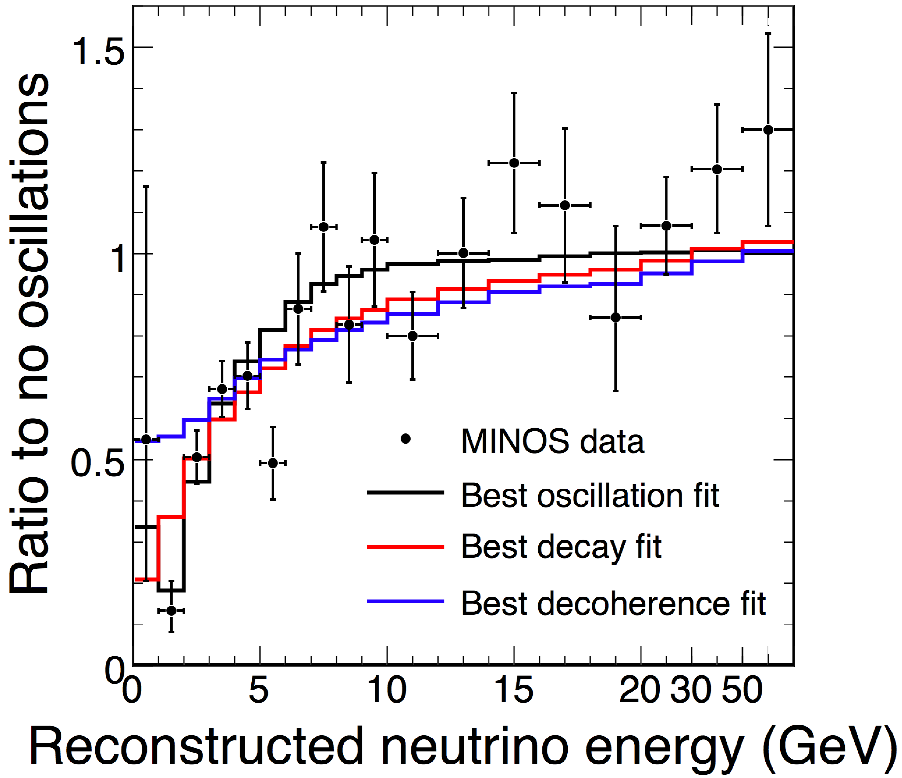
- $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% C.L.)
- $\sin^2(2\theta_{23}) > 0.90$ (90% C.L.)
- $\chi^2/N_{DoF} = 90/97$

Unconstrained fit

- $|\Delta m^2| = 2.33 \times 10^{-3}$ 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

The future

MINOS has doubled its dataset

- New results will be released this summer

We are also incorporating analysis improvements

Using events outside the fiducial volume

- Interactions in the detector and surrounding rock

Adding in events with poorly measured charge

- Recovers around half the events at low energy

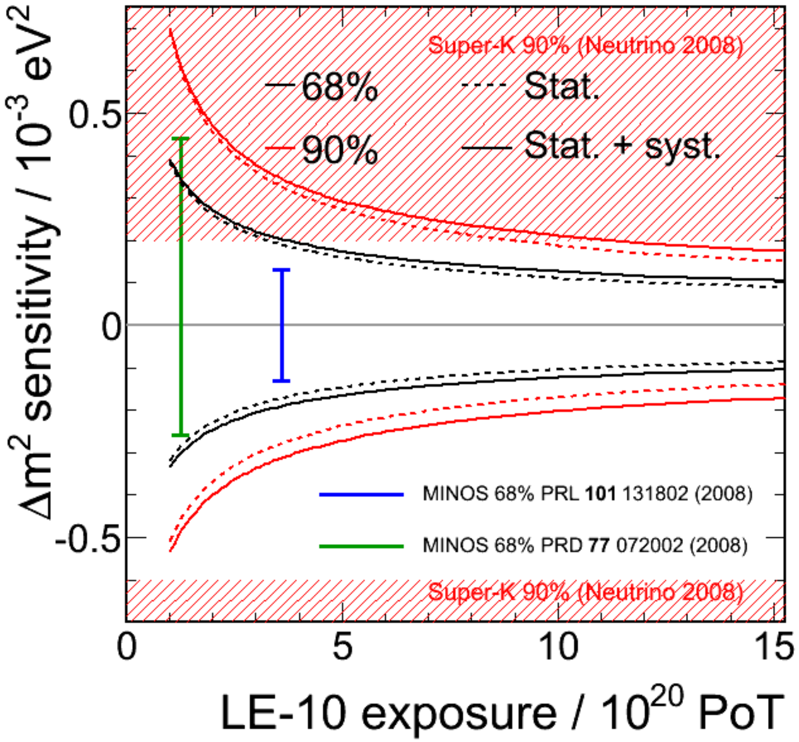
A new selection variable optimized for low energies

Grouping events according to their resolution

New hadronic shower energy estimator

- Based on a k-nearest-neighbour technique
- Significantly improves shower energy resolution

These improvements can increase our Δm^2 sensitivity by 15%



Selecting $\overline{\nu}_{\mu}$

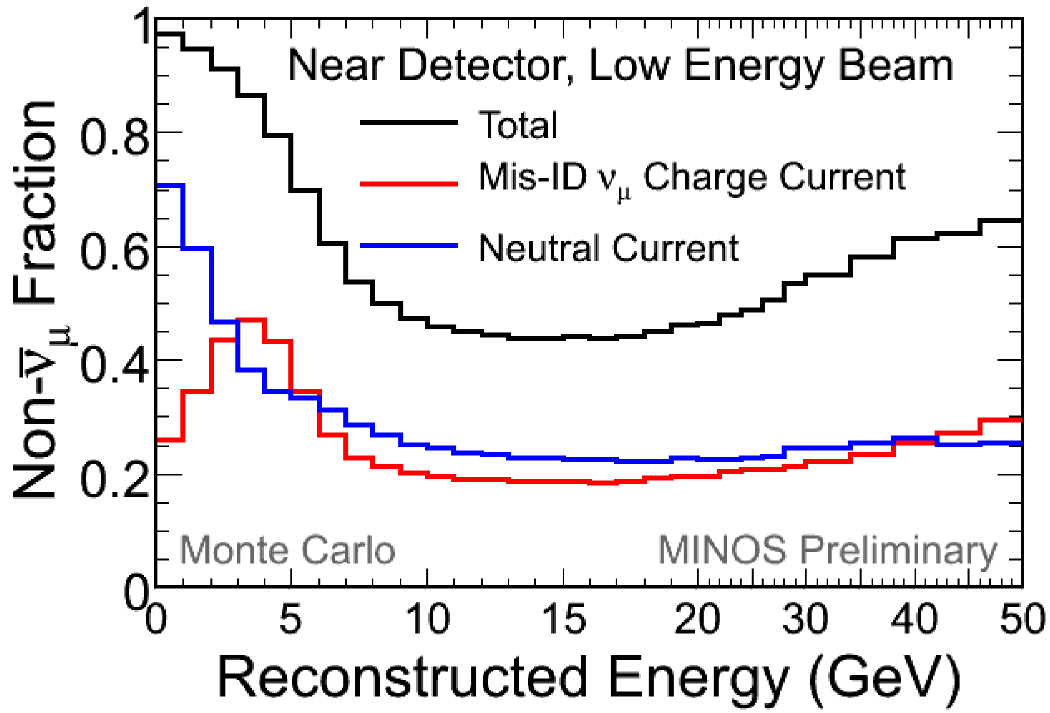
Selecting events with a track reconstructed with positive charge

We must work harder to select a pure sample of $\overline{\nu}_{\mu}$ events
- They are only 7% of all our CC events

Large backgrounds from other event-types
- Mis-identified CC- ν_{μ} with wrong charge sign
- NC events where another particle fakes a track

Three additional selection criteria are used

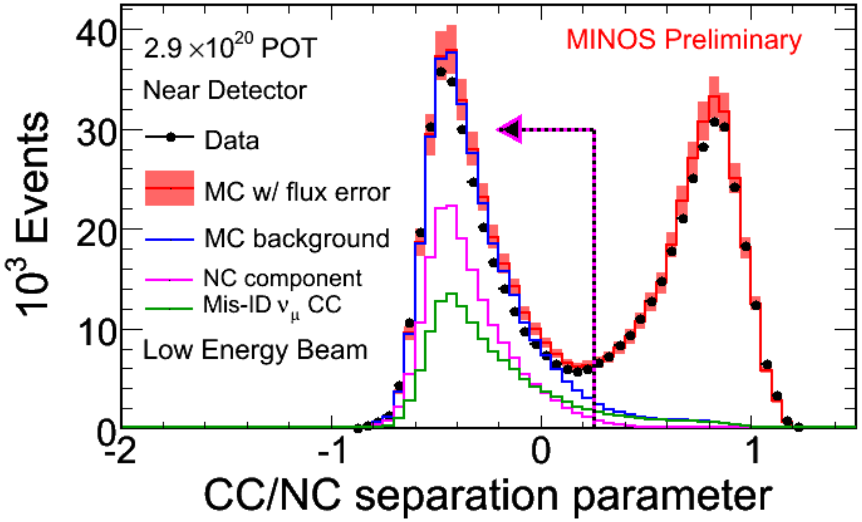
All events with a positive curvature track



Selecting $\bar{\nu}_\mu$

CC/NC separator

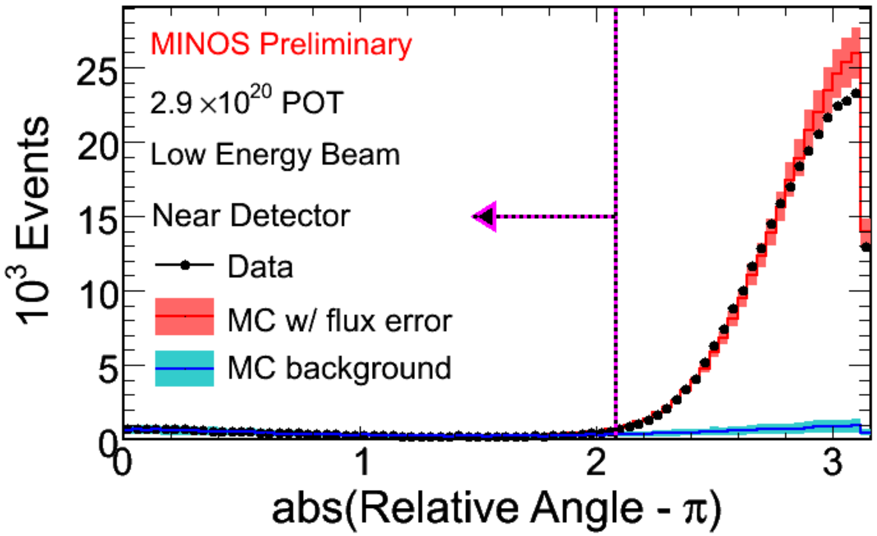
- Likelihood-based with 3 probability density functions
- Removes both NC and mis-identified CC events

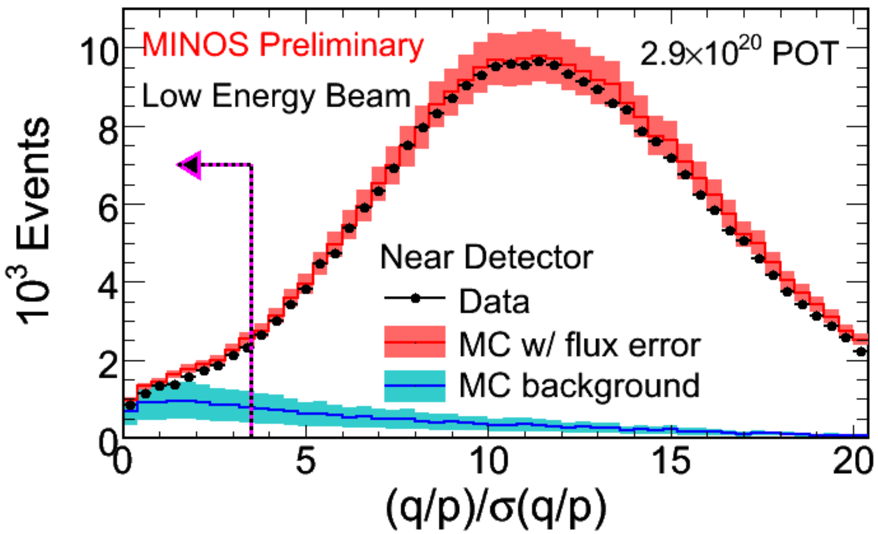


Track fit charge sign significance

Relative angle

- Whether the track curves towards or away from the coil hole relative to its initial direction





Selecting $\overline{\nu}_\mu$

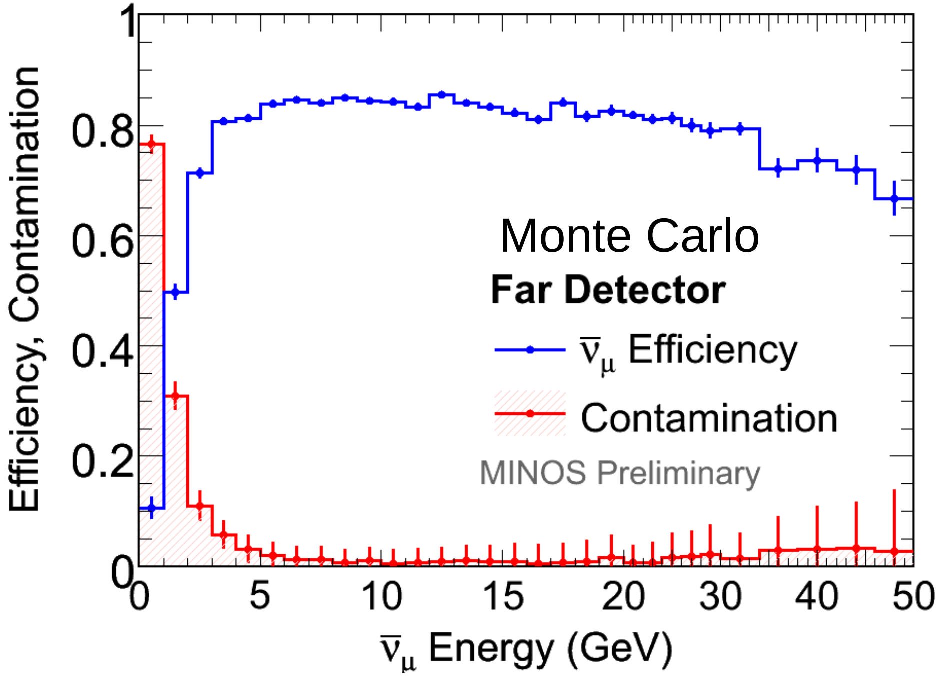
After all selection cuts:

Far detector

- Efficiency of 82%
- Contamination of 3%

Optimized for physics sensitivity to oscillations with neutrino best fit parameters

- Lower contamination is possible but at the cost of efficiency



$\overline{\nu}_\mu$ far detector spectrum

Observe 42 $\overline{\nu}_\mu$-CC events at the far detector

- First direct observation of $\overline{\nu}_\mu$ in an accelerator long-baseline experiment

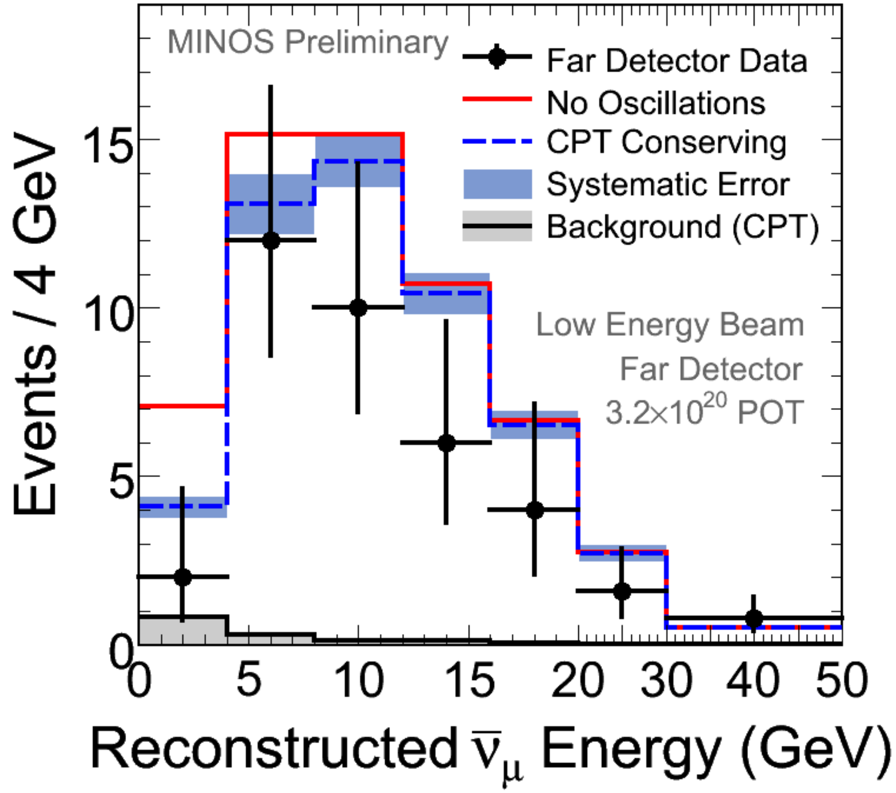
Predicted events with oscillations with the best-fit neutrino oscillation parameters

- 58.3 ± 7.6 (stat.) ± 3.6 (syst.)

Predicted with no oscillations

- 64.6 ± 8.0 (stat.) ± 3.9 (syst.)

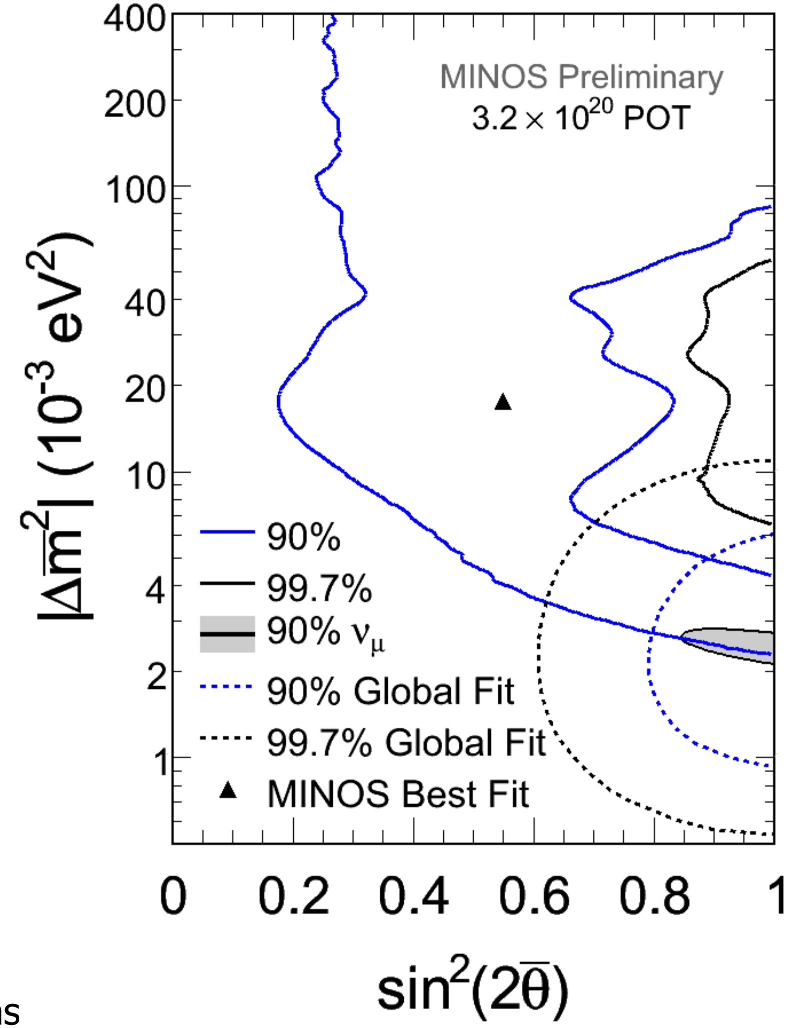
Significance of the deficit is 1.9σ



Fitting for $\bar{\nu}_\mu$ oscillations

- Feldman-Cousins contour, including systematics
- Null oscillation hypothesis excluded at 99%
- Previously allowed regions excluded at high confidence
- Allowed region from the ν_μ measurement is within the 90% contour

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

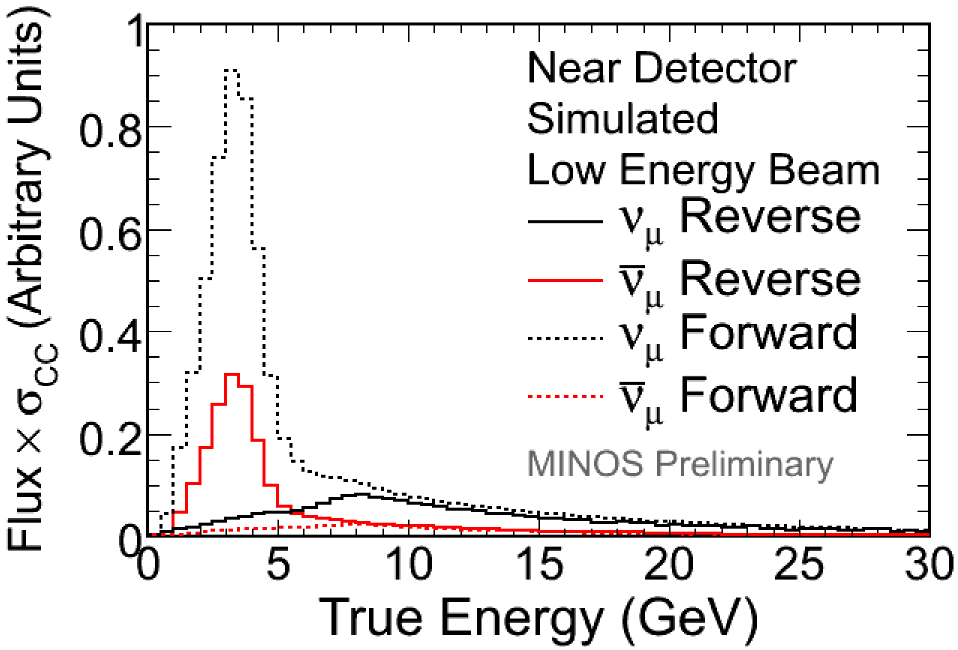


Dedicated $\overline{\nu}_{\mu}$ running

MINOS has now taken data with a dedicated $\overline{\nu}_{\mu}$ beam

- By reversing the current in the focusing horns
- From October 2009 to March 2010

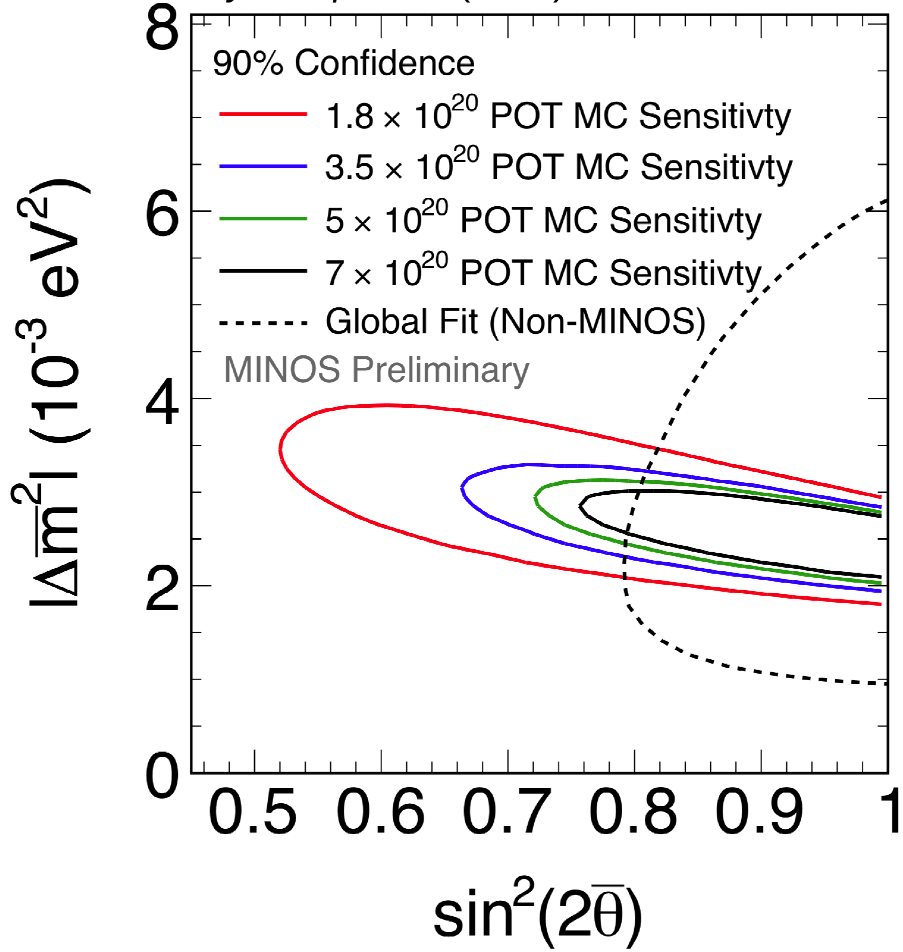
Significantly enhances the $\overline{\nu}_{\mu}$ flux in the oscillation signal region



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

- We will make the first ever precision measurement of the $\bar{\nu}_\mu$ oscillation parameters
- Significantly reduce the uncertainty on $\Delta\bar{m}^2$
- Results will be released this summer

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



Summary

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

First direct detection of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment

A new measurement of the ν_μ oscillation parameters will be released this summer

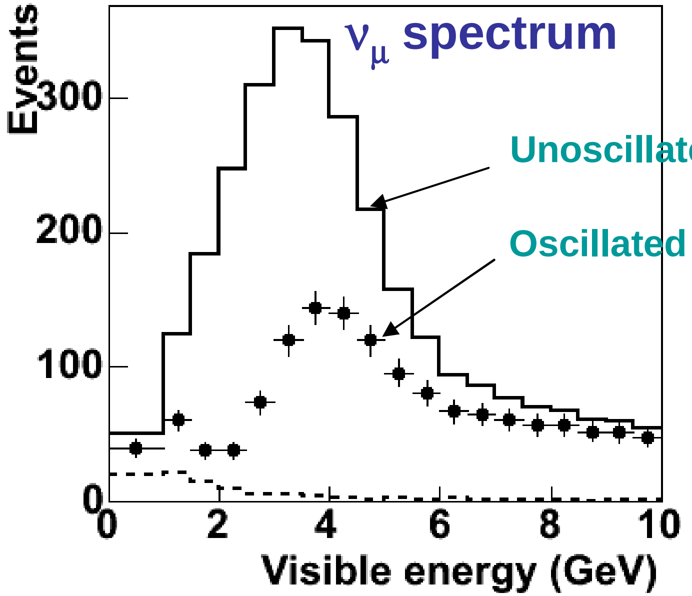
- Double the dataset
- Analysis improvements

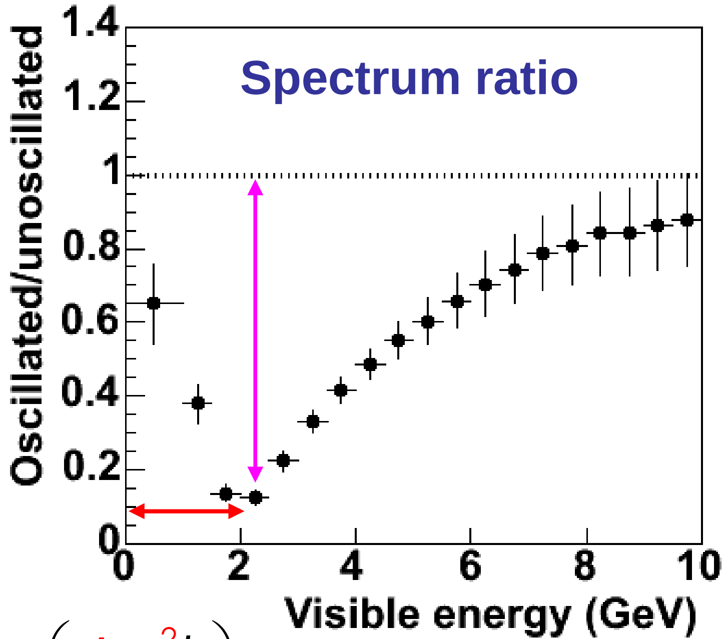
MINOS has taken data with a dedicated antineutrino beam

- The first precision measurement of the $\bar{\nu}_\mu$ oscillation parameters
- Results will be released this summer

Backup

Measuring oscillations





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

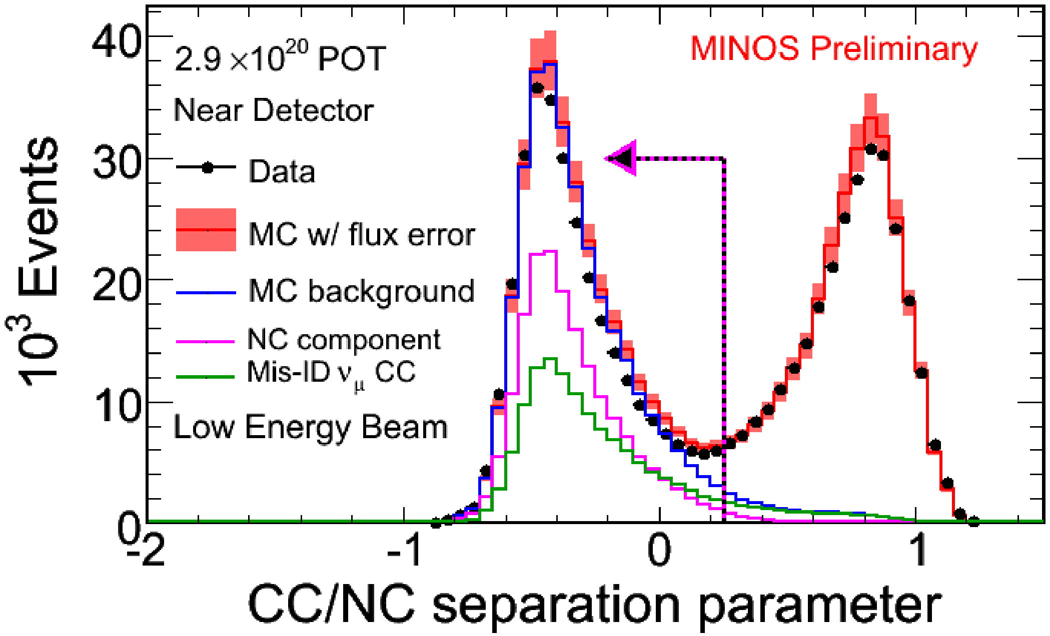
Near detector measures the energy spectrum before oscillations occur

At the FD we see an energy-dependent deficit due to oscillations

- Position of the dip give Δm^2
- Depth of dip gives $\sin^2(2\theta)$

An alternative disappearance model (e.g. decay or decoherence) would give a different energy-dependence

CC/NC separator



Likelihood-based with 3 Probability Density Functions:

- Track length
- Pulse height fraction in track
- Pulse height per plane

Use CC/NC separation parameter developed for previous analyses

- Cut removes both NC and mis-identified ν_μ CC events

Mis-ID ν_μ CC events tend to be inelastic events where the muon is obscured by a large hadronic shower

- high-y events

$\bar{\nu}_\mu$ systematic uncertainties

Errors that are the same as the ν_μ analysis

- **Normalization:** ±4%
  Relative reconstruction eff., detector livetime and mass
- **Muon energy:** range ±2%, curvature ±4%
  (Error from curvature increased slightly due to exiting tracks)
- **Beam extrapolation:** 1σ error band from beam fit
- **Relative shower energy:** ±3%
- **Absolute shower energy:** ±10%

Errors that are specific for this analysis

- **Decay pipe production**
- **Background:** ±50%