Latest Results from the MINOS Experiment

Justin Evans, University College London
for the MINOS Collaboration

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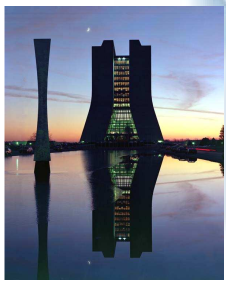
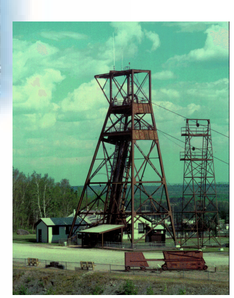
UCL

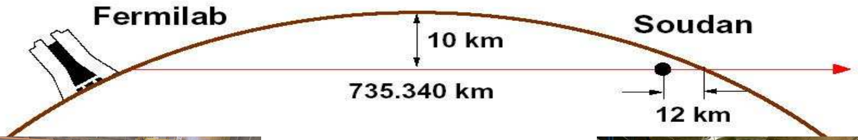
The MINOS experiment

Main Injector Neutrino Oscillation Search
- Long baseline: 735 km
- Neutrino energy ~3 GeV
- Atmospheric Δm^2





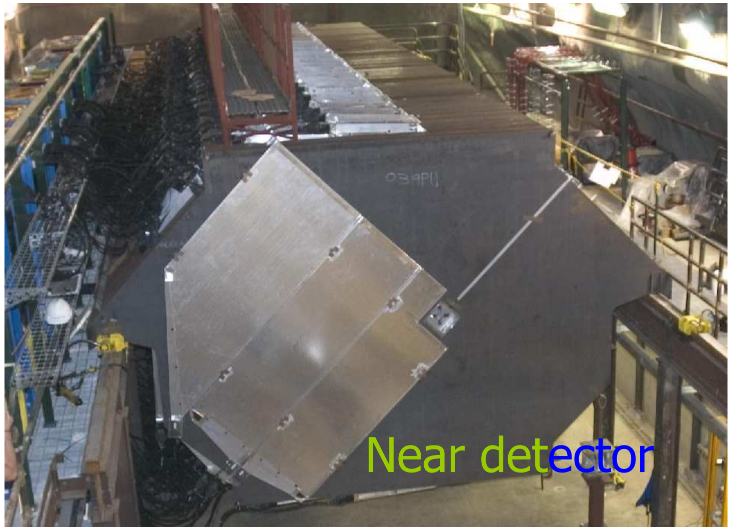
NuMI ν_μ neutrino beam



Near Detector at Fermilab
- Measure beam composition and energy spectrum

Far detector at Soudan mine
- Measure energy-dependent disappearance/appearance
- Characteristic of oscillations

The MINOS Detectors



Near detector, 1.0 ktonne, 1km from source

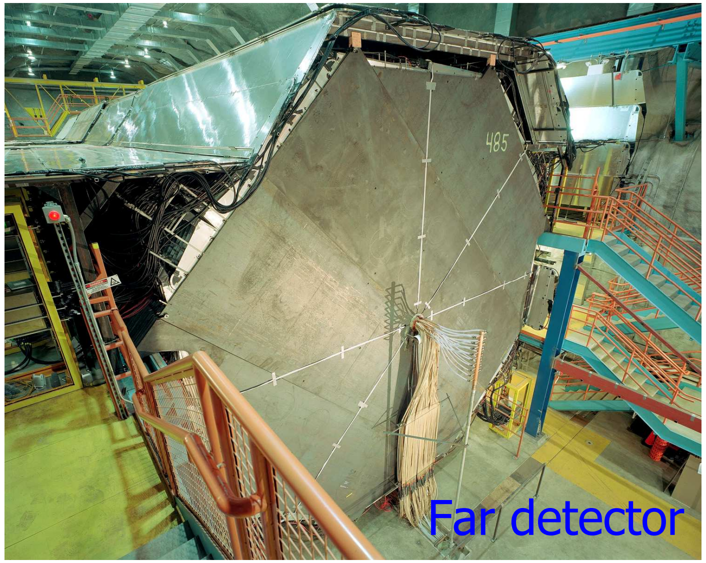
Far detector, 5.4 ktonne, 735 km from source

Tracking, sampling calorimeters

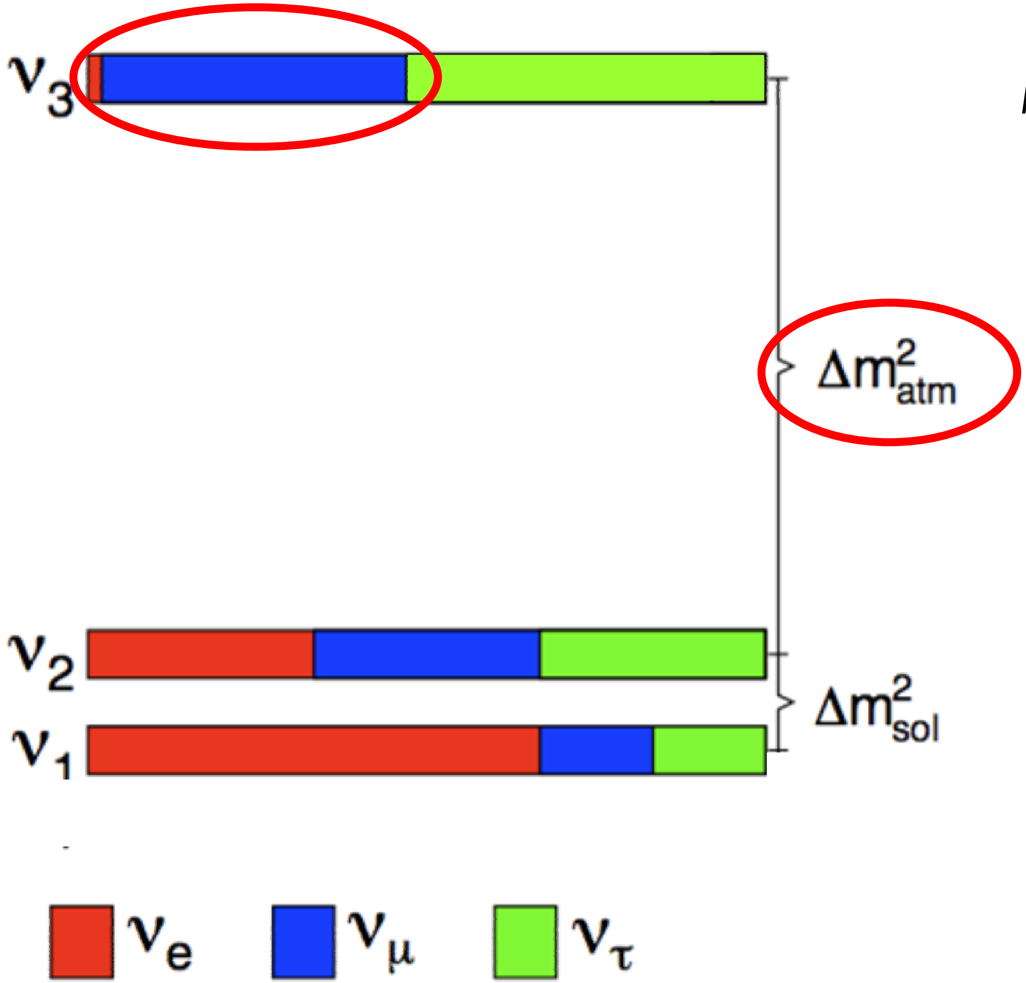
- Alternate steel and scintillator planes
- Functionally identical
- Magnetised to 1.3 T

Two detectors to mitigate systematics

- e.g. neutrino flux or cross section mismodelings



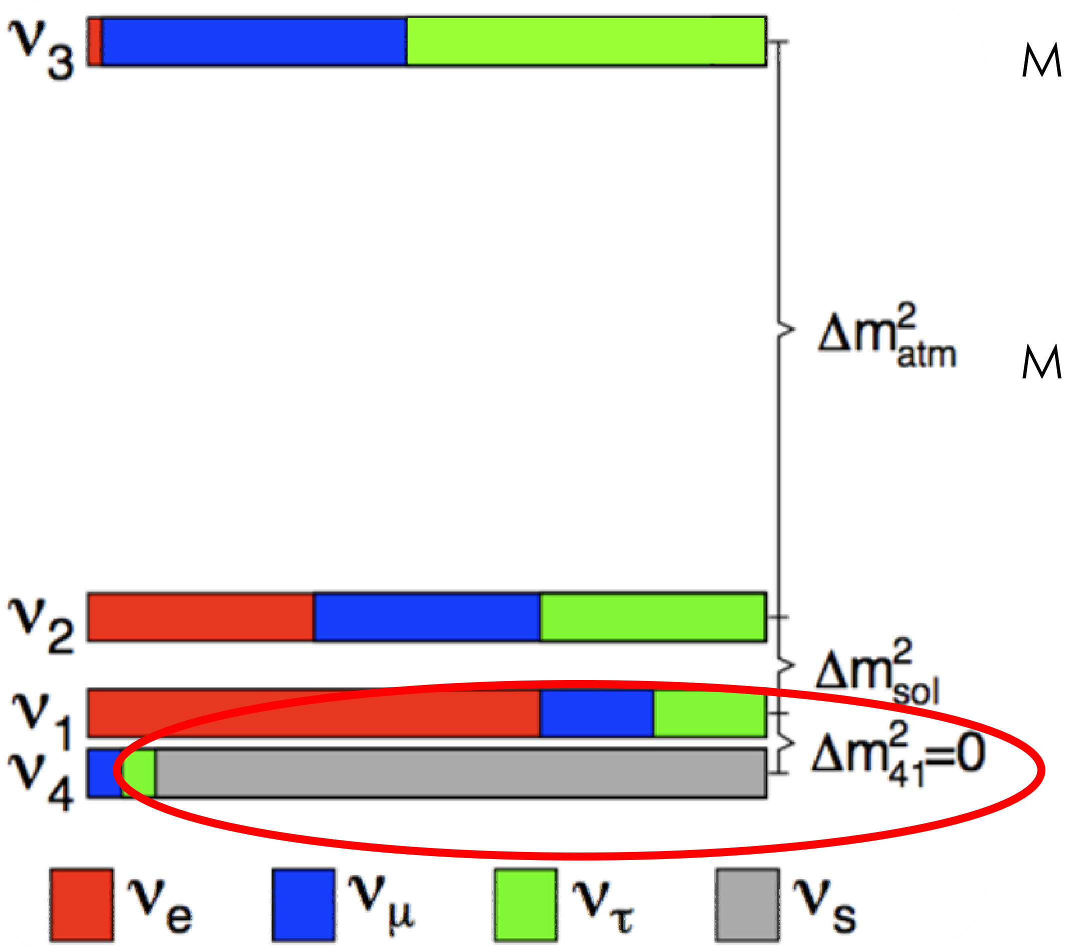
MINOS physics goals



Measure energy-dependent ν_μ disappearance

- Δm_{32} and $\sin^2(2\theta_{23})$
- Test oscillations v decay & decoherence

MINOS physics goals



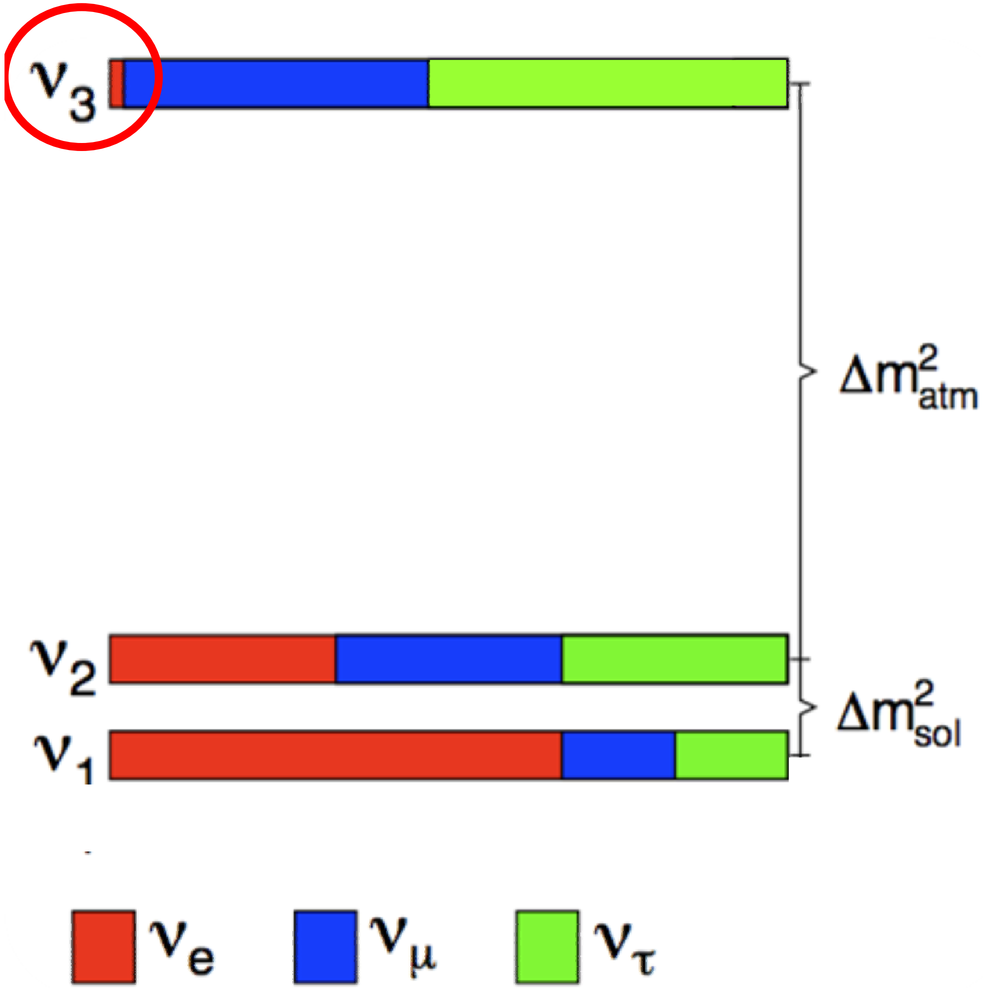
Measure energy-dependent ν_μ disappearance

- Δm_{32} and $\sin^2(2\theta_{23})$
- Test oscillations v decay & decoherence

Measure neutral current event rate

- Mixing to sterile neutrinos

MINOS physics goals



Measure energy-dependent ν_μ disappearance

- Δm_{32} and $\sin^2(2\theta_{23})$
- Test oscillations v decay & decoherence

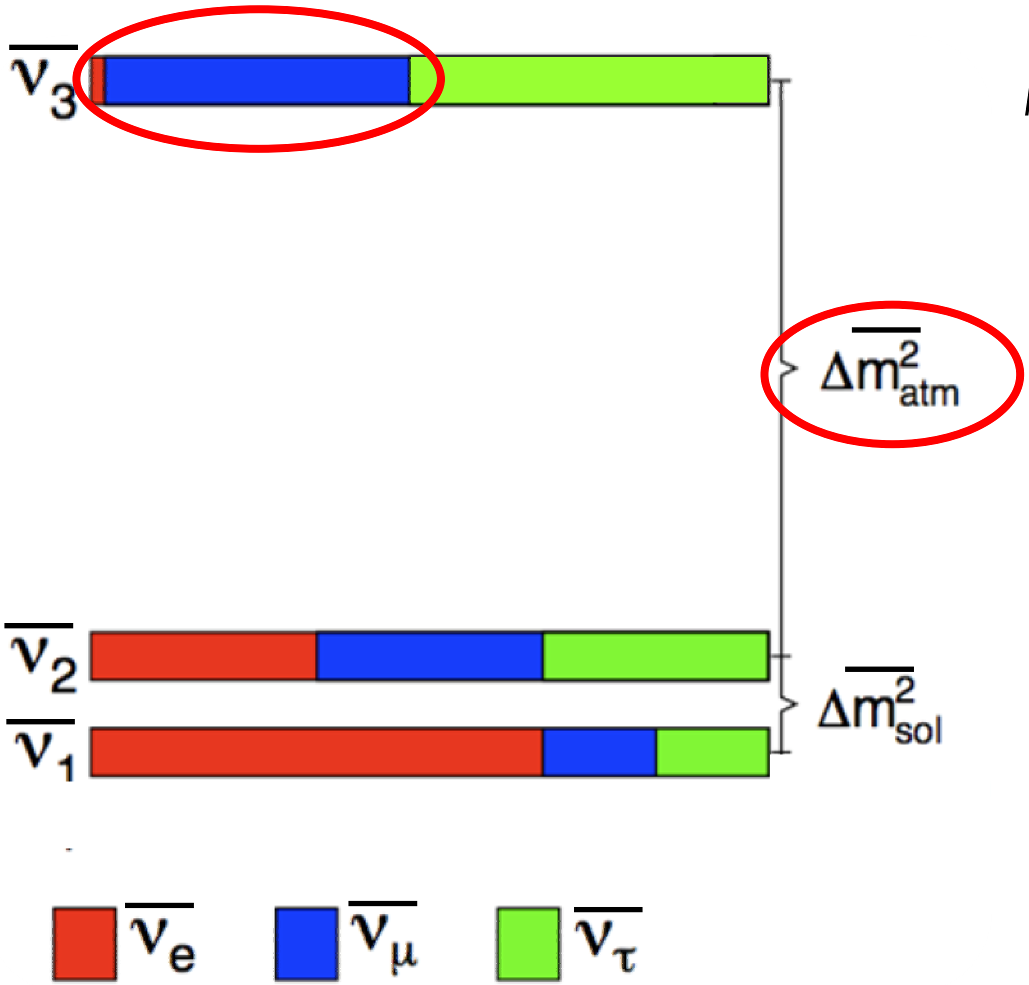
Measure neutral current event rate

- Mixing to sterile neutrinos

Look for ν_e appearance

- Measure θ_{13}

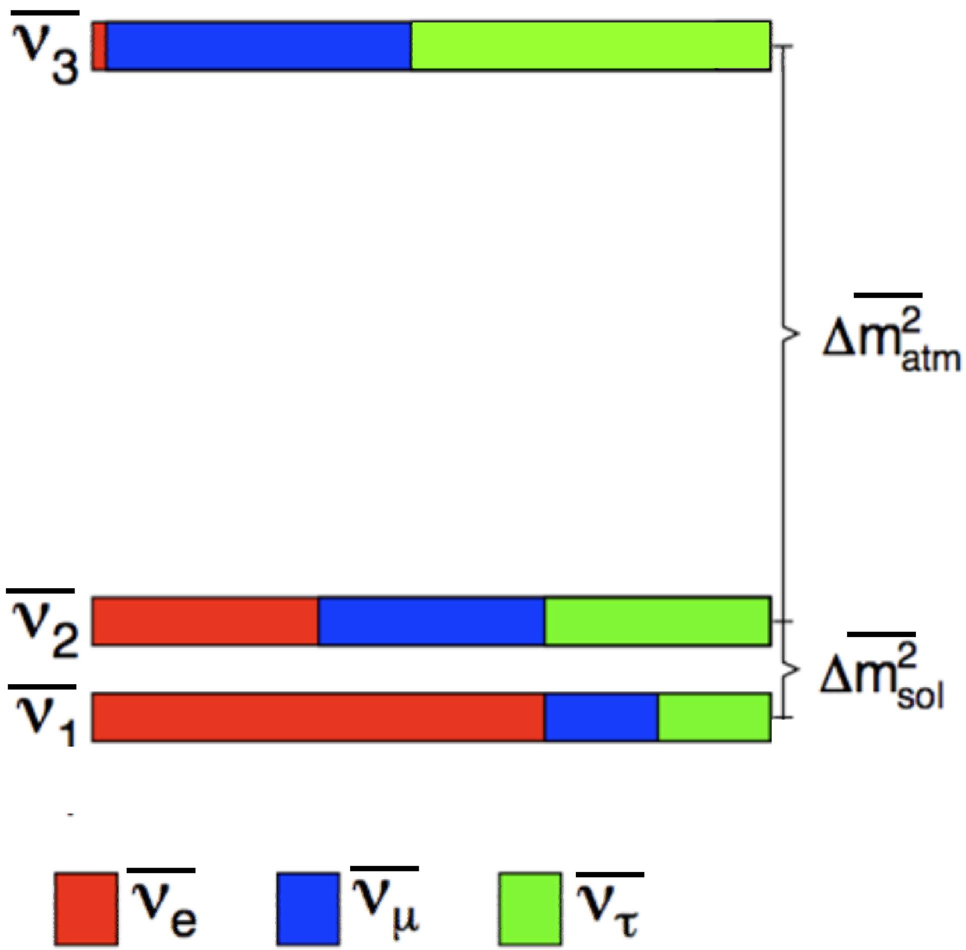
MINOS physics goals



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

- $\Delta\overline{m}_{32}$ and $\sin^2(2\overline{\theta}_{23})$
- Look for differences between neutrinos and antineutrinos

MINOS physics goals



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

- $\Delta\overline{m}_{32}$ and $\sin^2(2\overline{\theta}_{23})$
- Look for differences between neutrinos and antineutrinos

Other MINOS analyses

- Atmospheric neutrinos
  (poster by L. Corwin)
- Cross section measurements
- Lorentz invariance tests
- Cosmic rays

CC-ν_μ disappearance measurement

Measure $\sin^2(\theta_{23})$ and Δm^2_{32}

Analysis improvements

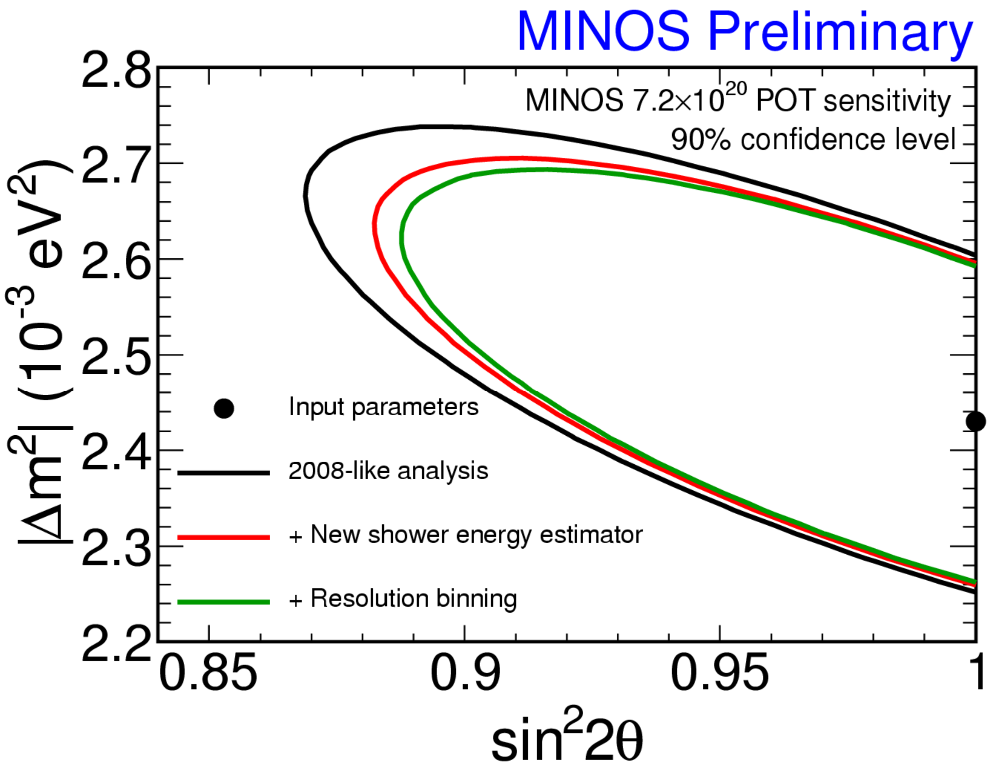
Since PRL 101:131802, 2008

Additional data

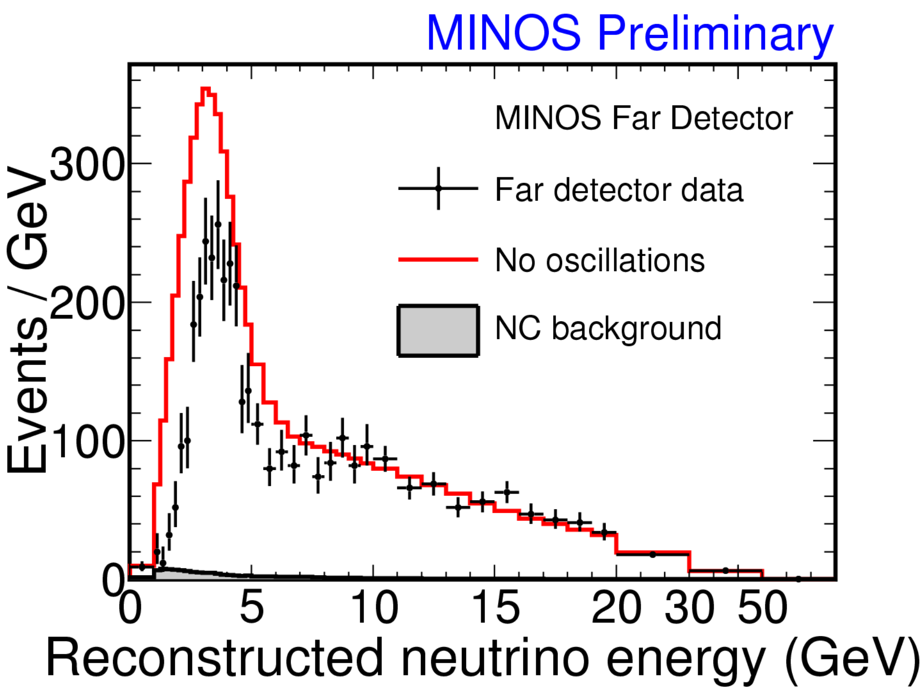
- $3.4 \times 10^{20} \rightarrow 7.2 \times 10^{20}$ protons on target

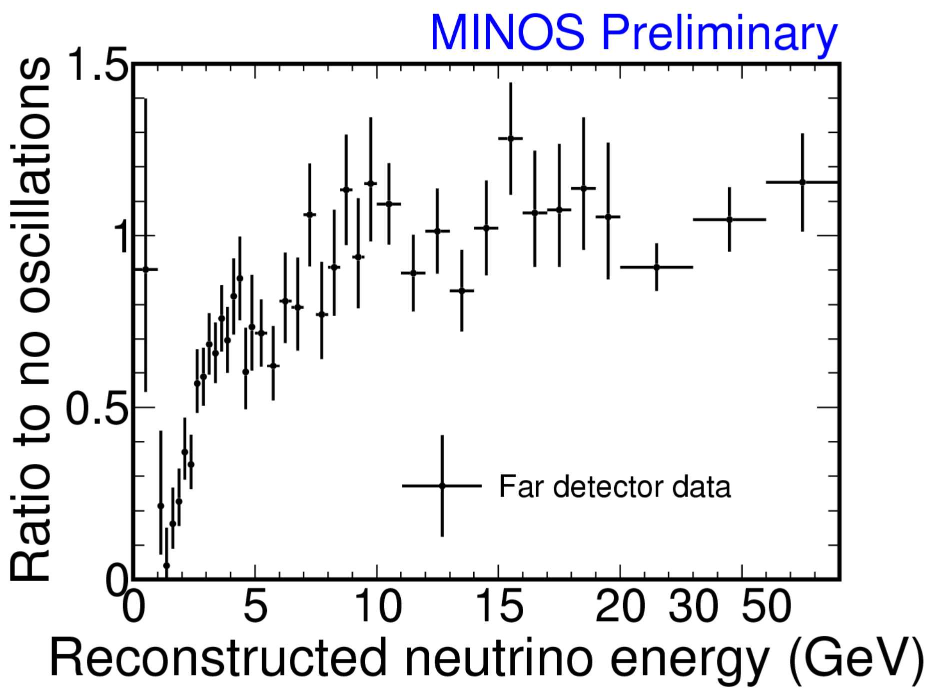
Analysis improvements

- Updated reconstruction and simulation
- New selection with increased efficiency
- No charge sign cut
- Improved shower energy resolution
- Separate fits in bins of energy resolution
- Smaller systematic uncertainties



Far detector energy spectrum

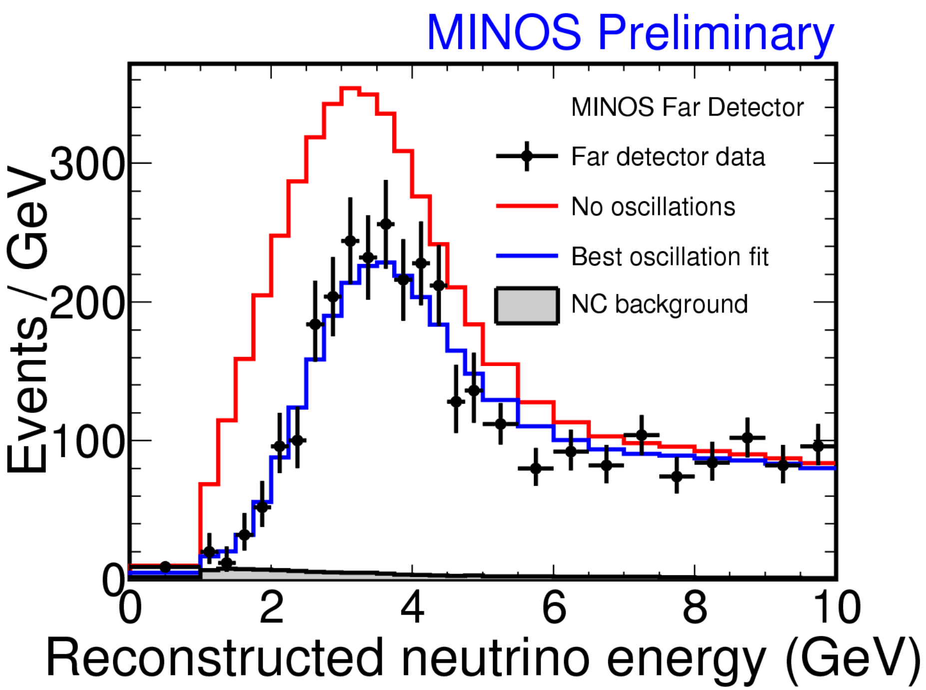


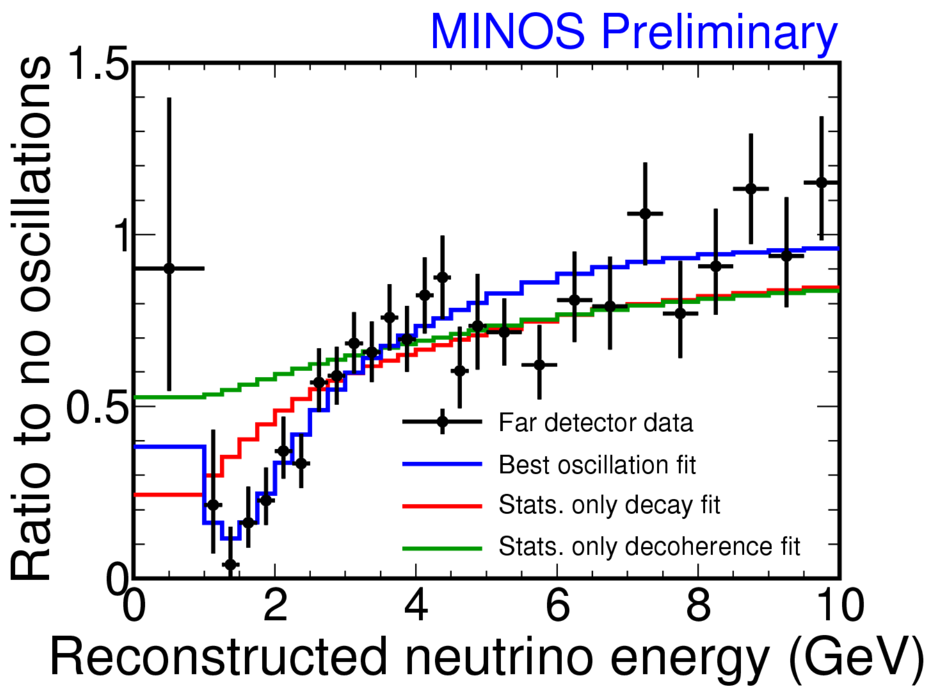


No Oscillations: **2451 events**

Observation: **1986 events**

Far detector energy spectrum





Oscillations fit the data well: 66% of experiments have worse χ^2

Pure decoherence† disfavored: > **8σ**

Pure decay‡ disfavored: > **6σ**

(**7.8σ** if NC events included)

†G.L. Fogli *et al.*, PRD 67:093006 (2003) ‡V. Barger *et al.*,PRL 82:2640 (1999)

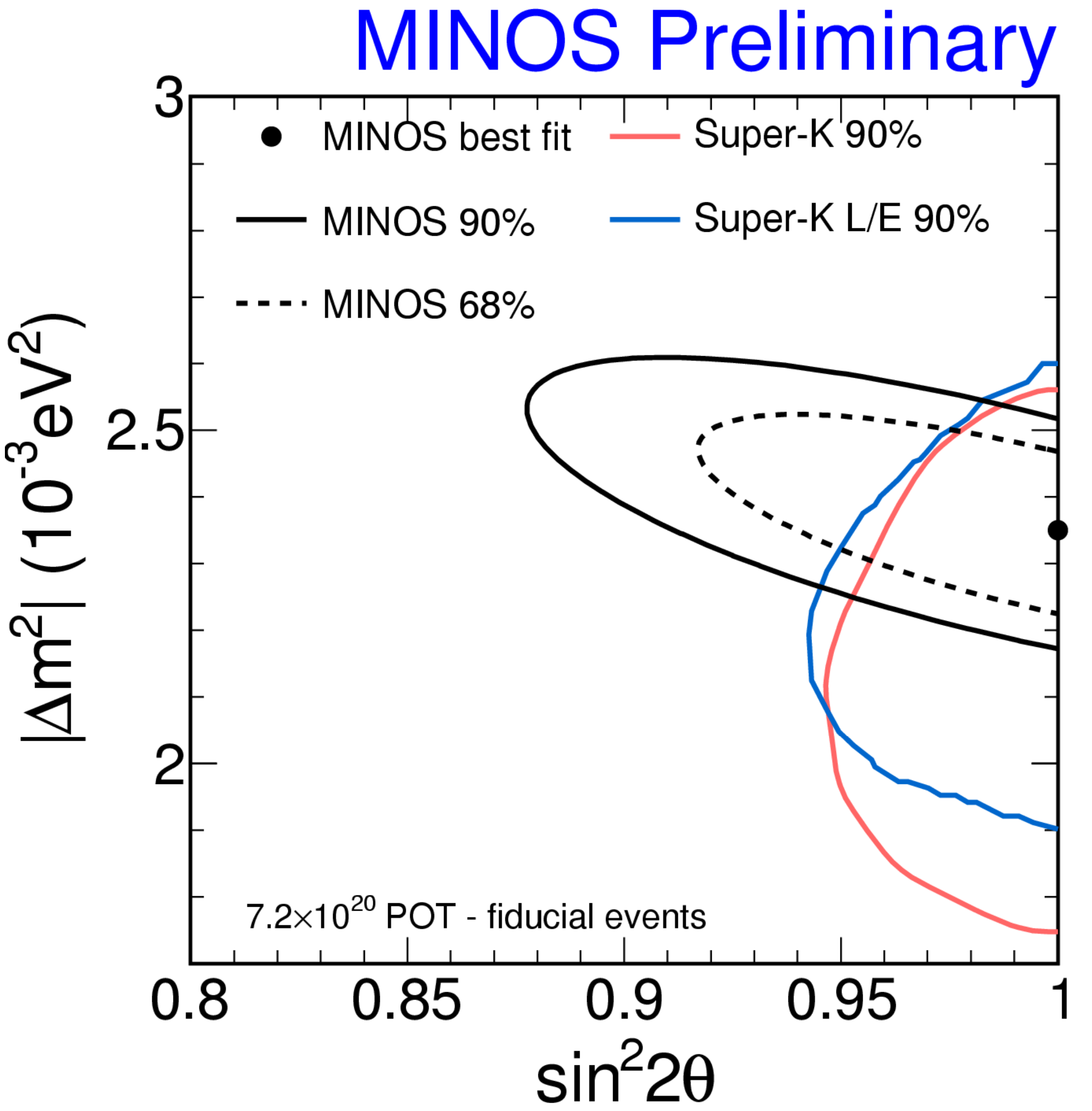
Allowed region

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

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

Contour includes effects of dominant systematic uncertainties

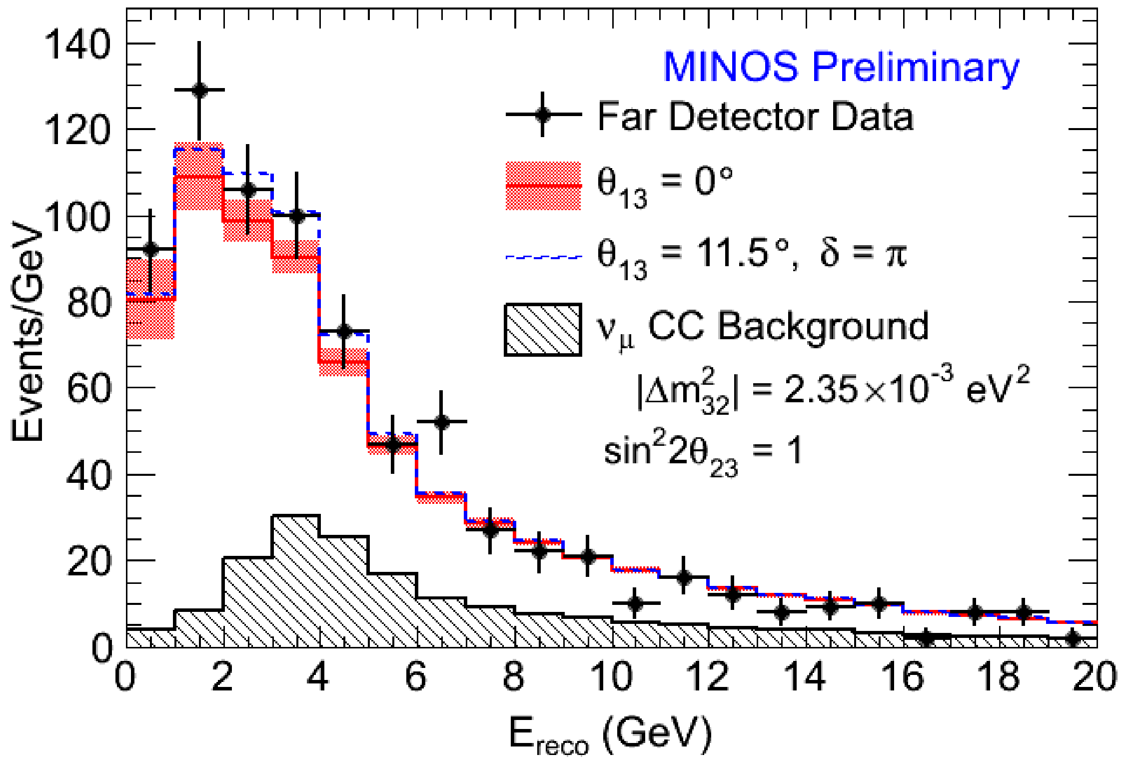
- normalization
- NC background
- shower energy
- track energy



Neutral current disappearance search

Look for evidence of sterile neutrinos

Neutral current results



Neutral Current event rate should not change in standard three-flavour oscillations

A deficit in the far detector event rate could indicate mixing to sterile neutrinos

ν_e CC events would be included in NC sample, so results depend on the possibility of ν_e appearance

Expect: **757** events

Observe: **802** events

No deficit of NC events

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ \ (0.40) \text{ at } 90\% \text{ C.L.}$$

no (with) ν_e appearance

CC-ν_e appearance search

Set limits on θ_{13}

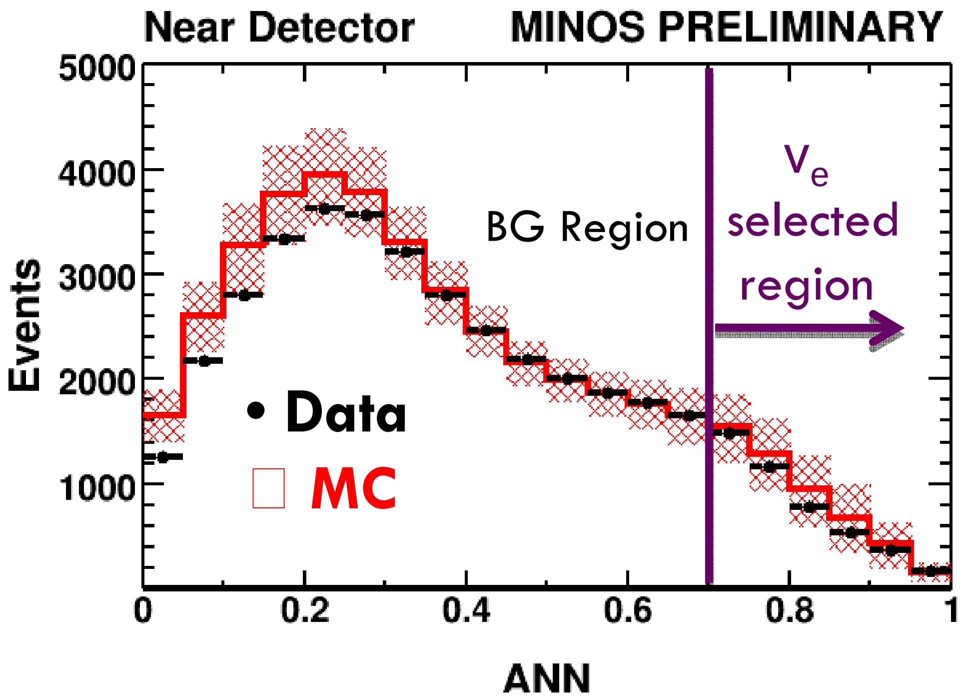
CC-ν_e selection

11 shape variables in a Neural Net (ANN)

- Characterize longitudinal and transverse energy deposition of shower

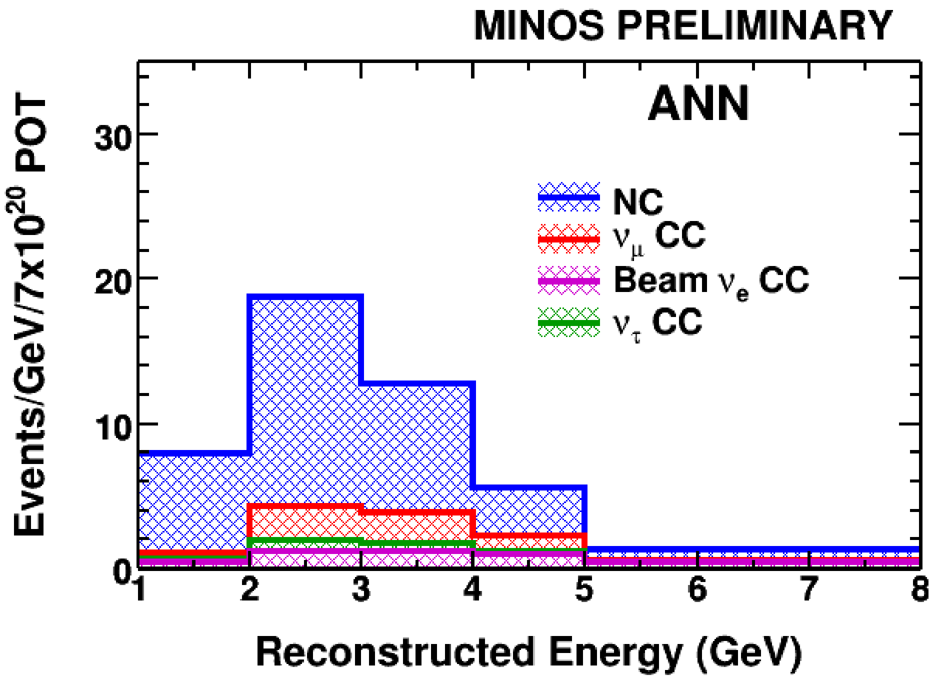
Apply selection to ND data to predict background level in FD

- NC, CC, beam ν_e each extrapolate differently
- Take advantage of NuMI flexibility to separate background components



ν_e appearance results

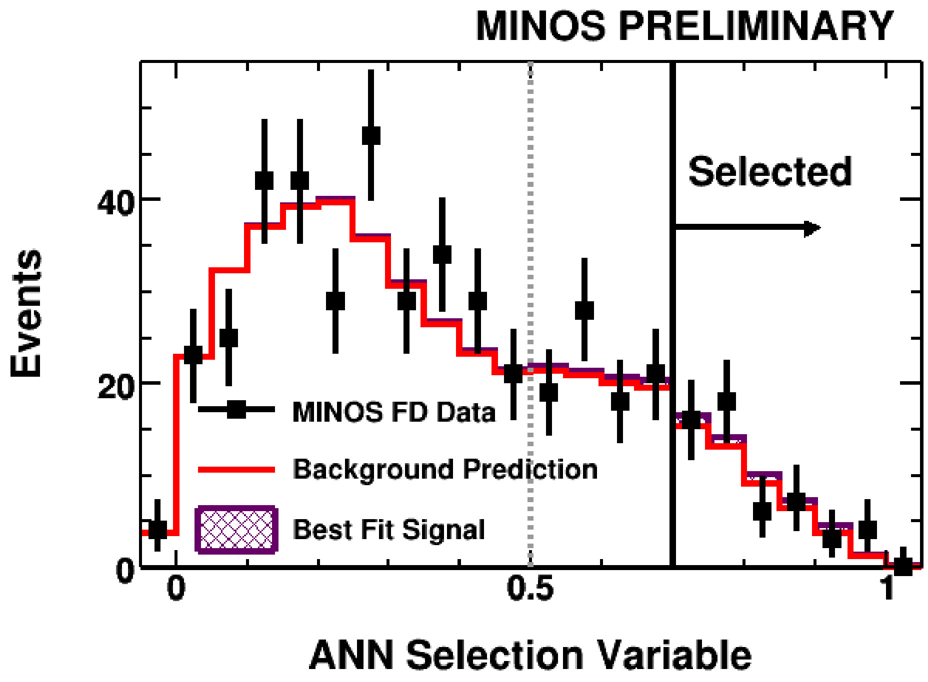
Based on ND data, expect **49.1±7.0(stat.)±2.7(syst.)** events

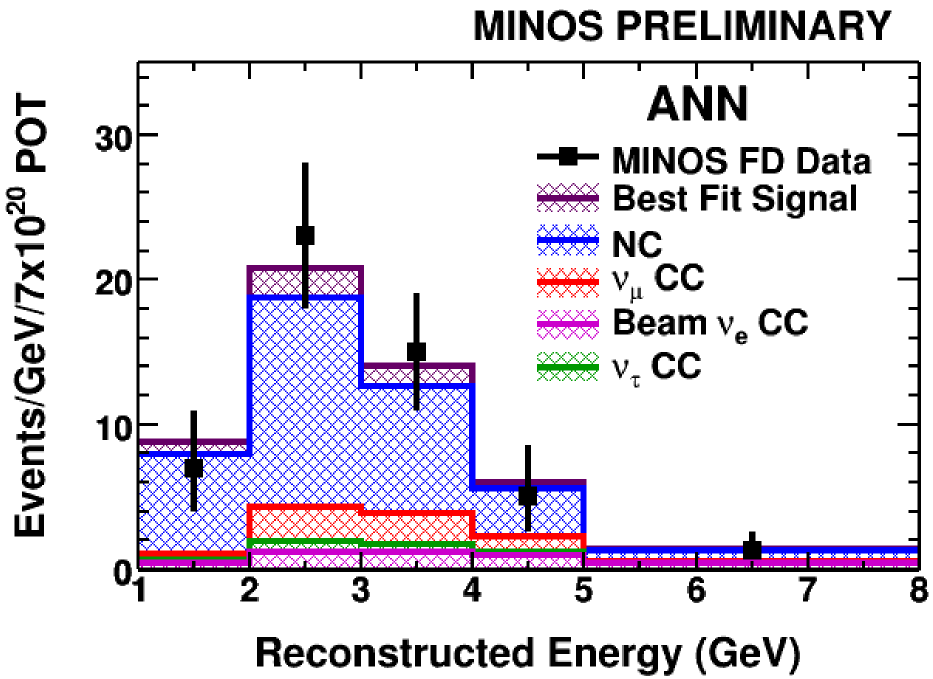


ν_e appearance results

Based on ND data, expect **49.1±7.0(stat.)±2.7(syst.)** events

Observe **54** events in the FD; a 0.7σ excess





ν_e appearance results

for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

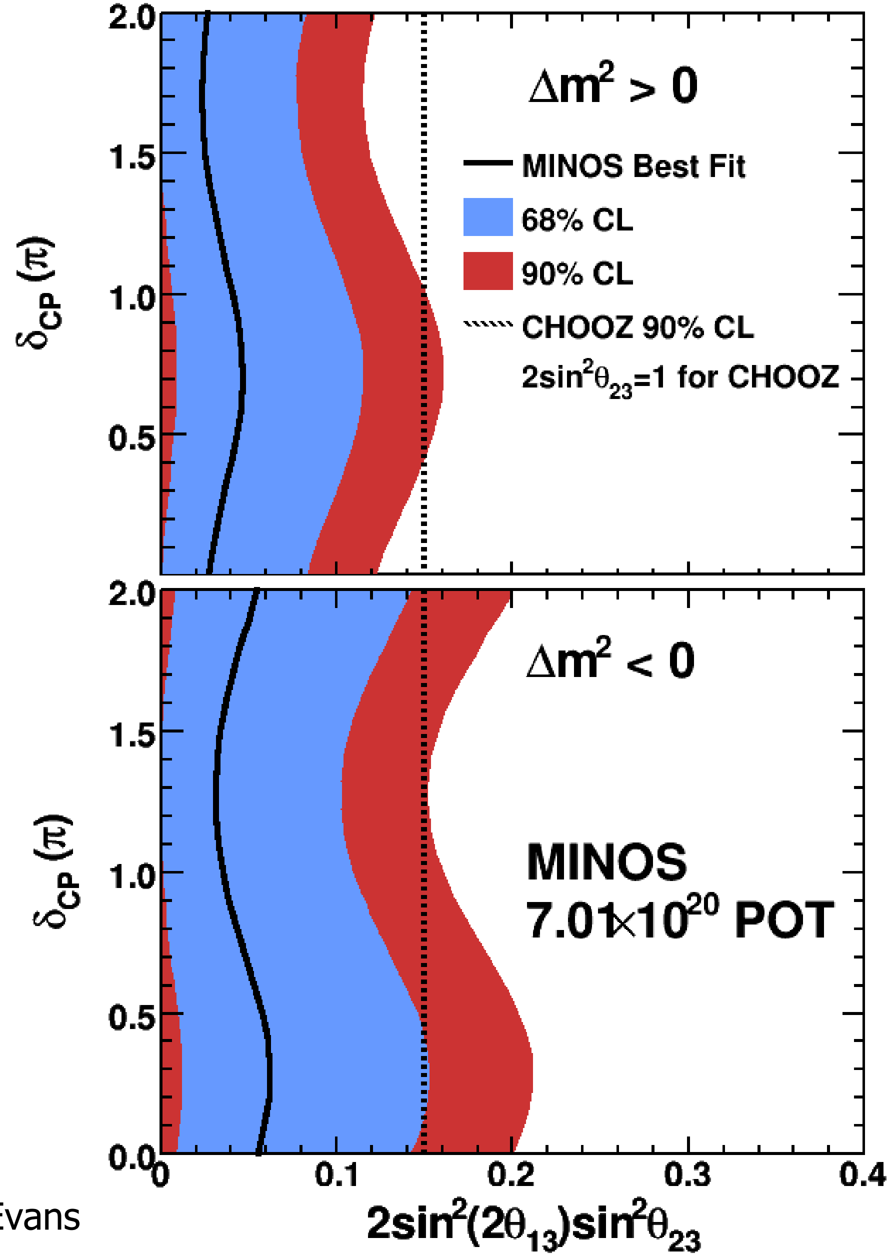
$|\Delta m^2_{32}| = 2.43 \times 10^{-3}\ \text{eV}^2$:

$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

$\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

at 90% C.L.

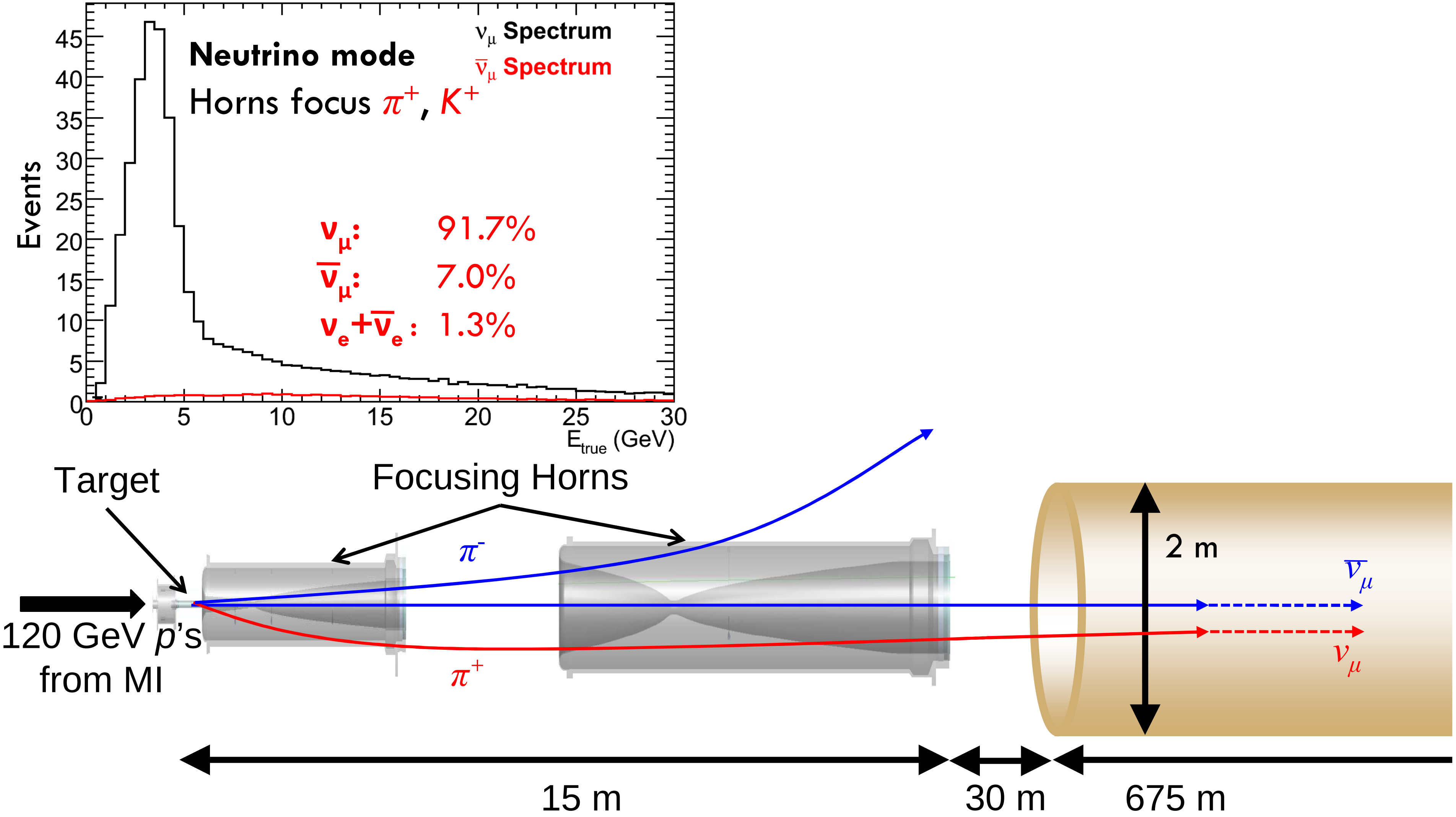
See poster by J. Evans & L. Whitehead



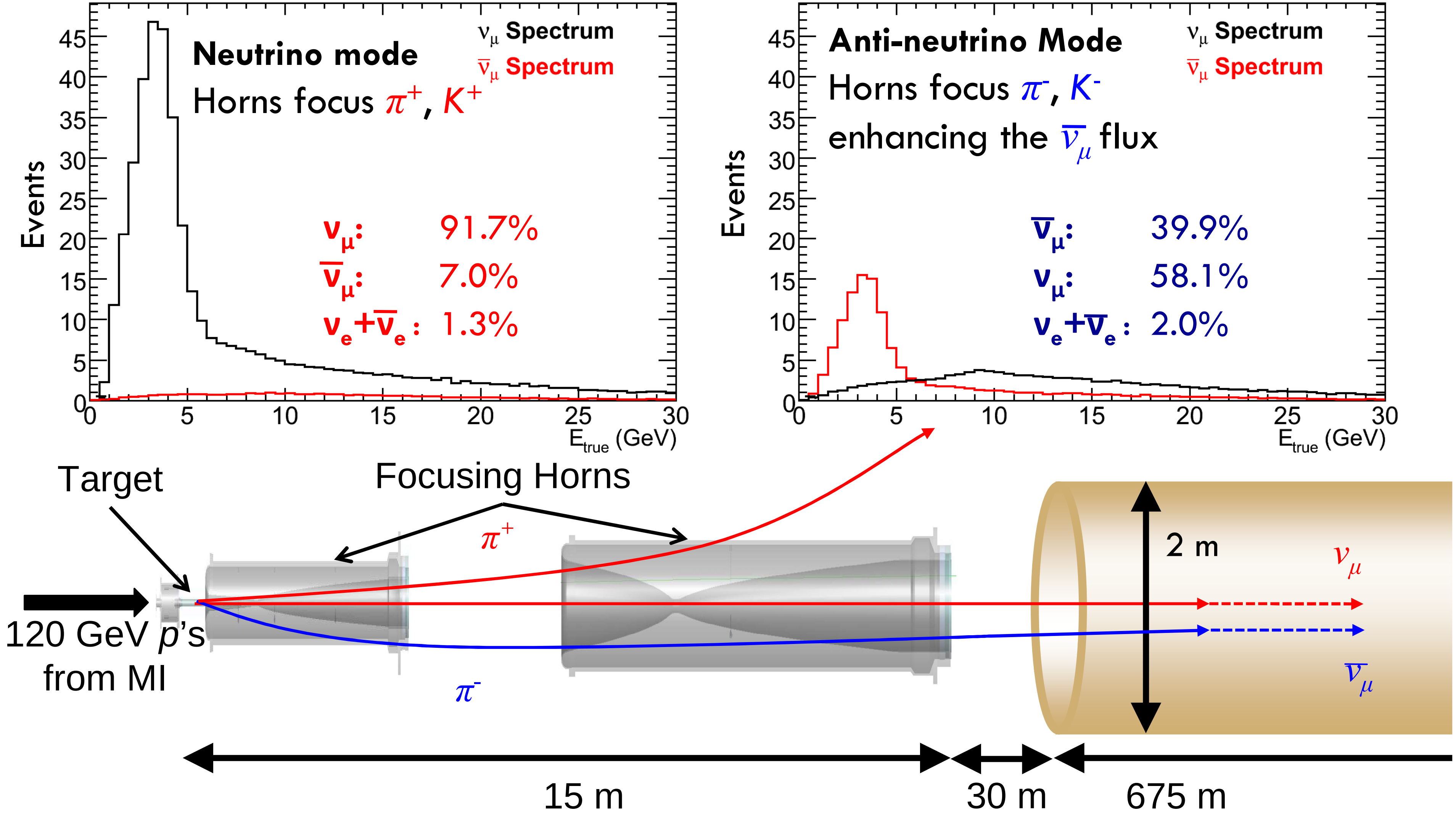
CC-$\bar{\nu}_{\mu}$ disappearance measurement

Measure $\sin^2(\bar{\theta}_{23})$ and $\Delta\bar{m}^2_{32}$

Making an antineutrino beam



Making an antineutrino beam

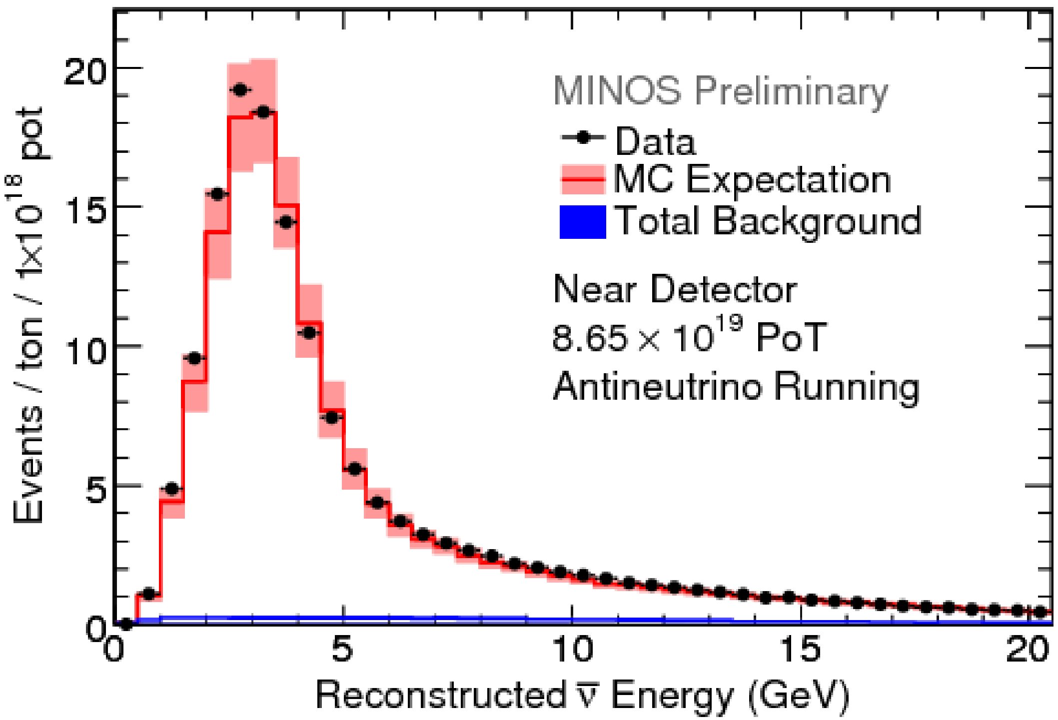


Near detector $\overline{\nu}_{\mu}$ data

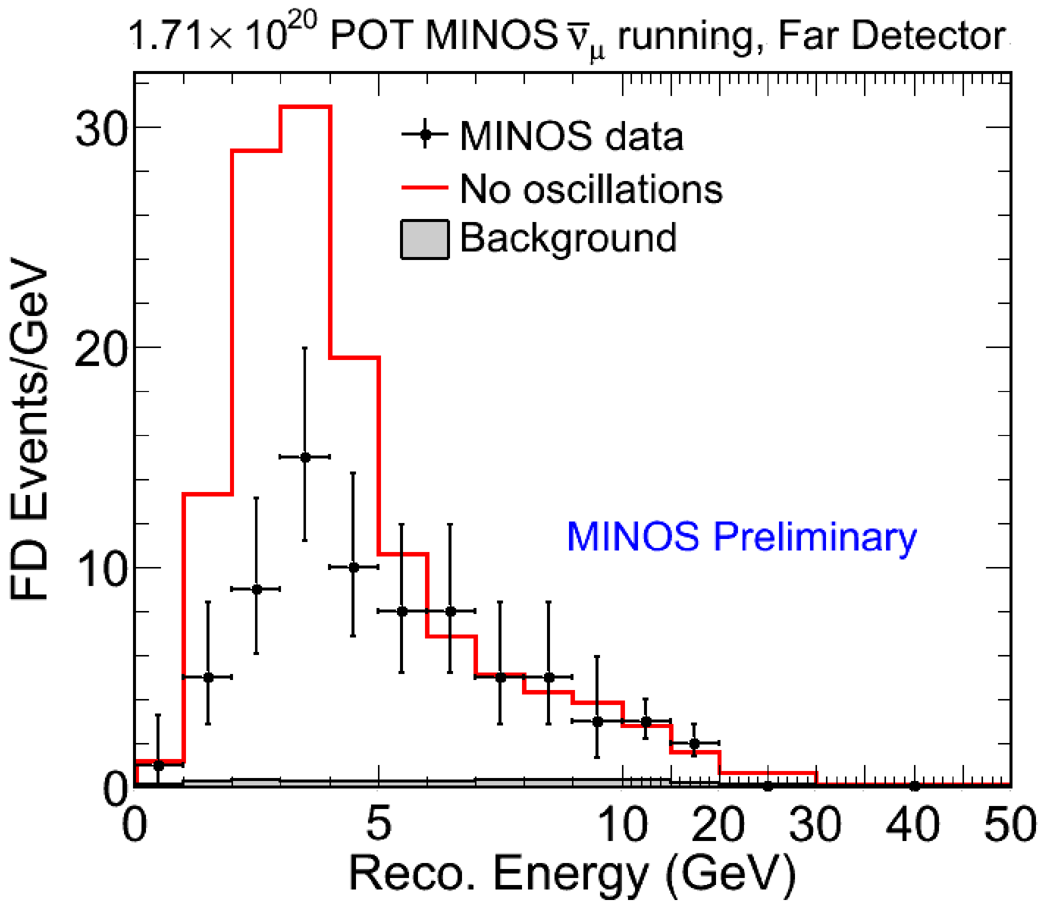
Focus and select positive muons
- Purity 94.3% after charge sign cut
- Purity 98% < 6GeV

Analysis proceeds as (2008) neutrino analysis

Data/MC agreement comparable to neutrino running



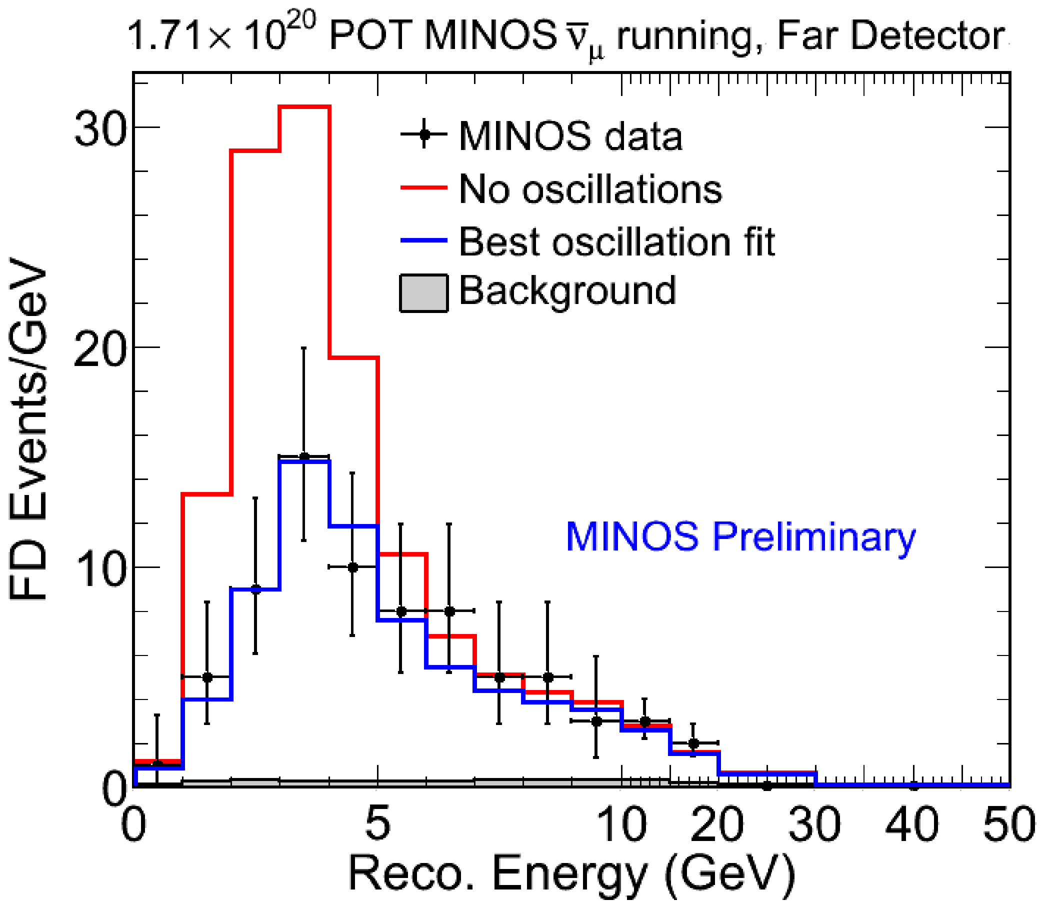
$\bar{\nu}_\mu$ results



At the far detector

- No oscillation prediction: **155 events**
- Observe: **97 events**
- No oscillations disfavored at 6.3σ

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



At the far detector

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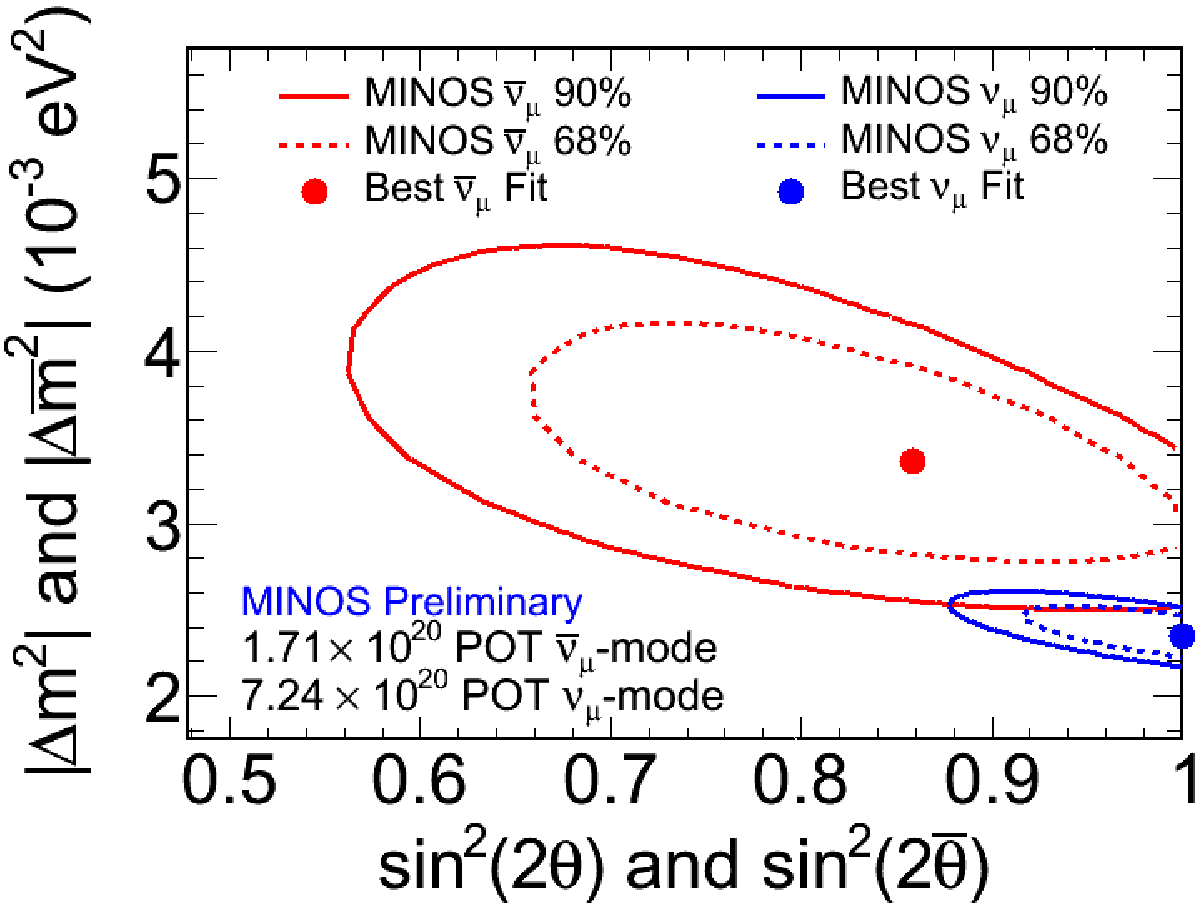
$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

$\bar{\nu}_\mu$ oscillation parameters

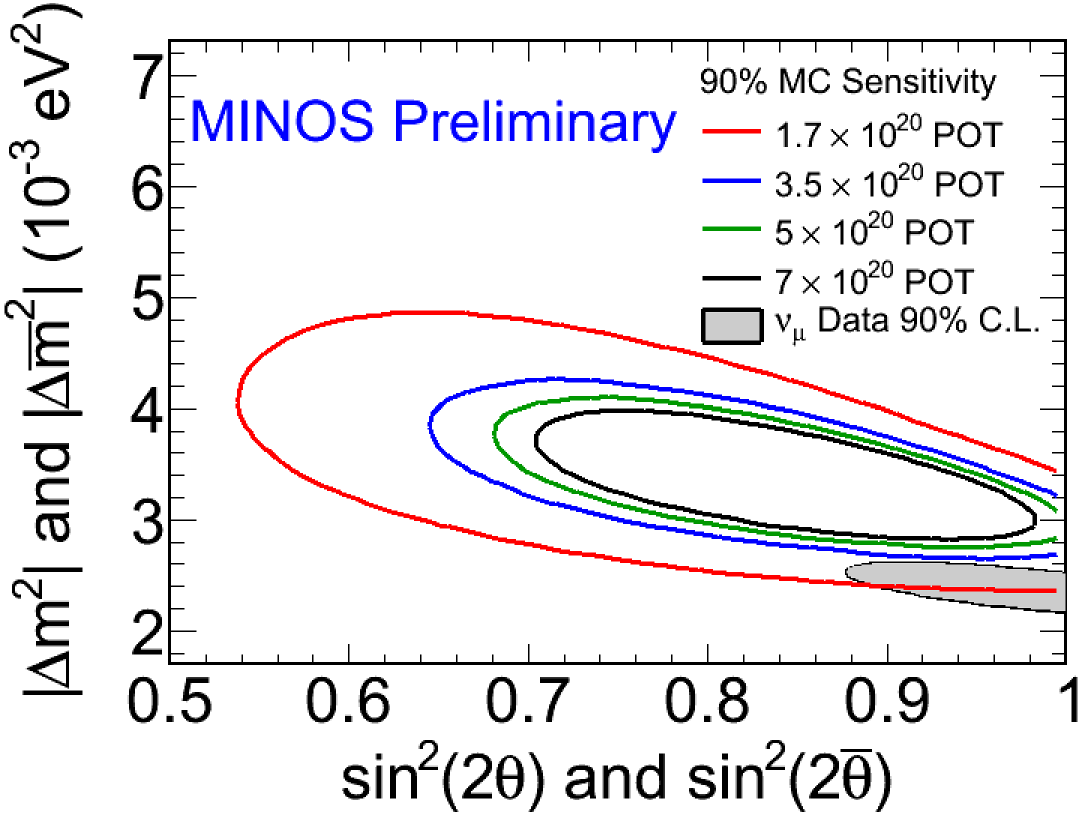


- Contours include the effects of systematic uncertainties

The future

With more antineutrino running, MINOS can quickly improve the precision by a significant amount

Doubling the current six-month data set would decrease the uncertainty by 30%



Summary

With 7x10[20] PoT of neutrino beam, MINOS finds:

- Muon neutrinos disappear

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

- NC event rate is not diminished

$$f_s < 0.22\,(0.40)\ \text{at}\ 90\%\ \text{C.L.}$$

- Electron-neutrino appearance search sets limits on θ_{13}

$$\sin^2(2\theta_{13}) < 0.12\ (0.20)\ \text{at}\ 90\%\ \text{C.L.}$$

With 1.71x10[20] PoT of antineutrino beam:

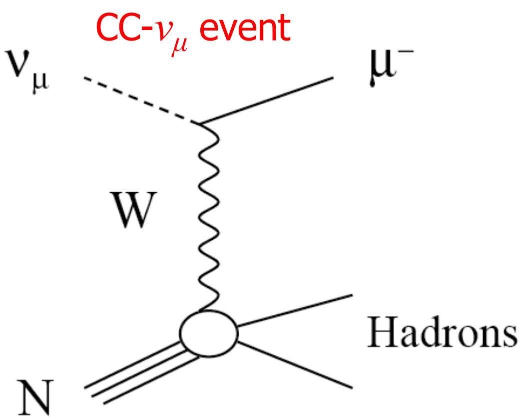
- Muon antineutrinos disappear

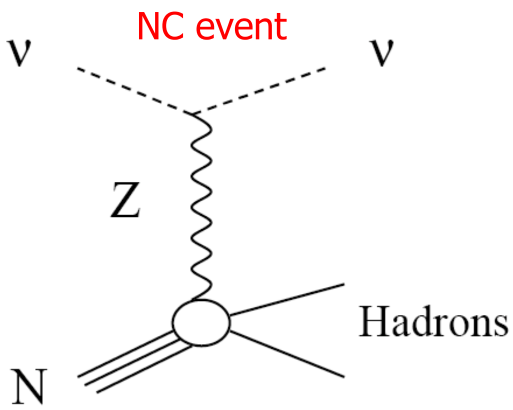
$$|\overline{\Delta m^2}| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\text{eV}^2,$$
$$\sin^2(2\overline{\theta}) = 0.86 \pm 0.11$$

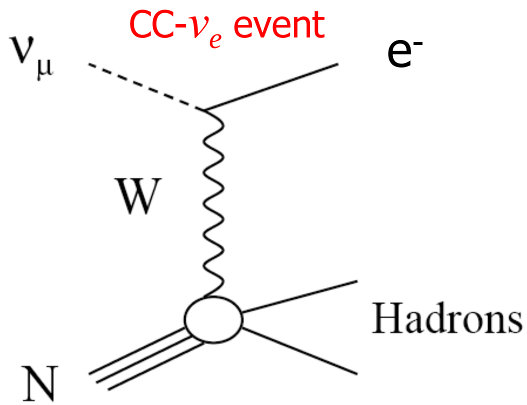
- We look forward to more antineutrino beam

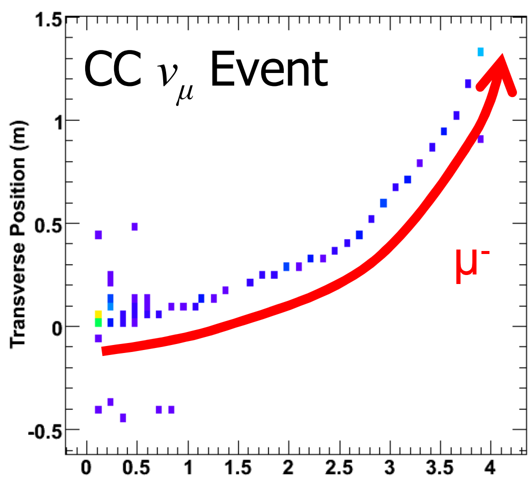
Backup

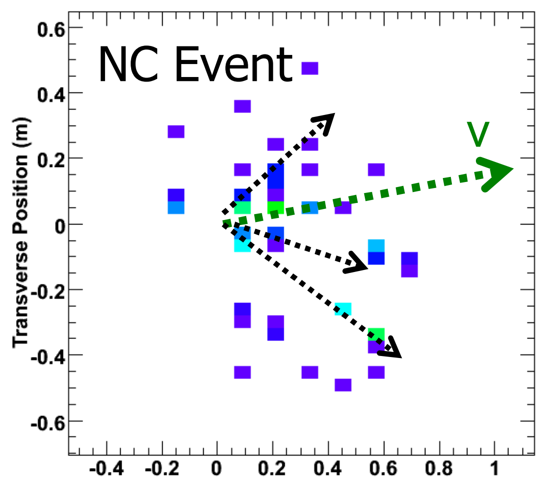
MINOS event topologies

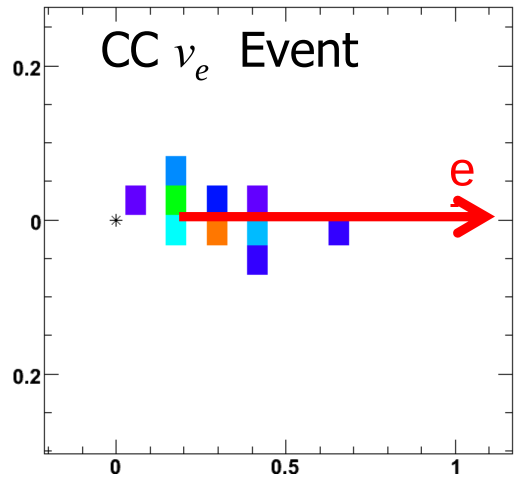




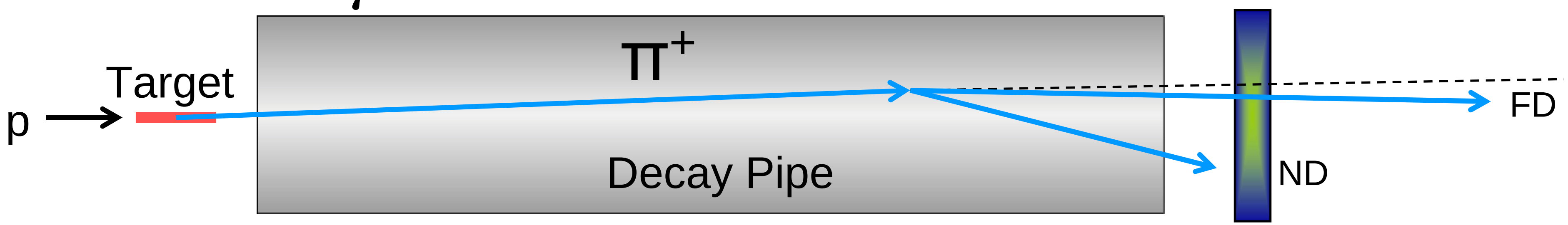








CC ν_μ beam extrapolation



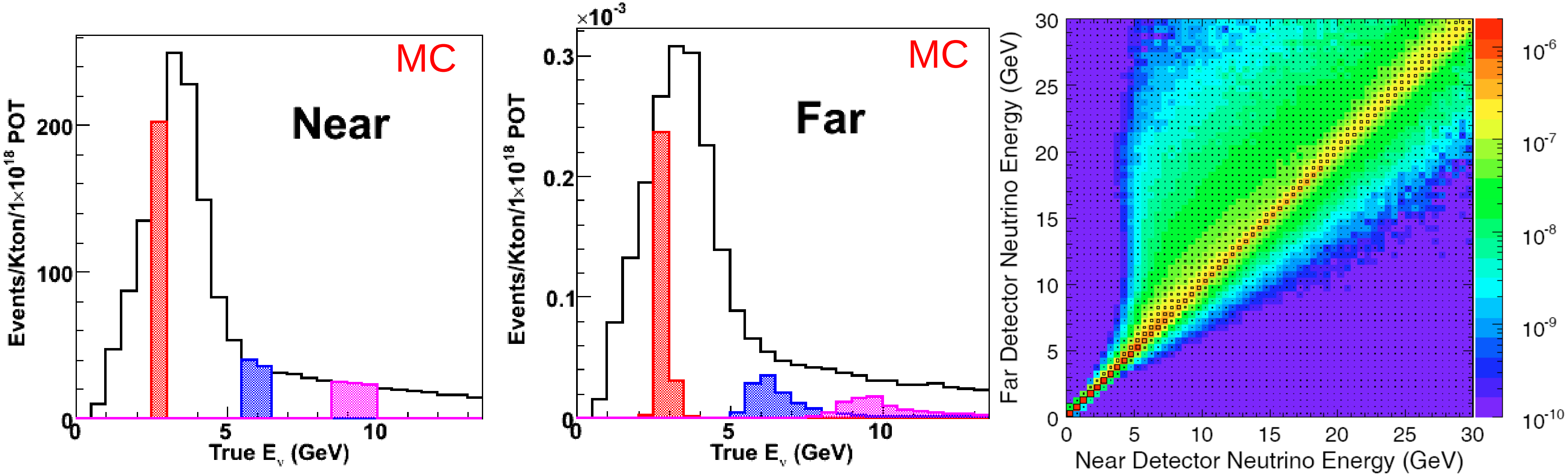
Use the measured ND energy spectrum to predict the FD spectrum:

Spread of pion decay directions smears neutrino energies

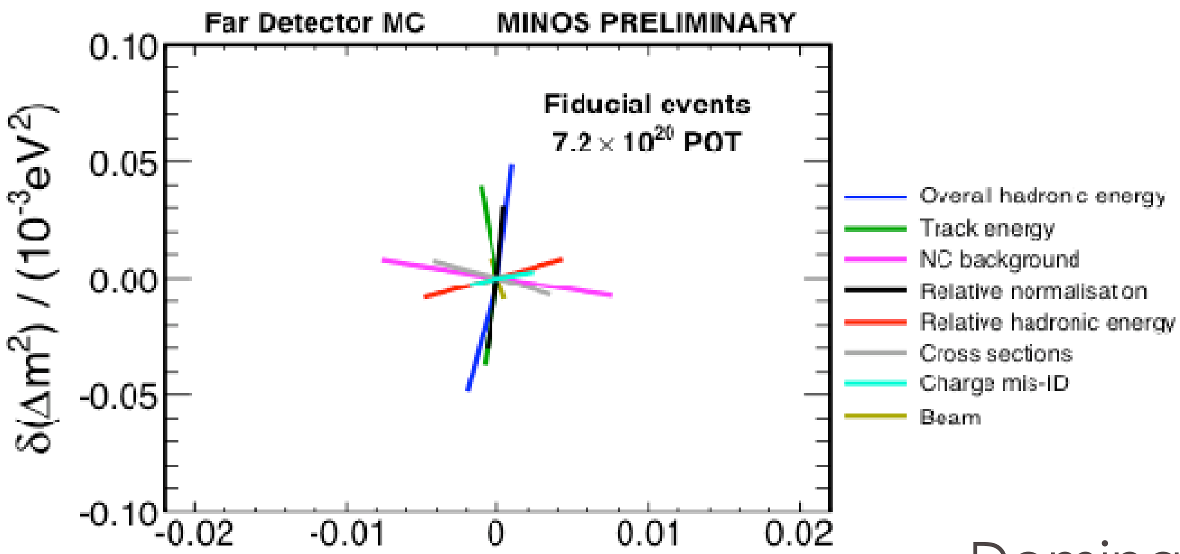
- Different energy spectra at the two detectors

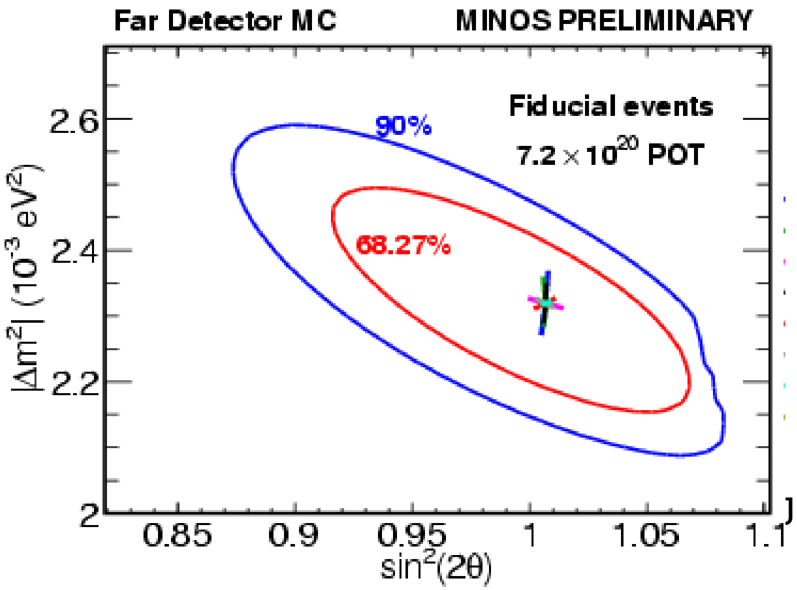
Encode the pion decay kinematics into a beam transfer matrix

- Convert ND to FD spectrum



CC ν_μ systematic uncertainties

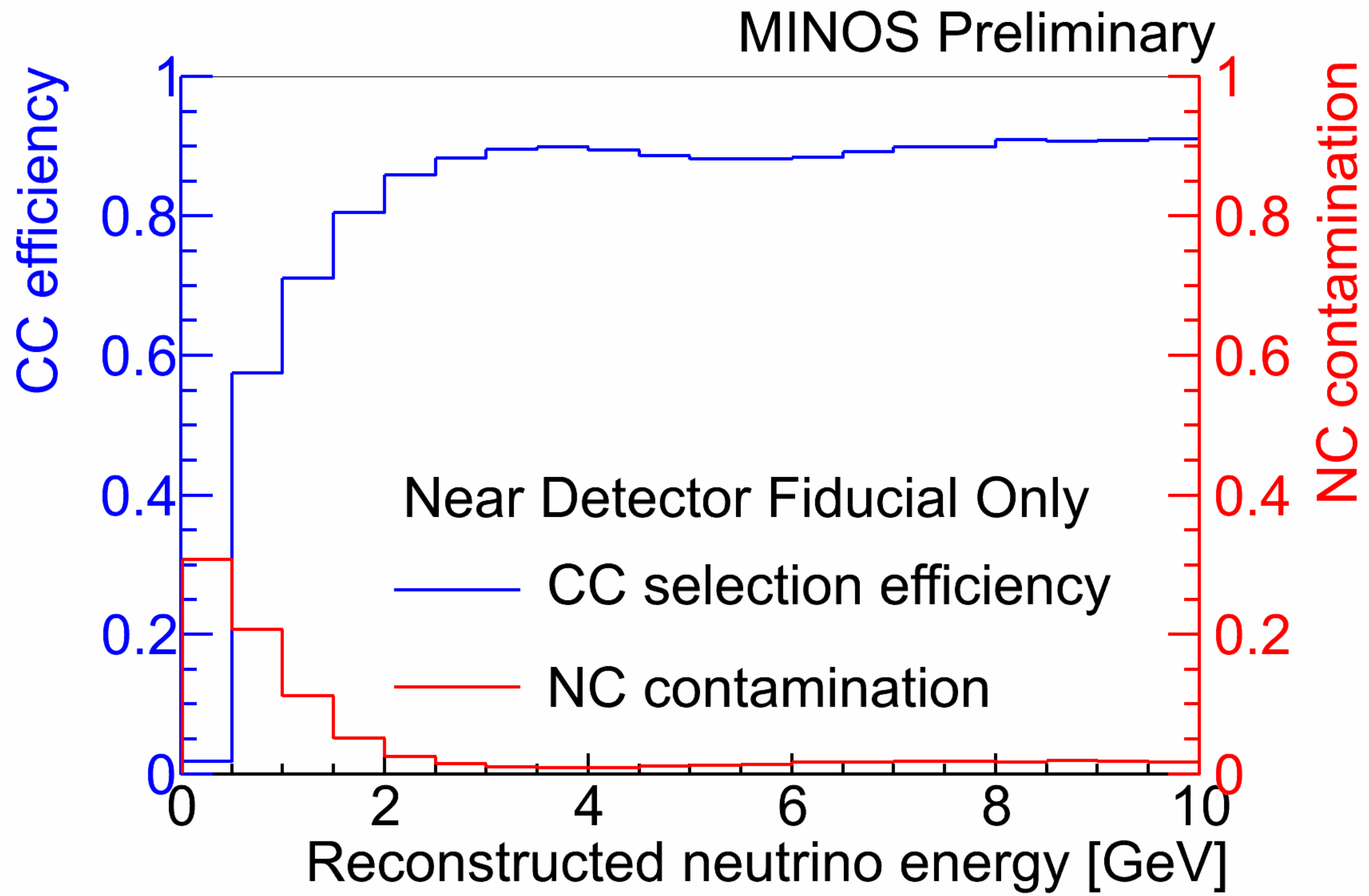




Dominant systematic uncertainties:

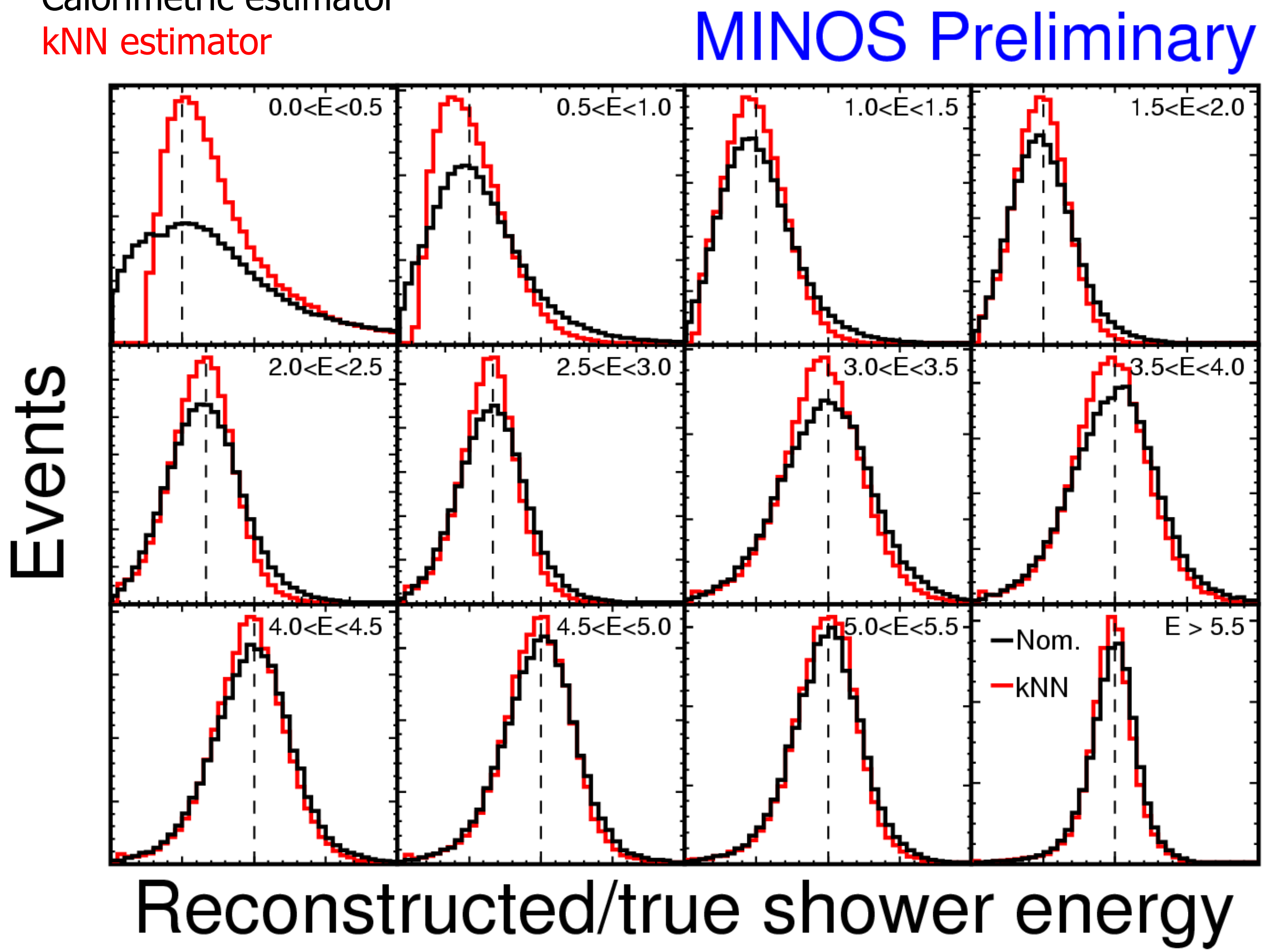
- Hadronic energy calibration
- Track energy calibration
- NC background
- Relative Near to Far normalization

New CC ν_μ selection

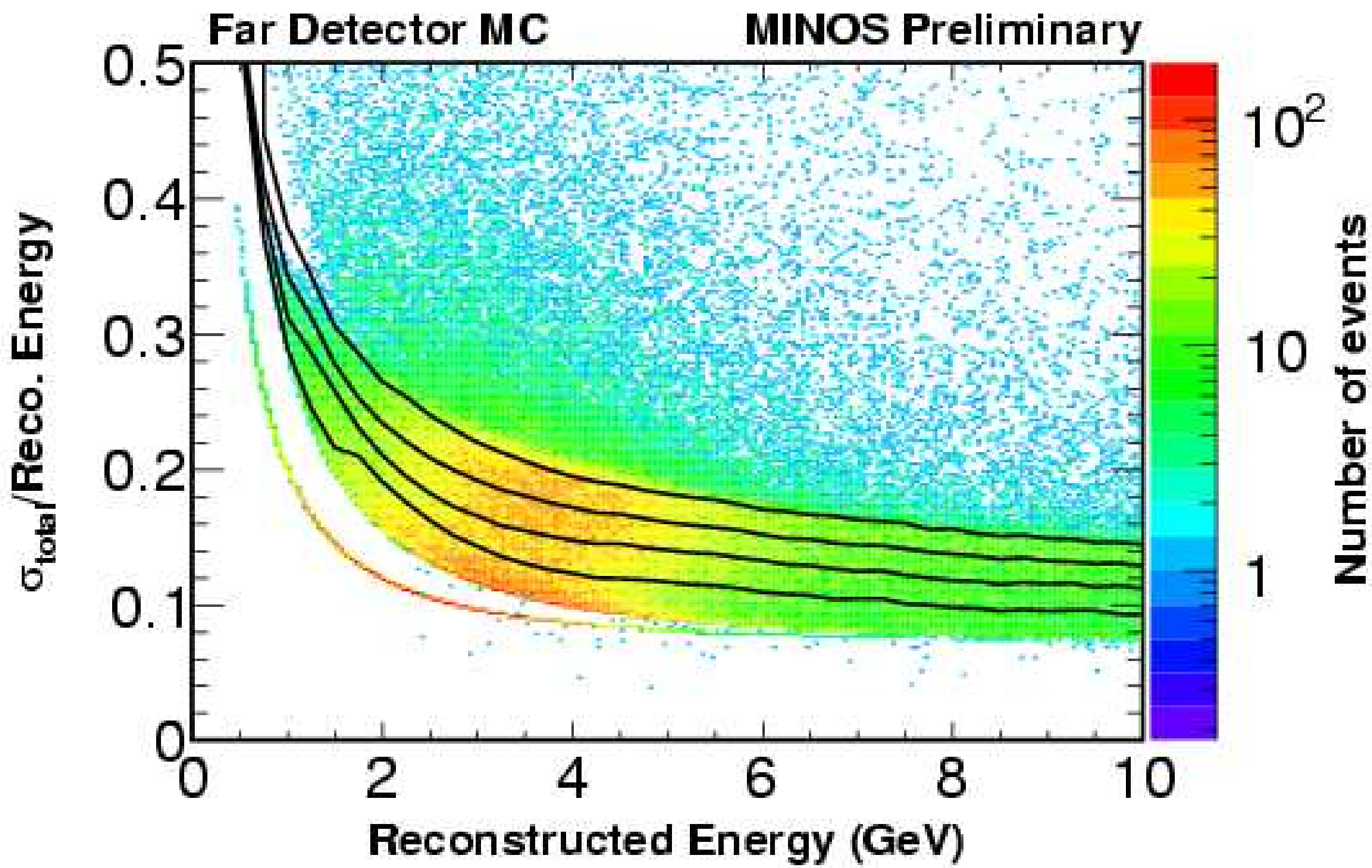


Shower energy resolution

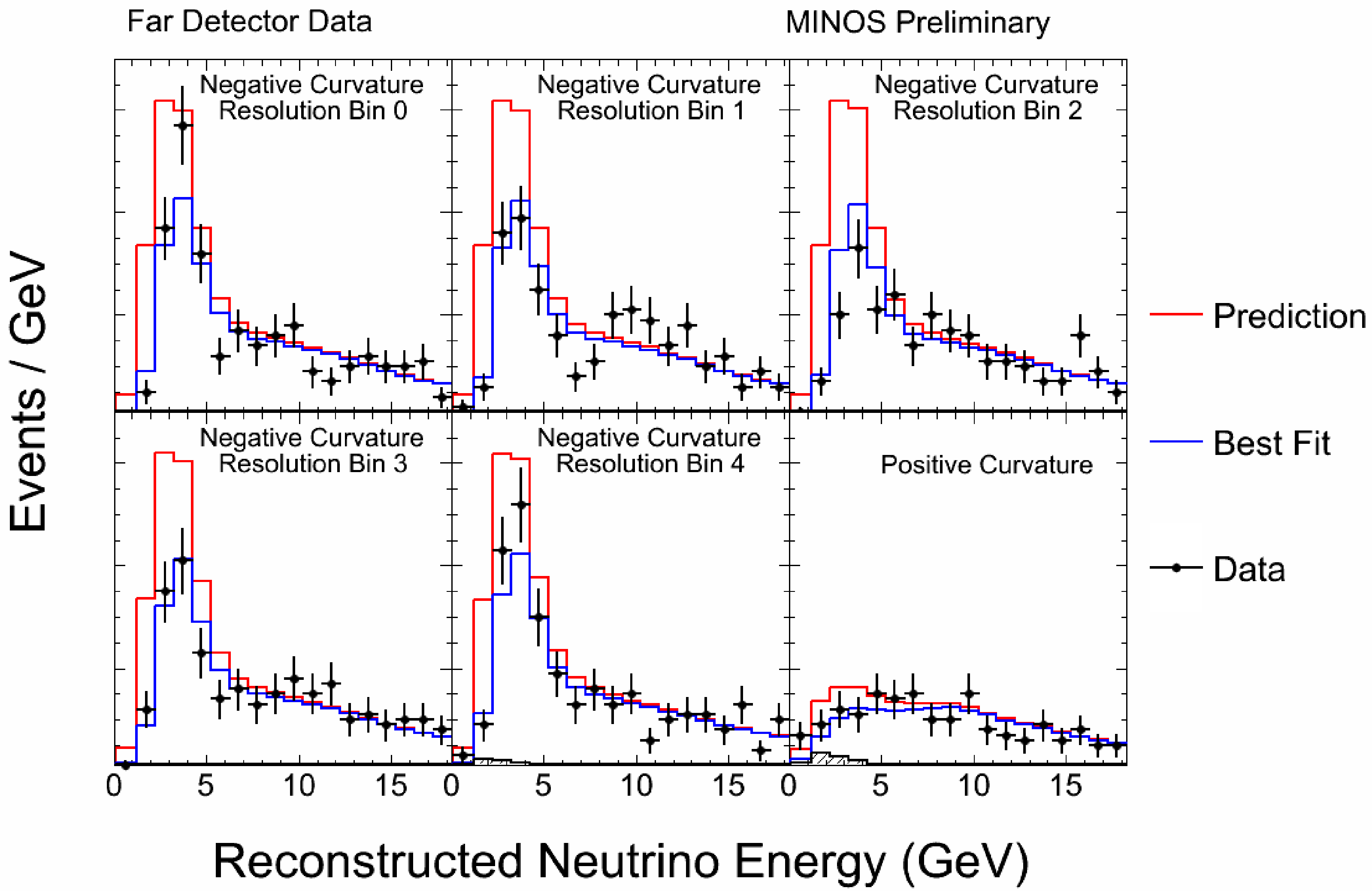
Calorimetric estimator
kNN estimator



Energy resolution binning

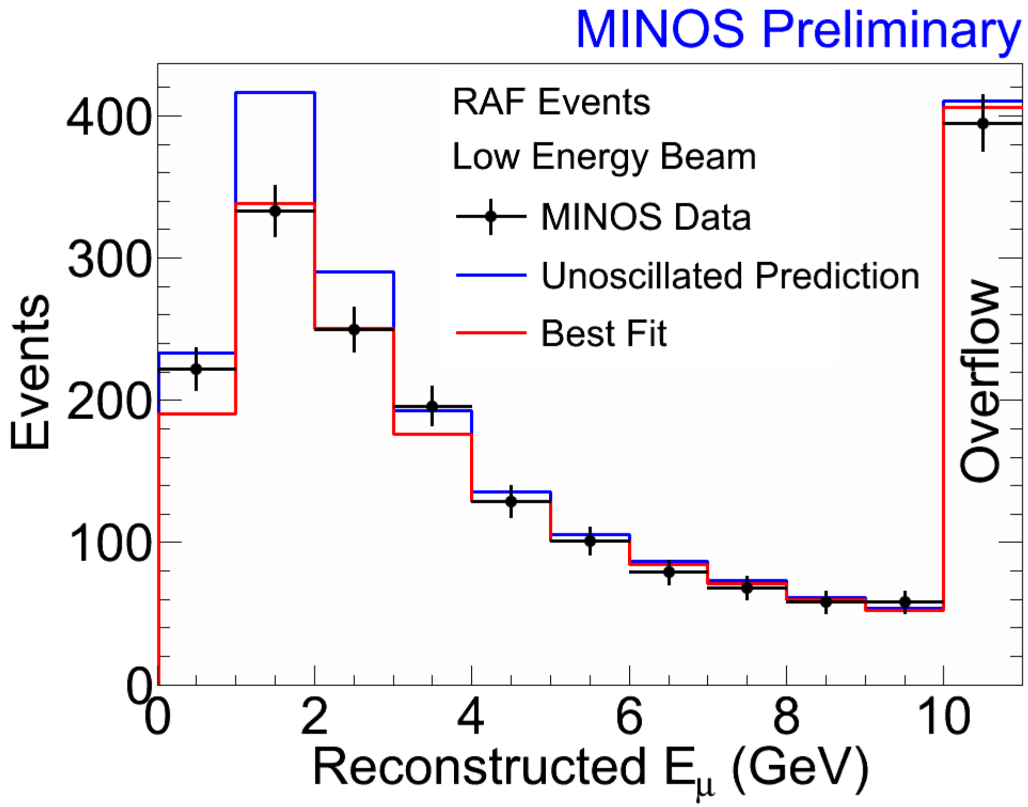


Resolution binning



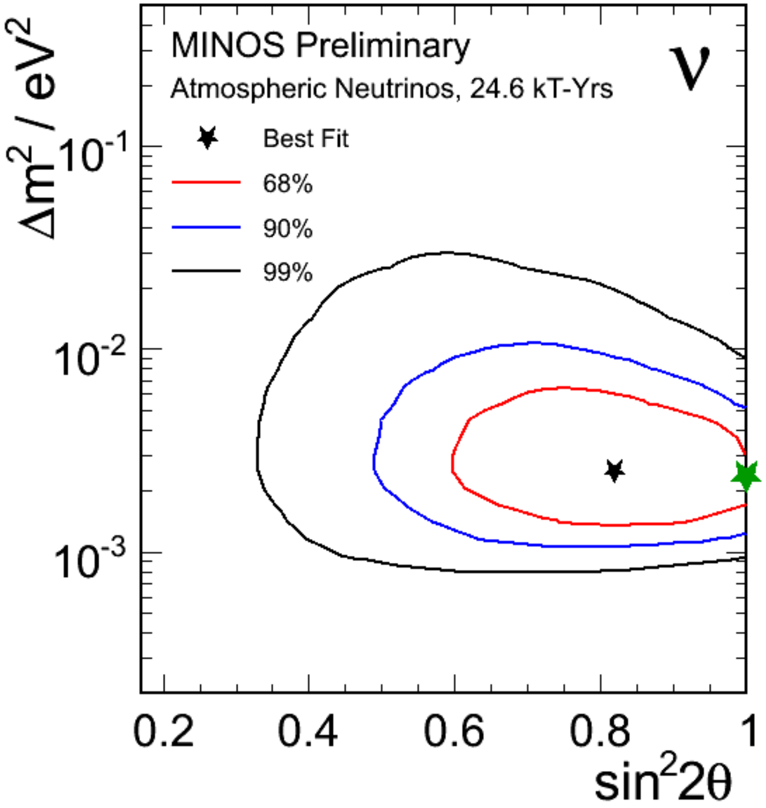
Rock and anti-fiducial events

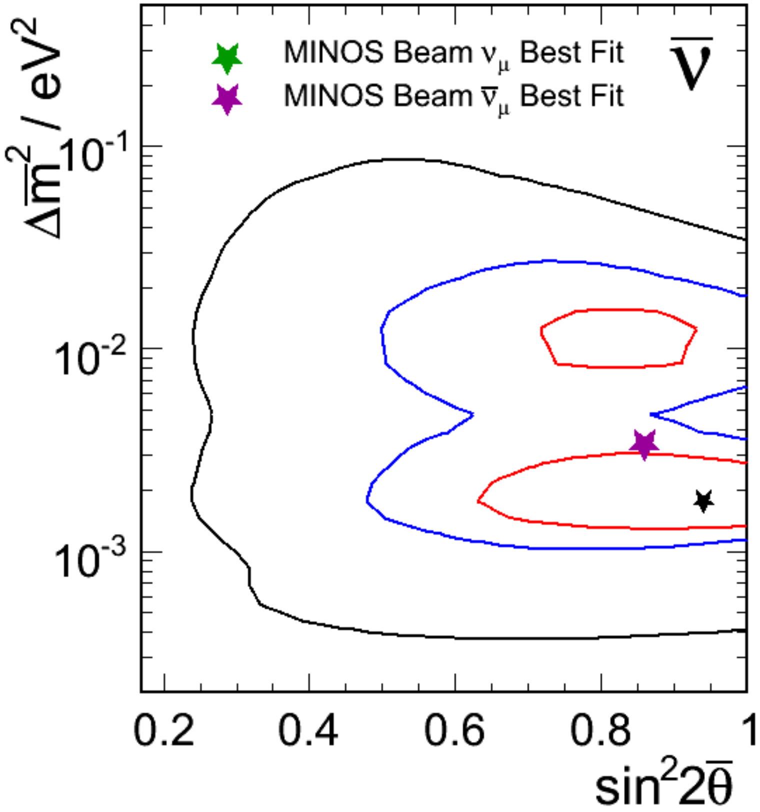
- Neutrinos interact in rock around detector and outside of fiducial region
- These events double sample size, events have poorer energy resolution



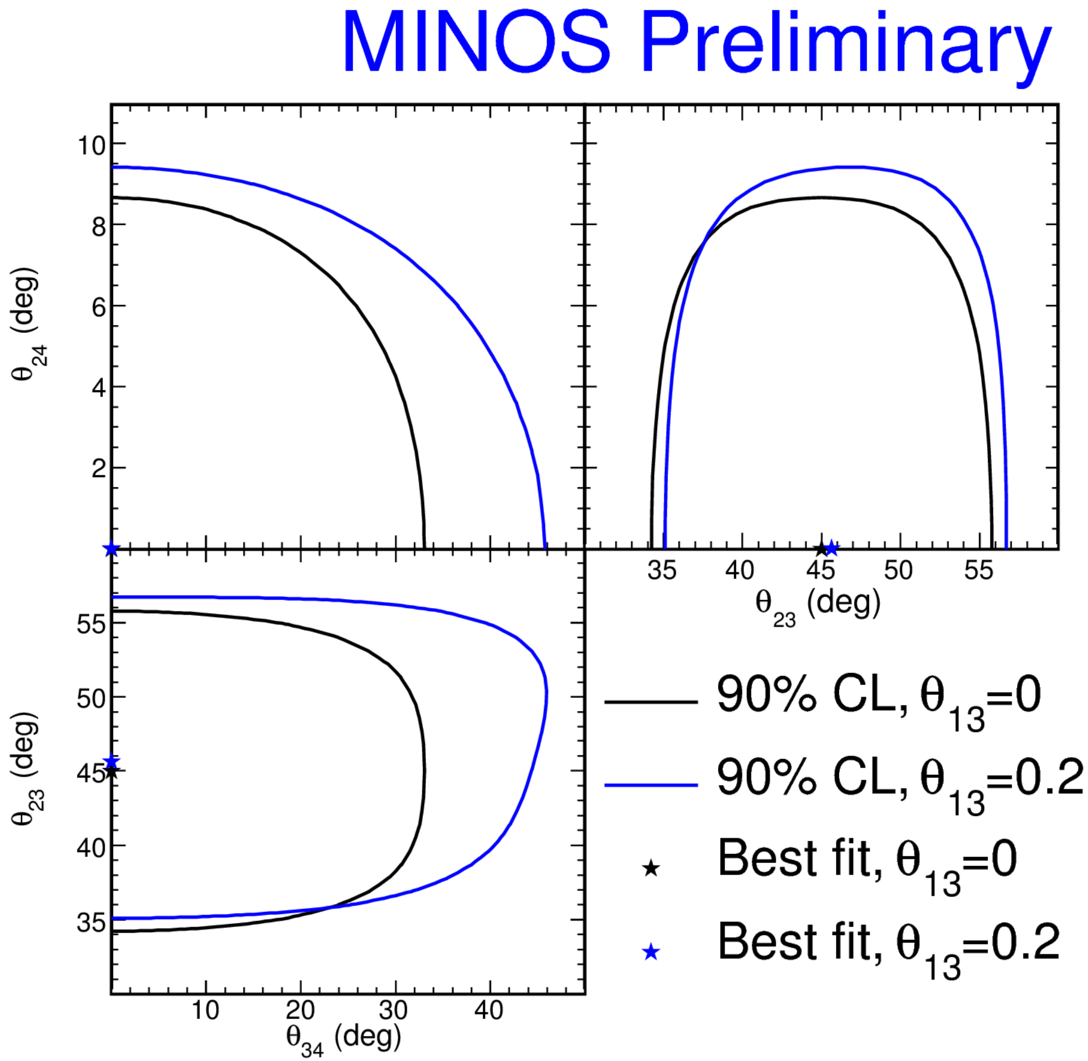
Combined fit coming soon

Atmospheric neutrinos





NC disappearance search

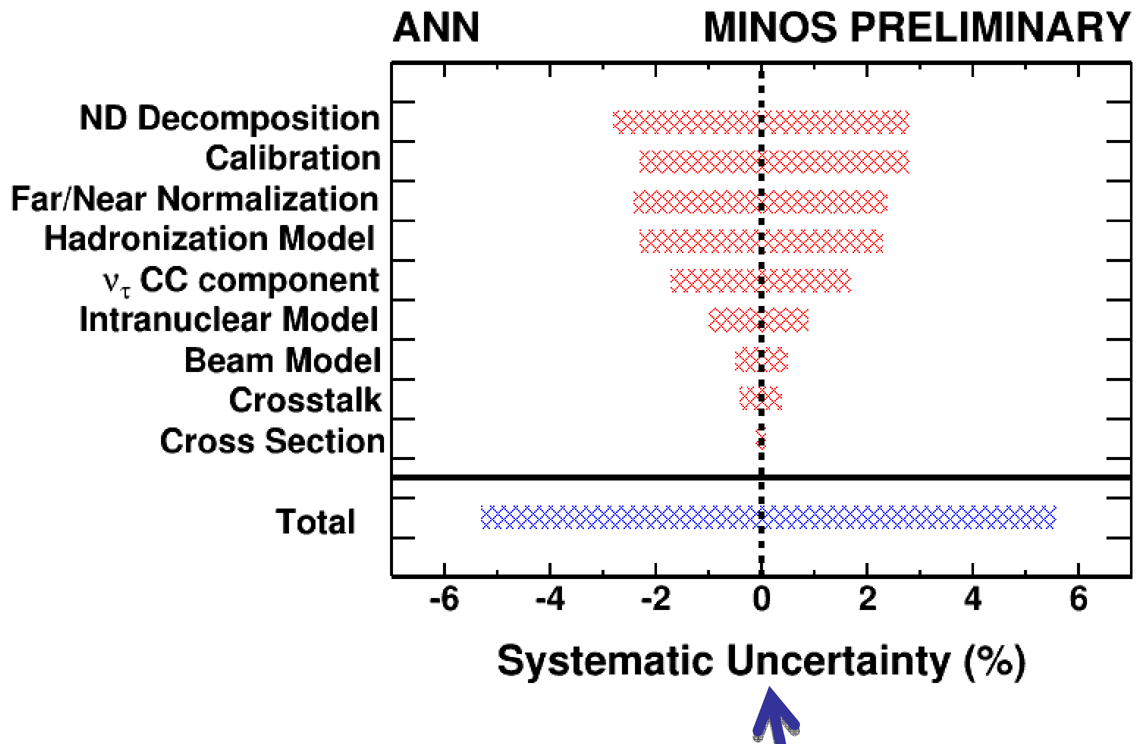


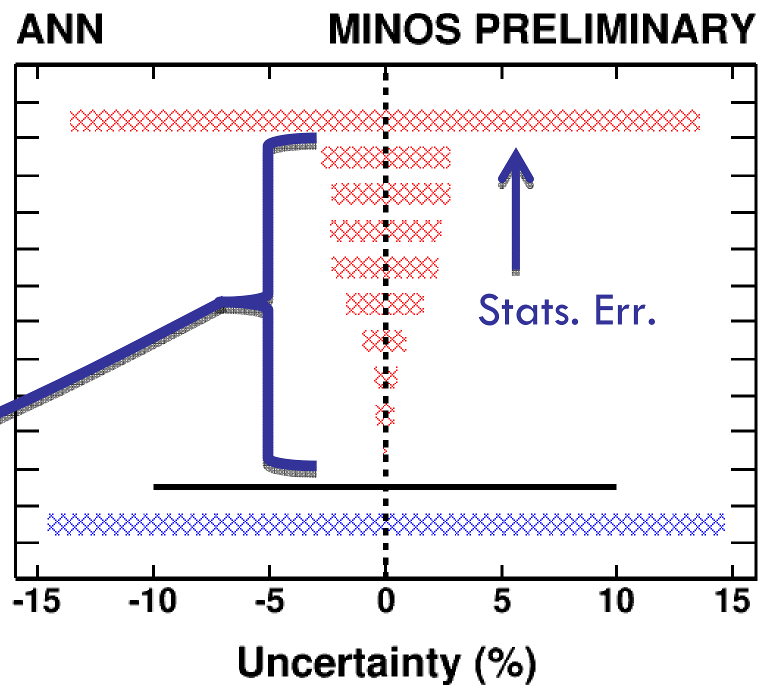
Fit CC/NC spectra simultaneously with a 4th (sterile) neutrino

2 choices for 4th mass eigenvalue

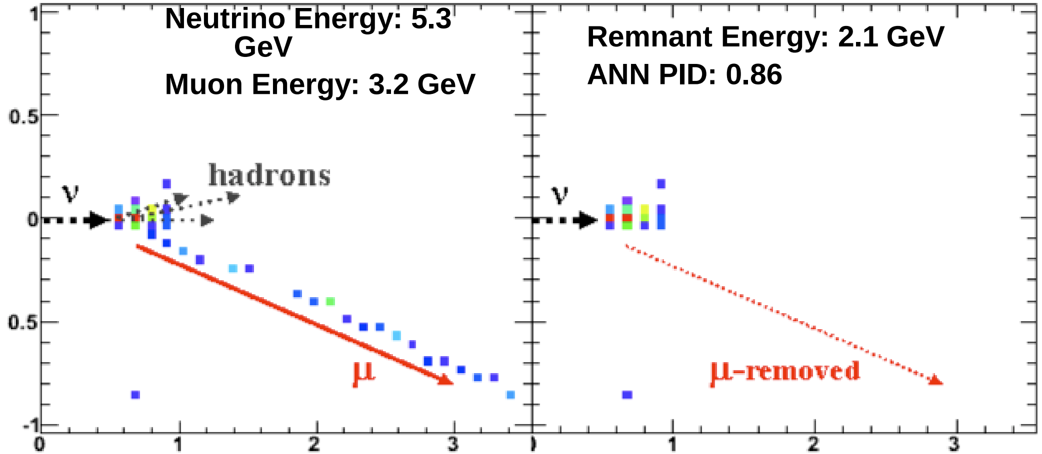
- $m_4 \gg m_3$
- $m_4 = m_1$

Electron neutrino systematics

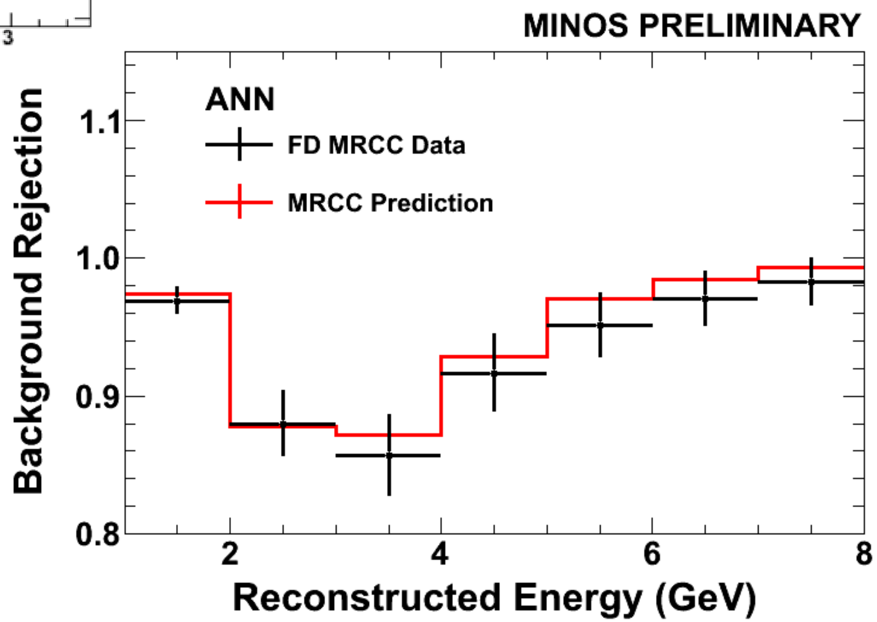




MRCC Background Rejection Check



Remove muons, test BG rejection on shower remnants



Mis-id rate:

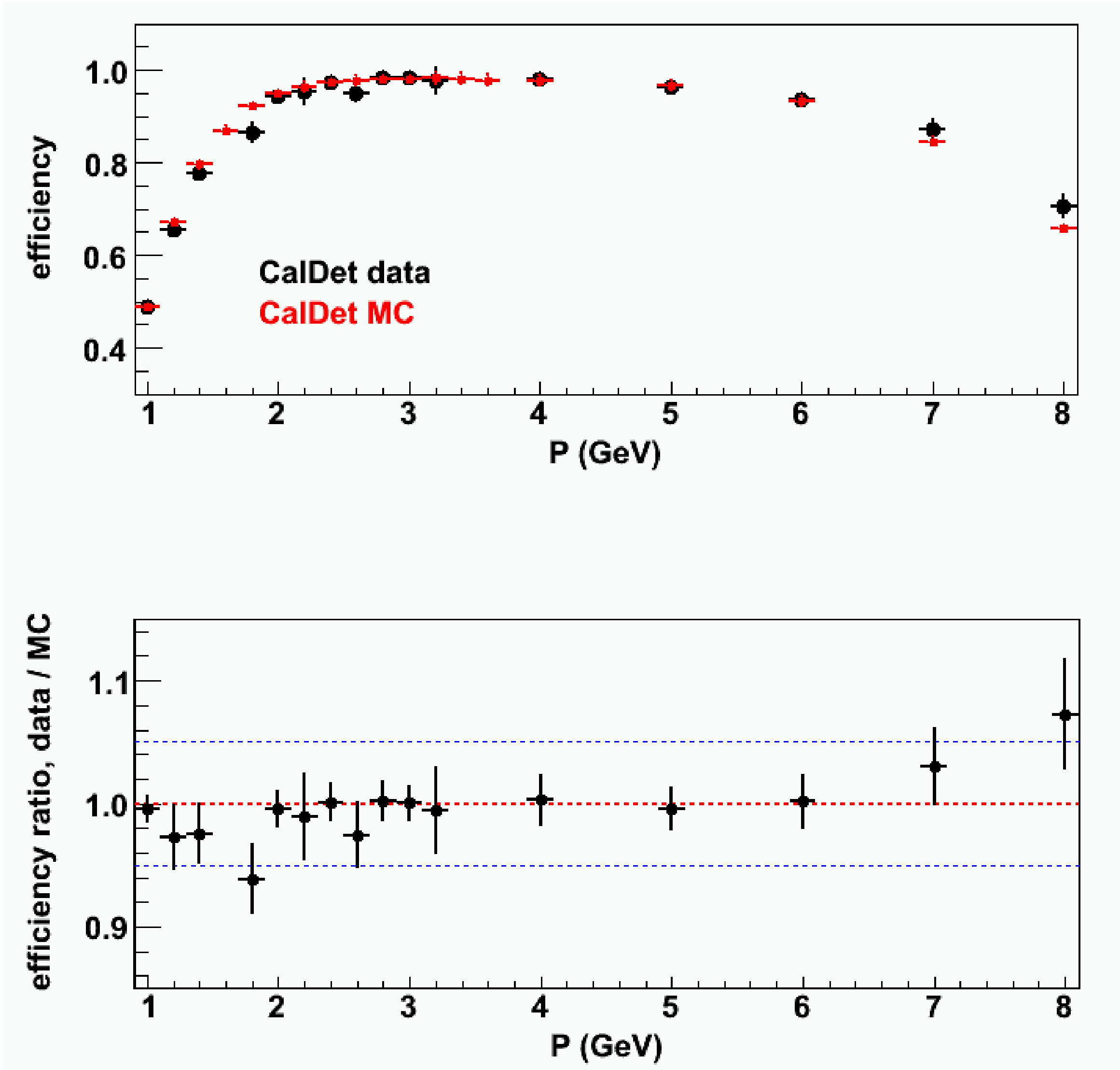
- pred (6.42±0.05)%
- data (7.2±0.9)%

(stats error only)

Compatible at 0.86σ

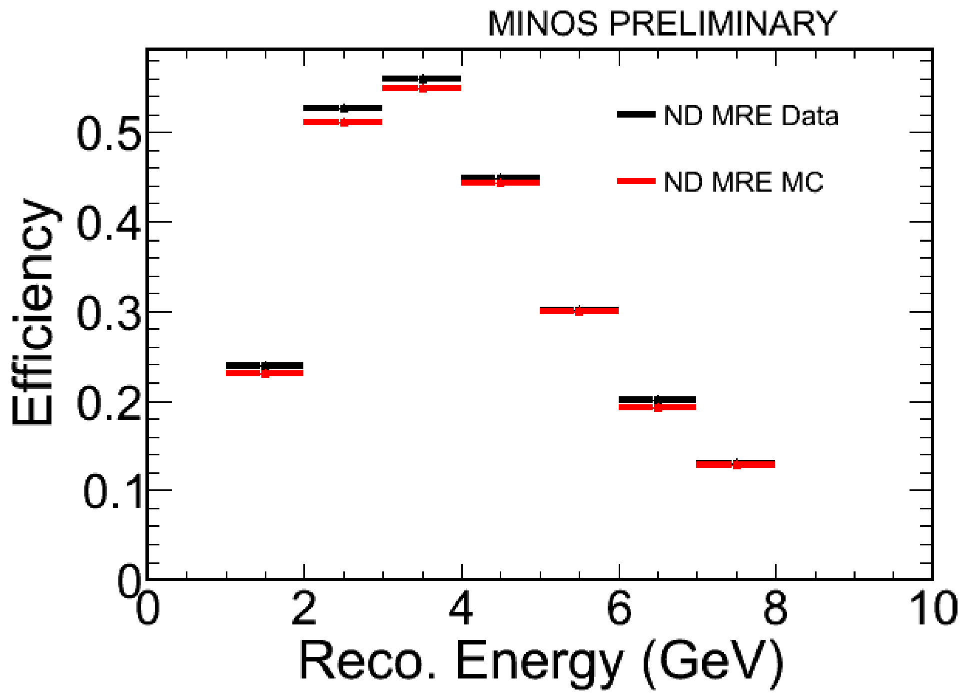
Checking signal efficiency

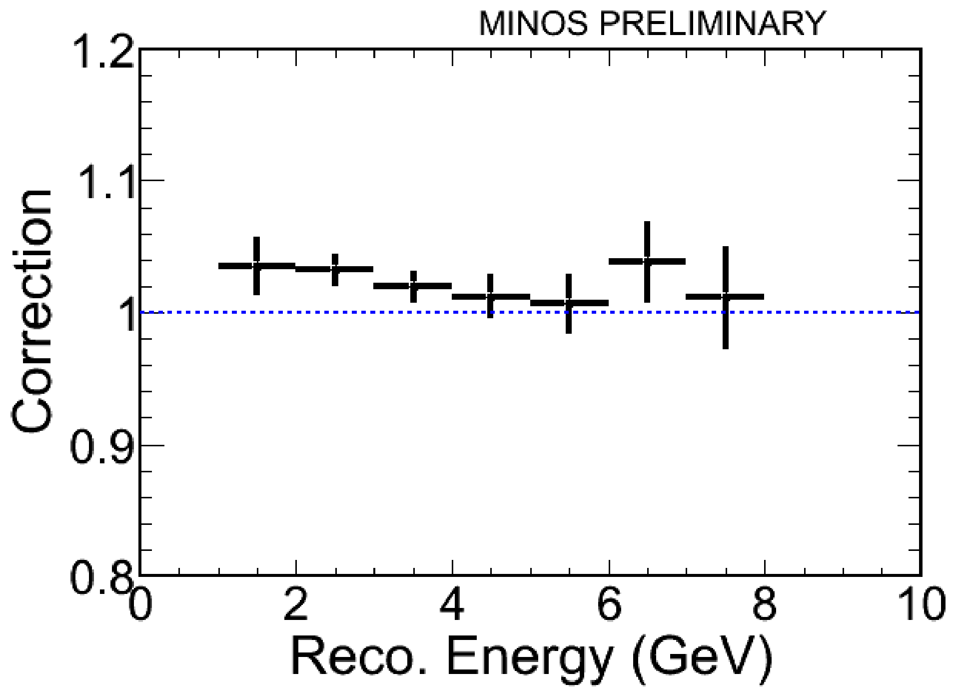
Test beam measurements demonstrate electrons are well simulated



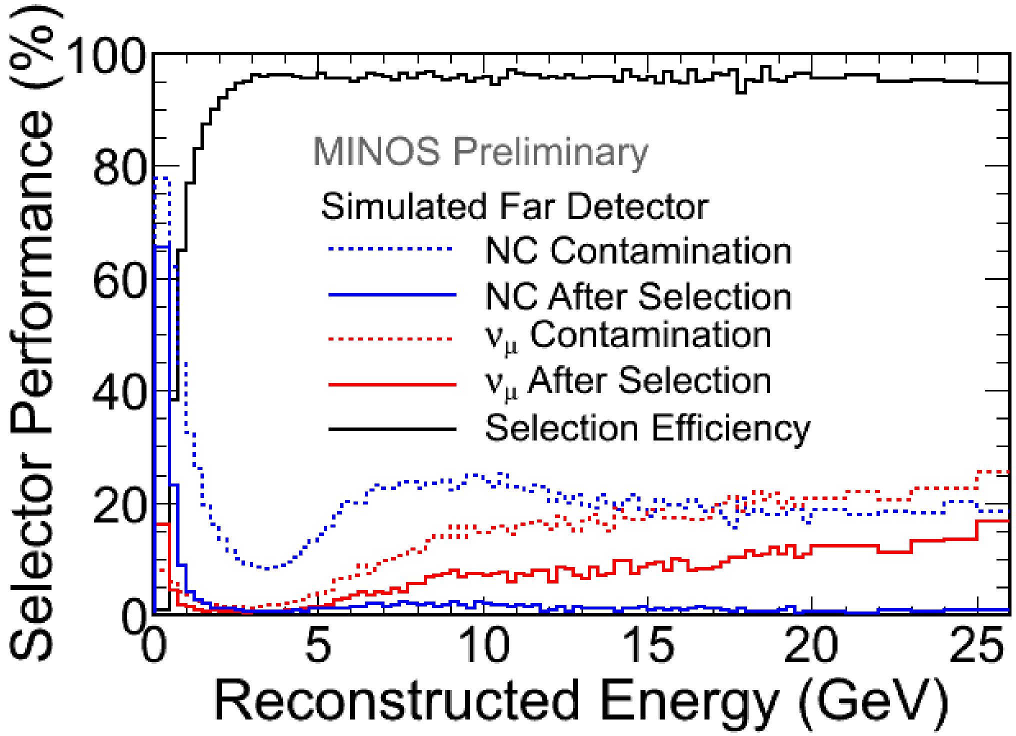
Checking signal efficiency

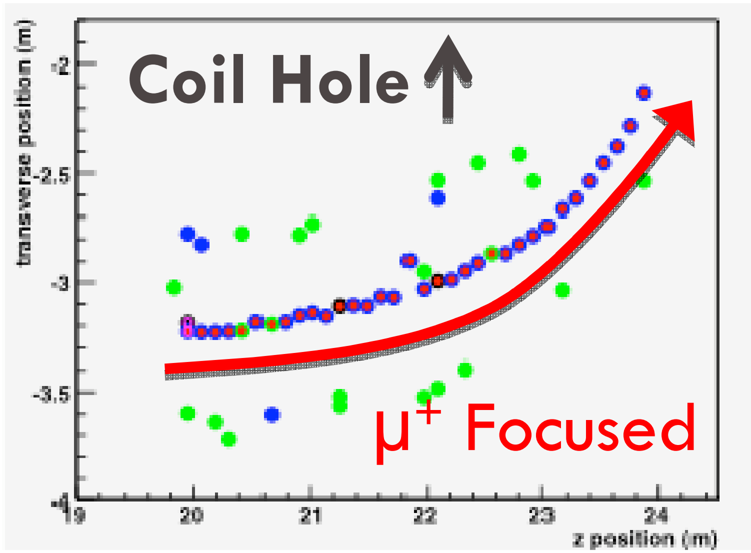
Check electron neutrino selection efficiency by removing muons, add a simulated electron

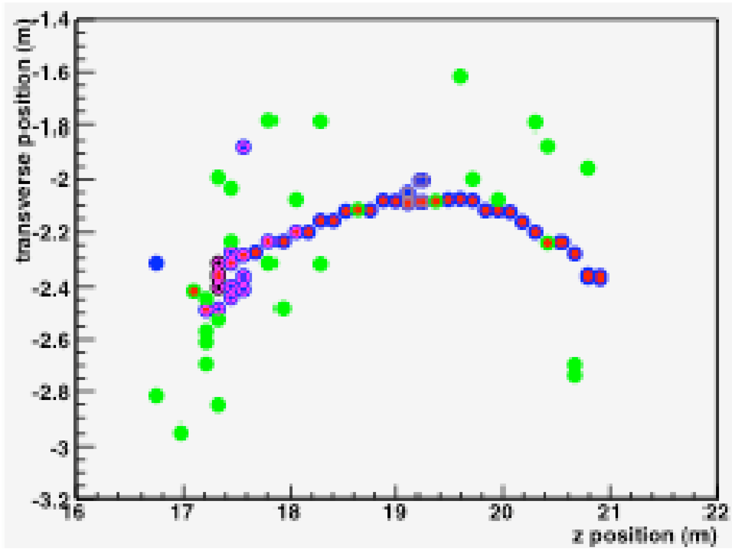




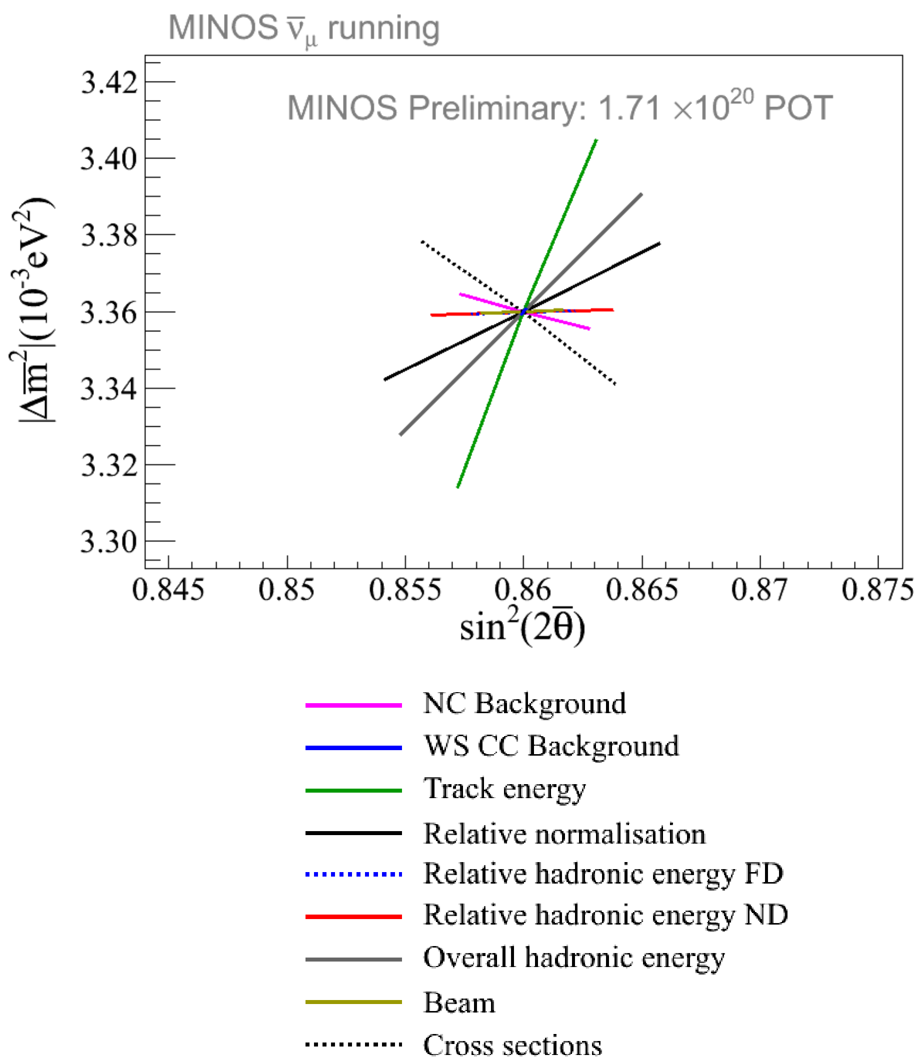
Antineutrino selection

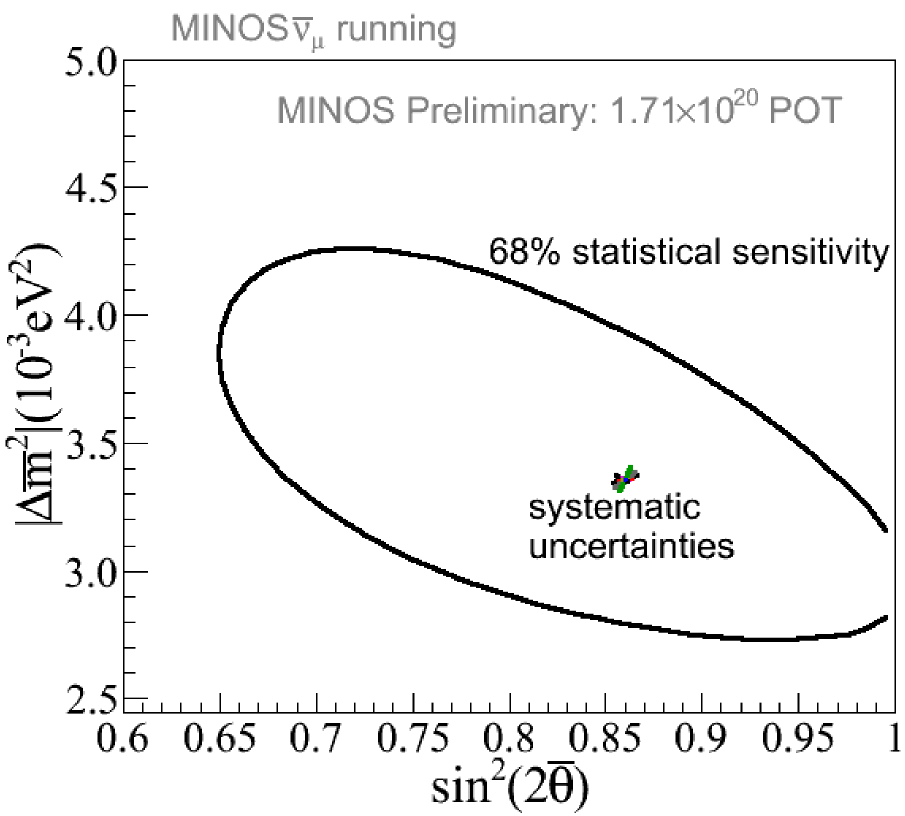




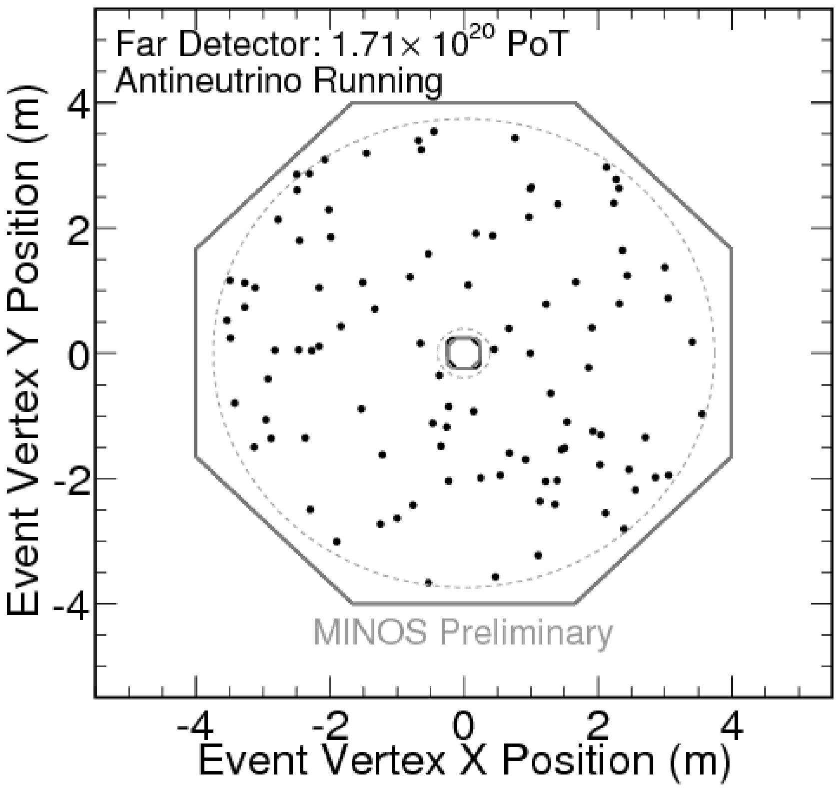


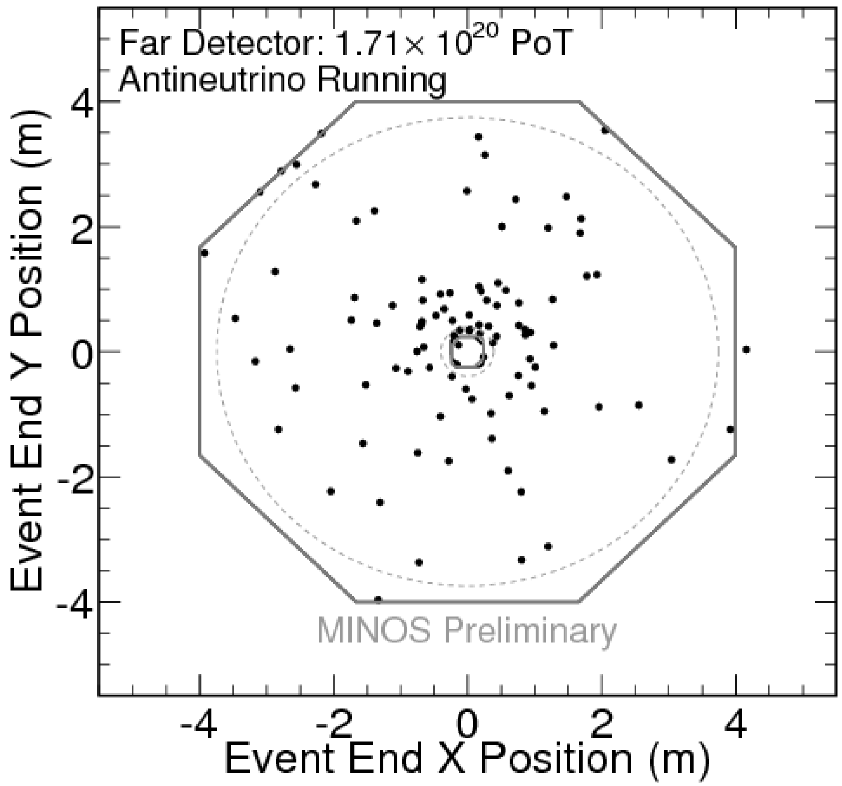
Antineutrino systematics





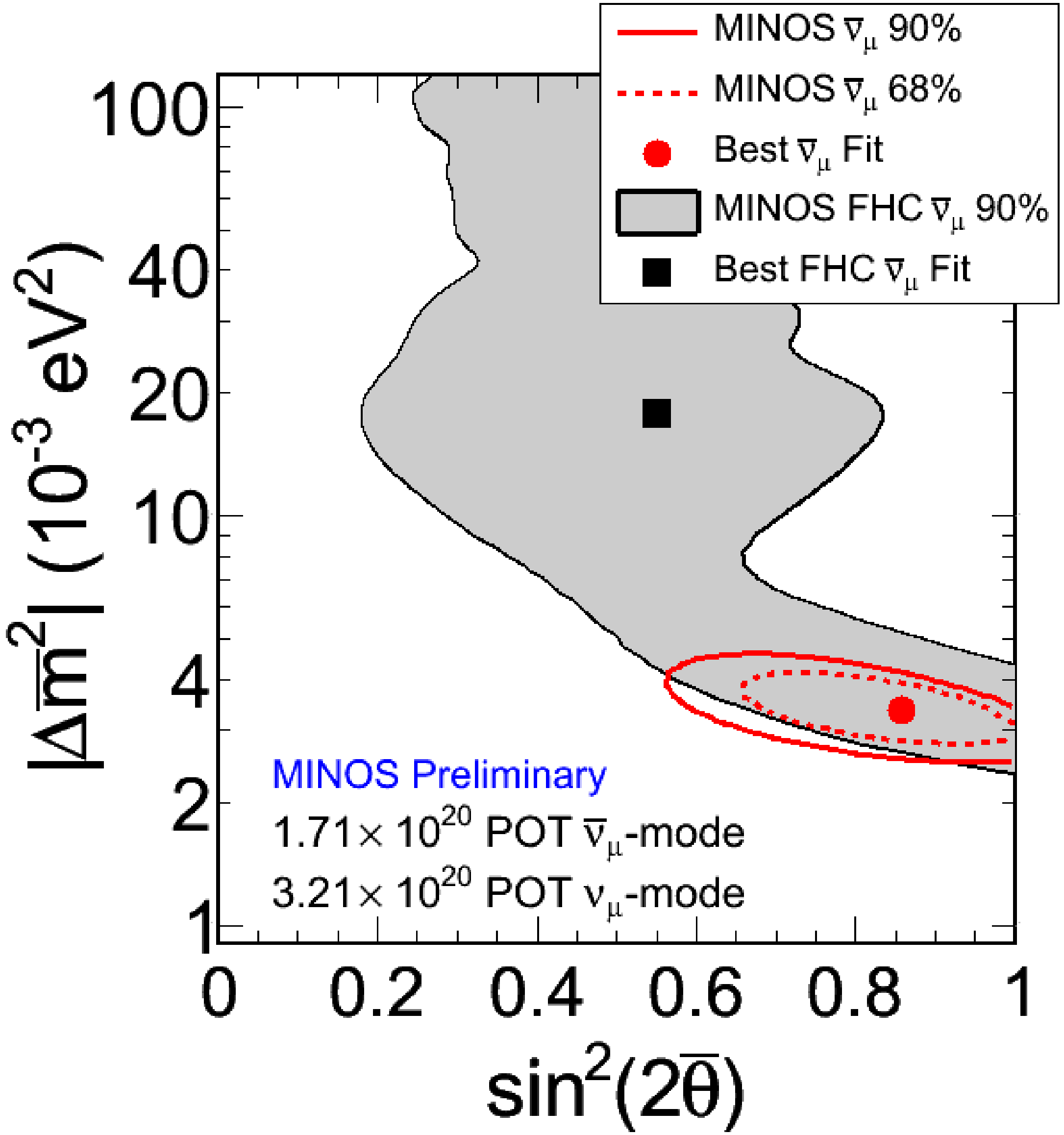
Far detector $\bar{\nu}_\mu$ data





- Vertices uniformly distributed
- Track ends clustered around coil hole

Previous antineutrino result



Results consistent with (less sensitive) analysis of anti-neutrinos in the neutrino beam

- Antineutrinos from unfocused beam component
- Mostly high energy antineutrinos

Analysis of larger exposure on going

$\overline{\nu}_\mu$ comparison to Super-Kamiokande