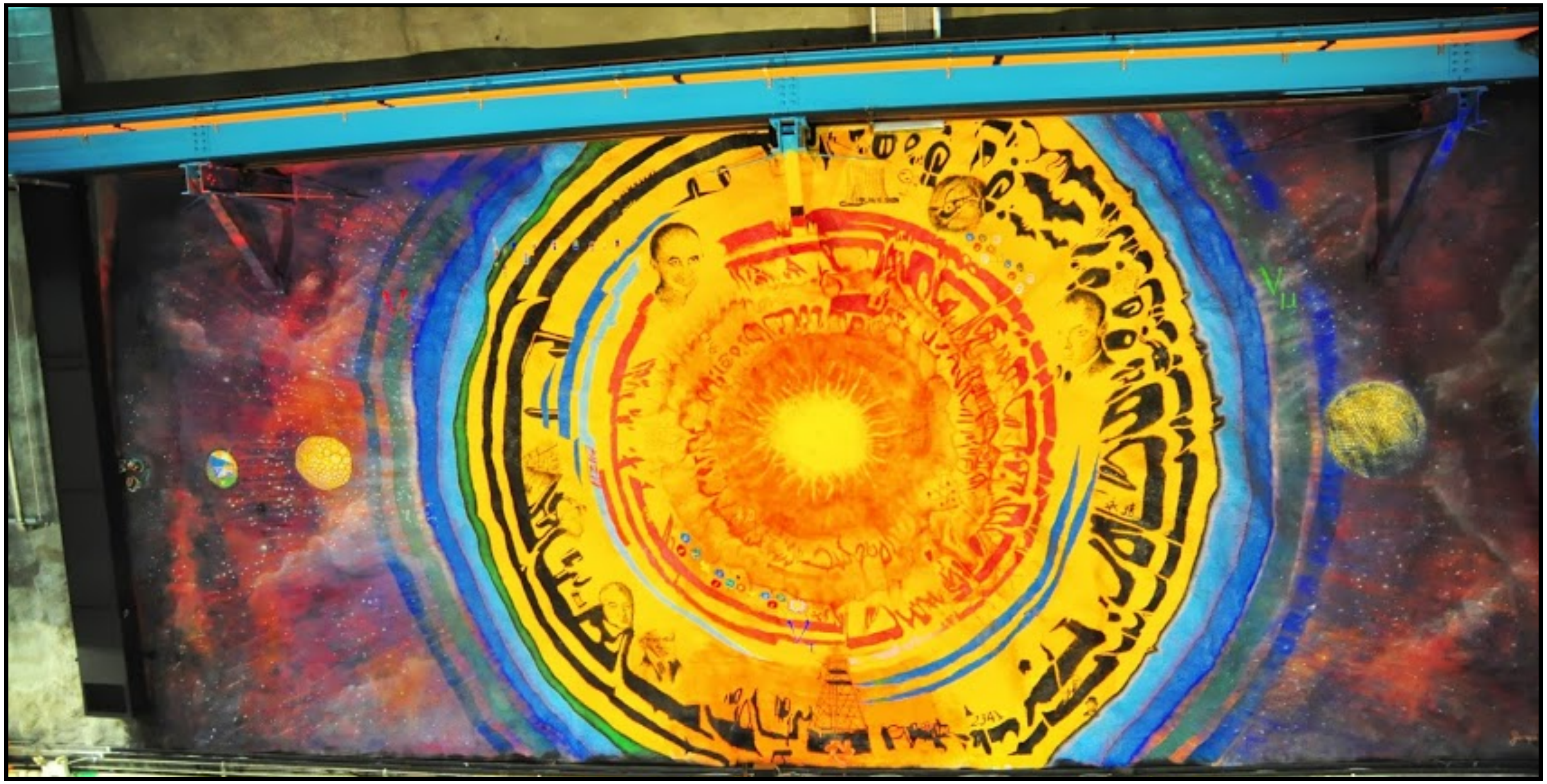


Searching for Sterile Neutrinos with MINOS

51th Rencontres de Moriond EW2016

Ashley Timmons

on behalf of the MINOS/MINOS+ collaboration

The University of Manchester

Fermilab

Intro – Neutrino Oscillations

Neutrino oscillations arise from mixture of mass and flavour eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \qquad (\alpha = e, \mu, \tau)$$

flavour state mass state

Many neutrino experiments observe data consistent with three-flavour model

θ_{12}, θ_{23}, θ_{13}, δ_{13}, Δm^2_{32} ($\sim 10^{-3} eV^2$) and Δm^2_{21} ($\sim 10^{-4}$ eV^2)

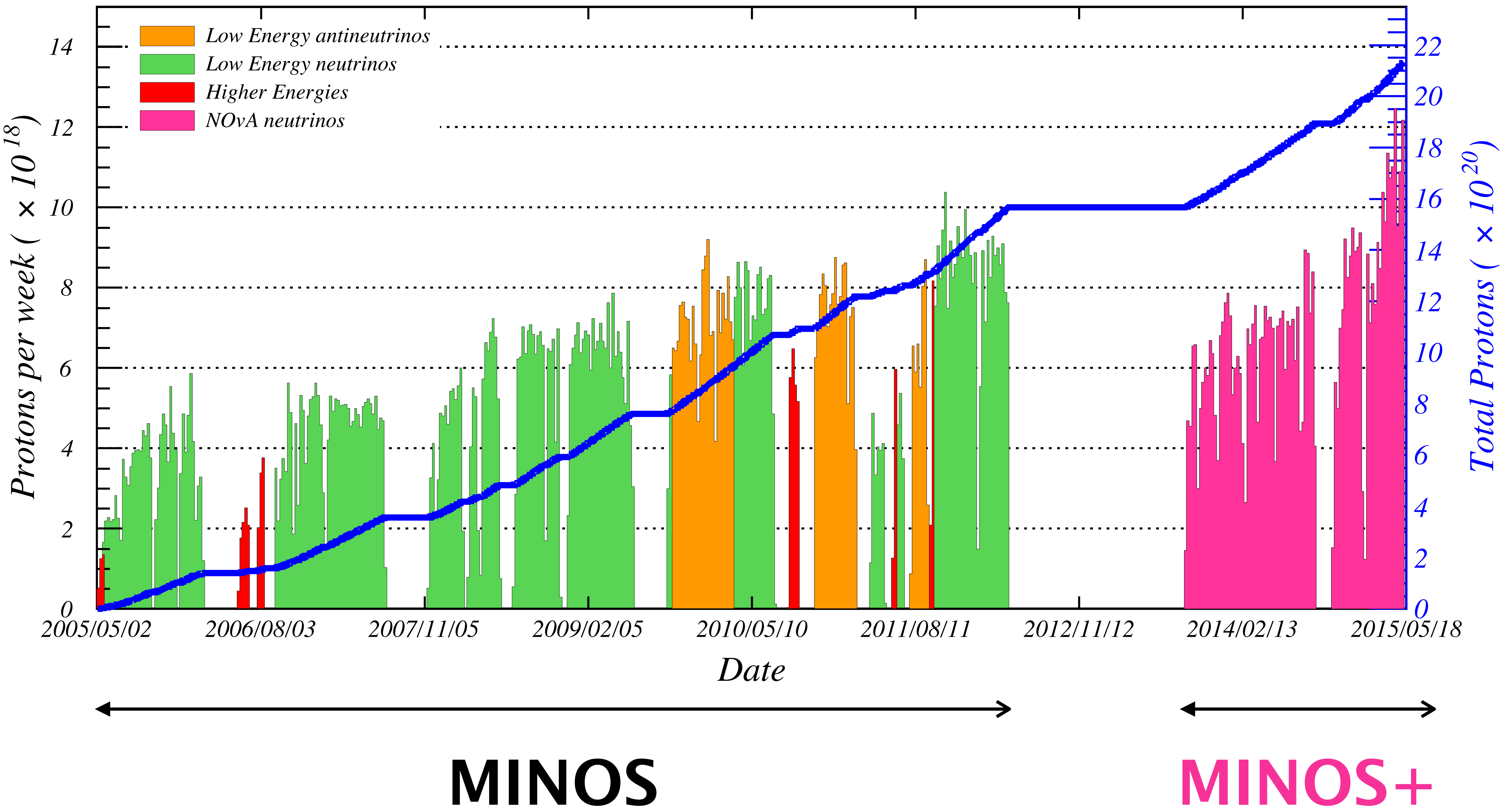
LSND, MiniBooNE at L/E ~ 1 km/GeV, interpret as oscillations if $\Delta m^2 \sim 1 eV^2$

we consider the model 3(active)+1(sterile)

Introduces: **θ_{14}, θ_{24}, θ_{34}, δ_{24}, δ_{14}** and **Δm^2_{41}**

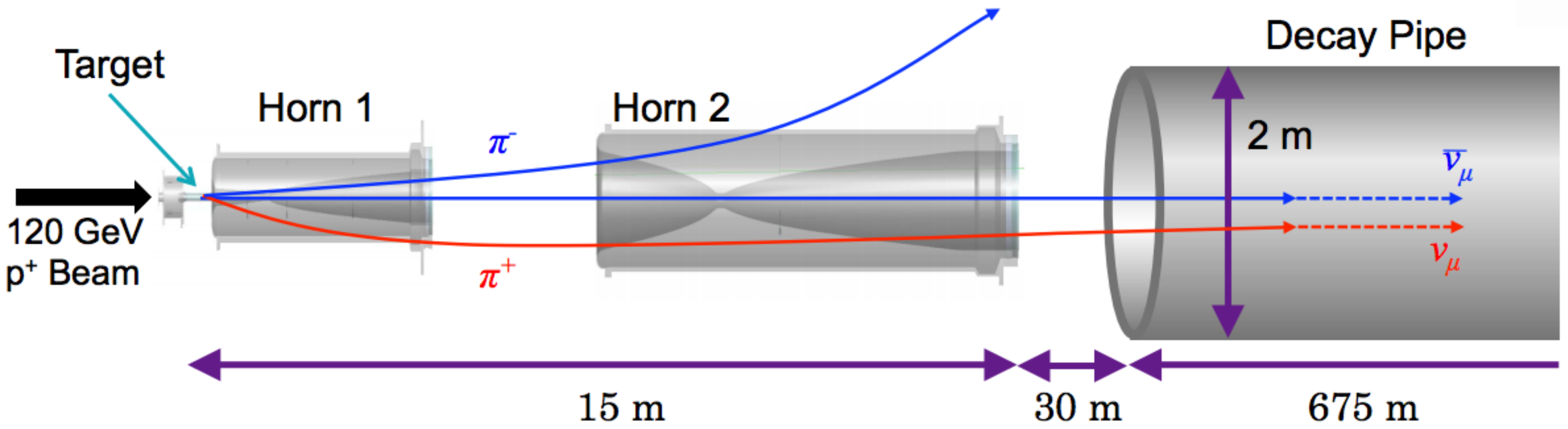
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

MINOS/MINOS+ Data Set

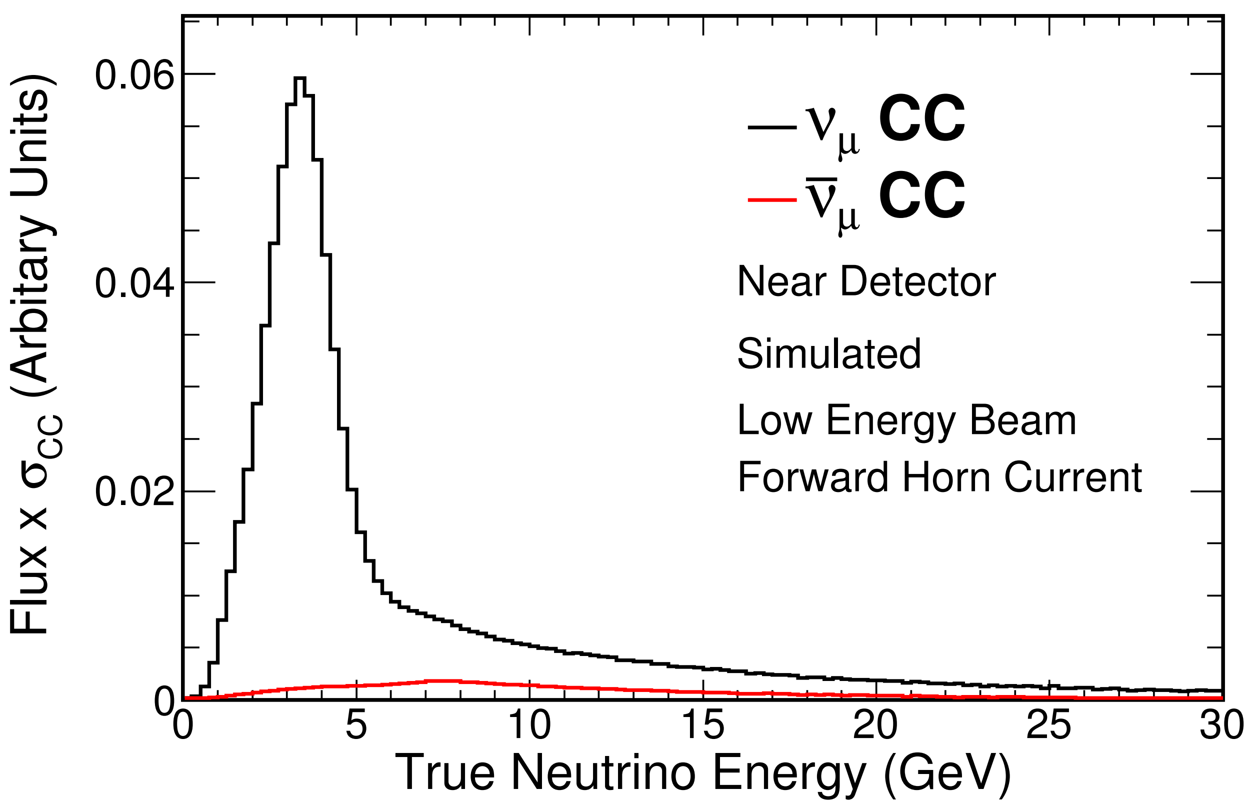


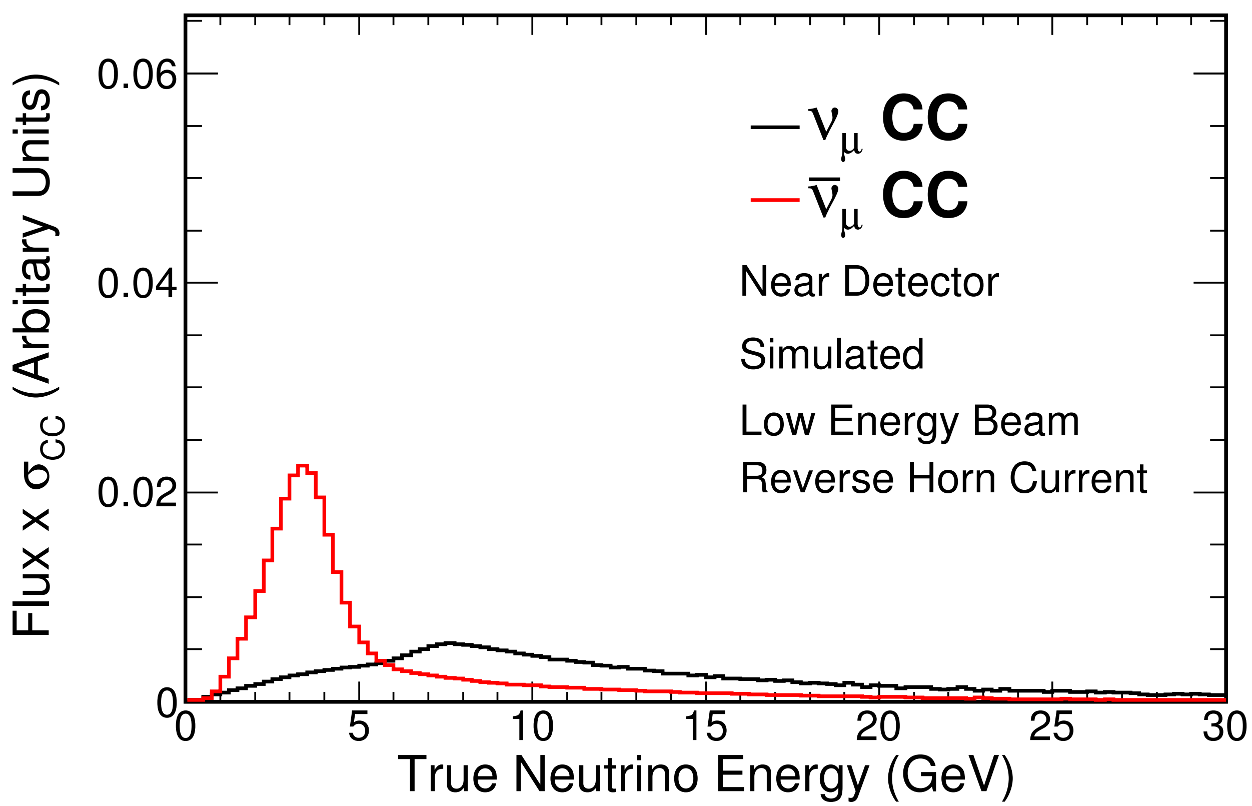
MINOS+ is the continuation of MINOS with the NuMI beam in the medium energy configuration.

The NuMI Beam

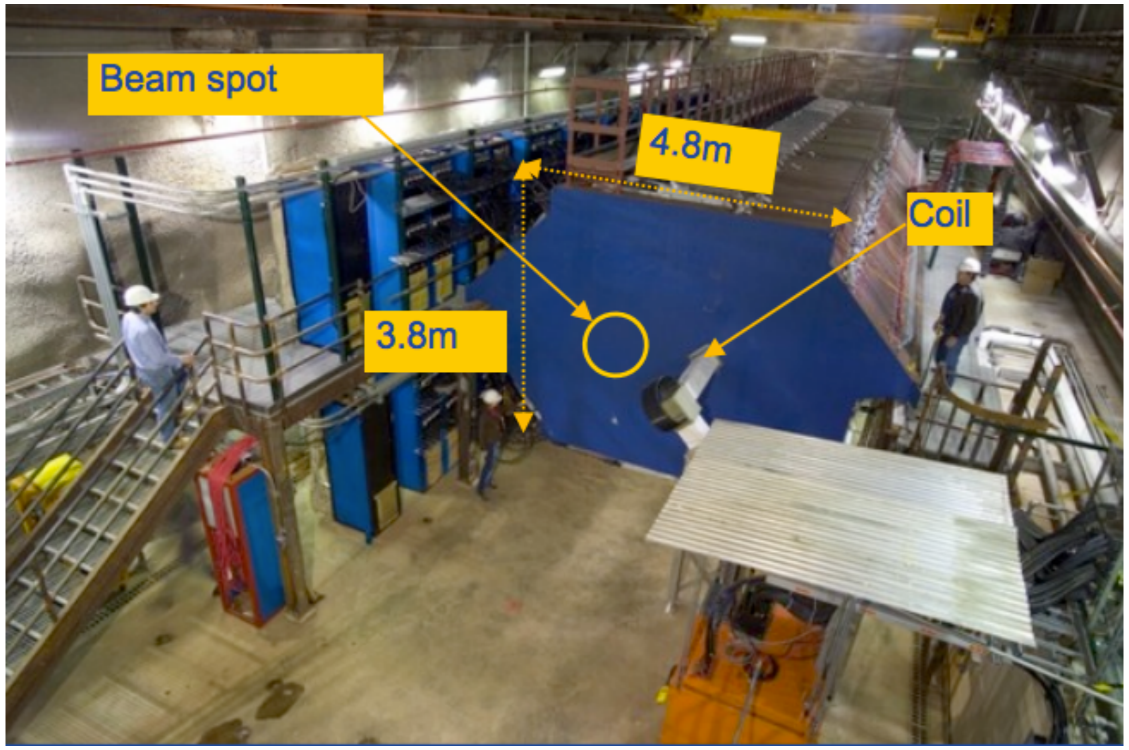


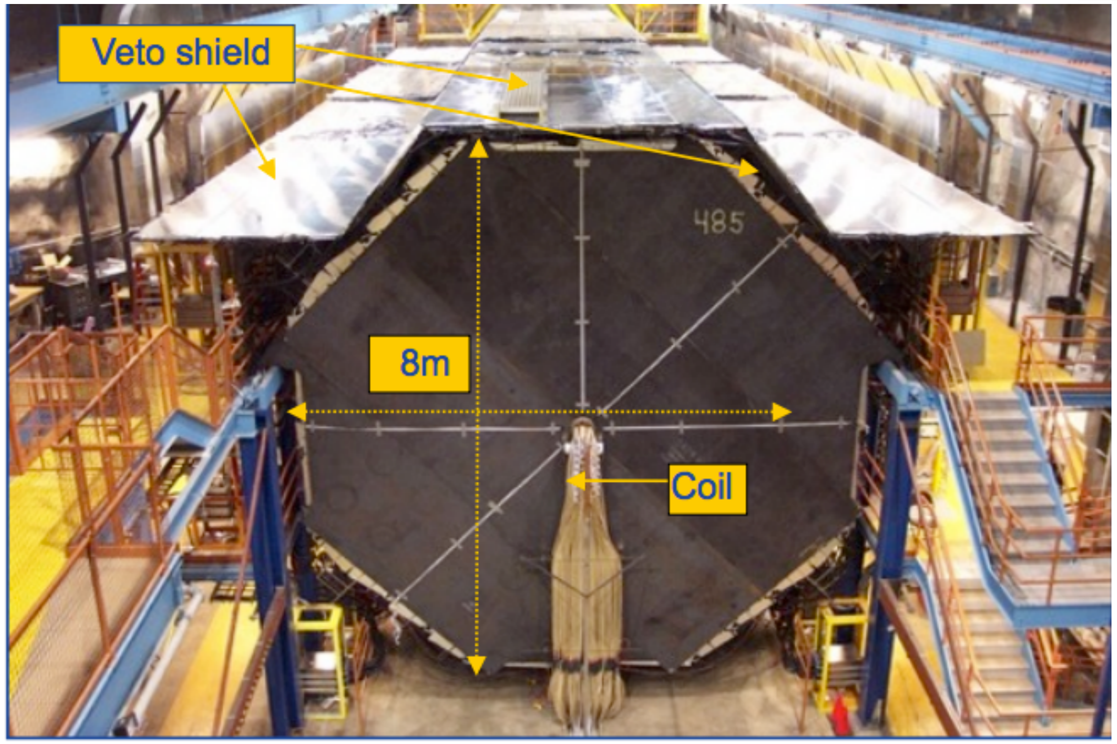
This analysis uses this beam mode





Detectors





Near

- 23.7 ton fiducial mass
- 1.04 km downstream from target

Far

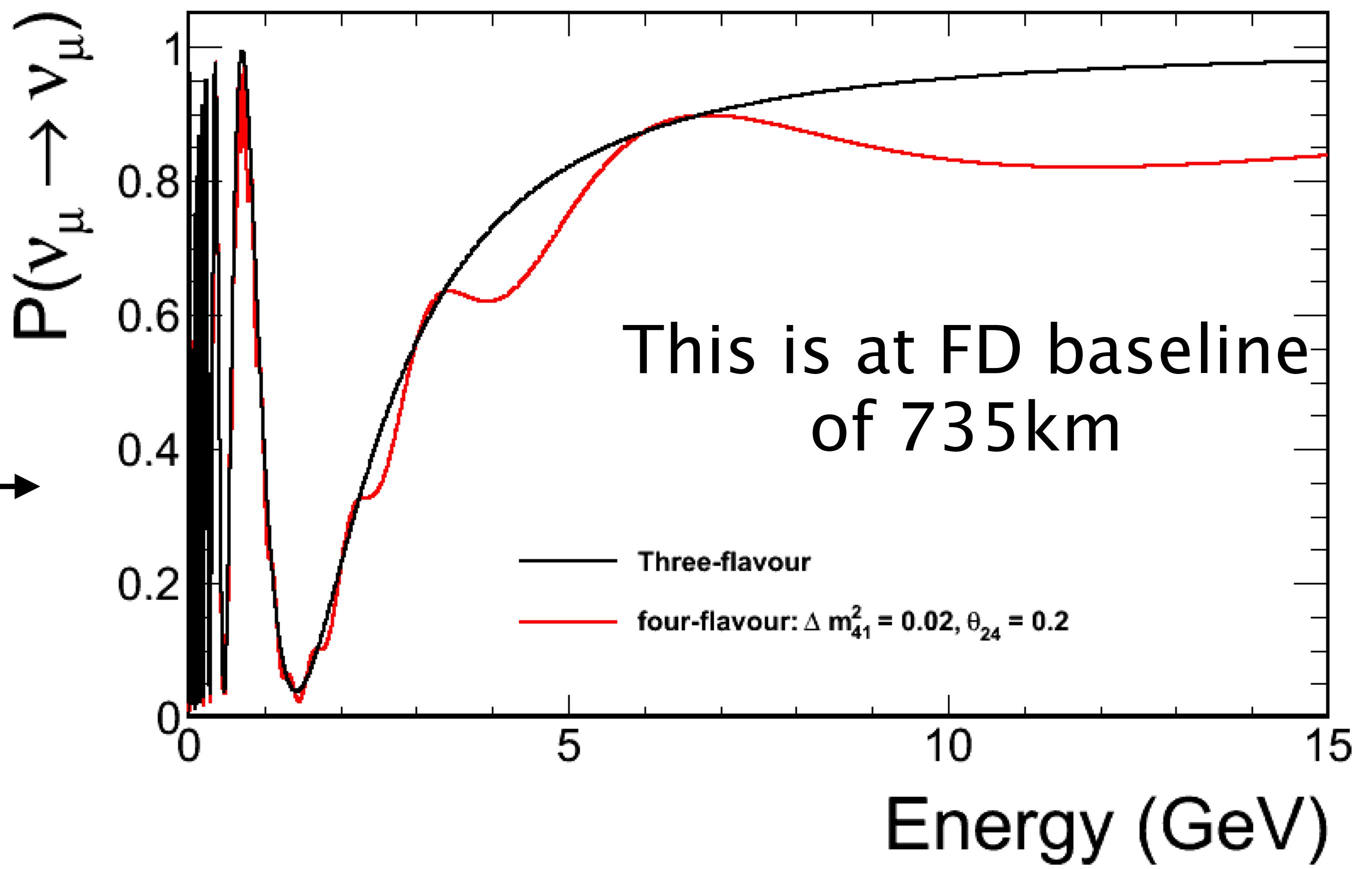
- 4.2 kiloton fiducial mass
- Veto shield for cosmic suppression
- 705m underground

- Both detectors are **magnetised** tracking/sampling calorimeters, segmented into planes composed of 2.54 cm-thick steel planes and 1 cm-thick scintillator strips
- Detectors designed to be functionality equivalent, cancels systematics uncertainties in flux modelling and cross section to first order.

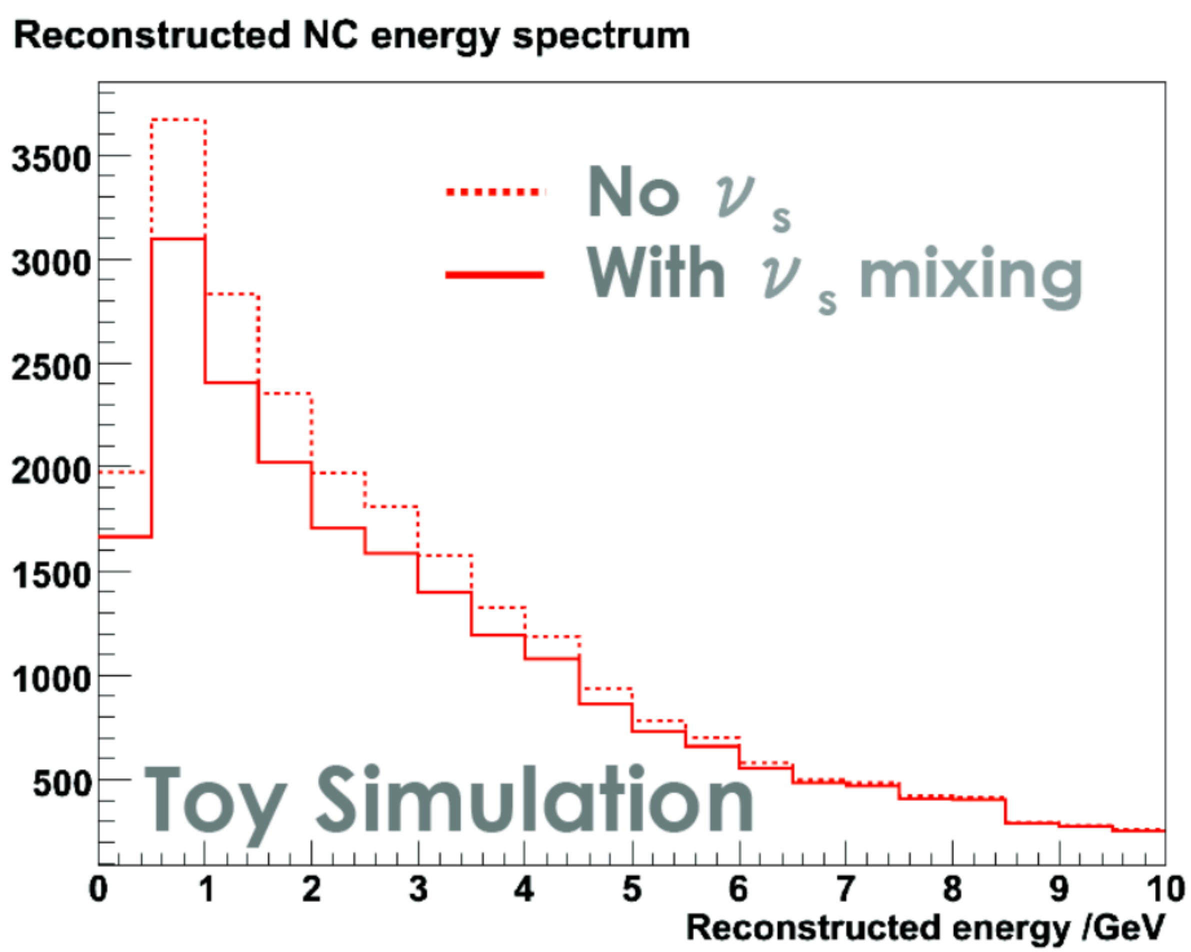
Long-Baseline Sterile Search

MINOS was built for measurement of Δm^2_{32} by looking for ν_μ disappearance optimised for L/E = 500km/GeV

Looking for perturbations from three-flavour disappearance (sensitive to θ_{24}, θ_{23})



This is at FD baseline of 735km

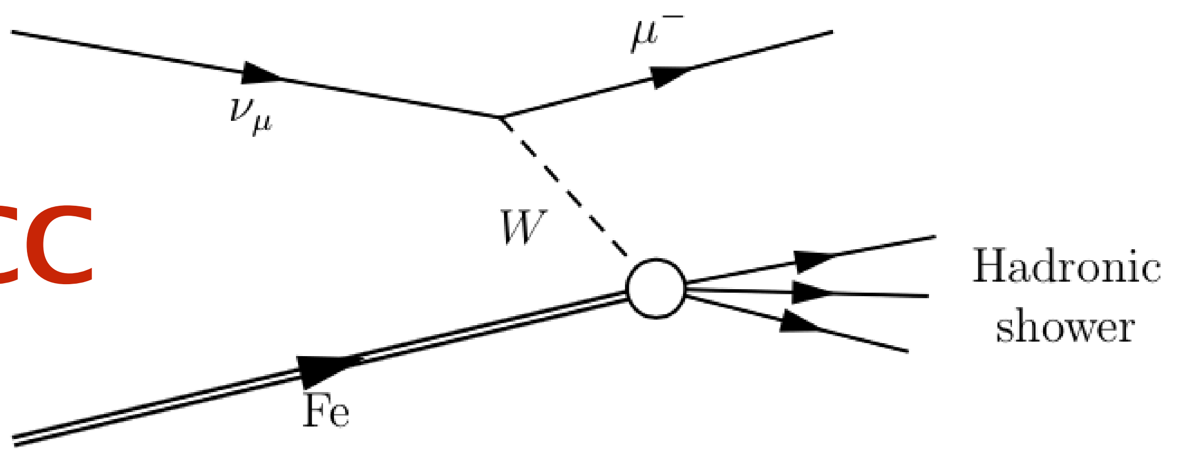


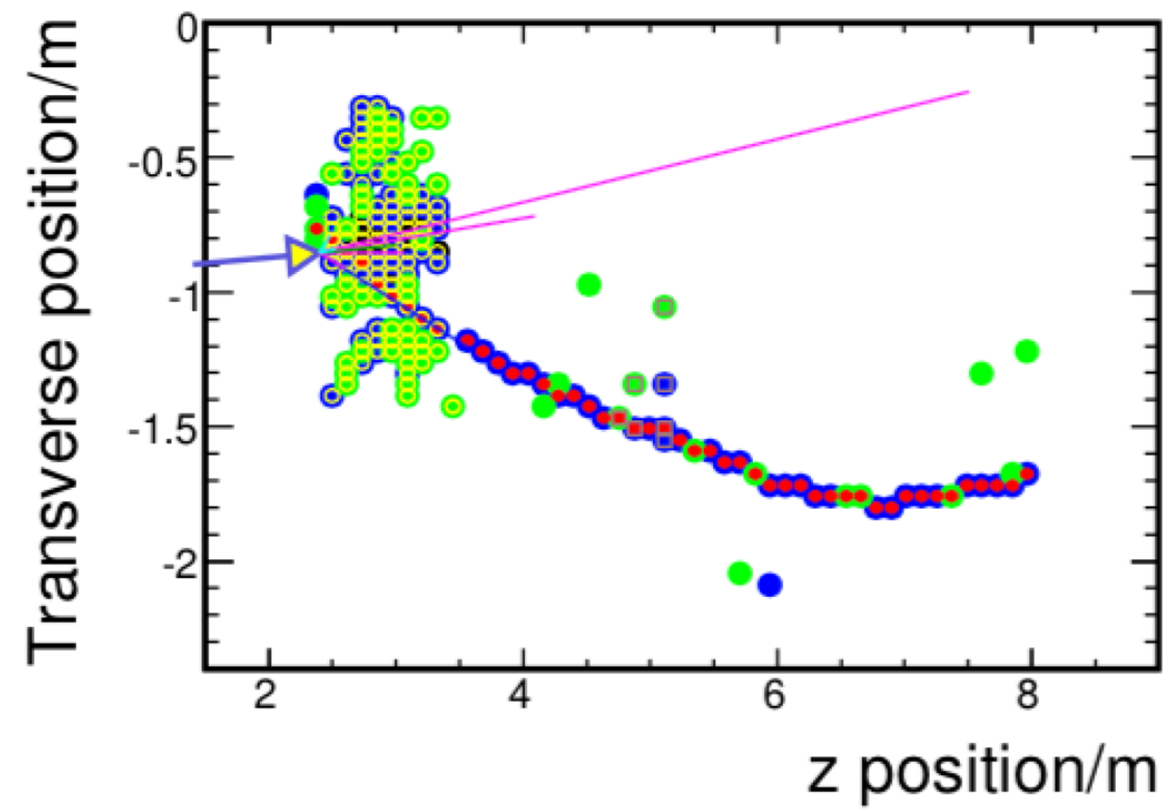
Neutral current interaction rate is the **same** for the **three active flavours**

$P(\nu_\mu \rightarrow \nu_s)$ depends on θ_{24}, θ_{34}, θ_{23},

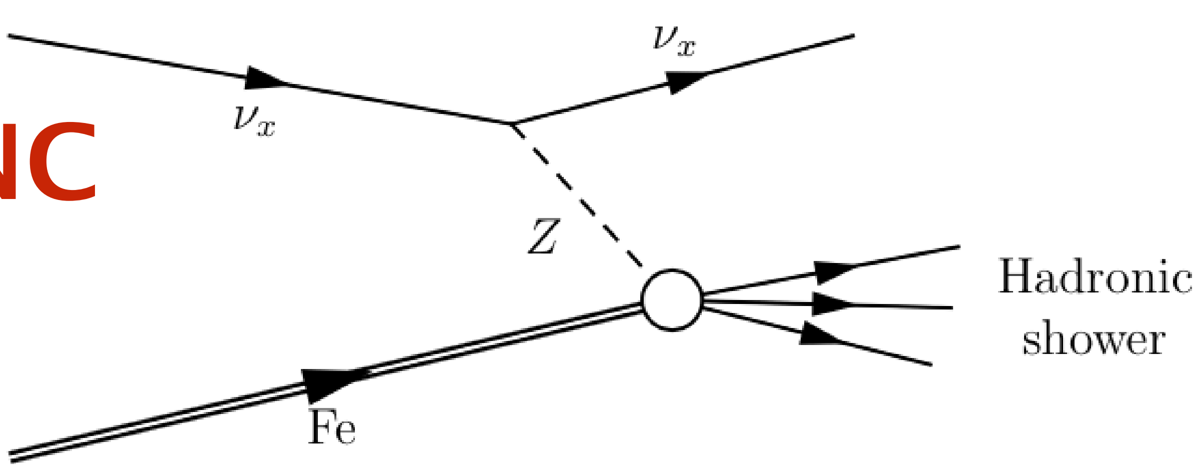
Event Topologies

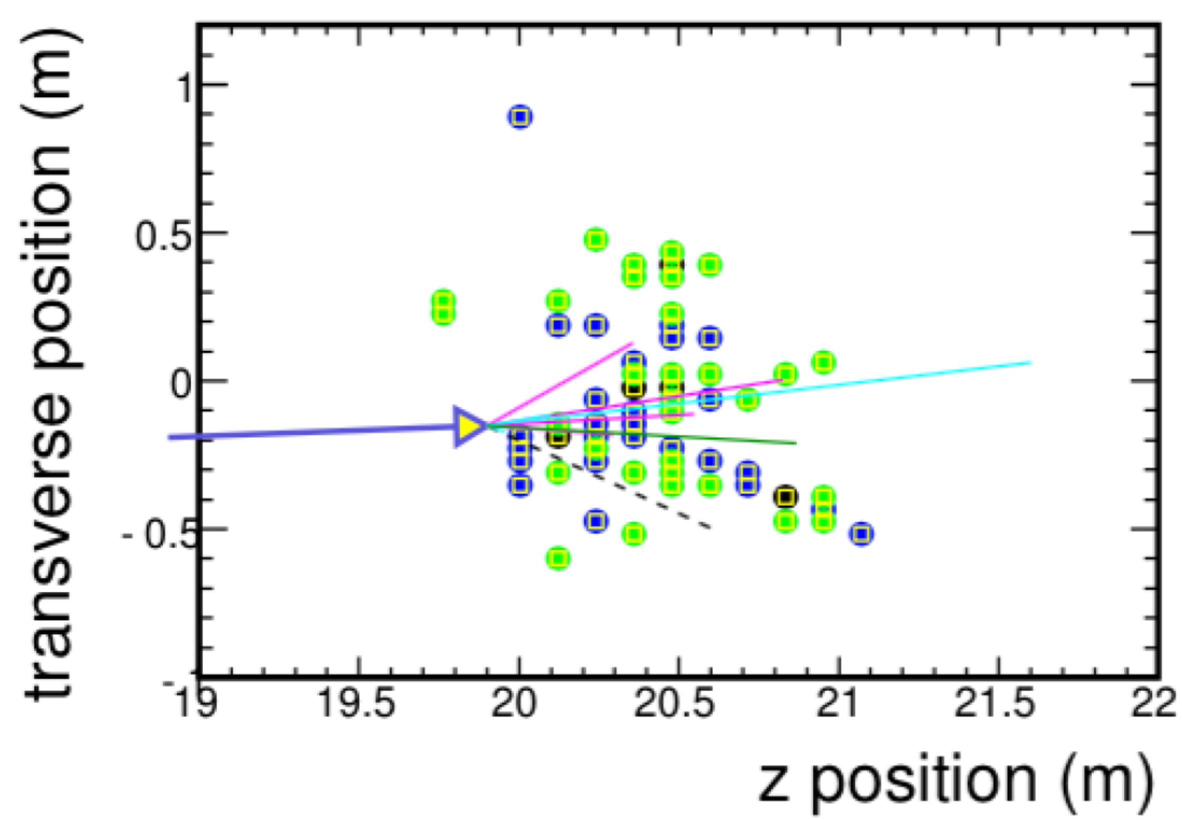
CC





NC

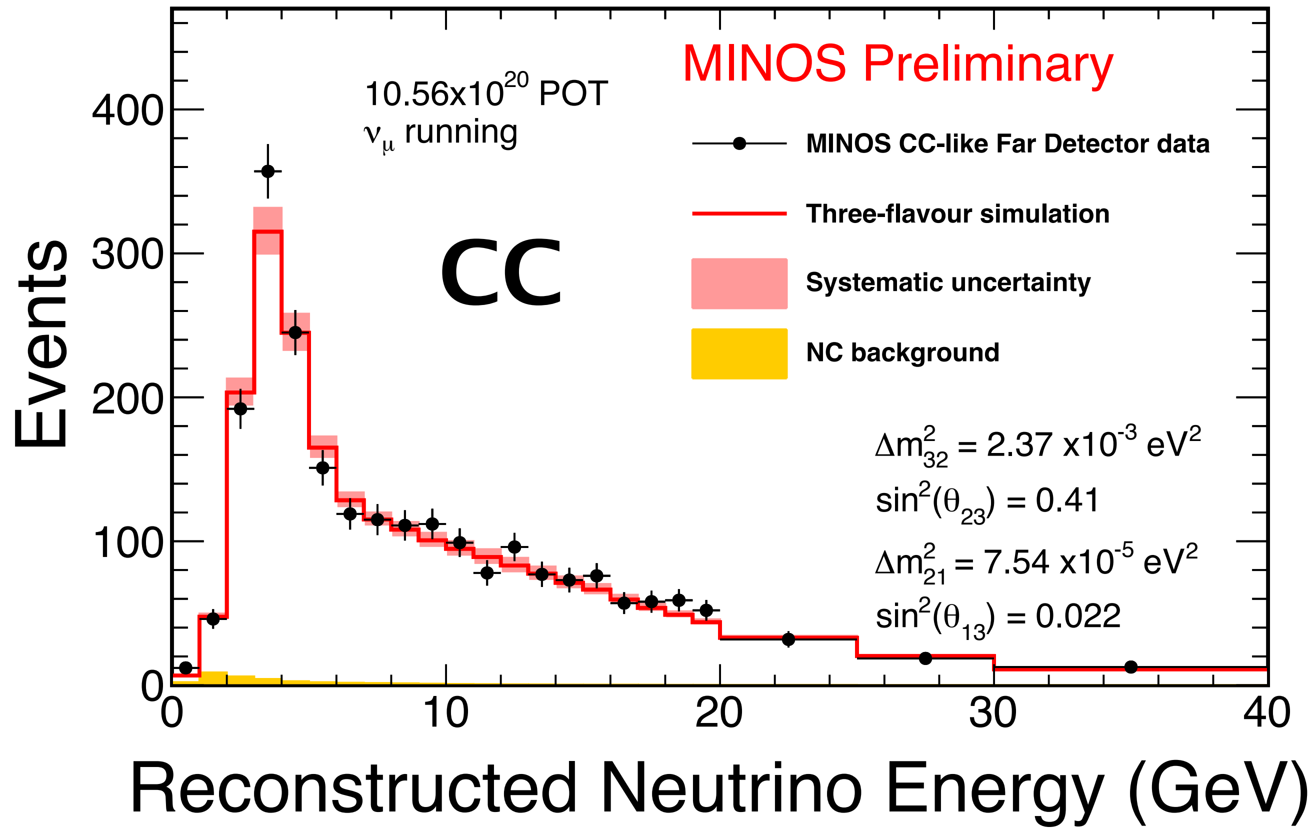




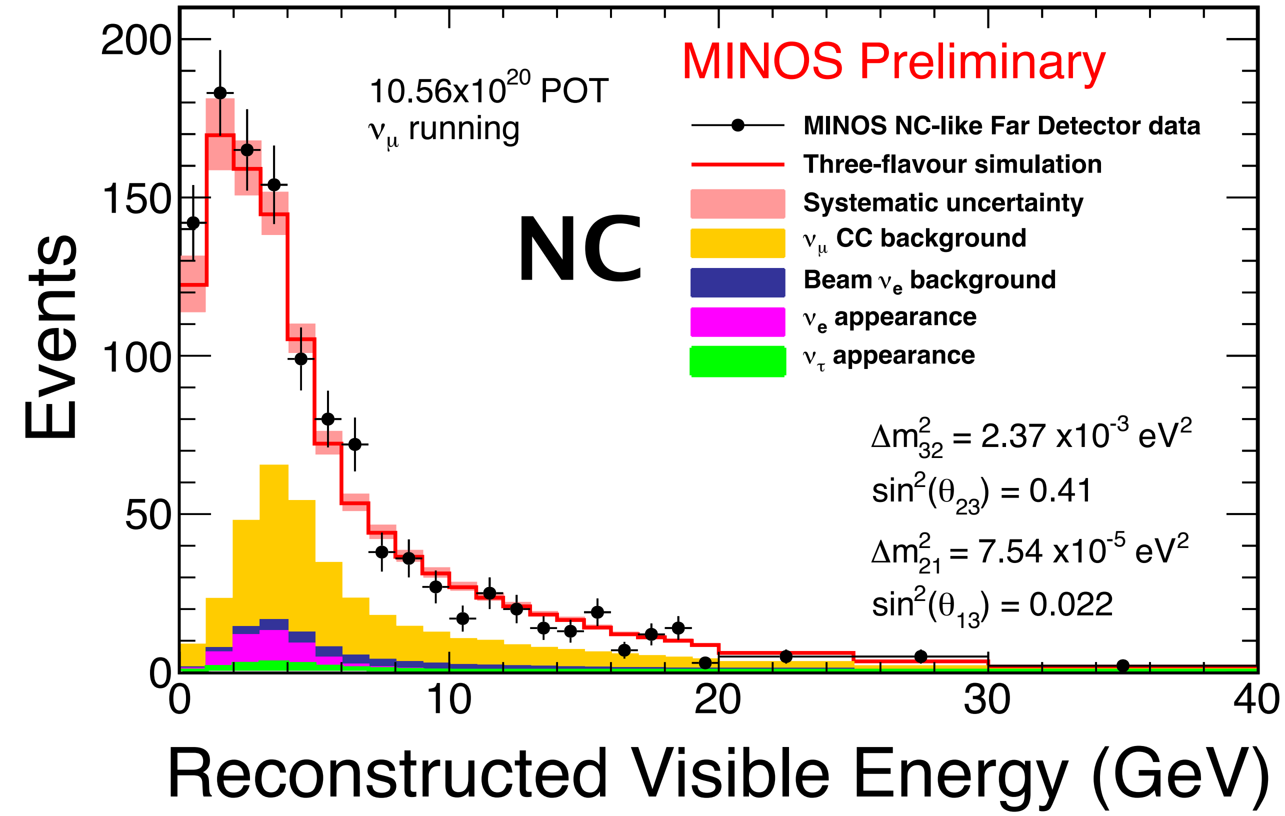
FD Spectra - Data

FD spectra three-flavour oscillated with MINOS 2012 CC-analysis fit values

This is NOT a fit



2563 CC-like events



1211 NC-like events

$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

Predicted CC background from all flavors

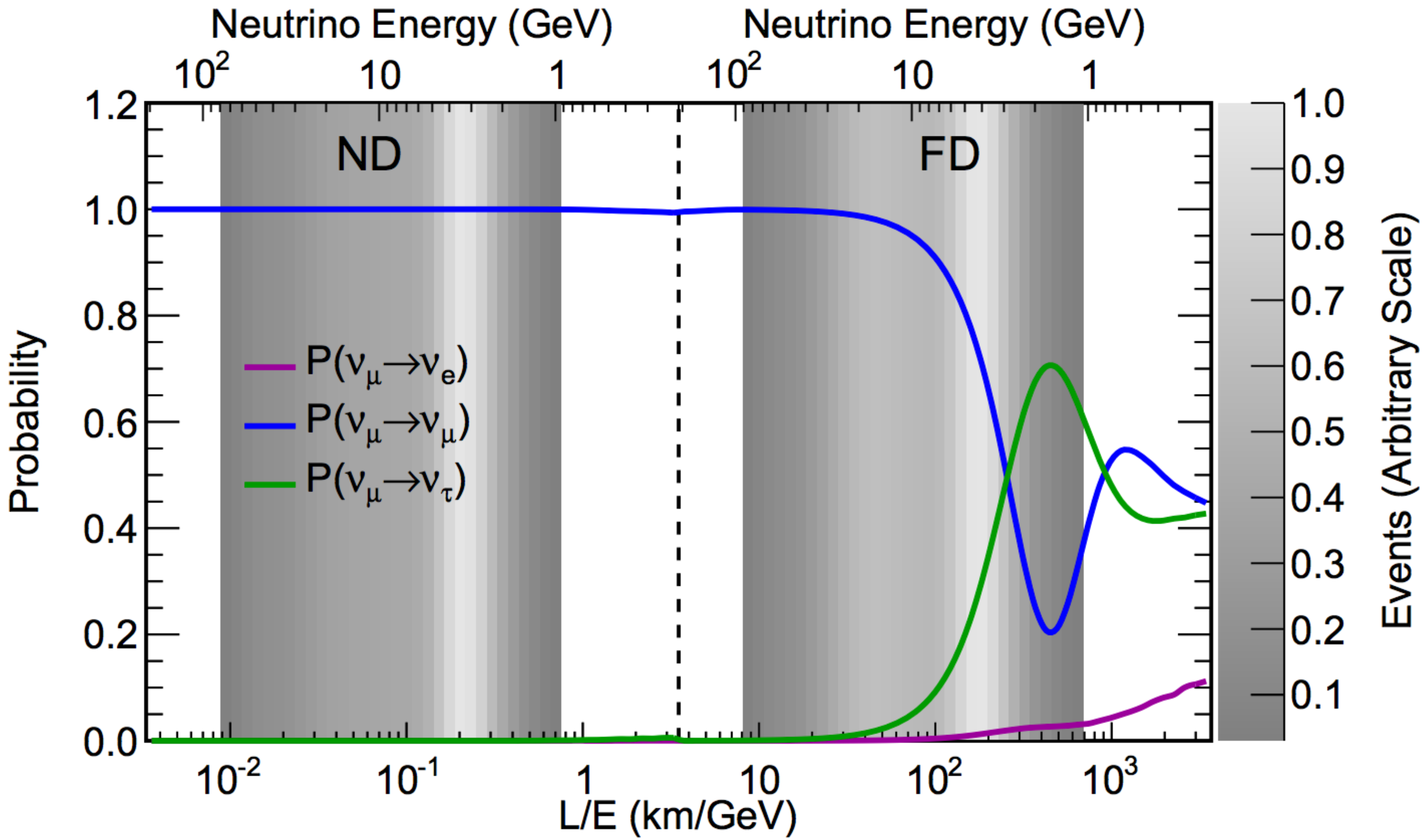
Predicted NC interaction signal

R [0-3 GeV] = 1.10 +/- 0.06 +/- 0.07

R [0-40 GeV] = 1.05 +/- 0.04 +/- 0.10

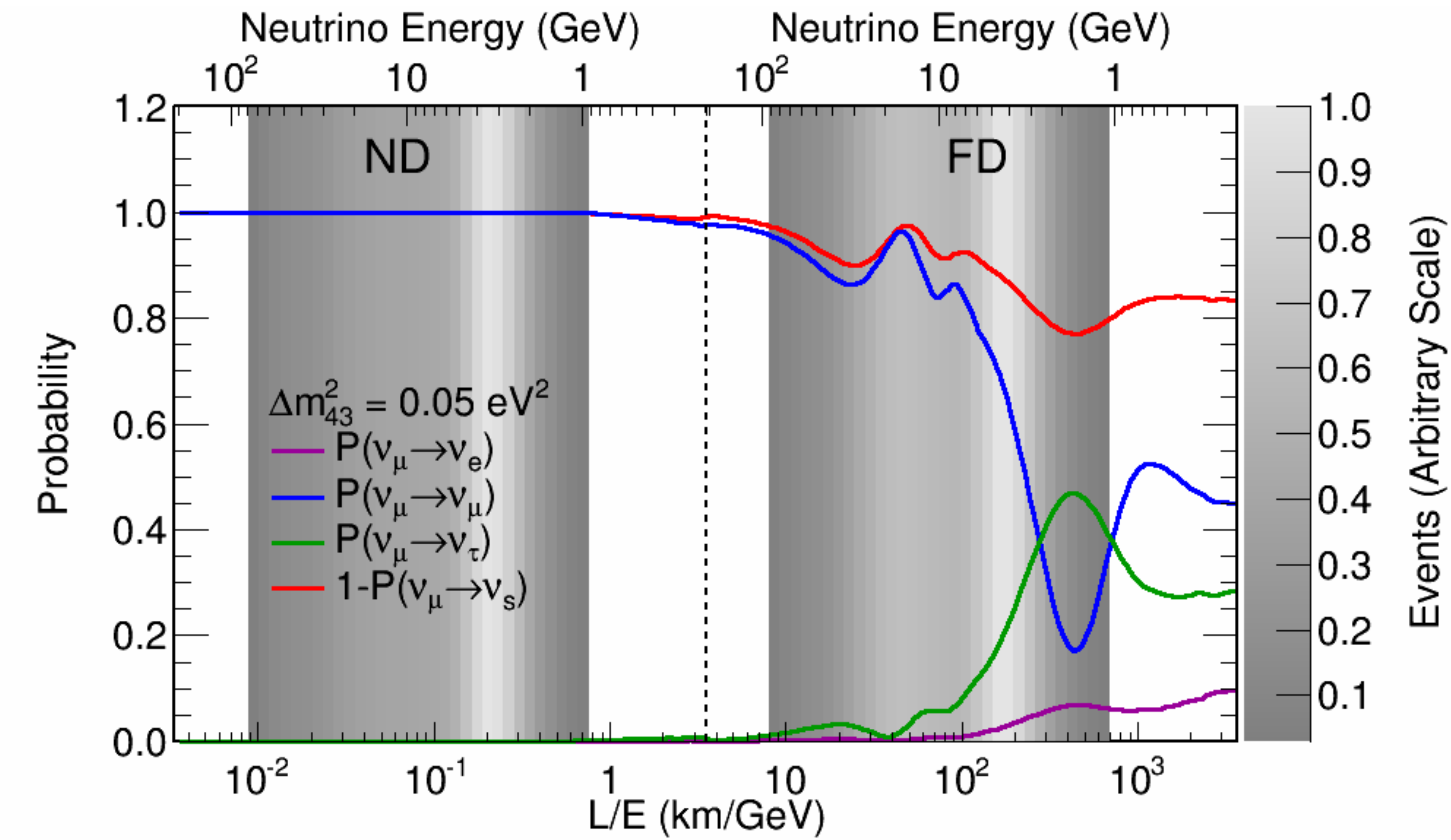
If no NC disappearance R = 1

Oscillations



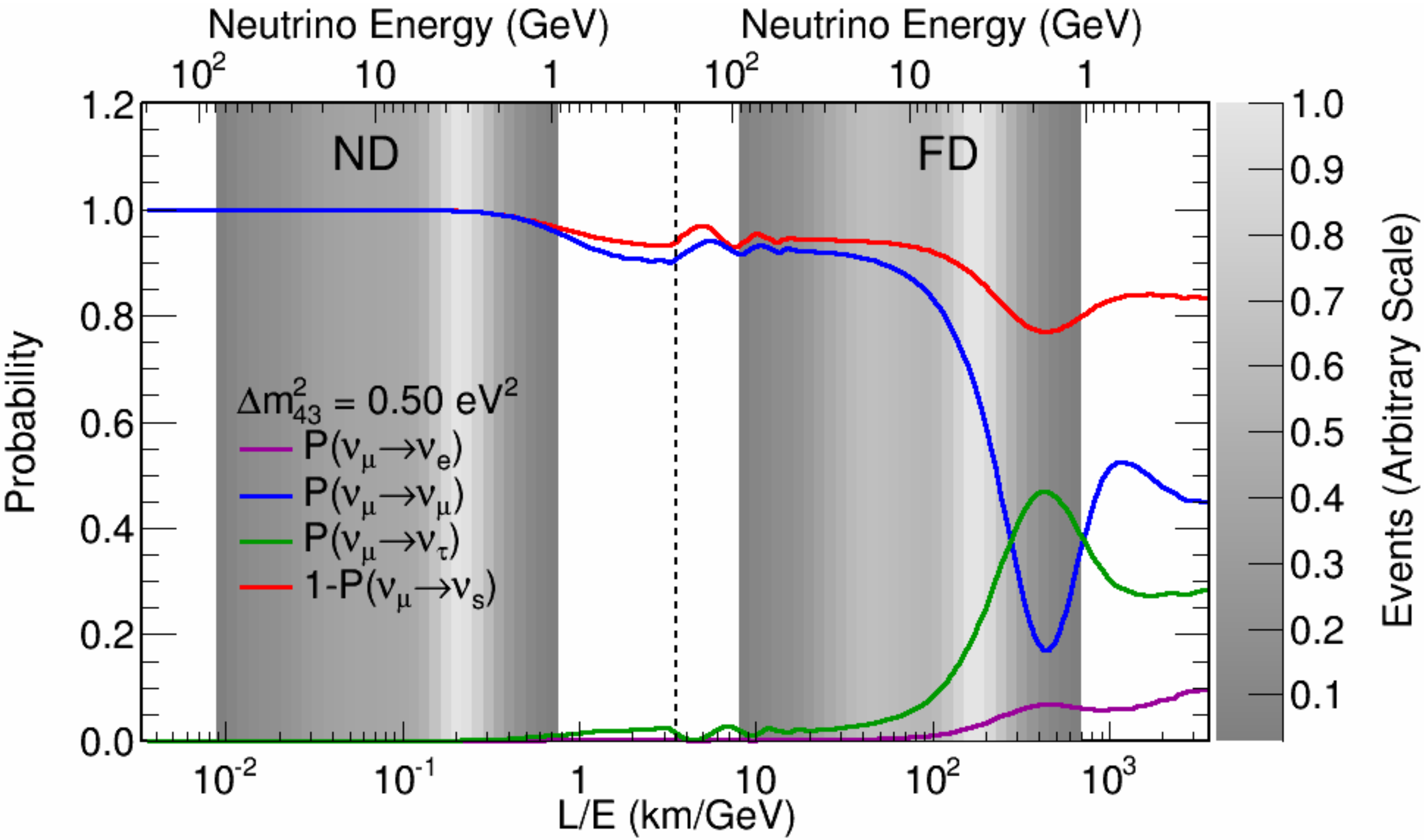
This is assuming a three-flavour model – **no sterile neutrinos**

Oscillations



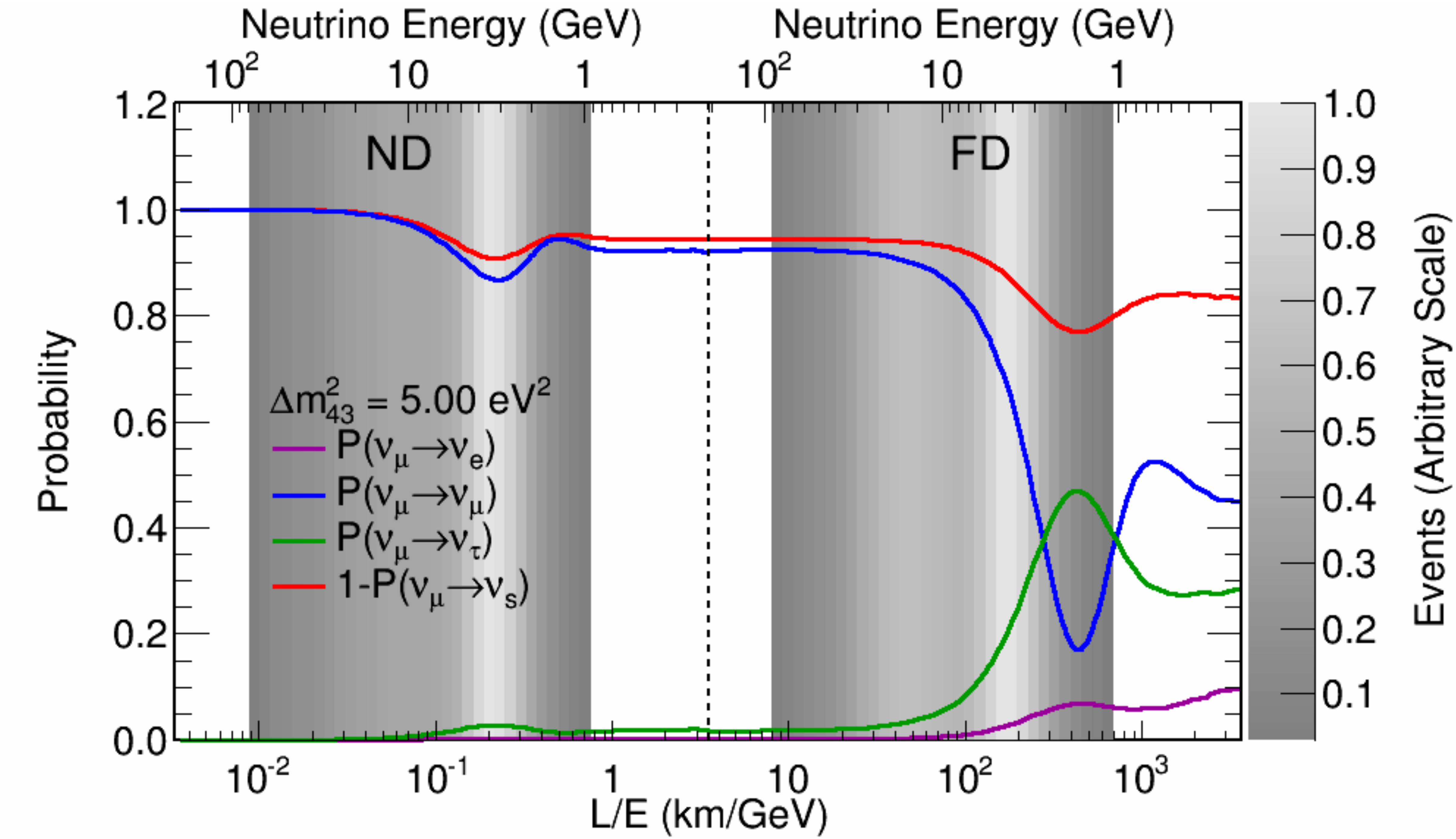
Sterile oscillations in the FD only.

Oscillations



Fast oscillations in the FD, counting experiment

Oscillations



oscillations now occur at the ND. Typical **extrapolation using ND data is no longer possible!**

Far Over Near Ratio

New analysis technique to probe many magnitudes of Δm^2_{41}

Direct fit to F/N ratio for CC and NC events

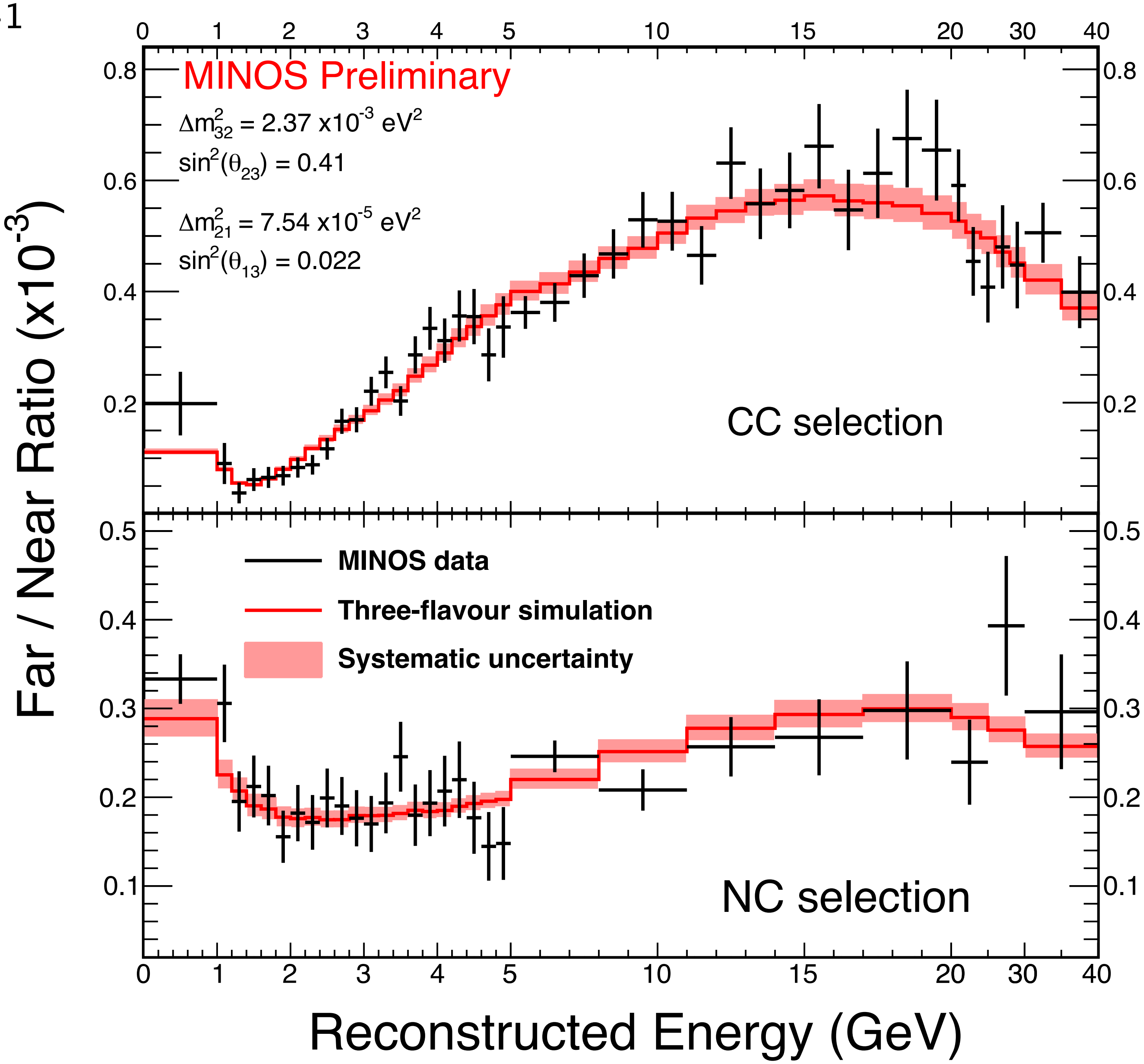
Assume 3+1 sterile model

Set δ_{13}, δ_{14}, δ_{24} and θ_{14} to zero

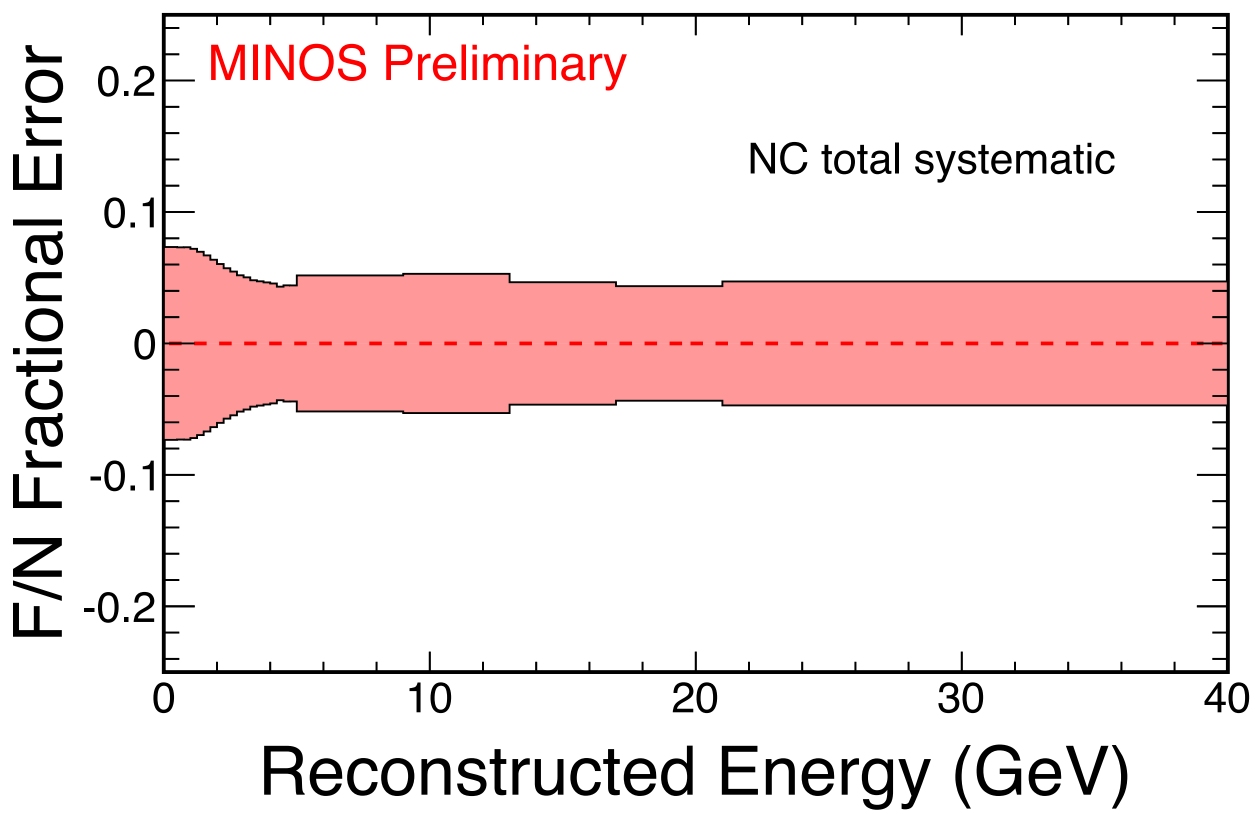
we assume no $\nu_e \rightarrow \nu_s$

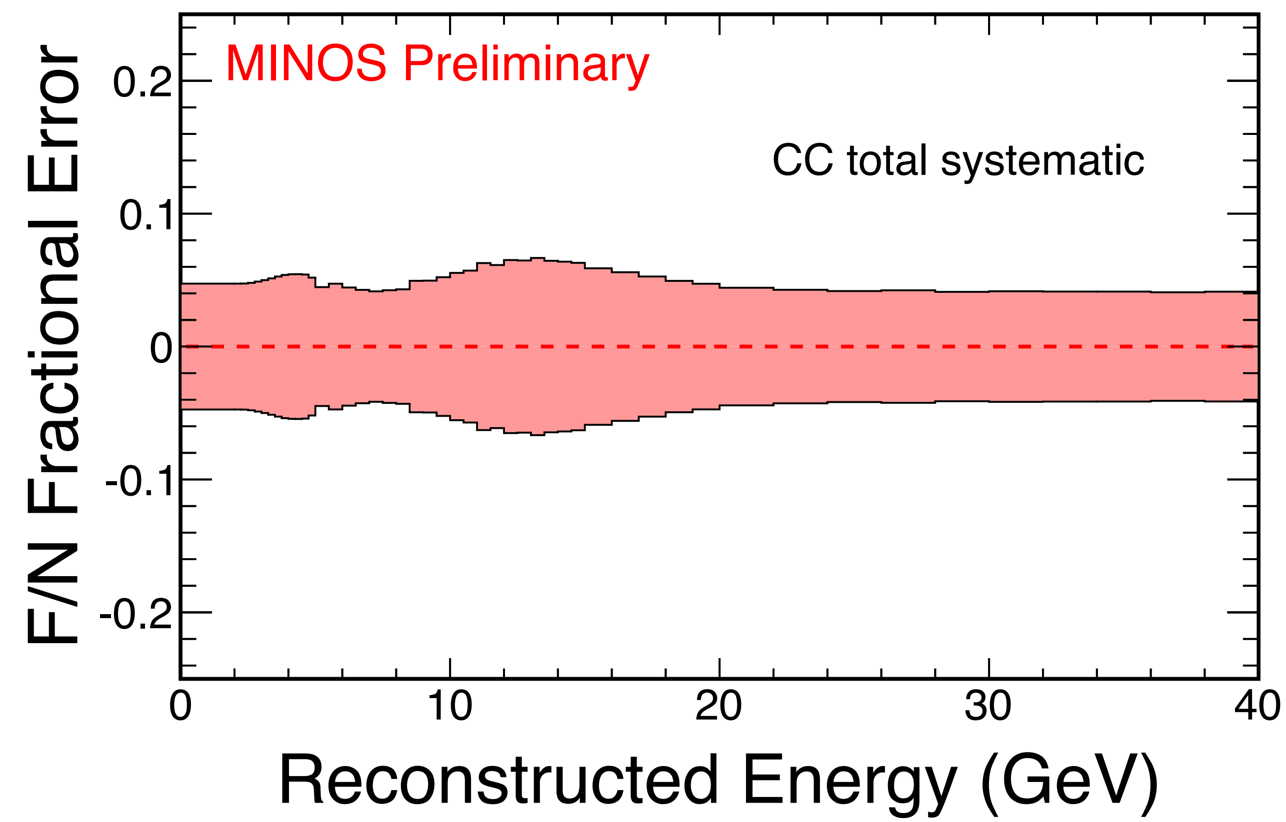
Parameters fit are: Δm^2_{32}, Δm^2_{41}, θ_{24}, θ_{23}, and θ_{34}

Moved from likelihood method towards χ^2 fit, containing covariance matrix with systematics



Total Uncertainties





Including 26 systematics into the fit via covariance matrix, accounting for:

Normalisation,
Detector acceptance,
NC selection,
Hadron production,
Beam focusing,
Cross sections,
Energy scale and background

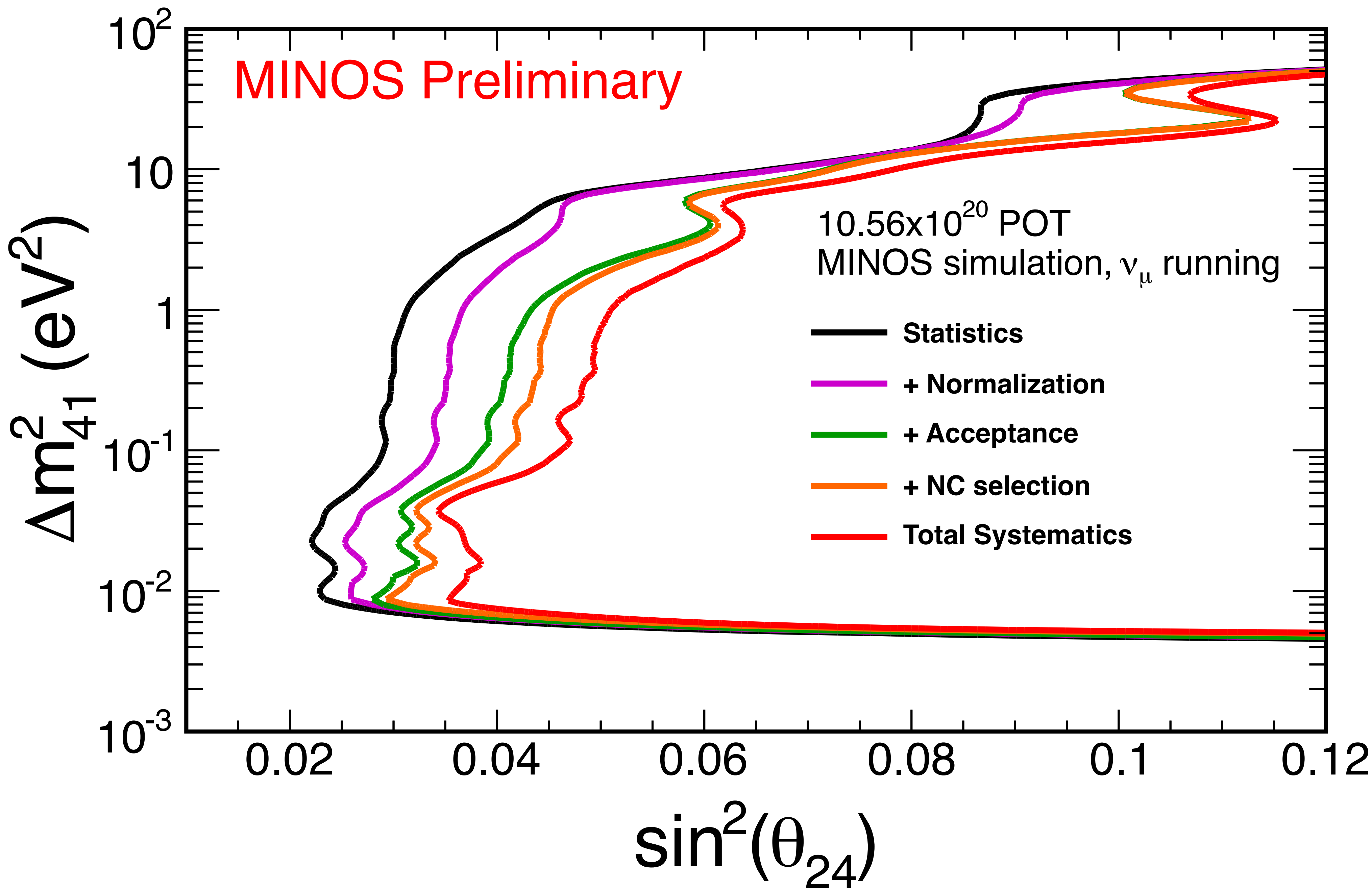
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T[V^{-1}]_{ij}(o_j - e_j)$$

o_i : Observed events in bin i

e_i : Predicted events in bin i

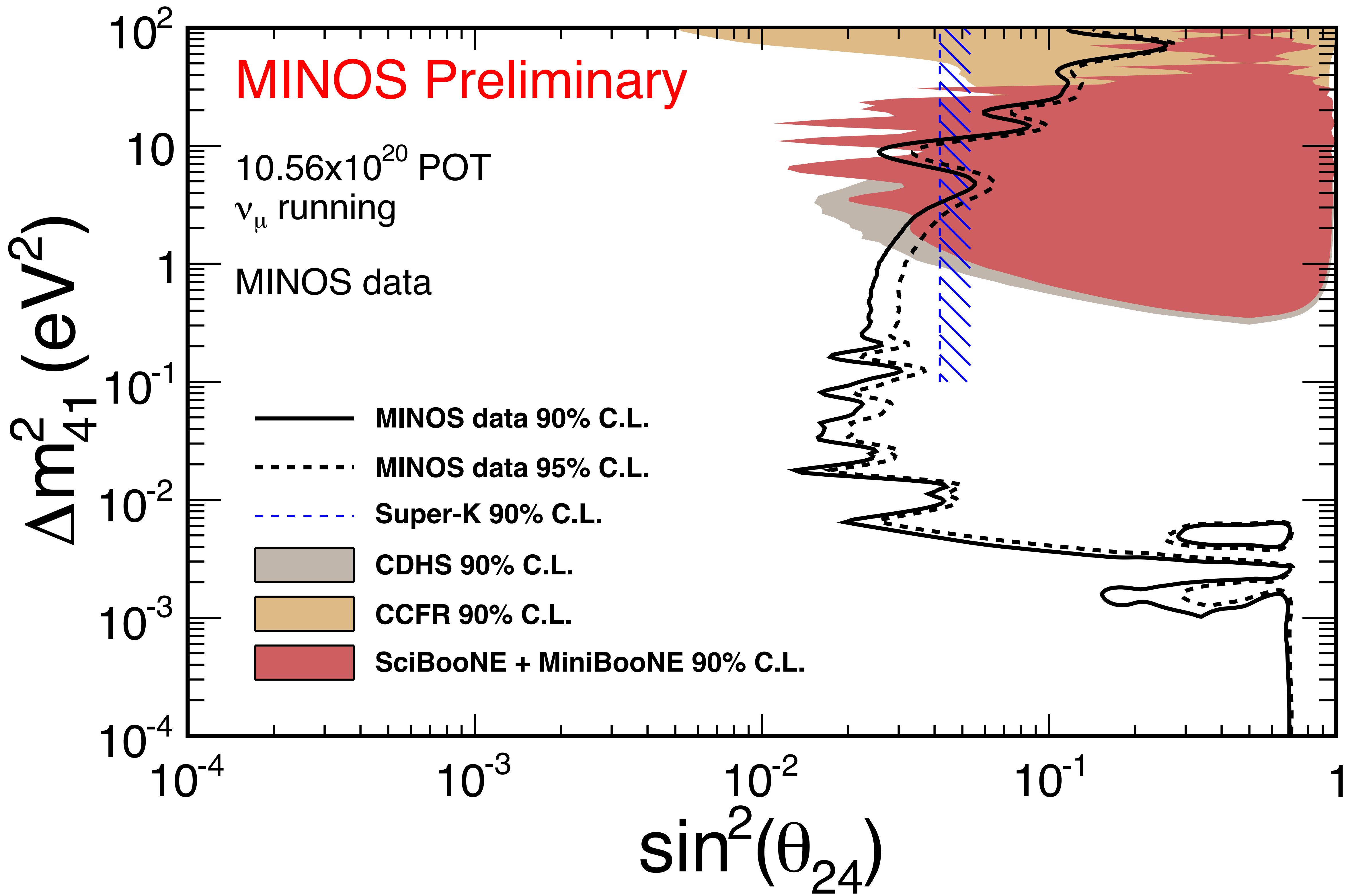
V : Covariance matrix

Total Uncertainties



Effect on the sensitivity when including largest systematics added incrementally.

Disappearance Limit



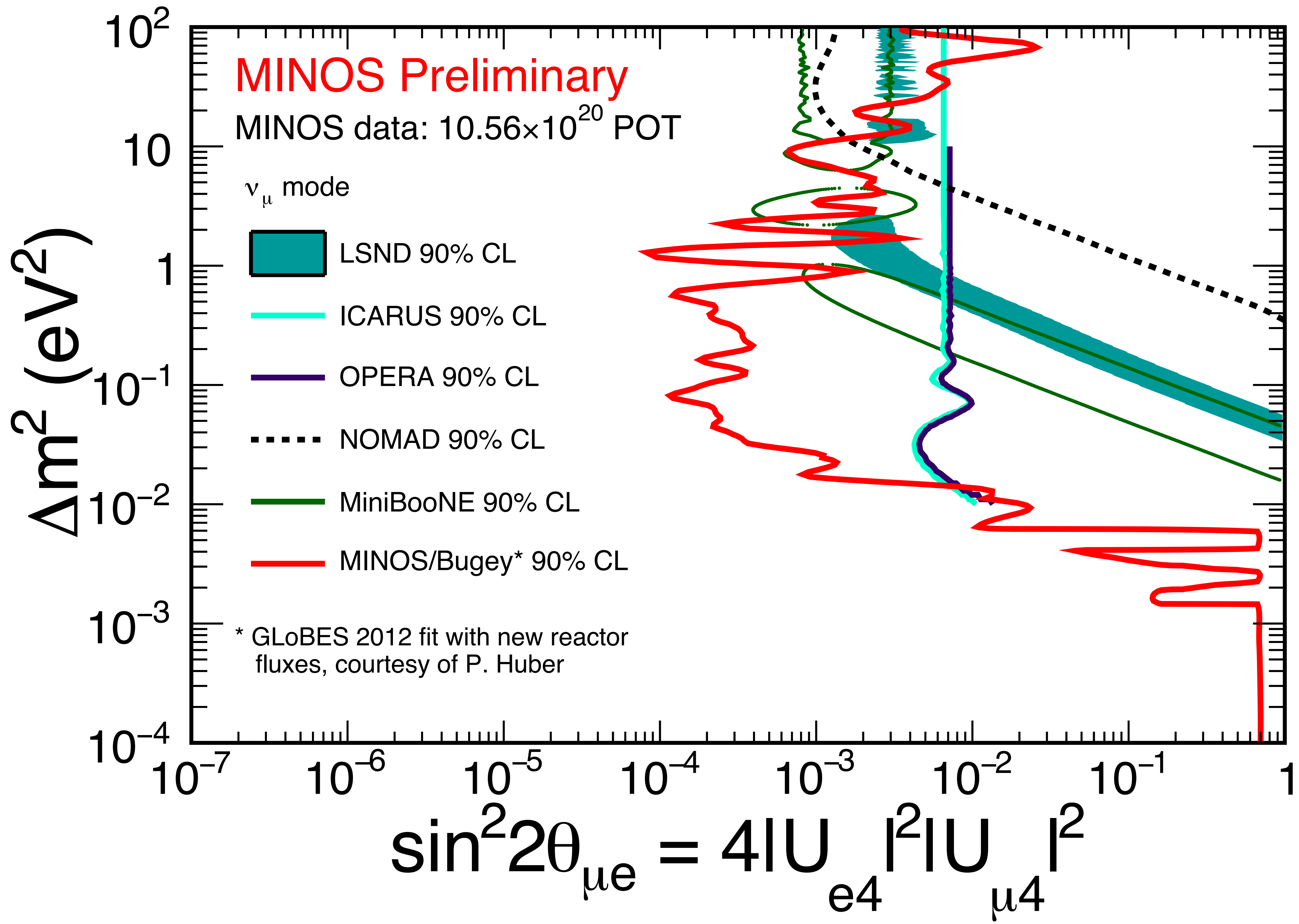
Feldman-Cousins procedure used for confidence limit

Combination with Bugey

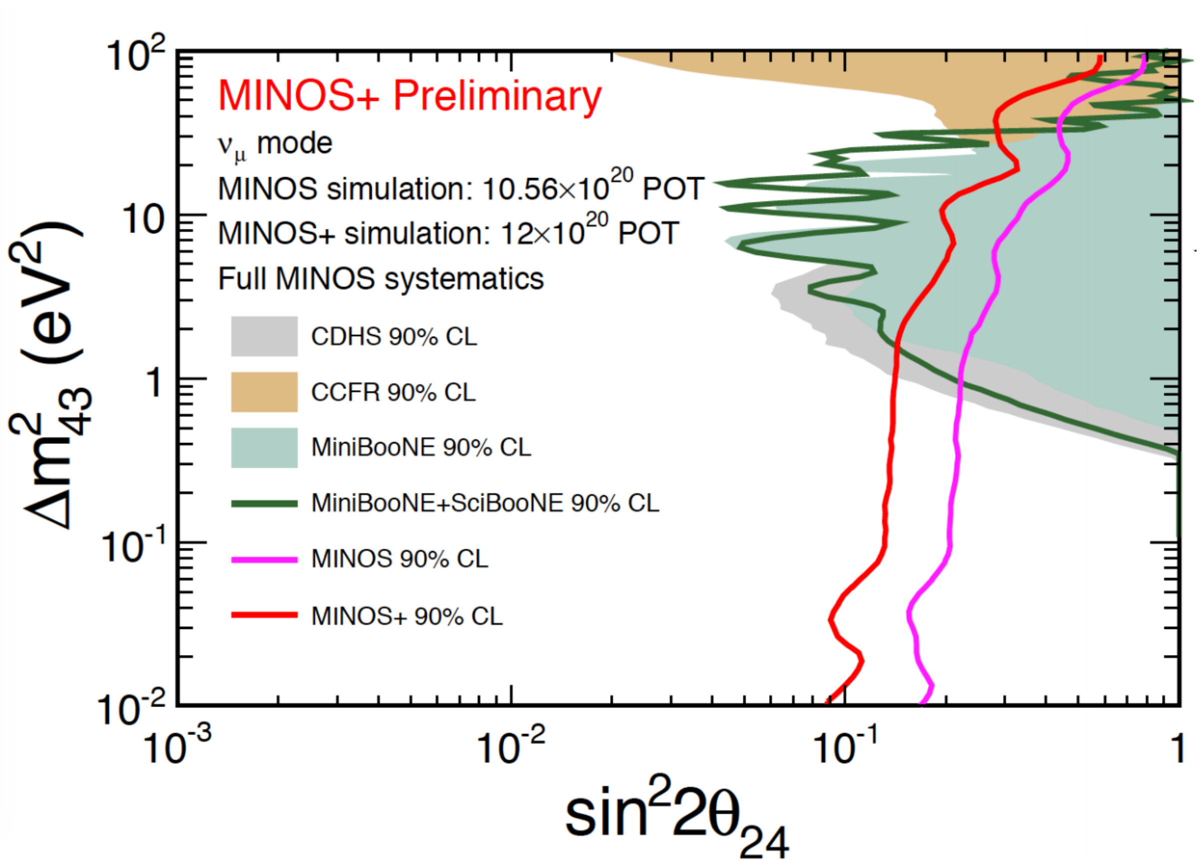
MINOS disappearance search sensitive mainly to θ_{24}

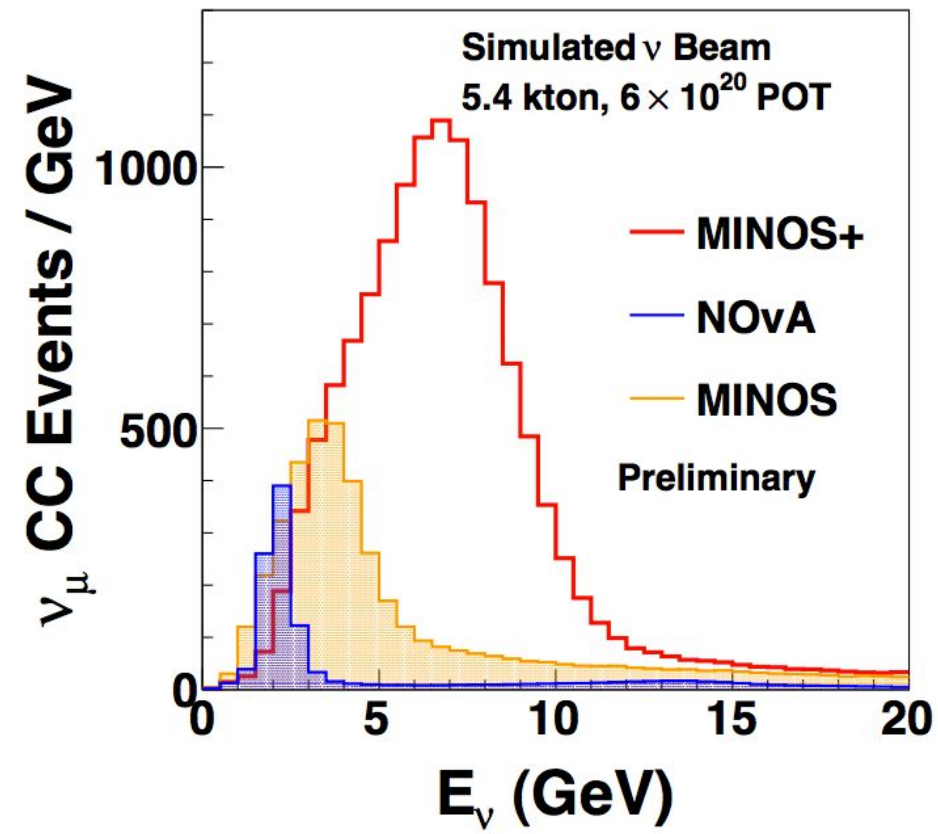
Bugey reactor experiment – electron anti-neutrino disappearance, θ_{14}

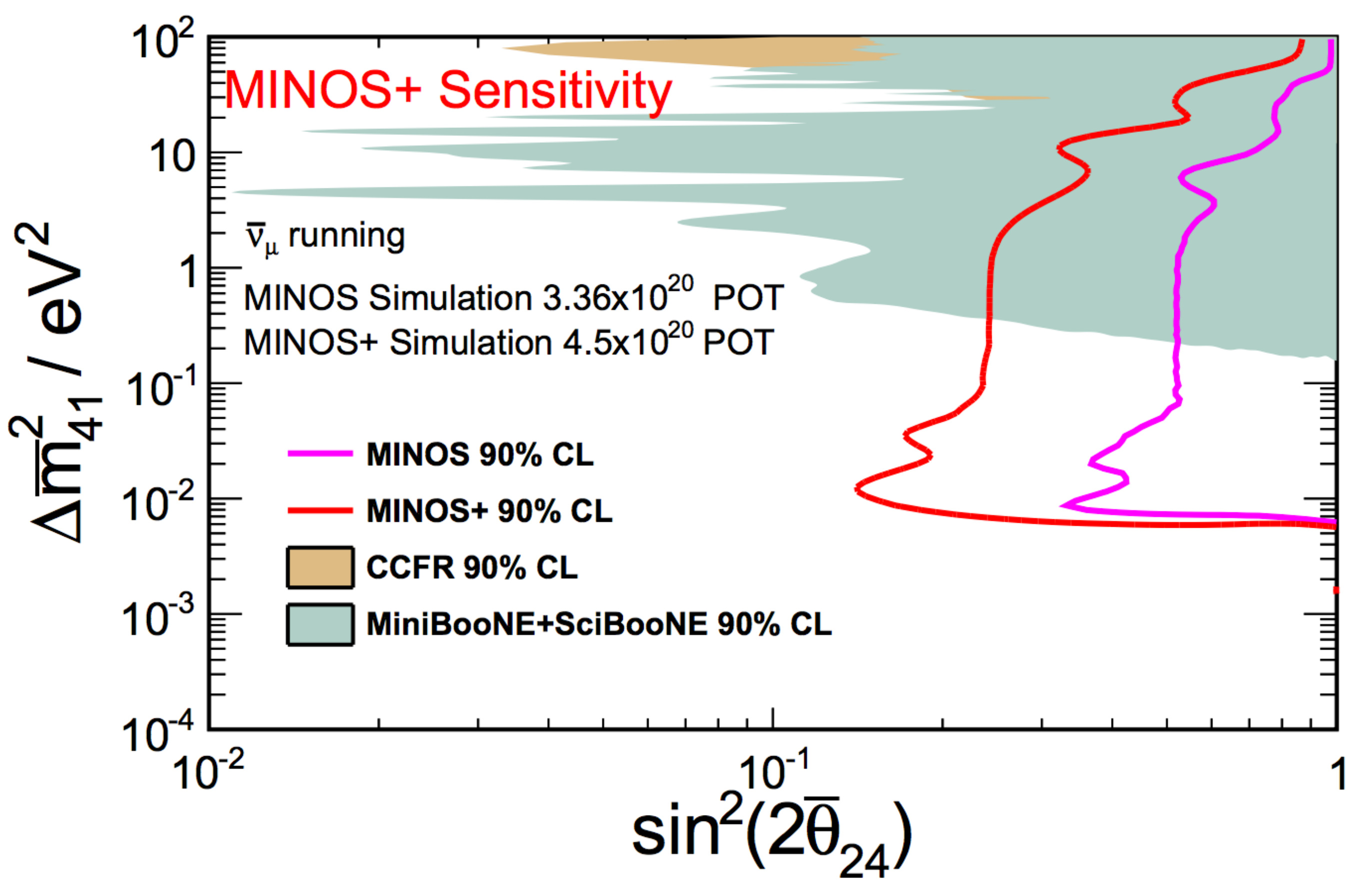
Accelerator and reactor – largely uncorrelated systematic uncertainties



The Future


MINOS+ Preliminary
ν_μ mode
MINOS simulation: 10.56×10^20 POT
MINOS+ simulation: 12×10^20 POT
Full MINOS systematics
CDHS 90% CL
CCFR 90% CL
MiniBooNE 90% CL
MiniBooNE+SciBooNE 90% CL
MINOS 90% CL
MINOS+ 90% CL
Δm^2_{43} (eV^2)
$\sin^2 2\theta_{24}$


Simulated ν Beam
5.4 kton, 6×10^20 POT
MINOS+
NOvA
MINOS
Preliminary
ν_μ CC Events / GeV
E_ν (GeV)


MINOS+ Sensitivity
$\bar{\nu}_\mu$ running
MINOS Simulation 3.36x10^20 POT
MINOS+ Simulation 4.5x10^20 POT
MINOS 90% CL
MINOS+ 90% CL
CCFR 90% CL
MiniBooNE+SciBooNE 90% CL
$\Delta \bar{m}^2_{41}$ / eV^2
$\sin^2(2\bar{\theta}_{24})$

Summary

MINOS uses CC+NC sample to look for sterile neutrinos via deviations from the three-flavour model using a 3+1 model on the F/N Ratio

Use of covariance matrices for systematics, show power of two detector experiment with cancellation of large systematics

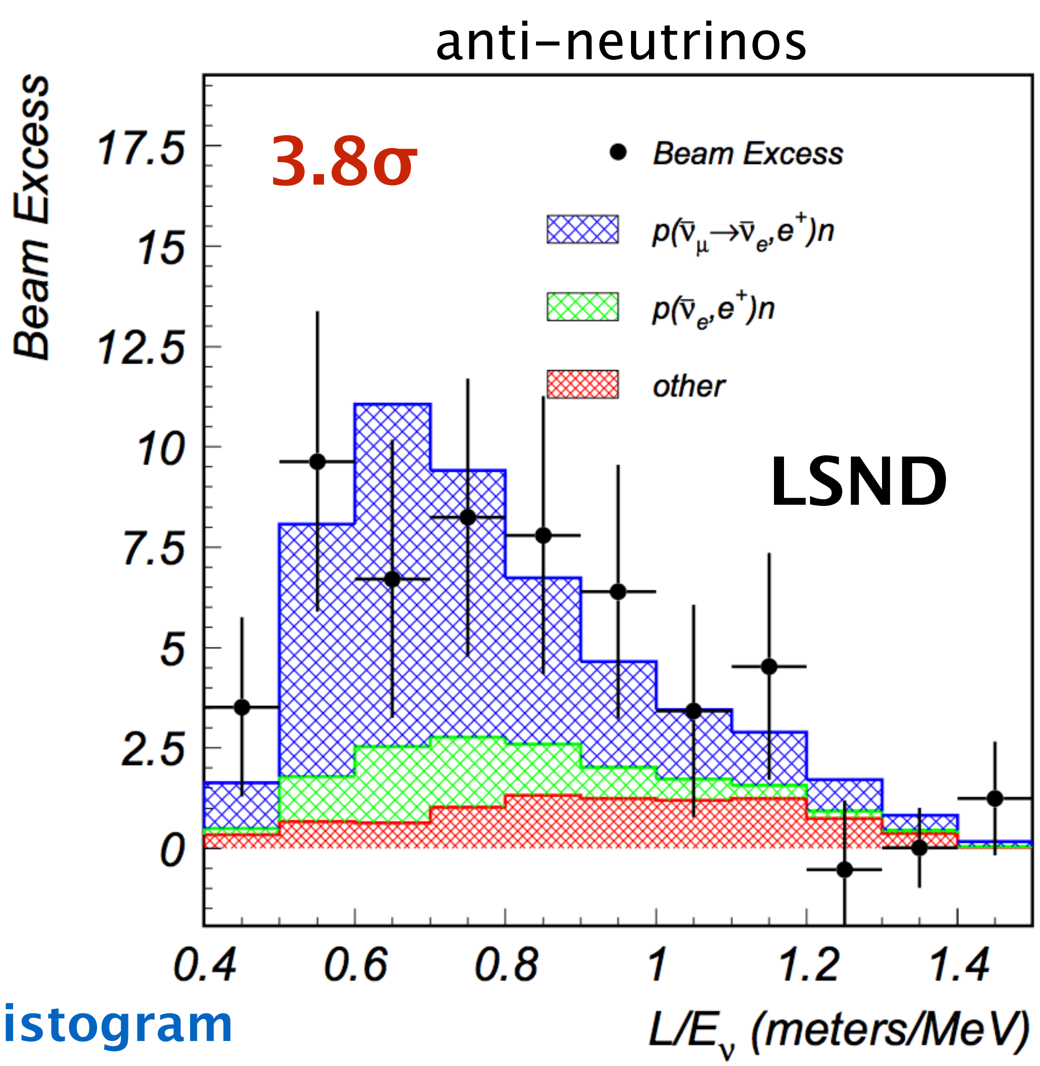
Combination with reactor experiment Bugey allows for limit on same parameter space as LSND etc

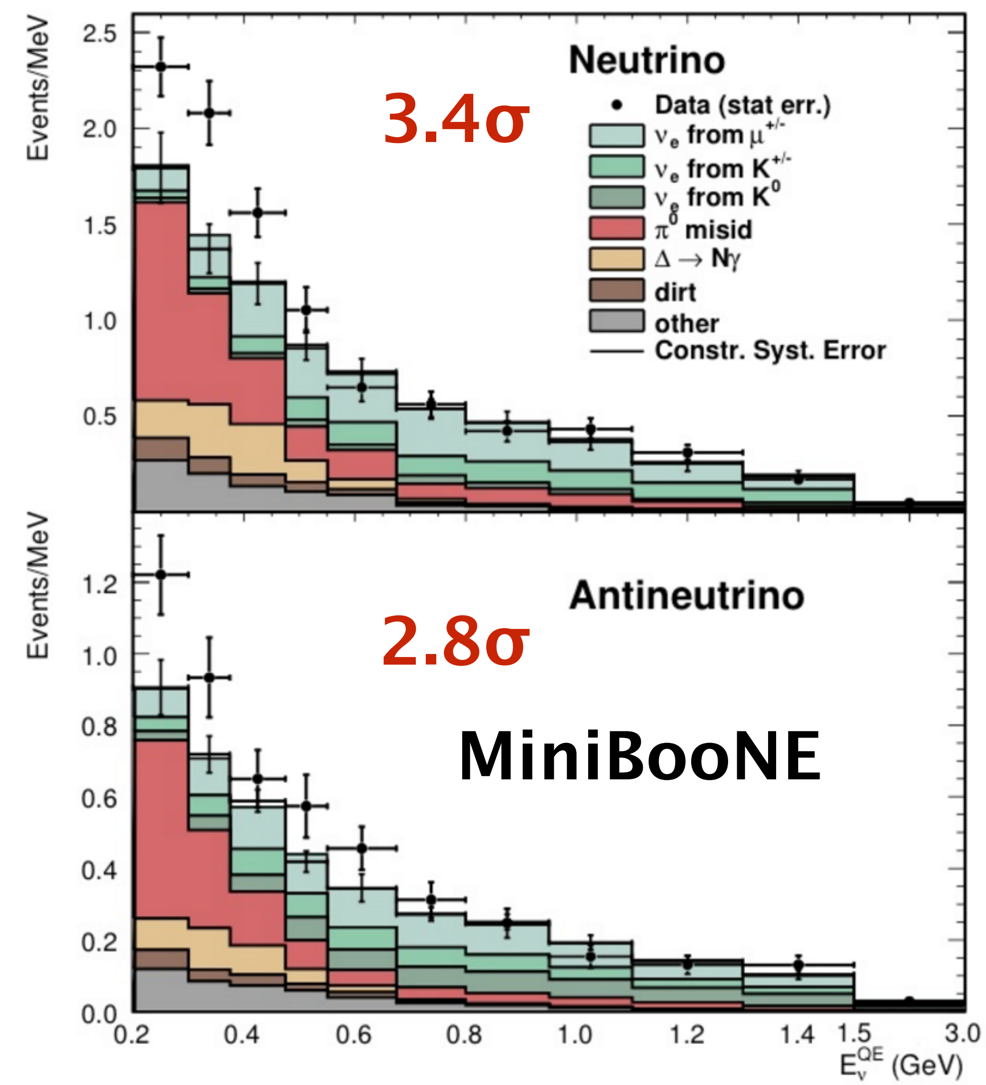
Future with additional data from MINOS+ with higher stats at higher energies.

BACK UP

Sterile Neutrinos?

Looking for ν_e appearance in a ν_μ beam





Blue histogram includes oscillations for $\Delta m^2 \sim 1 eV^2$

E ~ 20–200 MeV
L ~ 30m

E ~ 0.2 – 3 GeV
L ~ 540m

L/E ~ 1 km/GeV

Sterile Neutrinos

An experiment with L/E ~ 1 km/GeV could only observe oscillations if $\Delta m^2 \sim 1 eV^2$

LEP measurements of the Z width show three active neutrinos. Therefore any additional ones must be sterile

experimentally we consider the model 3(active)+1(sterile)

Introduces: θ_{14}, θ_{24}, θ_{34}, and Δm^2_{41}

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

energy dependence of oscillations

$$\Delta_{41} = \frac{\Delta m^2_{41} L}{4E_\nu}$$

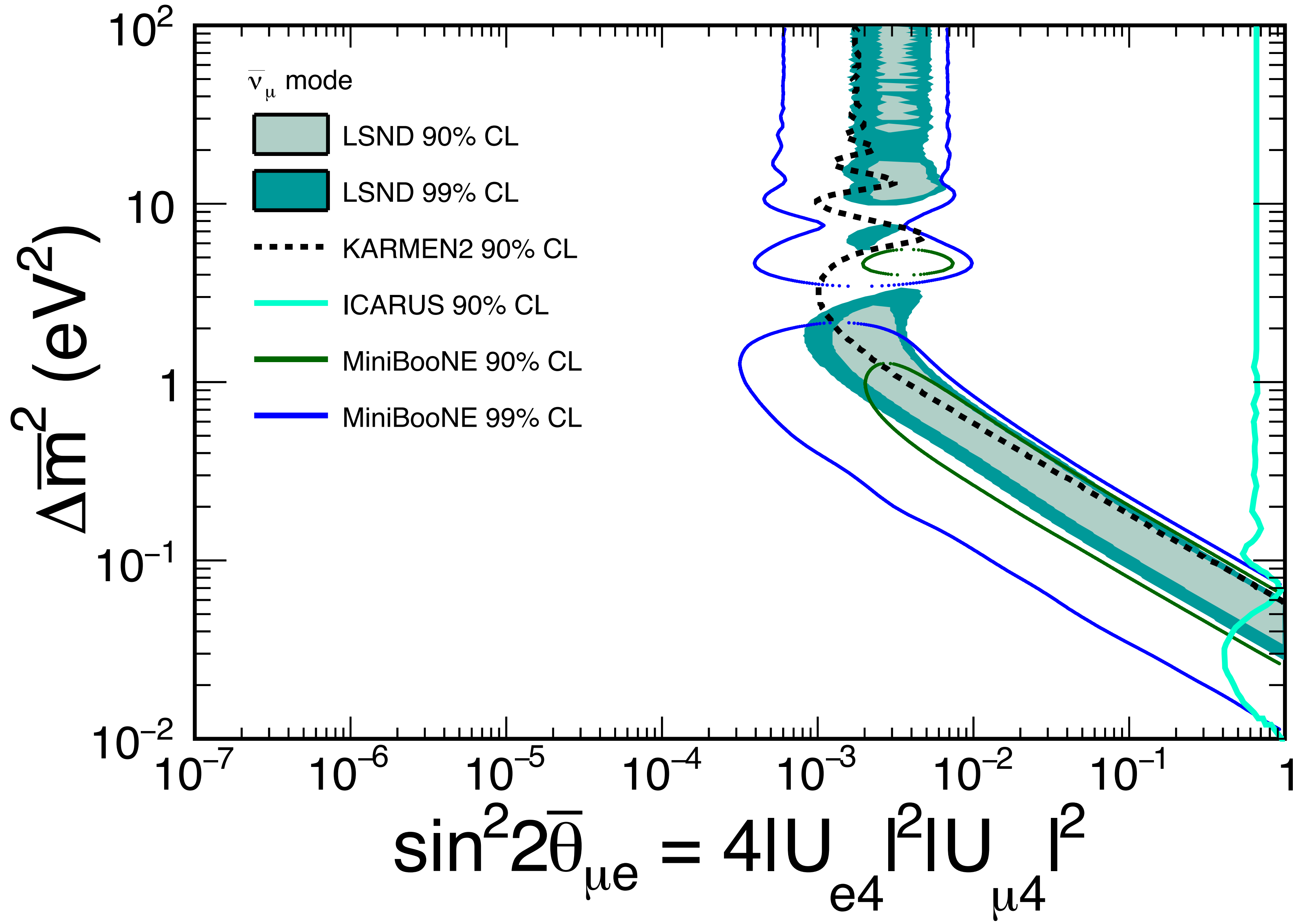
amplitude of oscillations

$$P(\nu_\mu \to \nu_e) = 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2 \Delta_{41}$$

L/E ~ 1 km/GeV

$|\Delta m^2_{41}| >> |\Delta m^2_{32}|, |\Delta m^2_{21}|$

Sterile Neutrinos



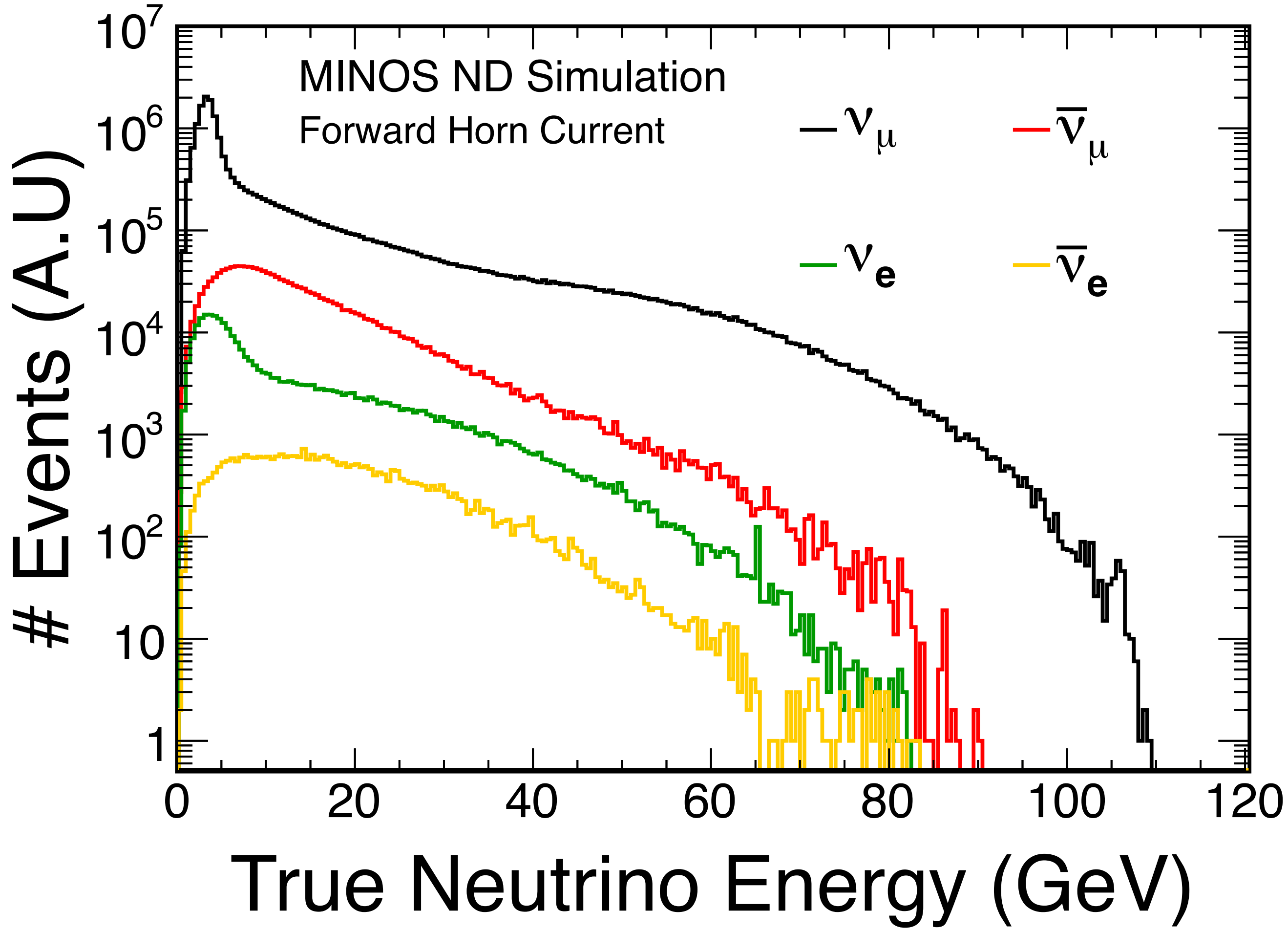
$$|U_{e4}|^2 = \sin^2\theta_{14},$$

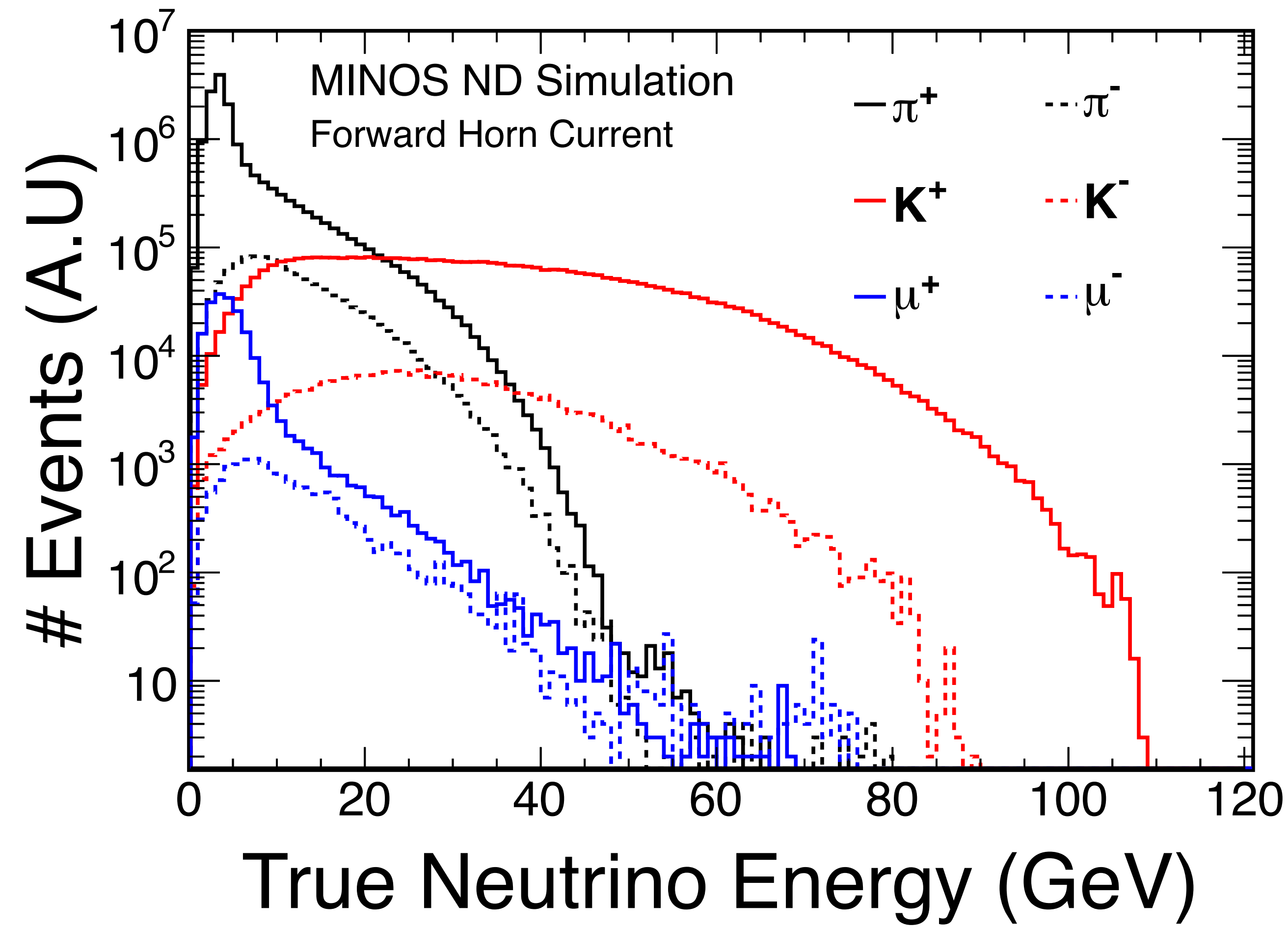
$$|U_{\mu4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14},$$

$$4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}.$$

The University of Manchester

The NuMI Beam

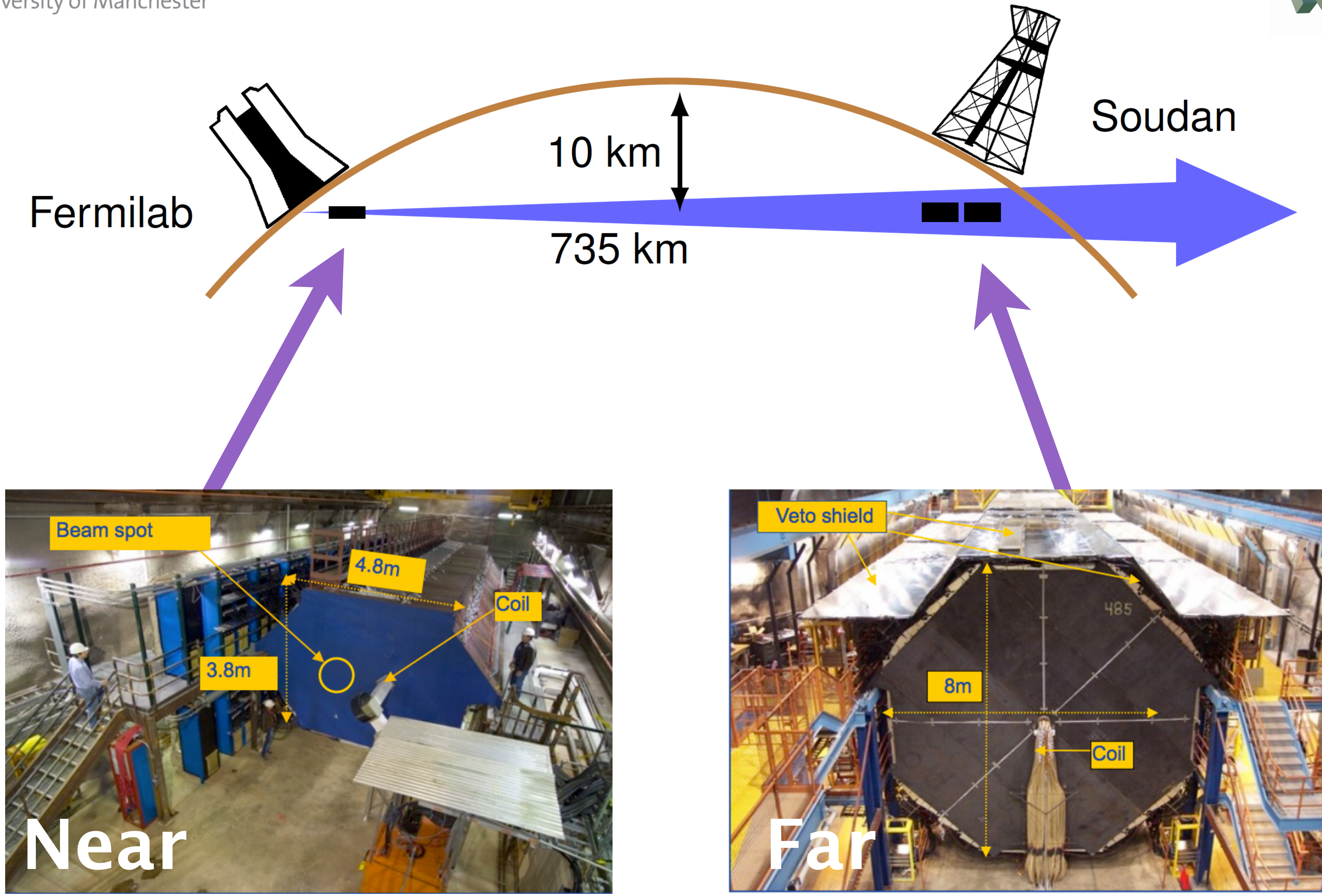




- Anti-neutrino background, high energies, hard to defocus
- Intrinsic electron neutrino component.

- Neutrino parents
- Mainly pions, significant koan component at higher energies

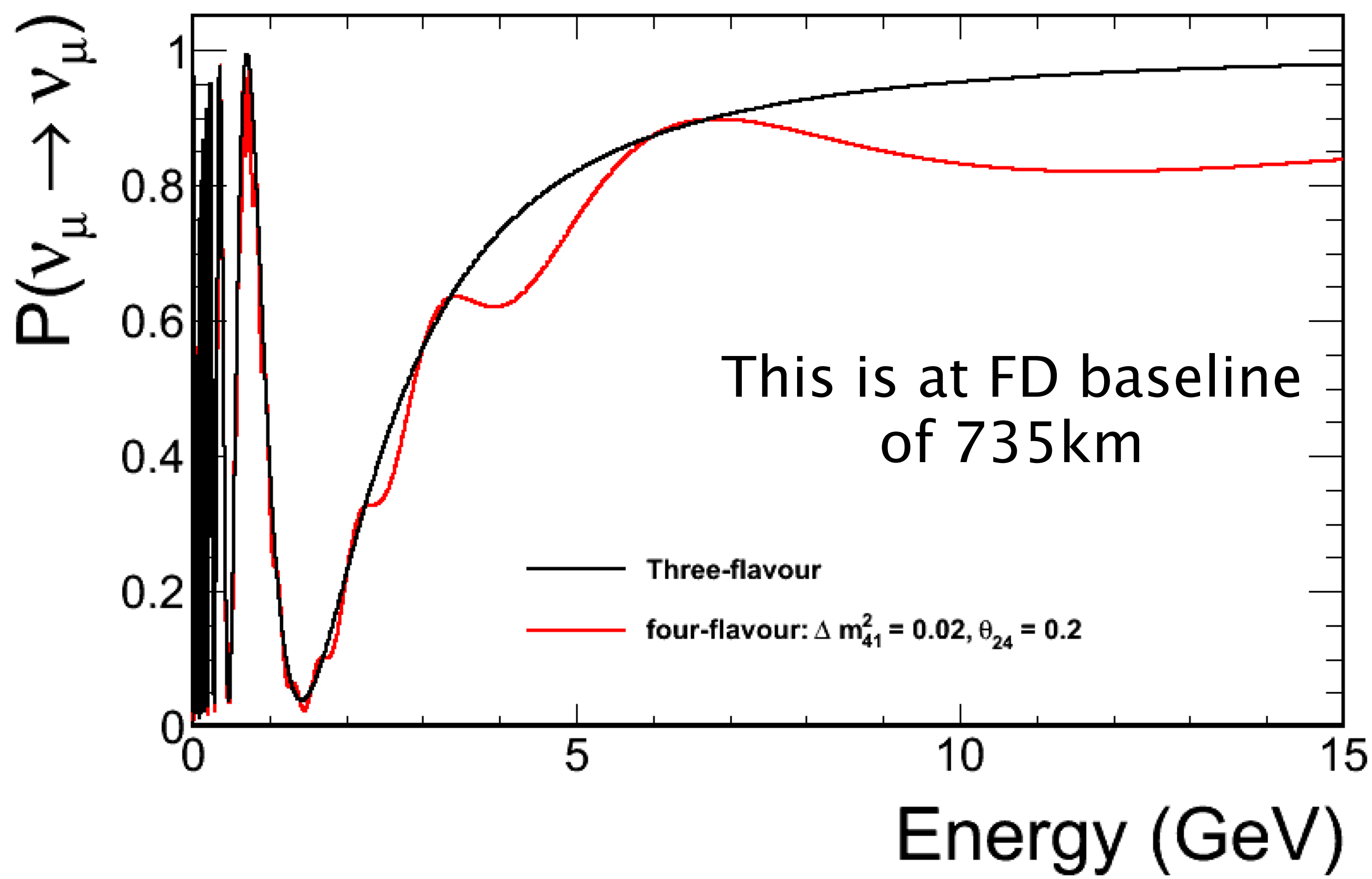
Experimental Setup



Long-Baseline Sterile Search

MINOS was built for measurement of Δm^2_{32} by looking for ν_μ disappearance optimised for L/E = 500km/GeV

Looking for perturbations from three-flavour disappearance.



MINOS sensitive to θ_{24} through muon disappearance

$|U_{\mu 4}|^2$

$|\Delta m^2_{41}| >> |\Delta m^2_{31}|$ to first order the survival prob:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$

Long-Baseline Sterile Search

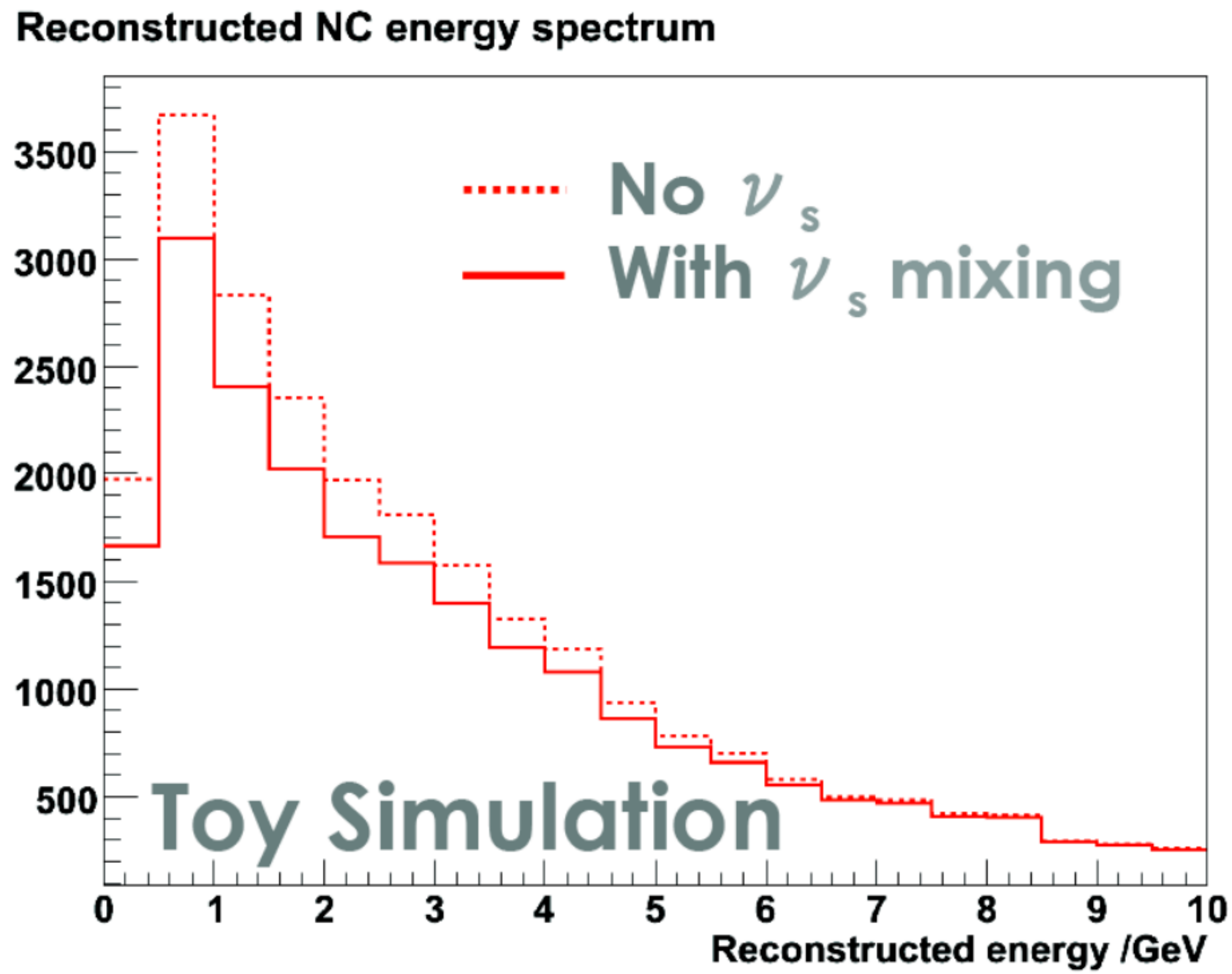
Neutral current interaction rate is the same
for the three active flavours

$\nu_\mu \rightarrow \nu_s$ will reduce the NC rate

$$P_{NC} = 1 - P(\nu_\mu \rightarrow \nu_s)$$

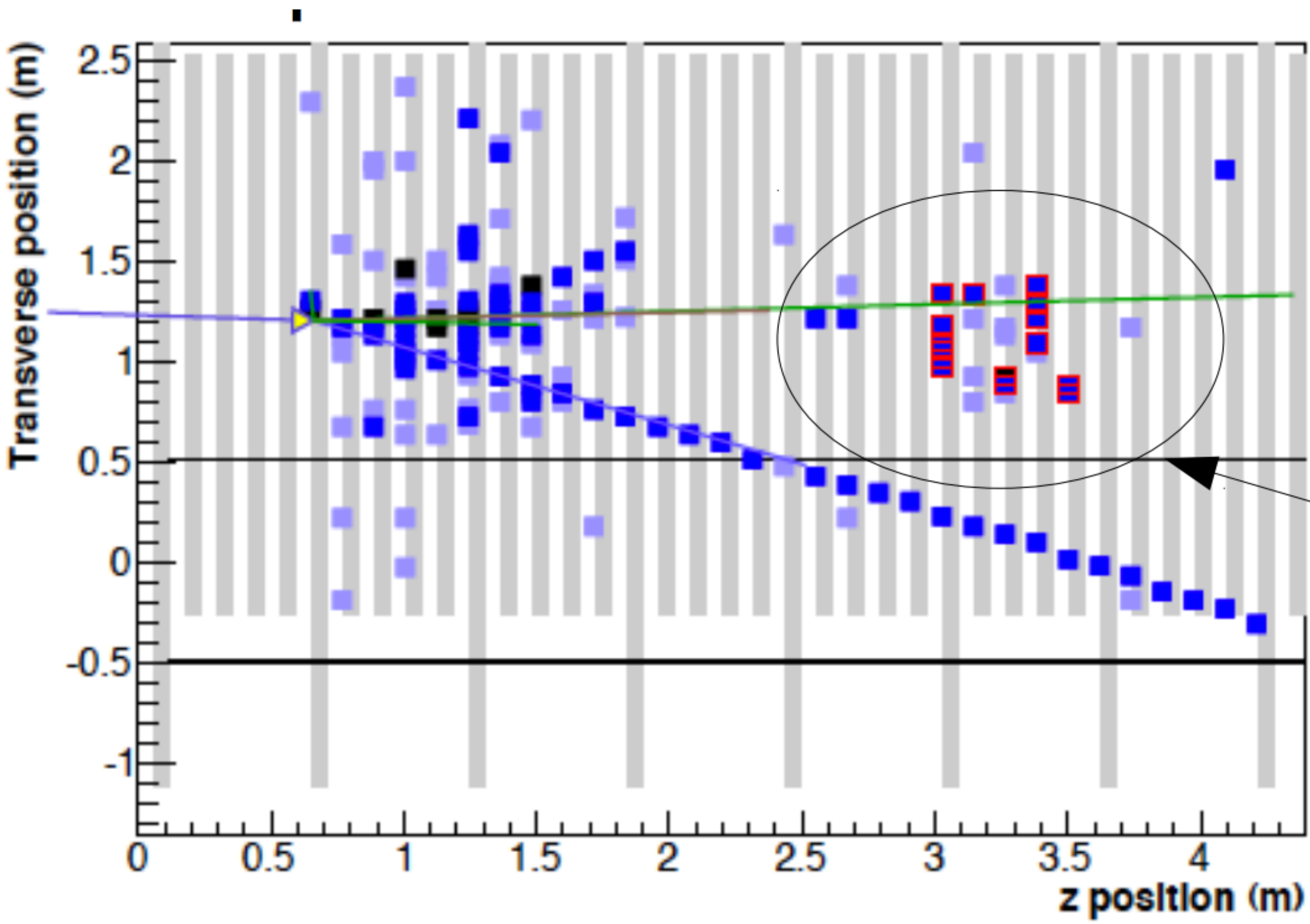
$P(\nu_\mu \rightarrow \nu_s)$ depends on $\theta_{24}, \theta_{34}, \theta_{23}$,

$$|U_{\tau 4}|^2$$



The problem with NC events for sterile searches is
the inability to estimate the true neutrino energy.

Poorly Reconstructed Events



Fake NC event

Definition:

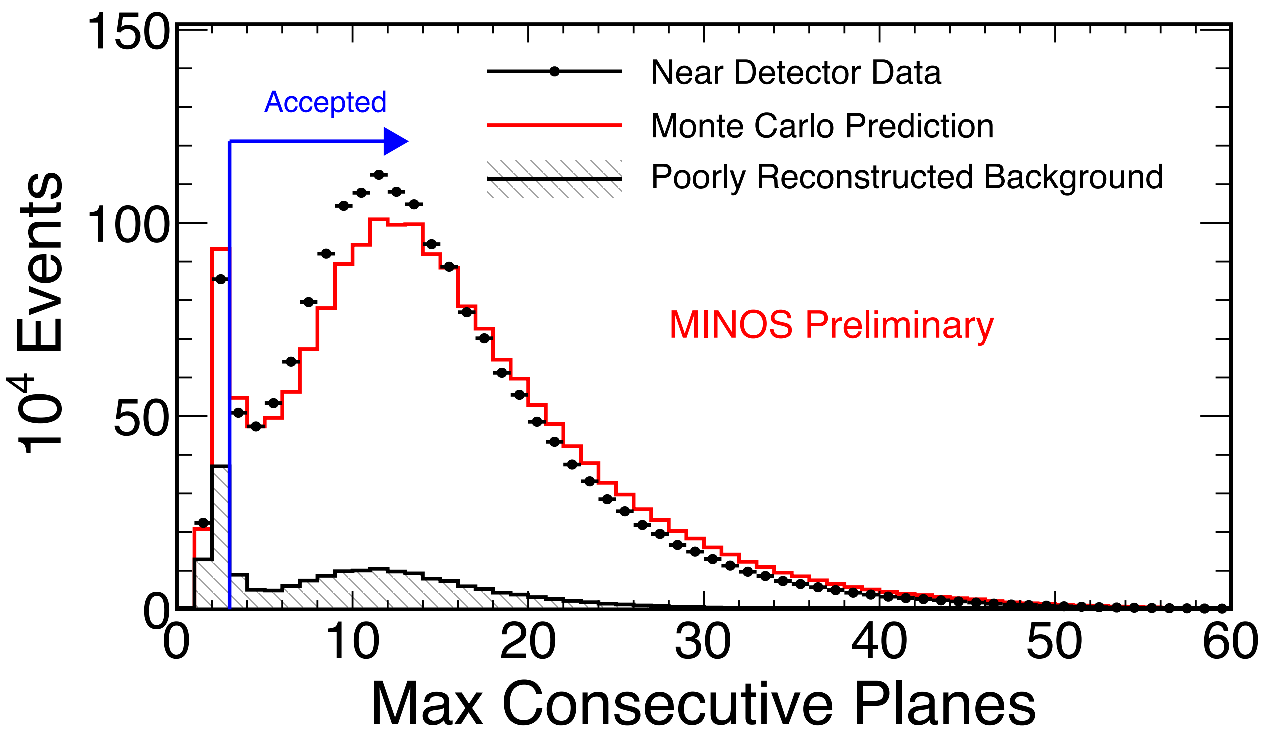
$$\frac{E_{\mathrm{reco}}}{E_{\mathrm{true}}} < 0.3$$

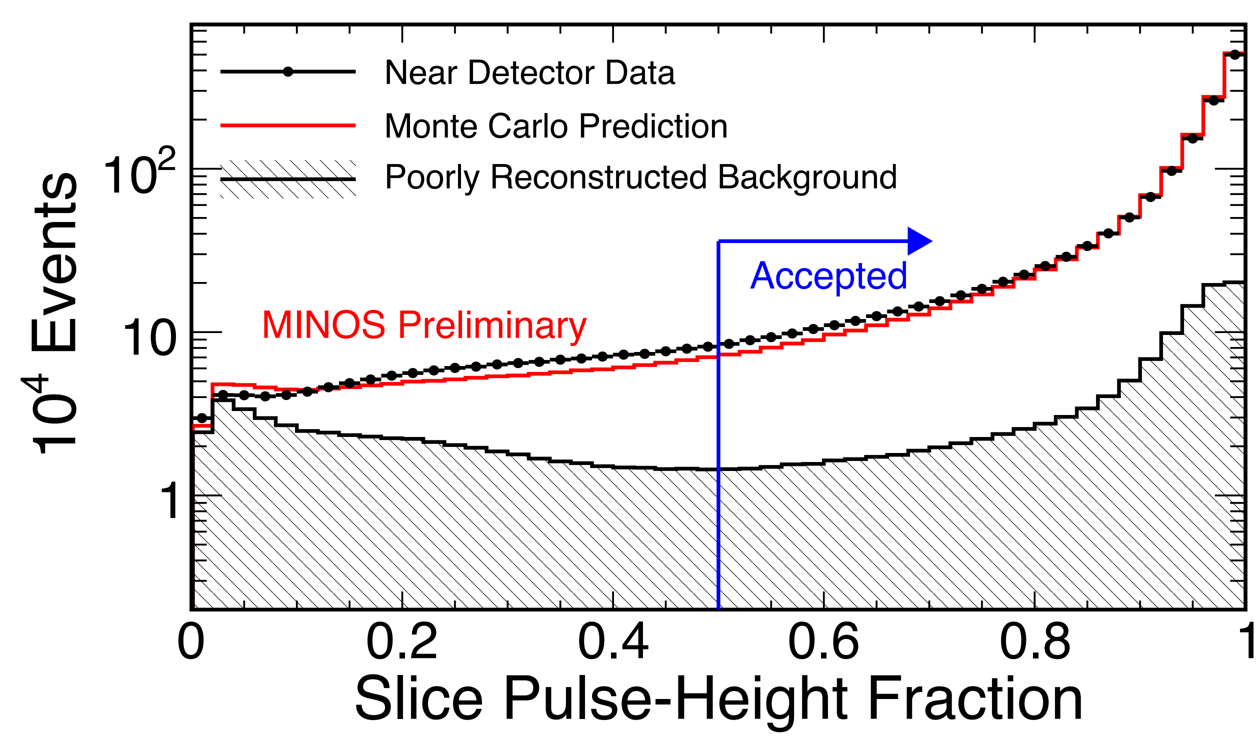
true visible energy expected for the neutrino interaction

the badly reconstructed events are unique to the near detector due to events overlapping in space and time

"chunks" of activity split off from larger events which look the same as small hadronic showers – contamination in NC sample

Poorly Reconstructed Events





Accept events with max planes > 3

Accept events with slice pulse height fraction > 0.5

When a shower develops longitudinally, it deposits energy in successive planes

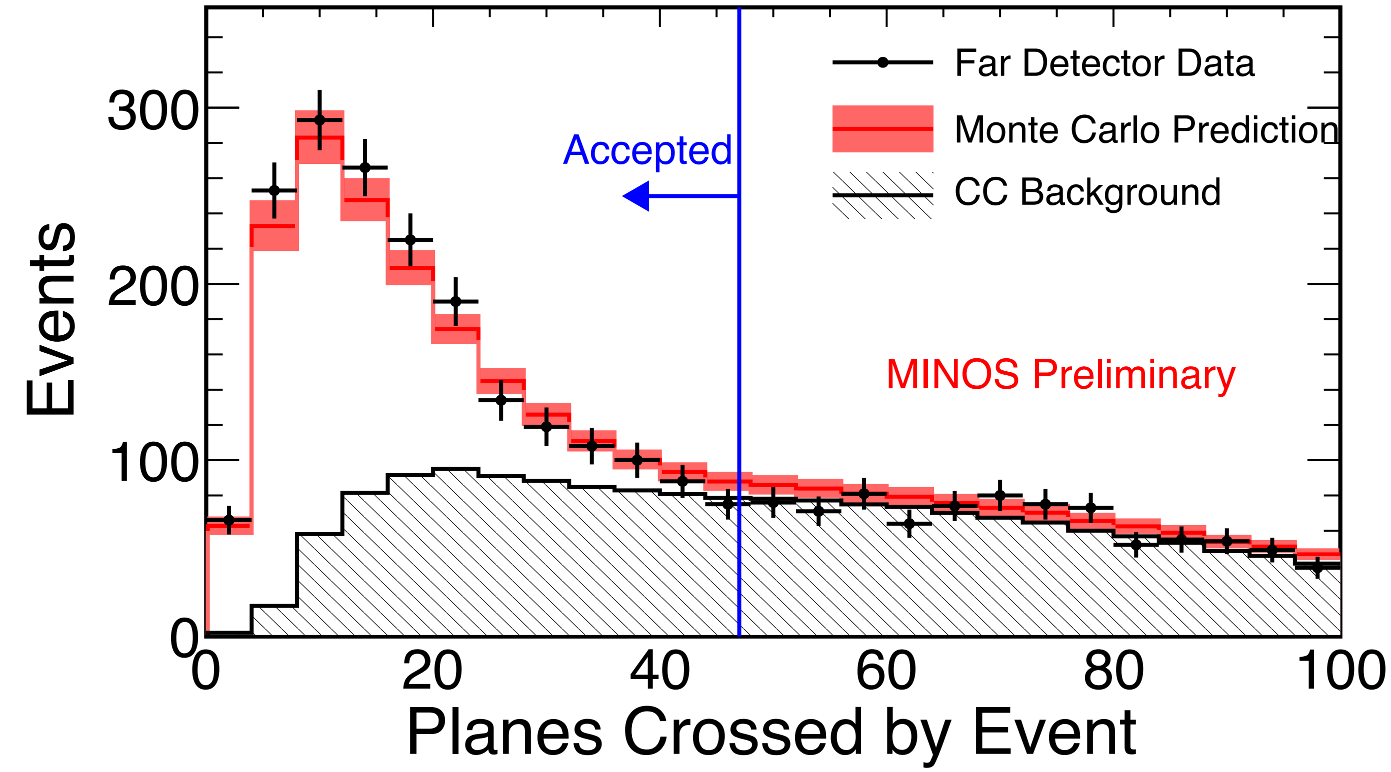
fraction of hits associated with event compared to all nearby hits (in space and time)

Remaining data/MC disagreement is taken as a systematic uncertainty.

NC Event Selection

Same cuts at the ND and FD

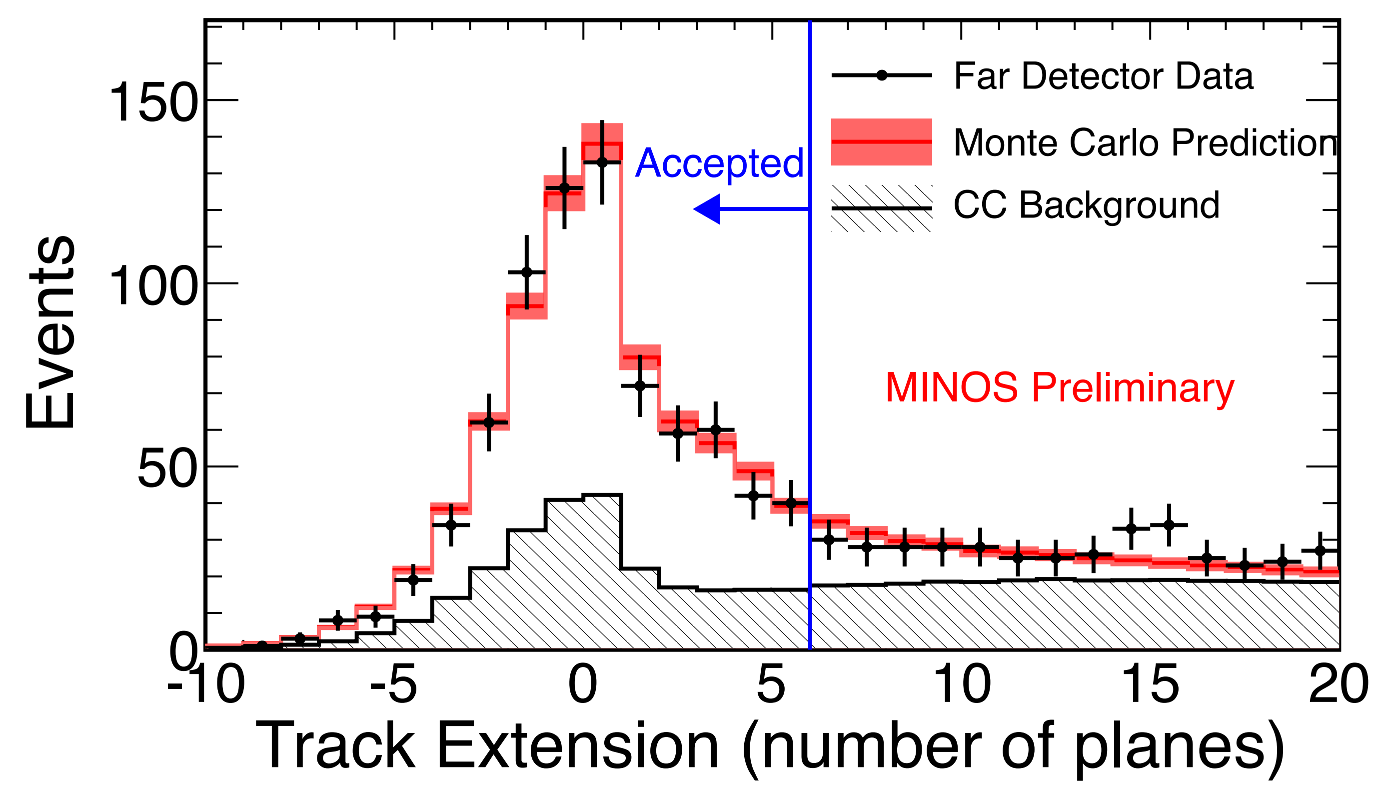
NC events don't typically cross as many planes in the detector, compared to CC events that have long tracks.



track extension defined as the number of planes the track extends out of the reconstructed shower.

relative size of track compared to shower

NC events will have short tracks

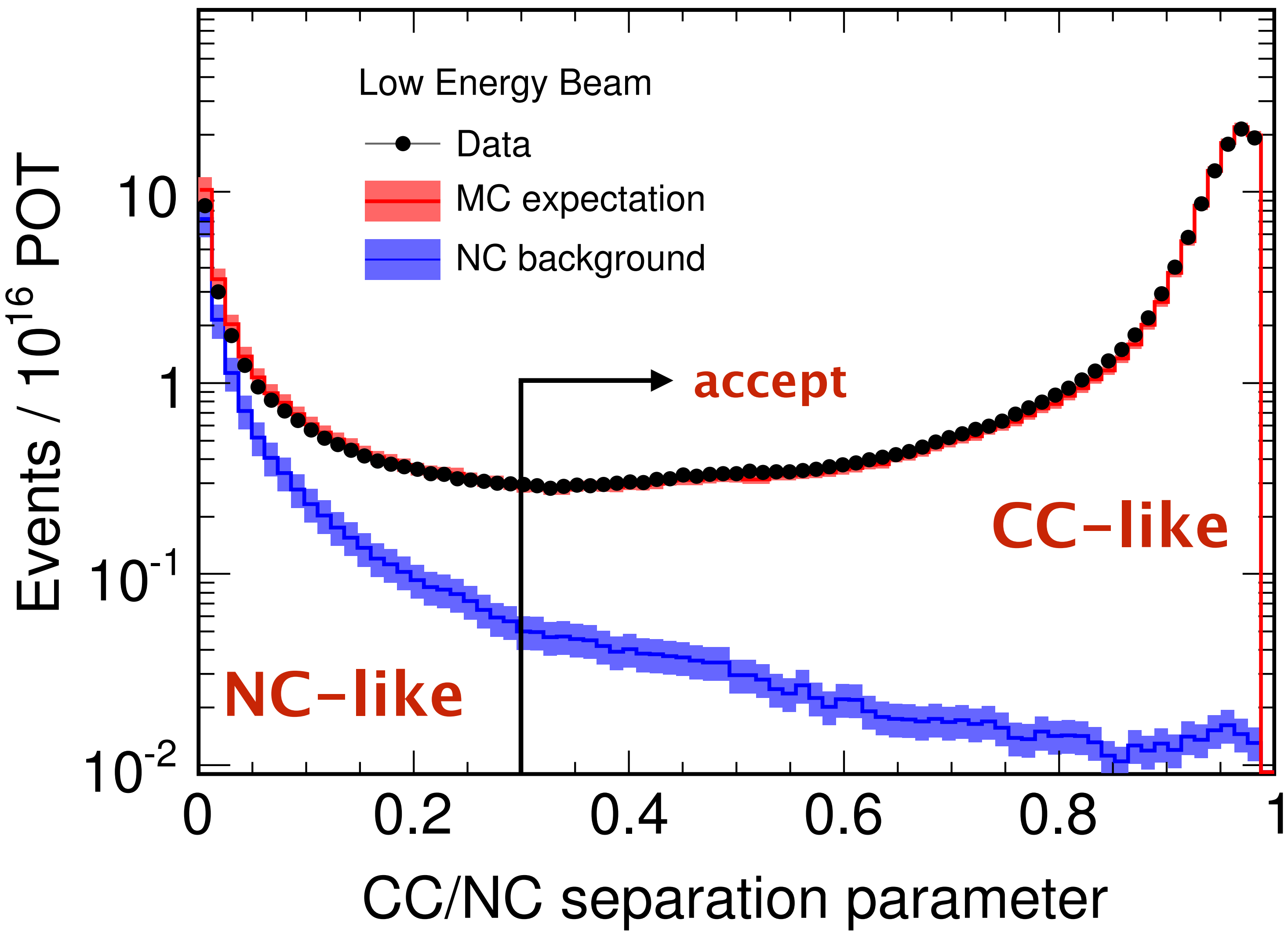


CC Event Selection

Next select all events that have a track

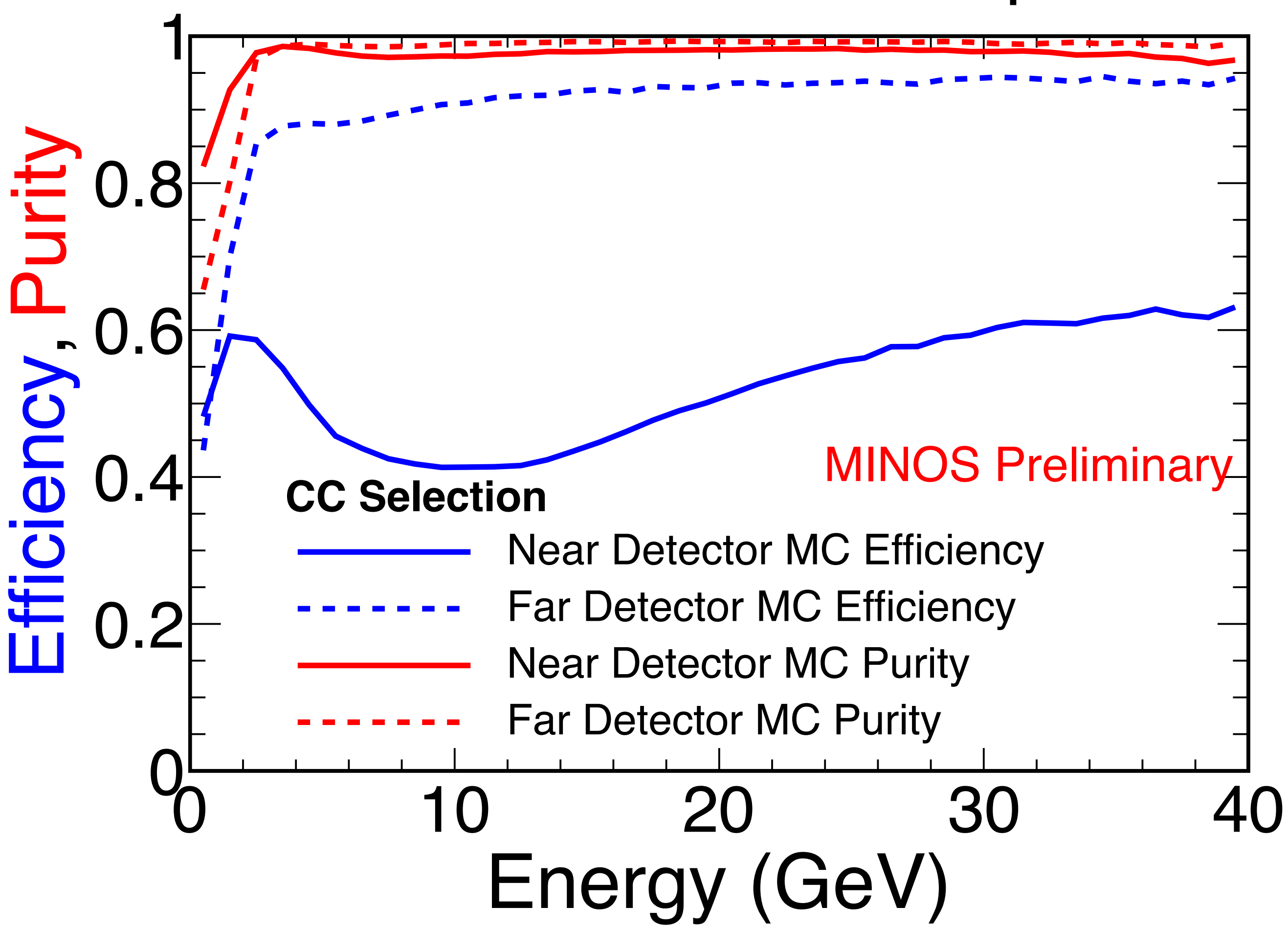
Four variable kNN algorithm used for CC selection

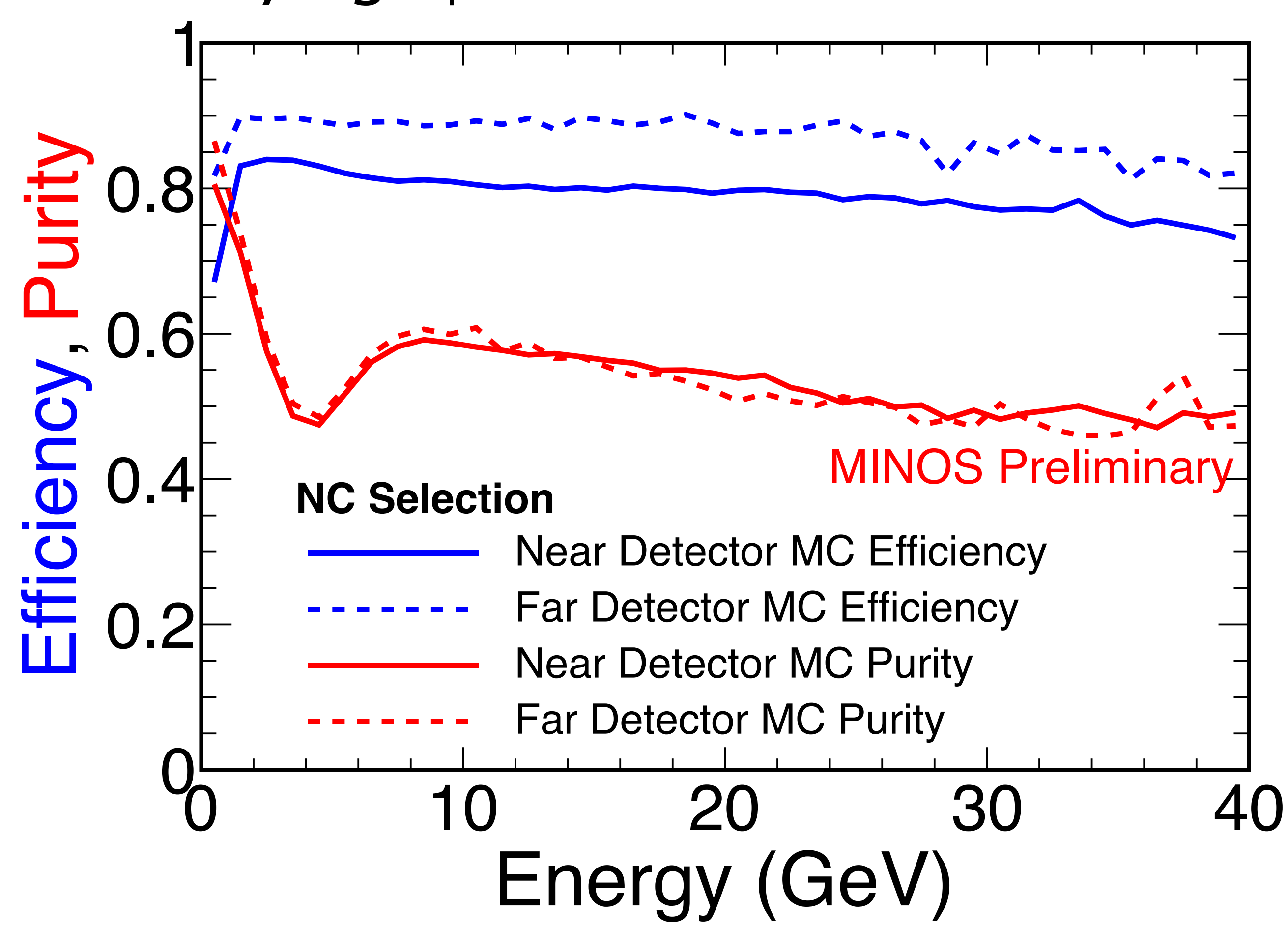
- # of scintillator planes in a track
- Ratio: energy deposited in track and deposited energy of entire event
- Mean pulse height of all track hits.
- Ratio of low pulse height to high pulse height hits.



Selector Performance

MINOS was optimised for identifying ν_μ CC events





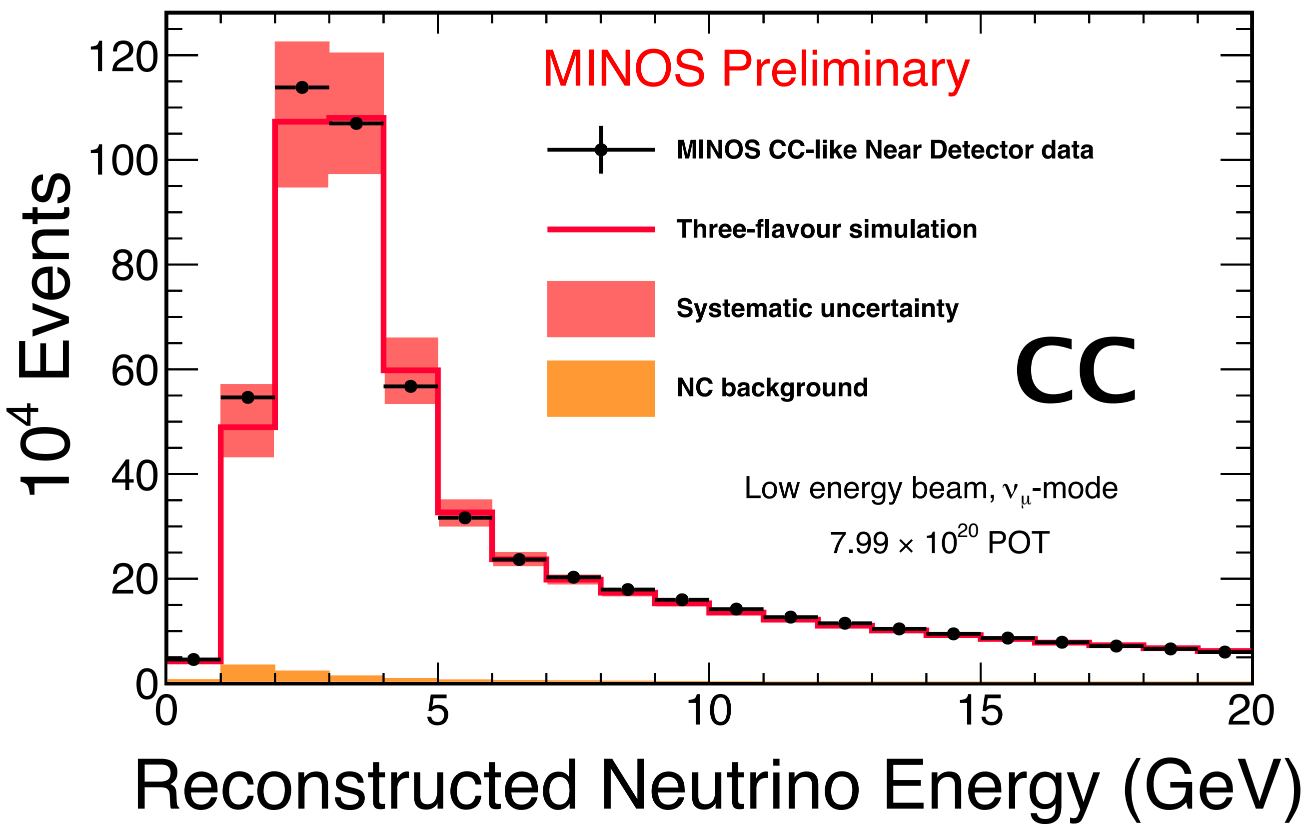
Purity= (# selected true signal events) / (total # selected events)

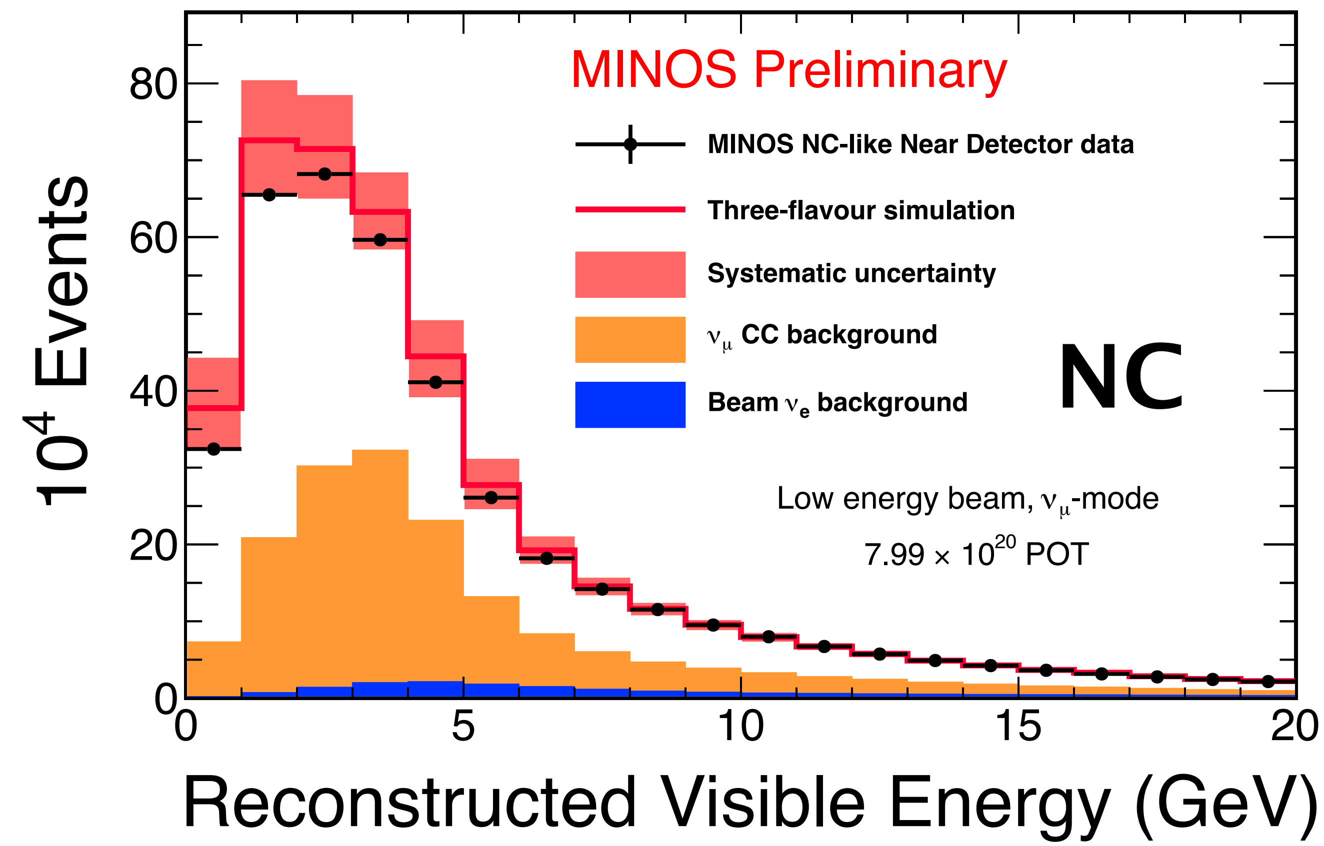
Eff = (# selected true signal events) / (total # selected signal events before selection)

CC ND eff is low due to events with tracks ending near the coil hole

NC events it is more difficult: 86% eff, 61% Purity at the FD
main bkg from inelastic ν_μ CC events

ND Spectra



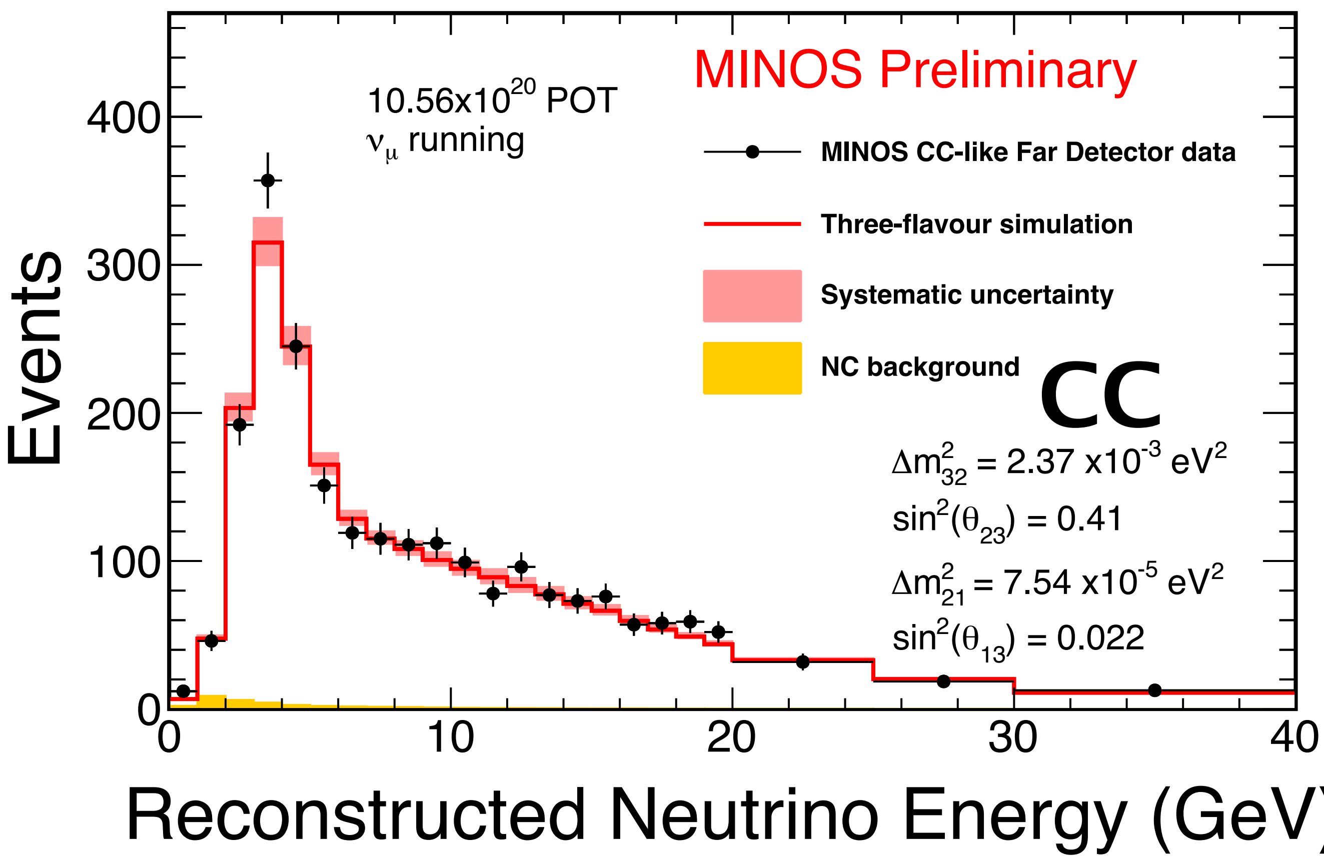


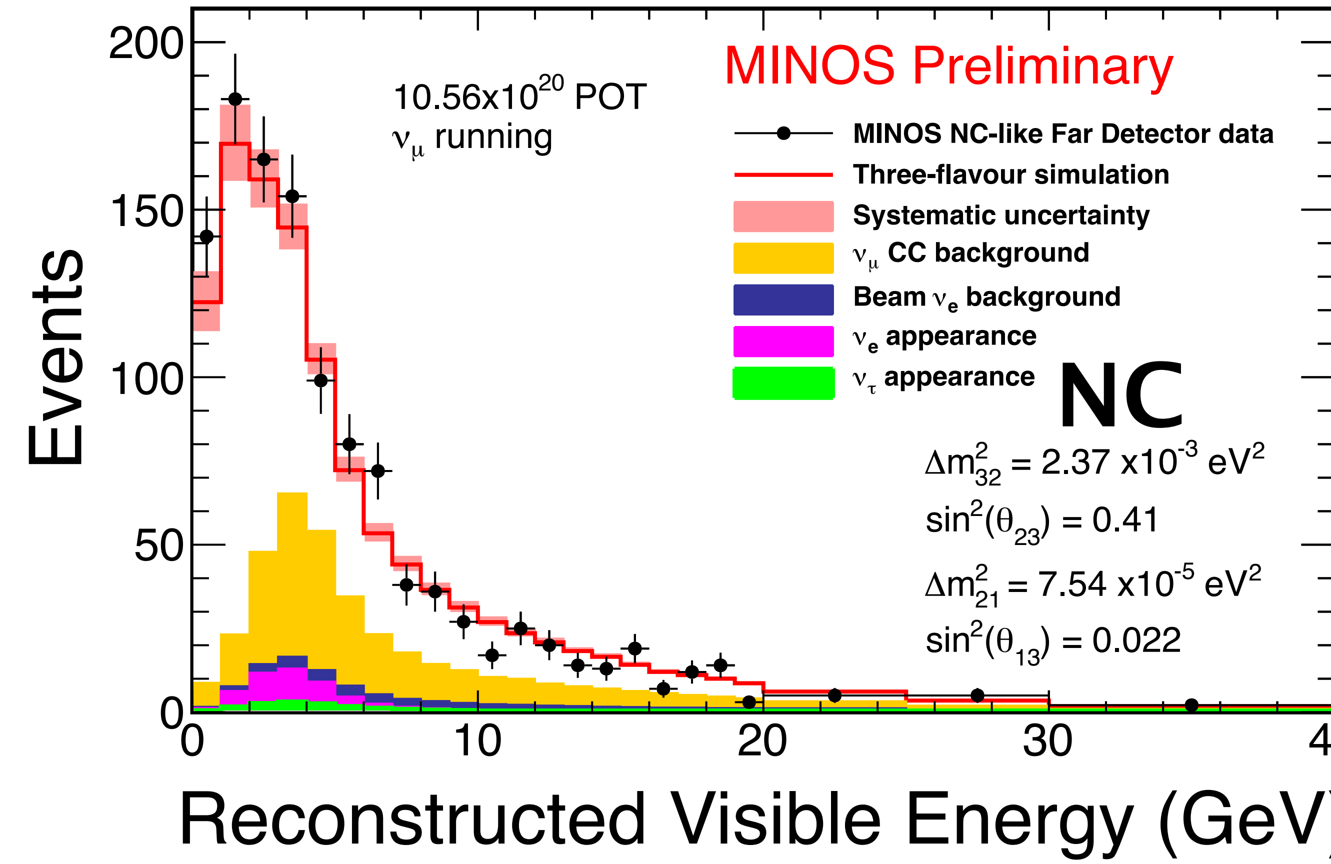
The measured Near Detector energy spectrum is used to predict the Far Detector spectrum via the Far/Near Ratio method.

This method relies on no parameterisation the ND data

For each bin of energy correct FD MC by scale factor from ND data/MC discrepancies. Robust method – reduces systematic errors

FD Spectra





FD spectra three-flavour oscillated with MINOS 2012 CC-analysis fit values

2563 CC-like events

1211 NC-like events

Already we see no significant deviations from the three-flavour model

NC R Values

Use NC FD spectrum to look for a deficit of NC events, compared to that expect from 3-flavour. Not assuming a particular sterile neutrino model

$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

Predicted CC background from all flavors

Predicted NC interaction signal

[stats] [sys]

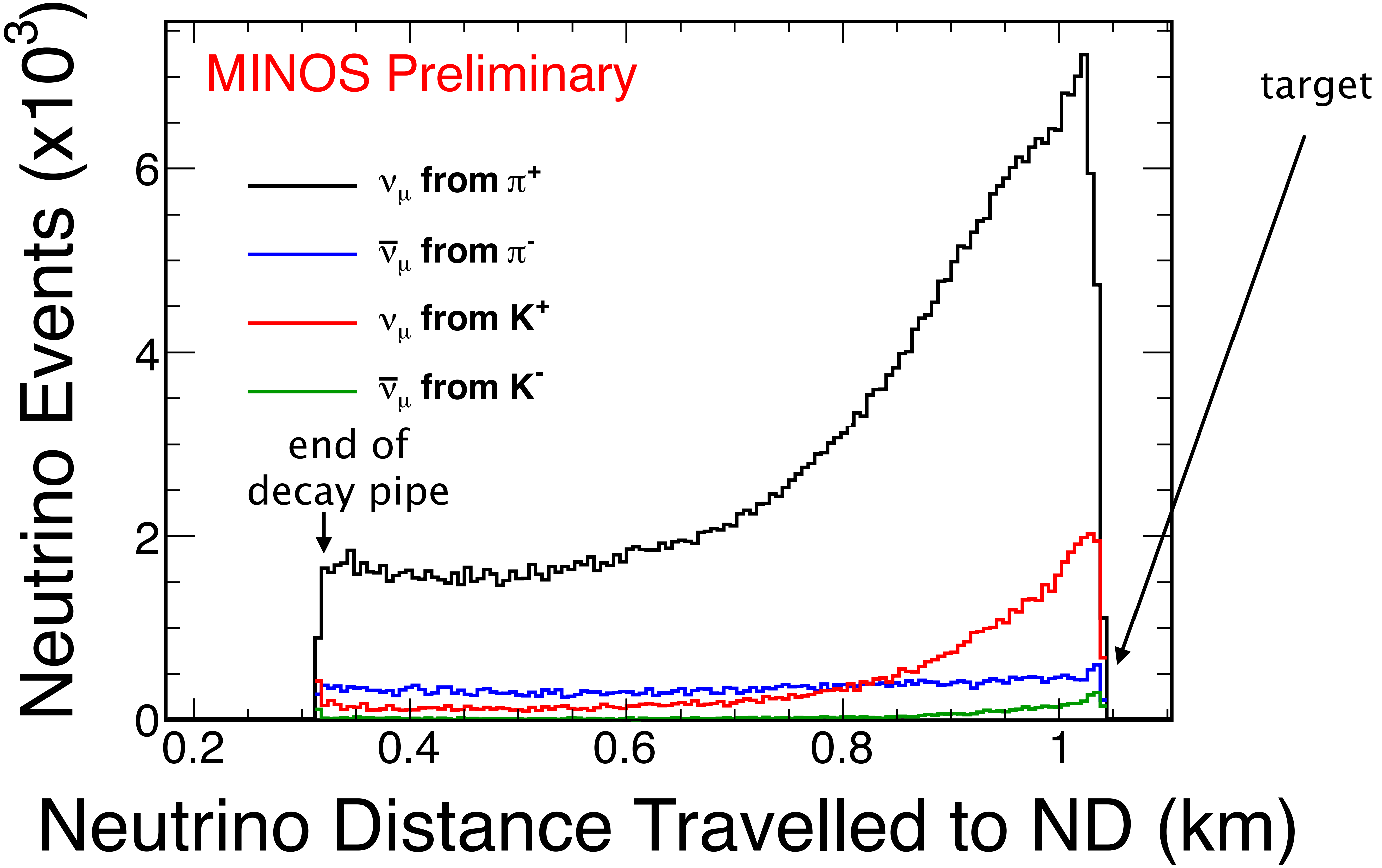
R [0-3 GeV] = 1.10 +/- 0.06 +/- 0.07

R [0-40 GeV] = 1.05 +/- 0.04 +/- 0.10

If no NC disappearance R = 1

Values seem consistent with seeing no deficit in NC event rate

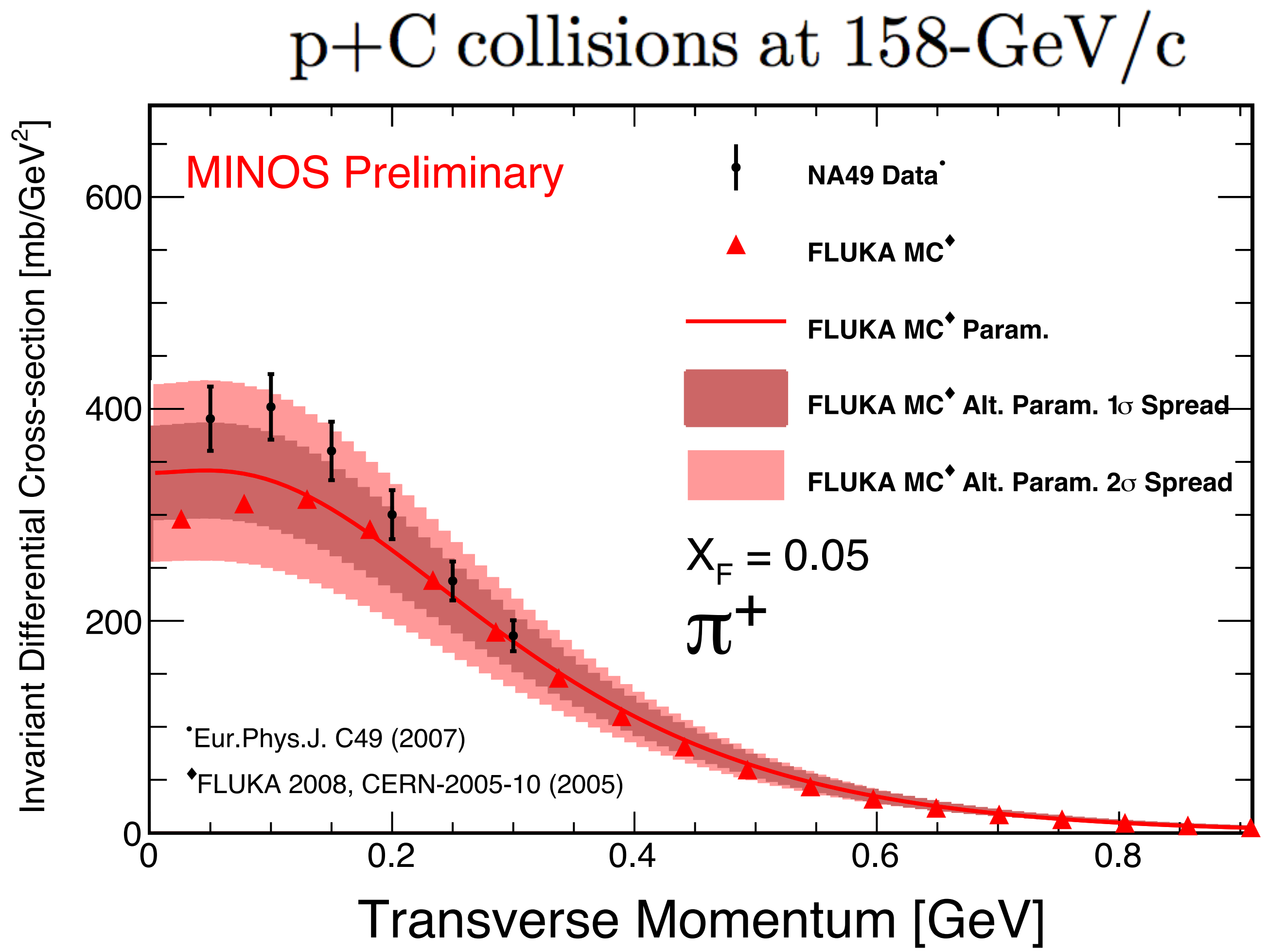
Varying Baseline



Because we now allow for short baseline oscillations, it is crucial that we account for the baseline varying due to the distribution of hadron decay points within the 675m decay pipe.

Hadron Production Uncertainty

Need to assign systematic to flux, can not use ND data



$$x_F = \frac{p_L}{\sqrt{s}/2}$$

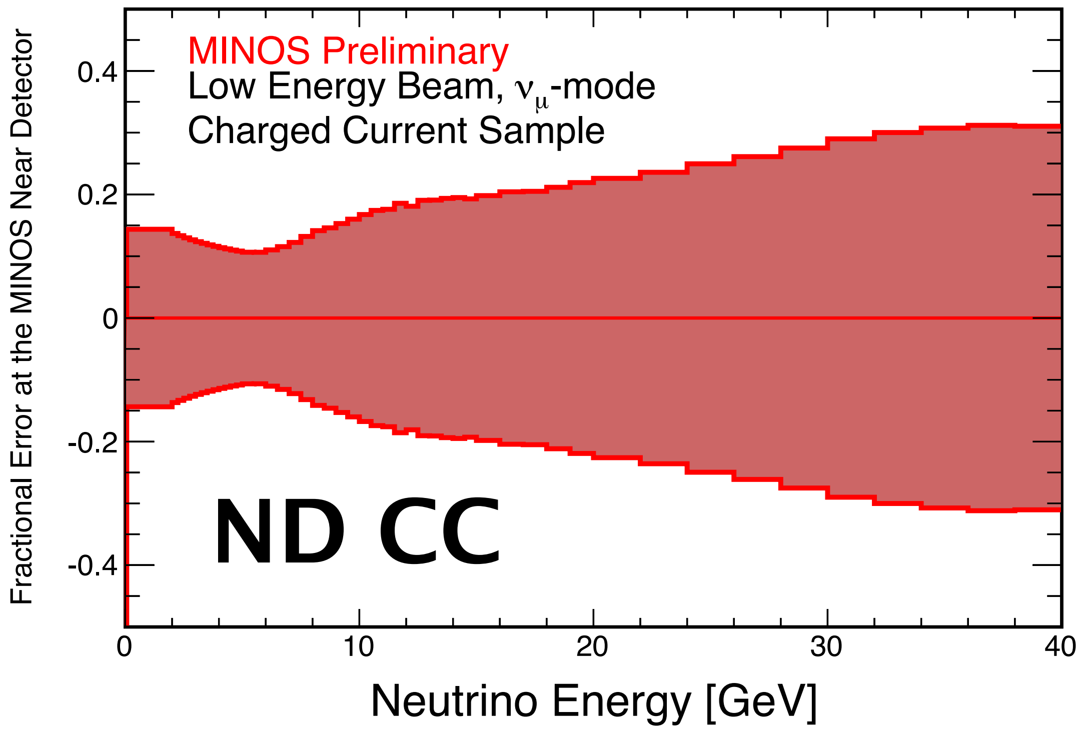
wide acceptance spectrometer for the study of hadron production

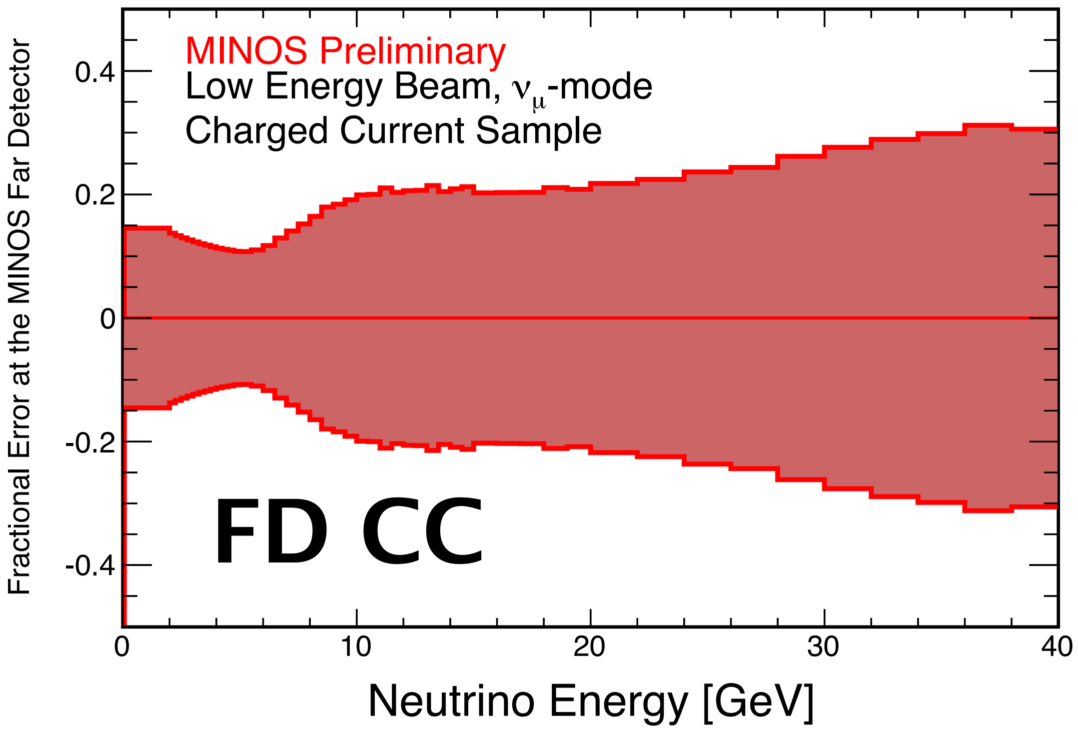
Fit a beam simulation (FLUKA) of the NA49 target to the BMPT parametrization.

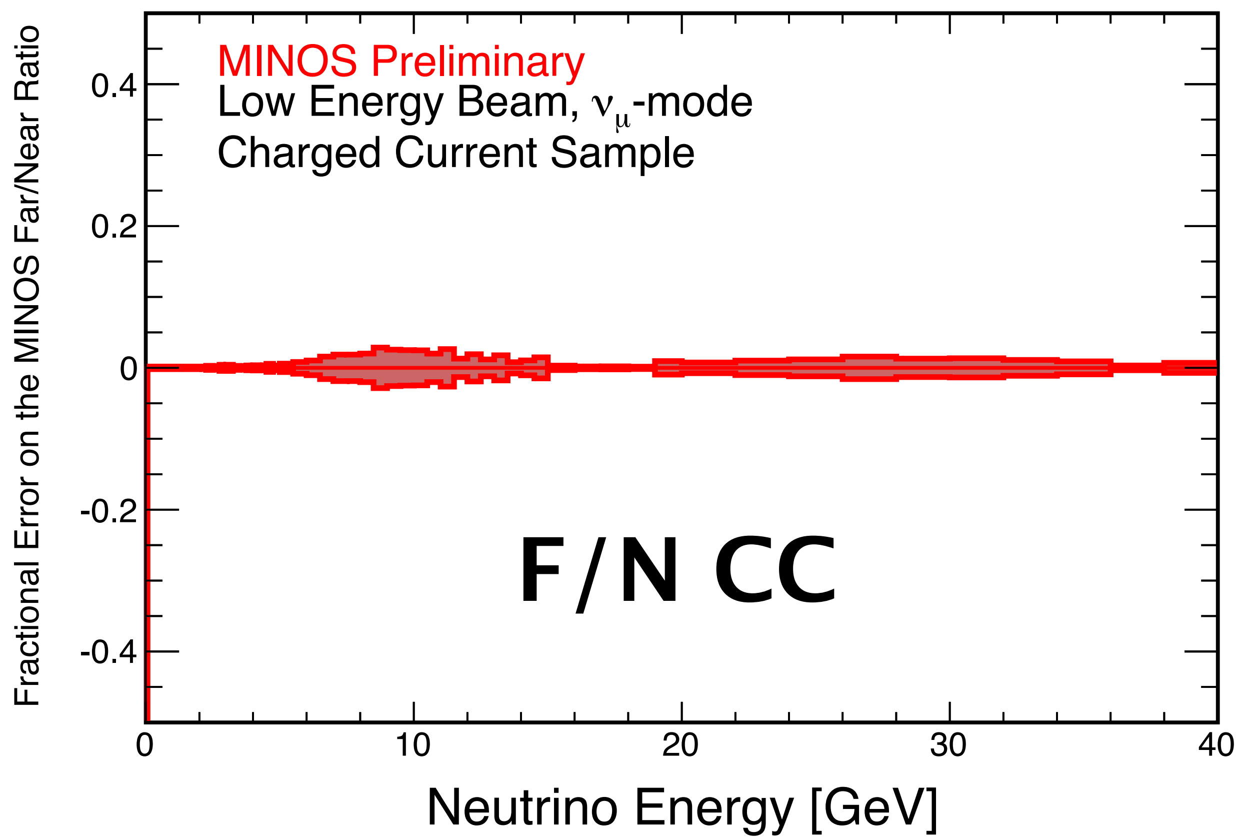
Vary fit parameters within their errors to create a collection of physically feasible alternate invariant differential cross-section parametrizations.

Scale up the errors given by the fit until the collection of alternate parametrizations cover the difference between the FLUKA MC and NA49 data.

Hadron Production Uncertainty





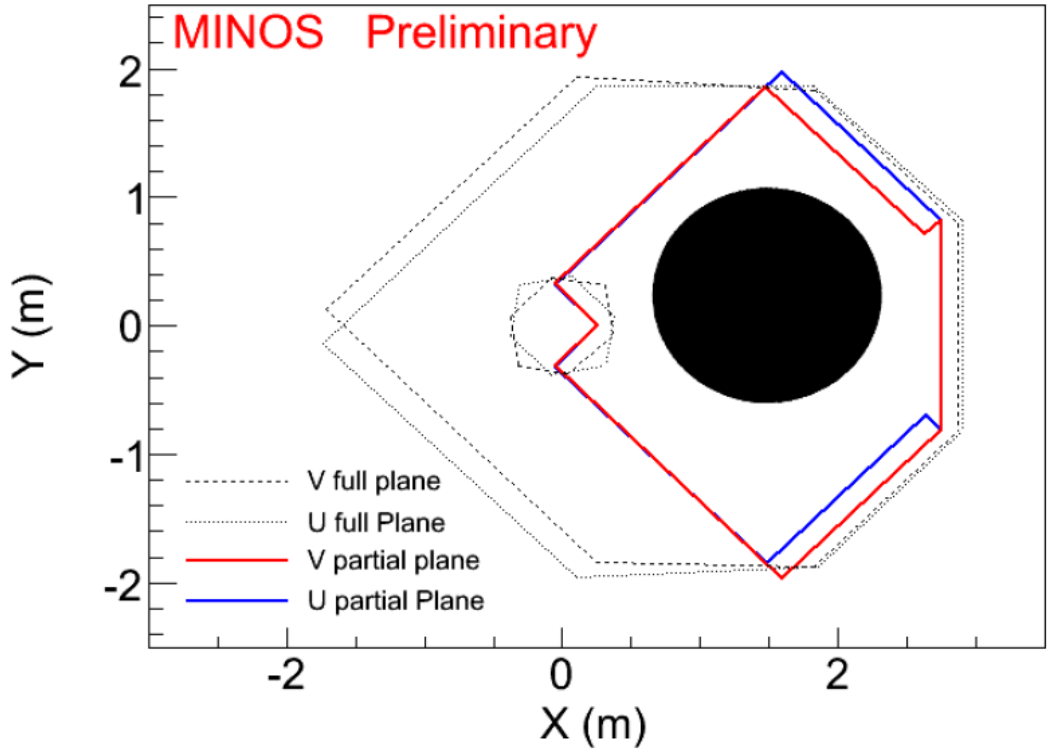


Detector Acceptance Uncertainty

Acceptance uncertainties are determined by comparing the effect of varying cuts on data/MC at the ND compared to the nominal cuts.

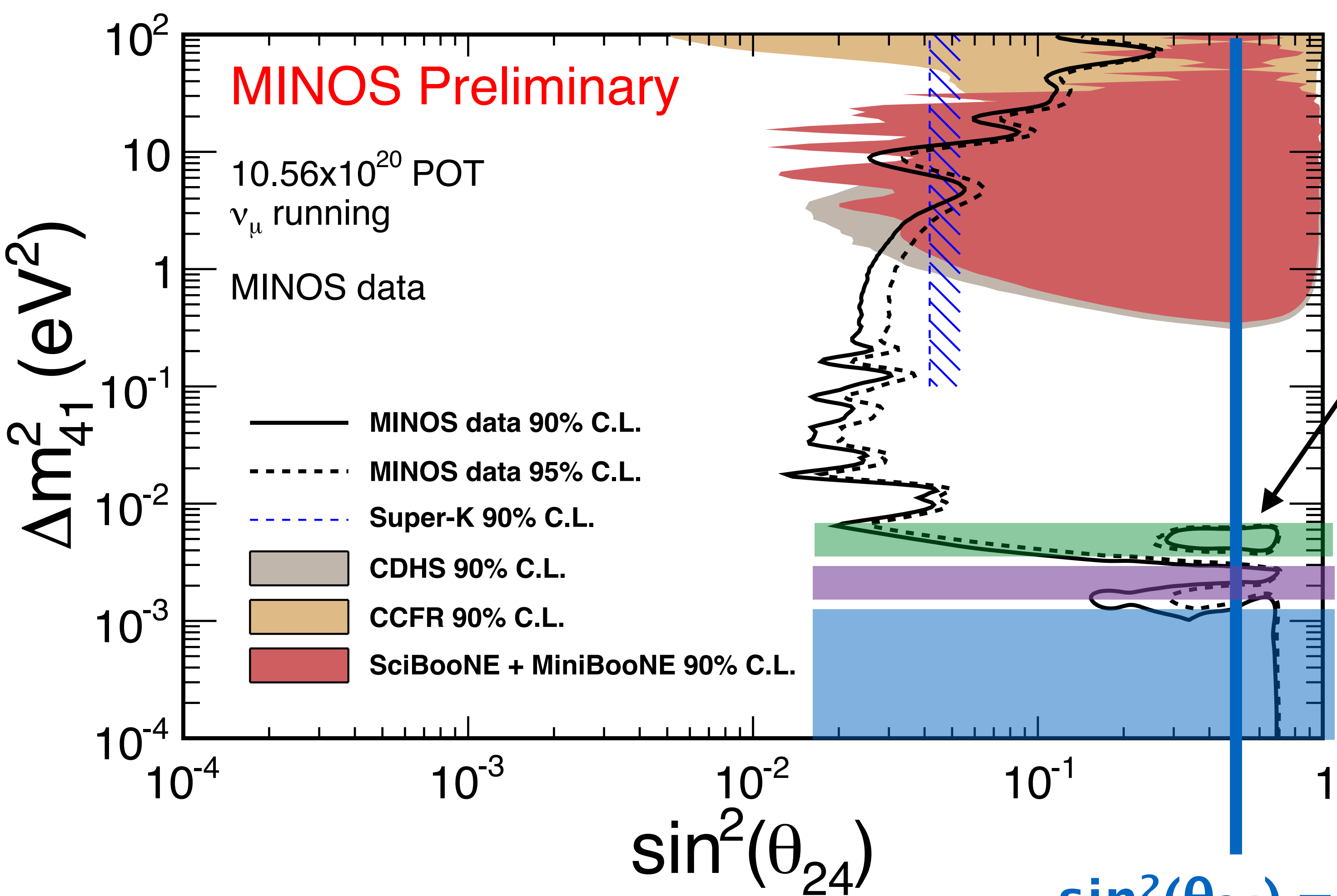
Looked at:

- Varying fiducial volume
- Varying the containment criteria
- Excluding tracks ending near the join between the
- calorimeter and spectrometer.
- Varying how close tracks can come to the coil hole.



Together these have the largest effect on the sensitivity

Degeneracies



$\Delta m^2_{41} = 2^* \, \Delta m^2_{31}$

$\Delta m^2_{41} \sim \Delta m^2_{31}$

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

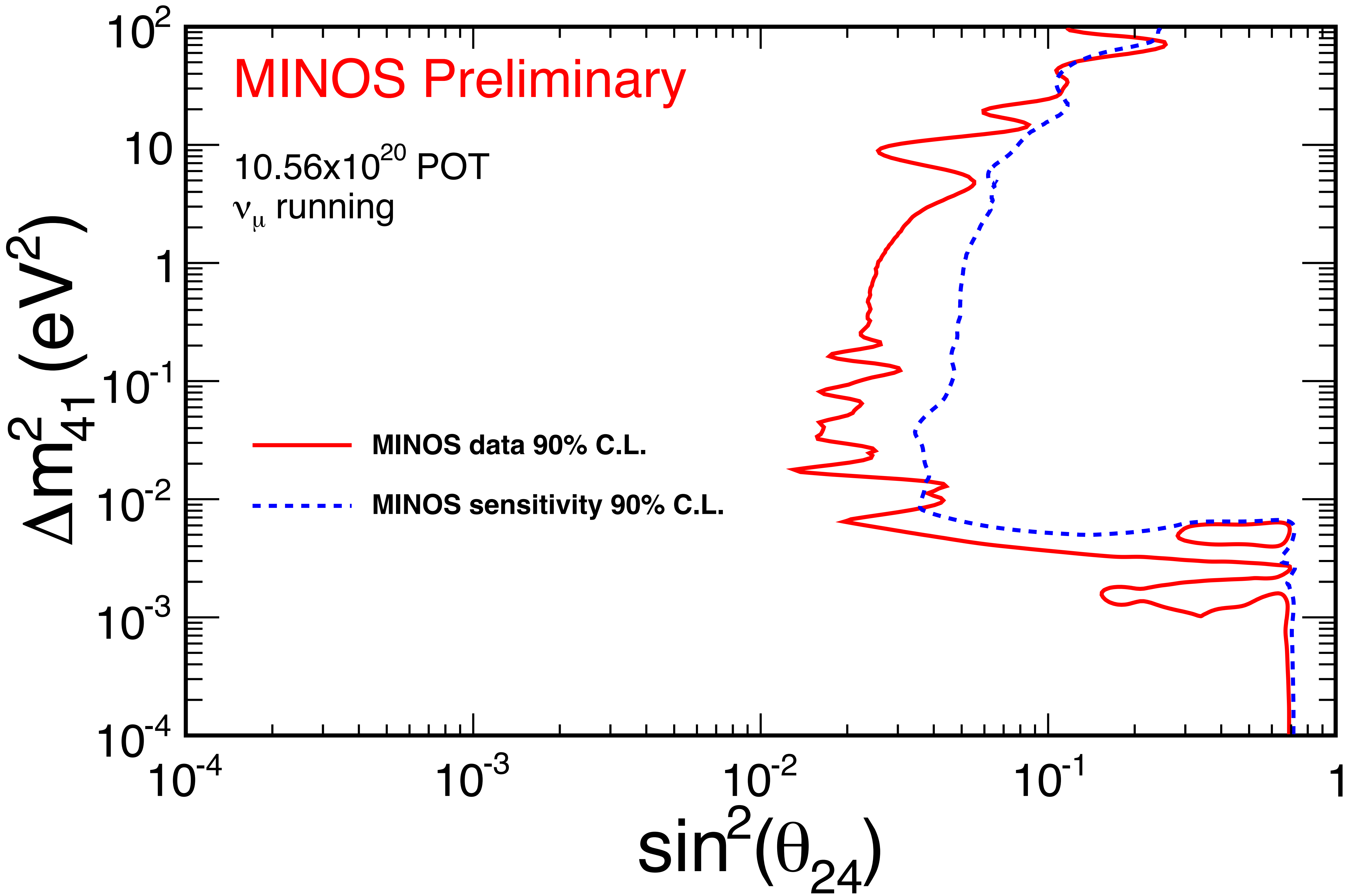
$\sin^2(\theta_{24}) = 0.5$

$\theta_{24} = \pi/4$

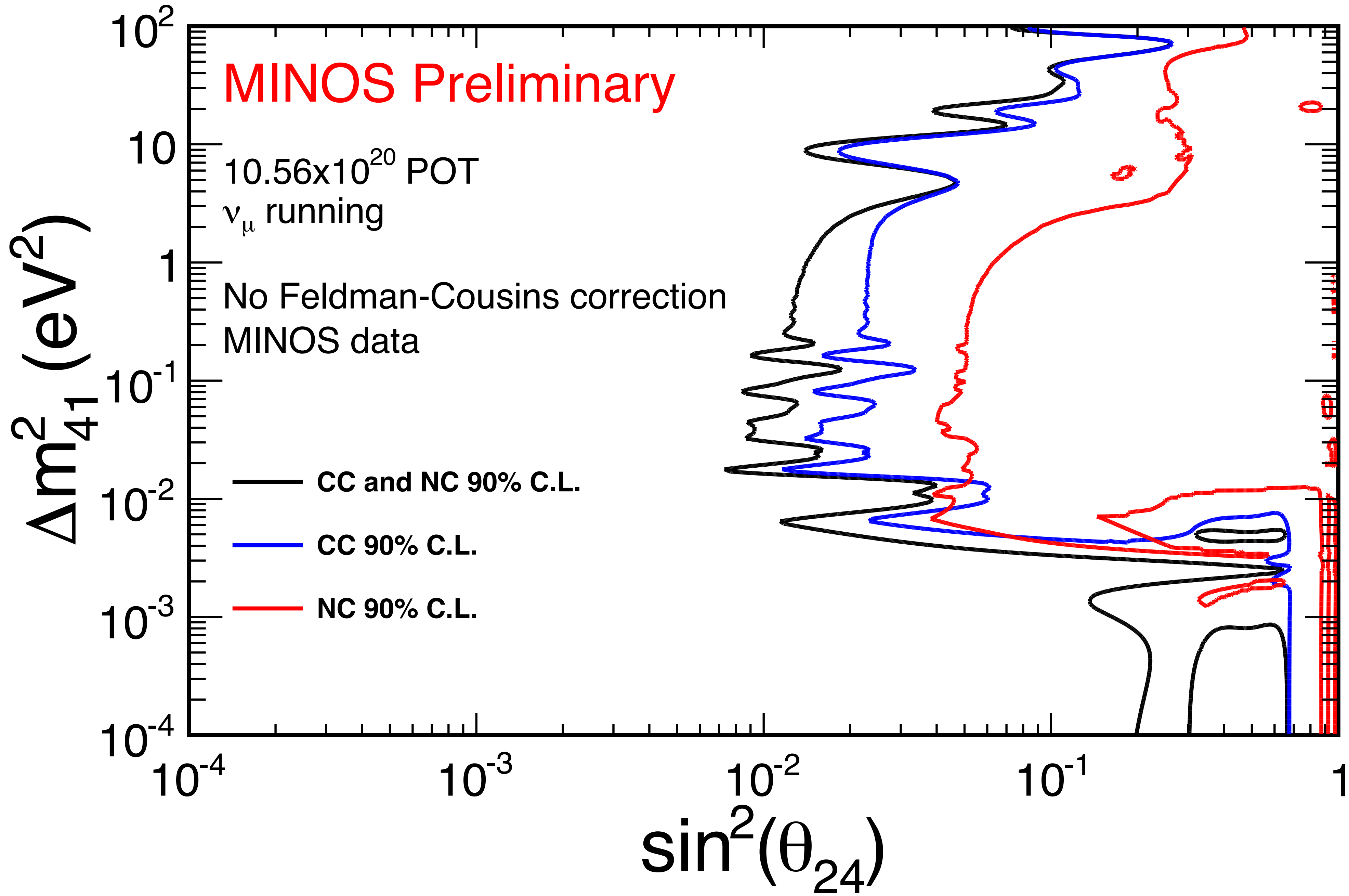
when probing large Δm^2_{41} to avoid large values of Δm^2_{31} a constraint is implemented in the fit

Non-negligible interference terms from atmospheric oscillations cause degenerates (regions where signal = three flavour)

Sensitivity

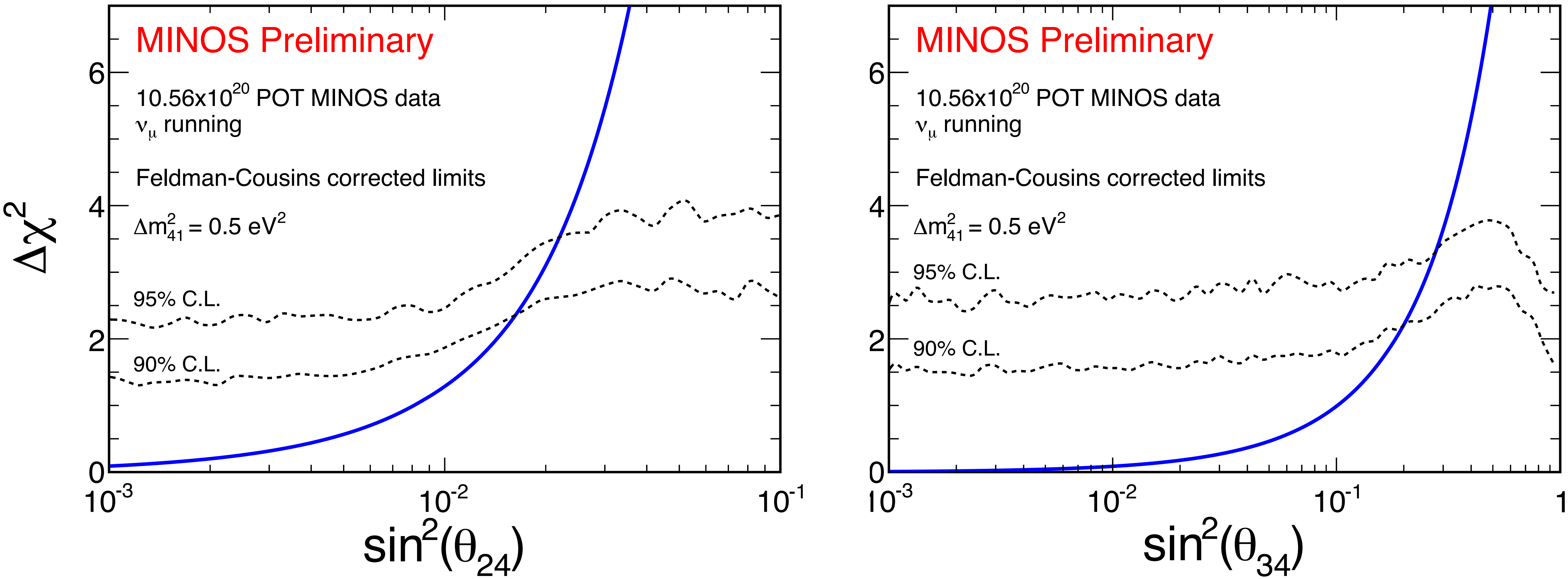


CC and NC component Data



Power comes from the CC sample

1D limits

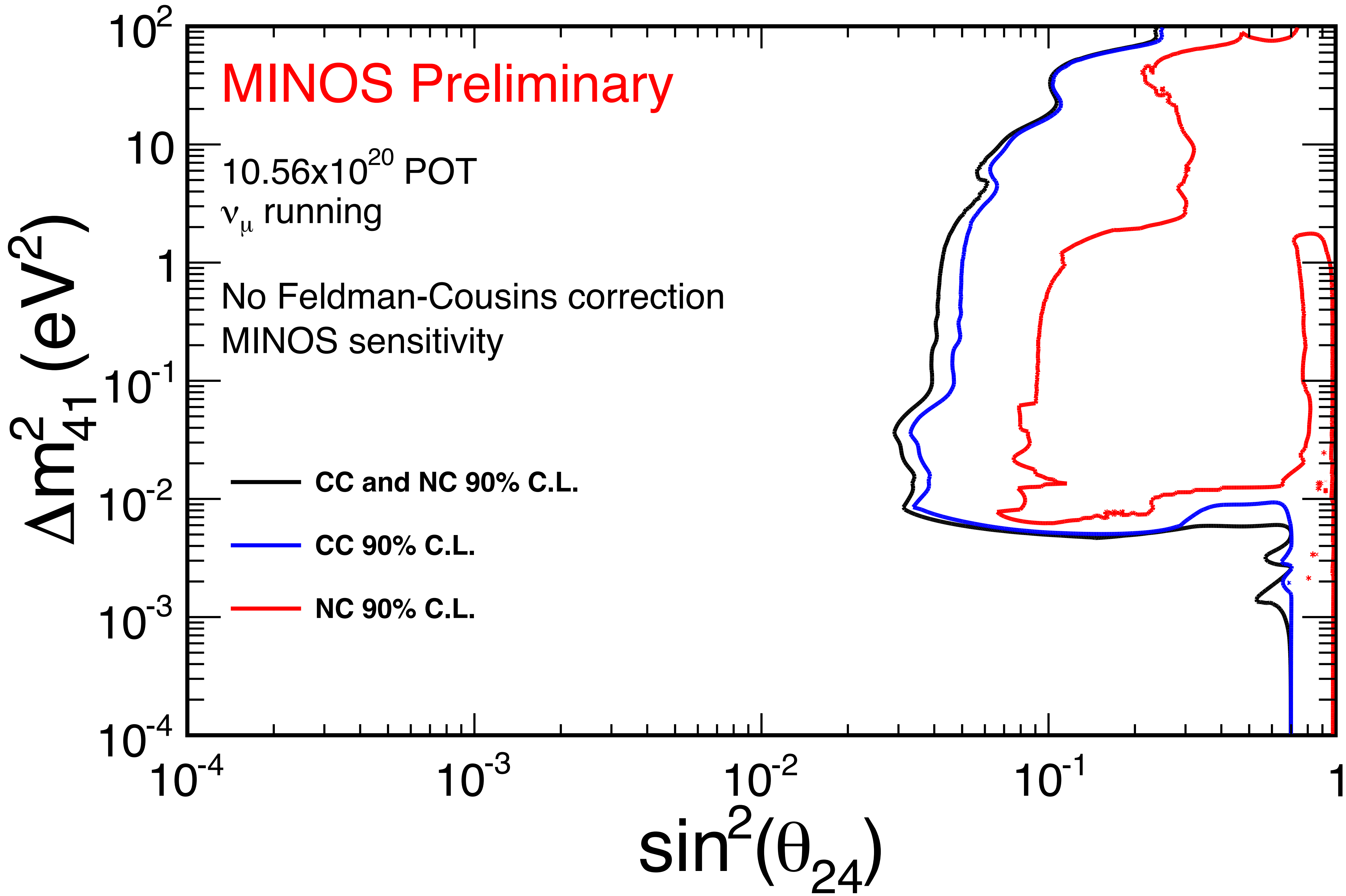


1D C.L limits for when $\Delta m^2_{41} = 0.5\text{eV}^2$

$\sin^2(\theta_{24}) < 0.016$ at 90% C.L.
$\sin^2(\theta_{24}) < 0.022$ at 95% C.L.

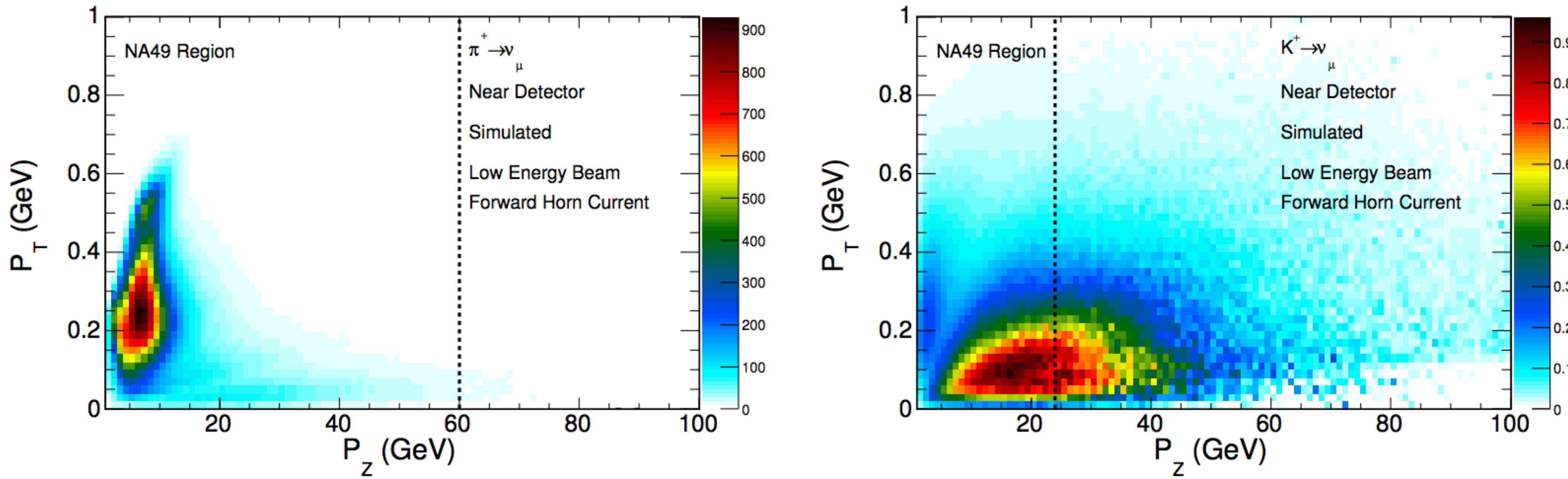
$\sin^2(\theta_{34}) < 0.20$ at 90% C.L.
$\sin^2(\theta_{34}) < 0.28$ at 95% C.L.

CC and NC component Sensitivity



Power comes from the CC sample

NA49


NA49 Region
$\pi^+ \rightarrow \nu_\mu$
Near Detector
Simulated
Low Energy Beam
Forward Horn Current
P_T (GeV)
P_Z (GeV)
NA49 Region
$K^+ \rightarrow \nu_\mu$
Near Detector
Simulated
Low Energy Beam
Forward Horn Current
P_T (GeV)
P_Z (GeV)