Searches for Sterile Neutrinos at MINOS/MINOS+

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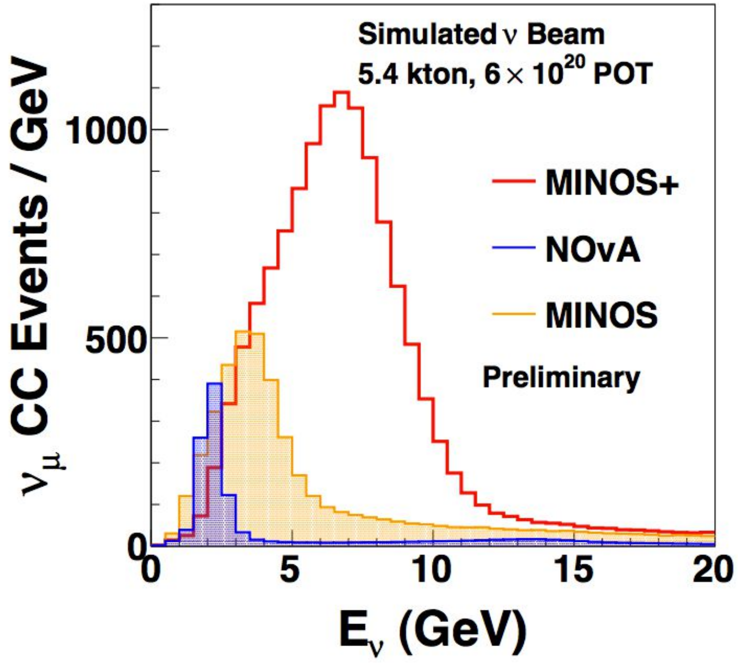
MINOS/MINOS+ Overview

- MINOS (Main Injector Neutrino Oscillation Search)
- NuMI neutrino beam from 120 GeV Main Injector-accelerated protons
- Neutrino energy spectrum measured with two functionally identical iron-scintillator tracking calorimeters
  - Near Detector at Fermilab
    - 1 km from target
    - 1 kton mass
  - Far Detector, deep underground in the Soudan mine
    - 735 km from target
    - 5.4 kton mass
- Compare Far Detector observations with extrapolation of Near Detector measurement to study neutrino oscillations.

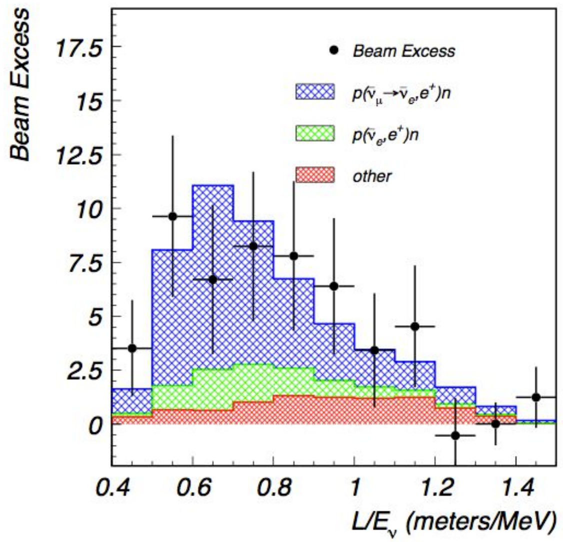
MINOS/MINOS+ Overview

- From 2005-2012, the NuMI beam operated in low energy mode (MINOS era)
- Since 2013, the NuMI beam has operated in the medium energy mode (MINOS+ era)
  - Higher energy ideal for long-baseline sterile neutrino searches.

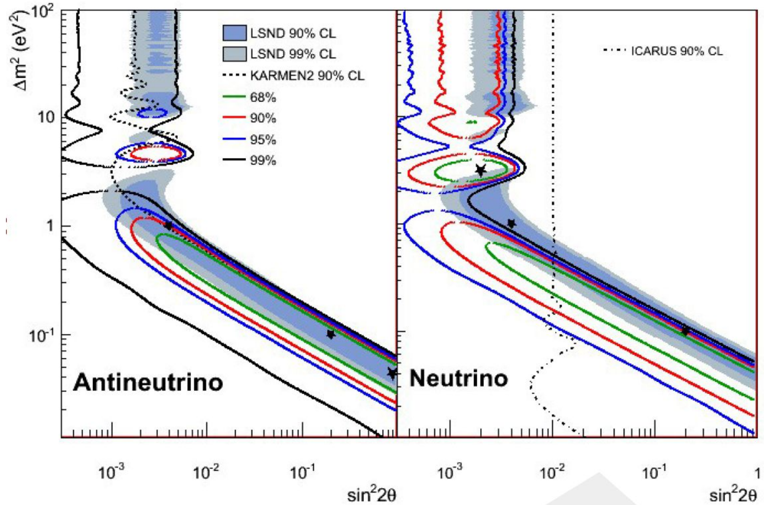


Status of Sterile Neutrinos

- LSND and MiniBooNE have both seen excesses in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance at short baselines.
  - Consistent with large Δm^2 sterile neutrino oscillations.
- No evidence for sterile oscillation seen by disappearance experiments.
- Unlike in disappearance experiments, oscillation probability in appearance experiments is quadratically suppressed by the matrix elements in the amplitude.
  - Must resolve this conflict → sterile neutrinos can complicate measuring CP violation at DUNE or HyperK.
- In this talk, I will discuss two strategies for searching for sterile neutrinos at long baselines.



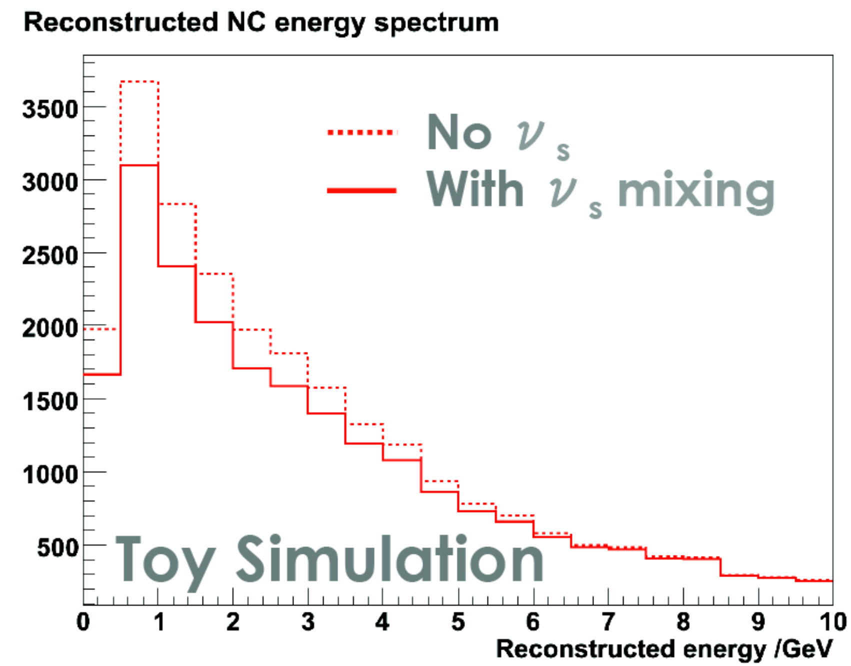
Phys. Rev. D 64, 112007 (2001)

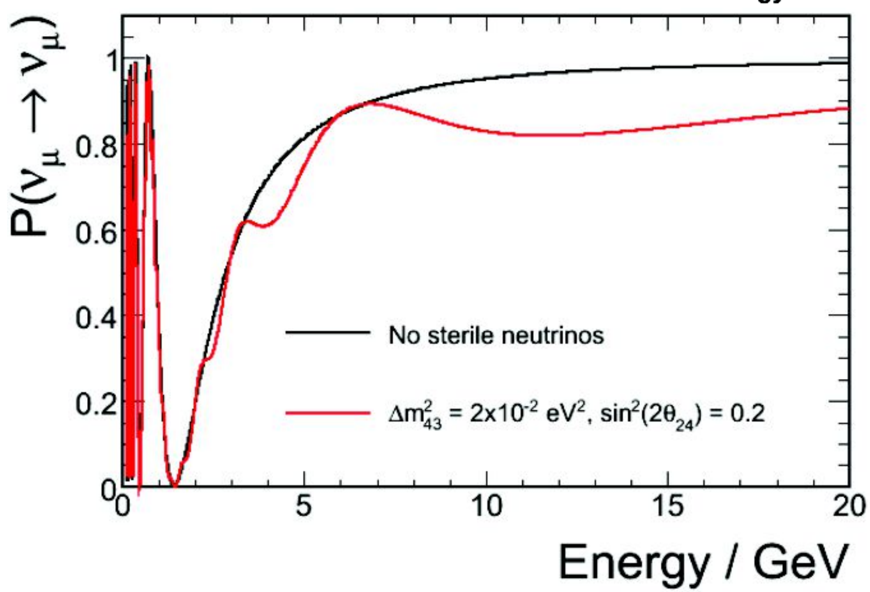


Phys. Rev. Lett.110, 161801

Long-Baseline Sterile Searches

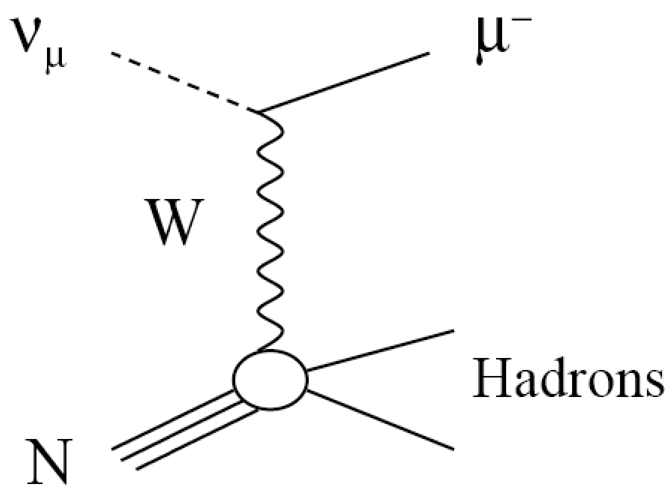
- Strategy 1:
  - Neutral current interaction rate is the same for the three active flavors.
    - Standard oscillations do not change NC rate.
  - $\nu_\mu \rightarrow \nu_s$ oscillations reduce the NC rate as ν_s do not interact in the detector.
  - Look for NC disappearance relative to 3-flavor predictions.
  - Model independent
- Strategy 2:
  - Sterile oscillations add modulations to standard 3-flavor picture, even in CC interactions.
  - Fit both NC and CC spectra to the 4-flavor model.
  - Constrain sterile mixing parameters

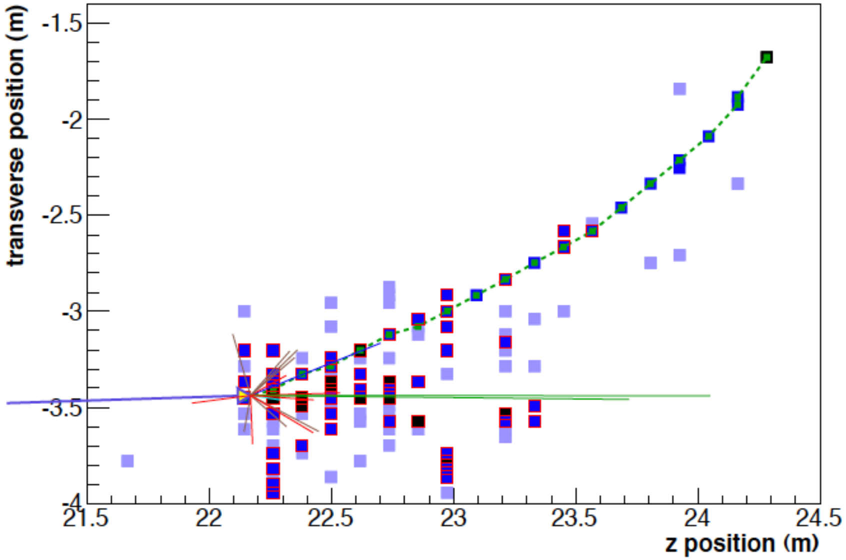




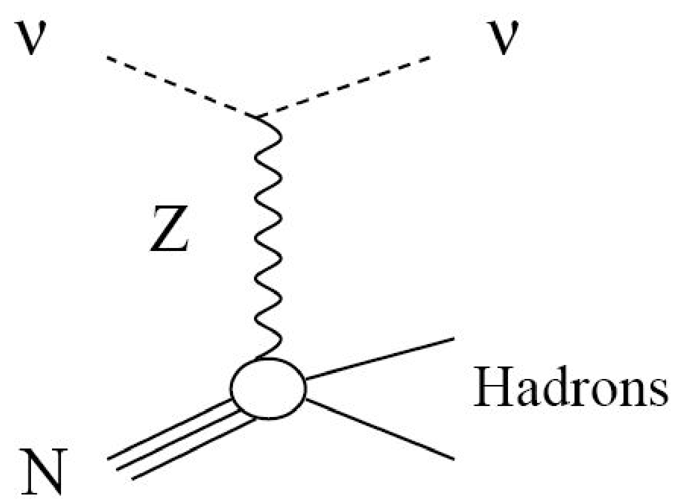
Event Topologies

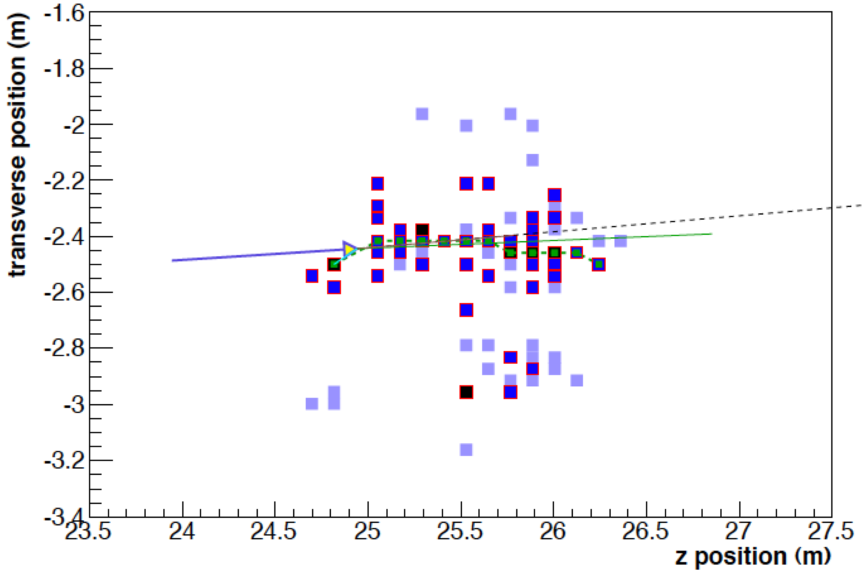
ν_μ CC





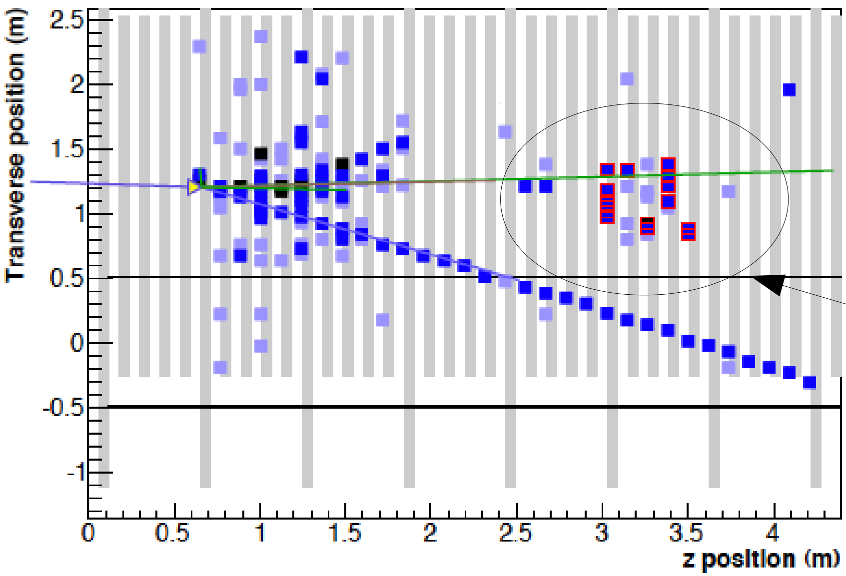
NC



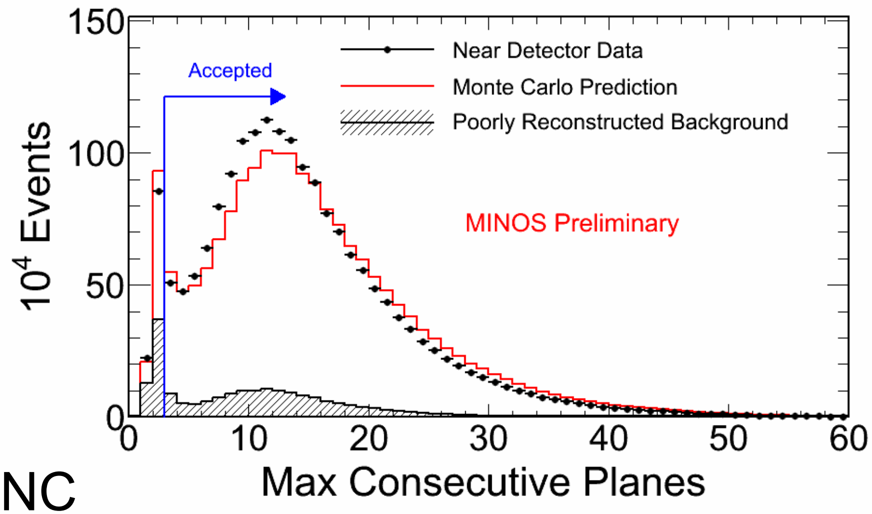


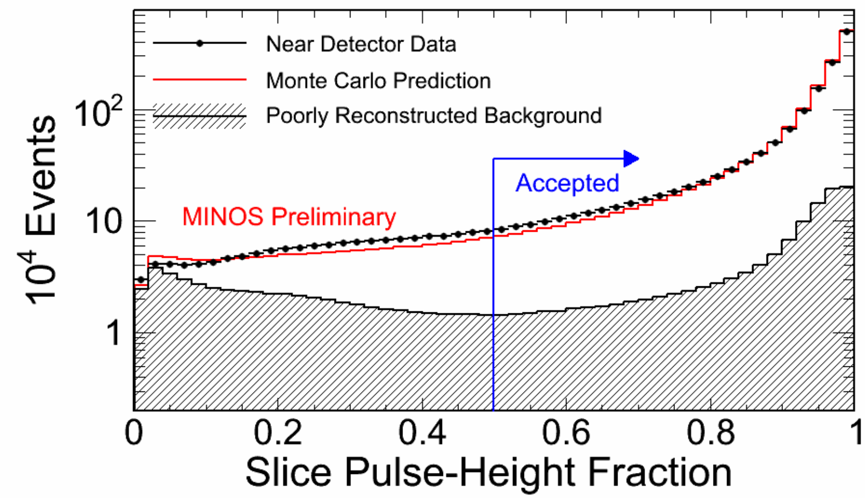
Poorly Reconstructed Events

High rate in Near Detector requires temporal and spatial slicing → may cause split events



Fake NC event



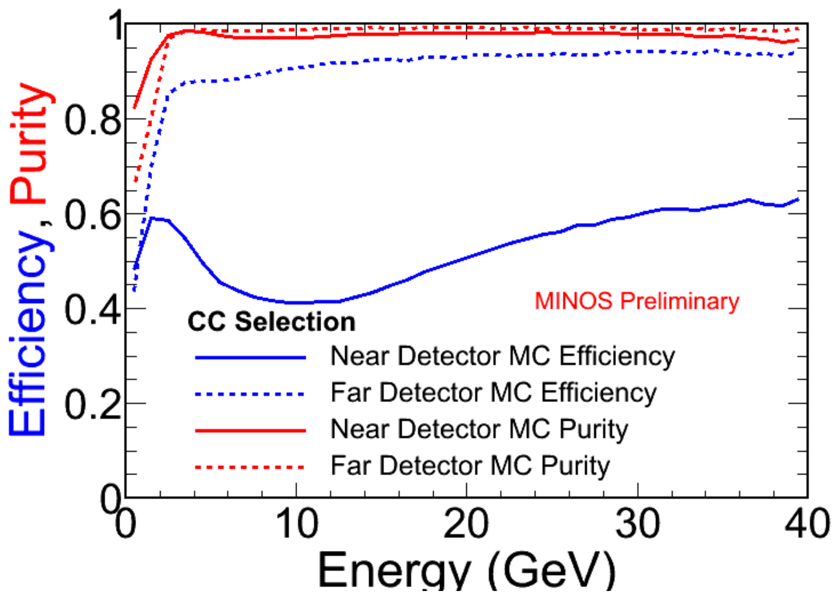


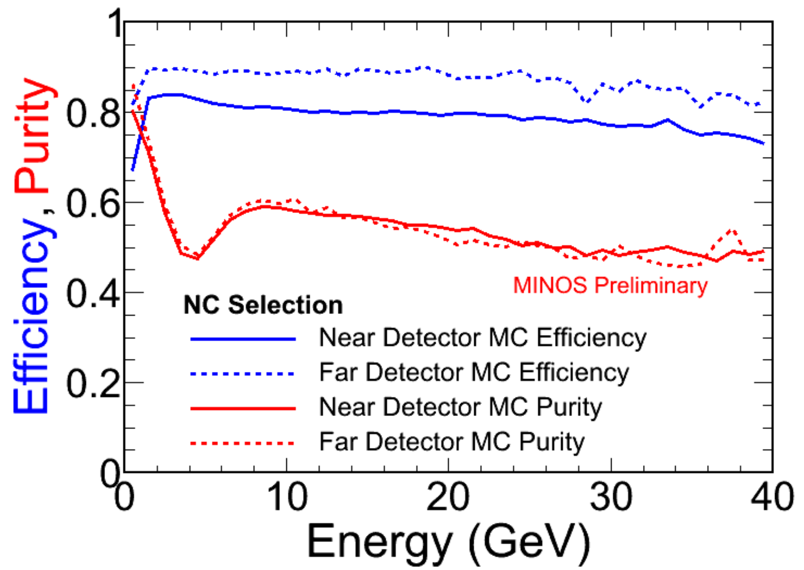
Minimize with pre-selection cuts on:
– Fraction of pulse height in slice
– The maximum number of consecutive planes

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

CC and NC Selection

- MINOS was optimized for identifying ν_μ CC interactions.
- Identifying NC events is more difficult.
  - 89% efficiency and 61% purity at the FD.
  - Main background is inelastic ν_μ CC events.
  - 97% of ν_e CC events are selected as NC.



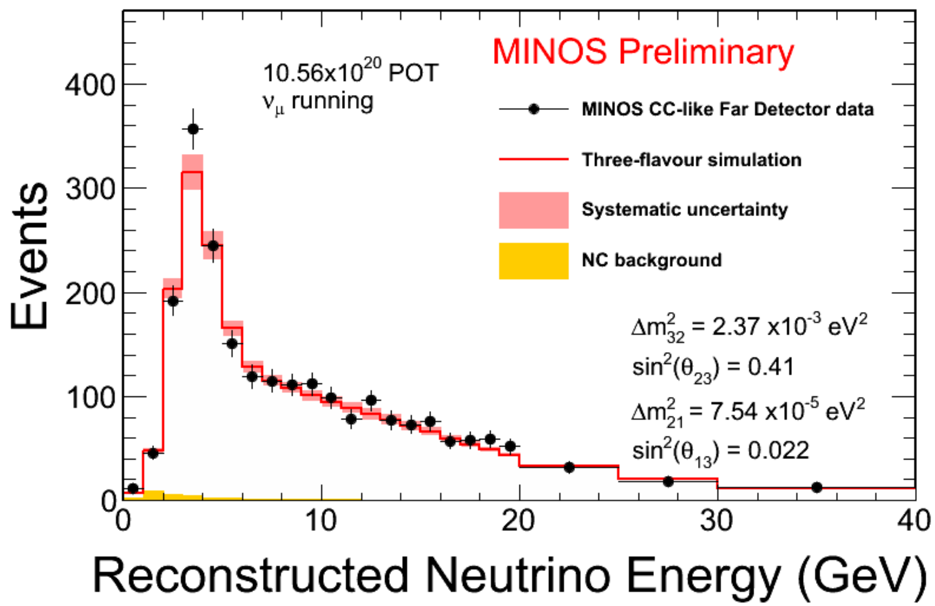


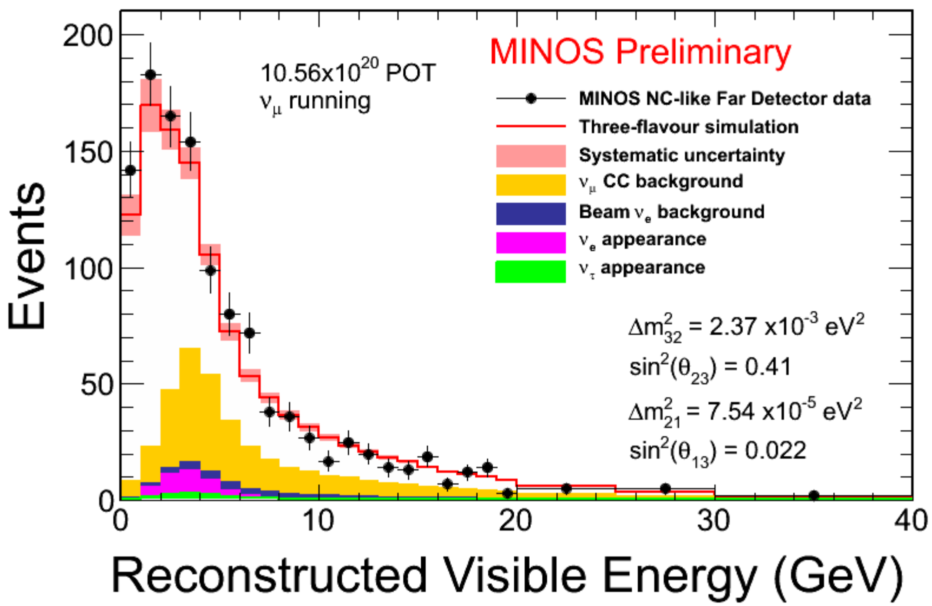
Model Independent Search

Far/Near Extrapolation

- The measured Near Detector energy spectrum is used to predict the Far Detector spectrum via the **Far/Near Ratio** method.
- The method uses the ND data without relying on a specific parametrization.
- Correct each energy bin in the FD MC using the ND data/MC differences as a scale factor.
- Simple, robust to most systematic uncertainties.

FD Energy Spectrum





- Oscillate CC events using the 2012 MINOS ν_μ CC disappearance best fit.
- 2563 ν_μ-CC-like events in FD.
- 1211 NC-like events in FD.

Comparison to 3-Flavor Prediction

- Compare the NC energy spectrum in FD data (10.56x10[20] POT exposure) with the expectation from standard 3-flavor neutrino oscillation physics using the R statistic.
  - No NC disappearance → R = 1.

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

Predicted CC background from all flavors

Predicted NC interaction signal

<u>0 – 40 GeV</u>
R = 1.05 +/- 0.04 +/- 0.10

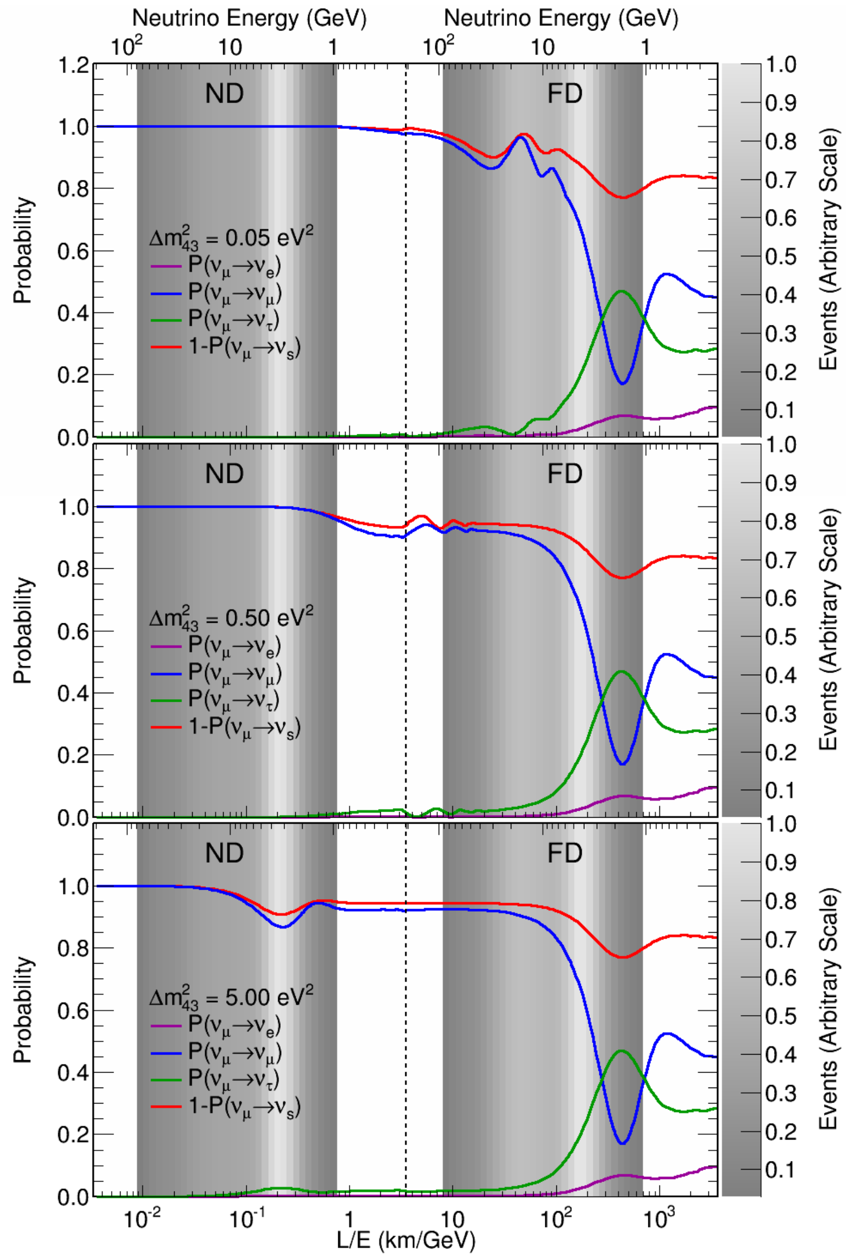
<u>0 – 3 GeV</u>
R = 1.10 +/- 0.06 +/- 0.07

No evidence for NC disappearance

4-Flavor Search

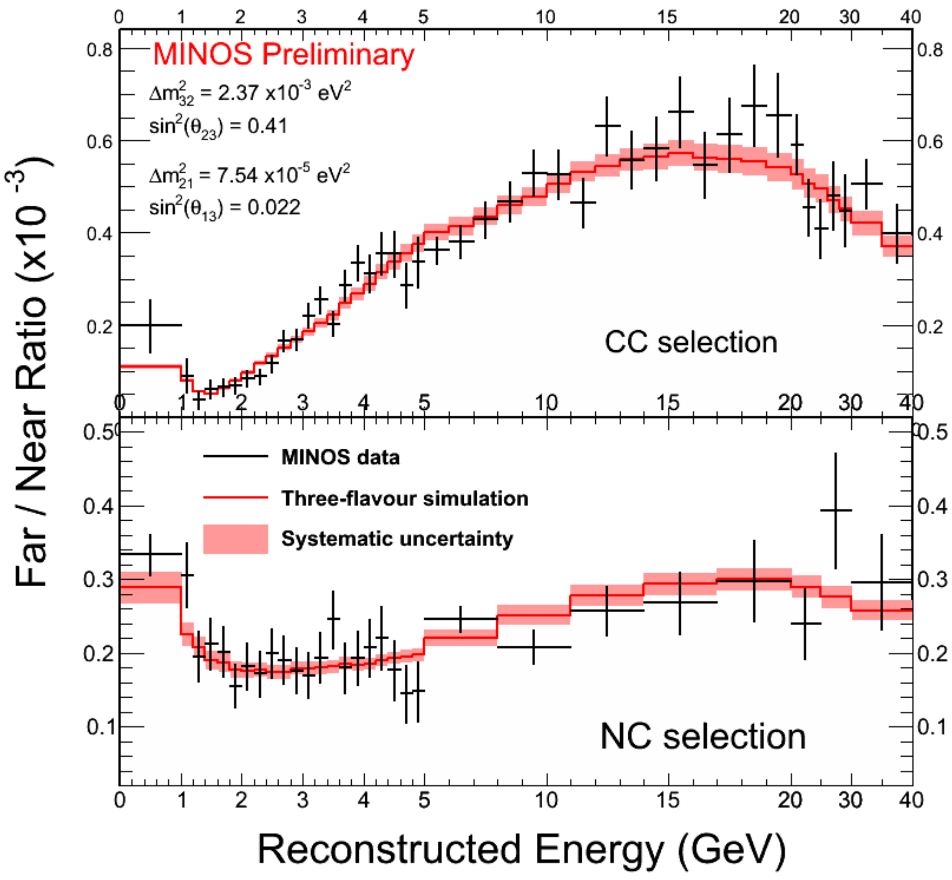
4-Flavor Oscillations

- Small Δm^2_{41}:
  - Oscillations at high energies in the Far Detector.
  - No oscillations at the Near Detector
- Medium Δm^2_{41}:
  - Rapid oscillations at the Far Detector average out.
  - No oscillations at the Near Detector.
  - Counting experiment
- Large Δm^2_{41}:
  - Rapid oscillations at the Far Detector average out.
  - Oscillations at the Near Detector affect extrapolation to the Far Detector.

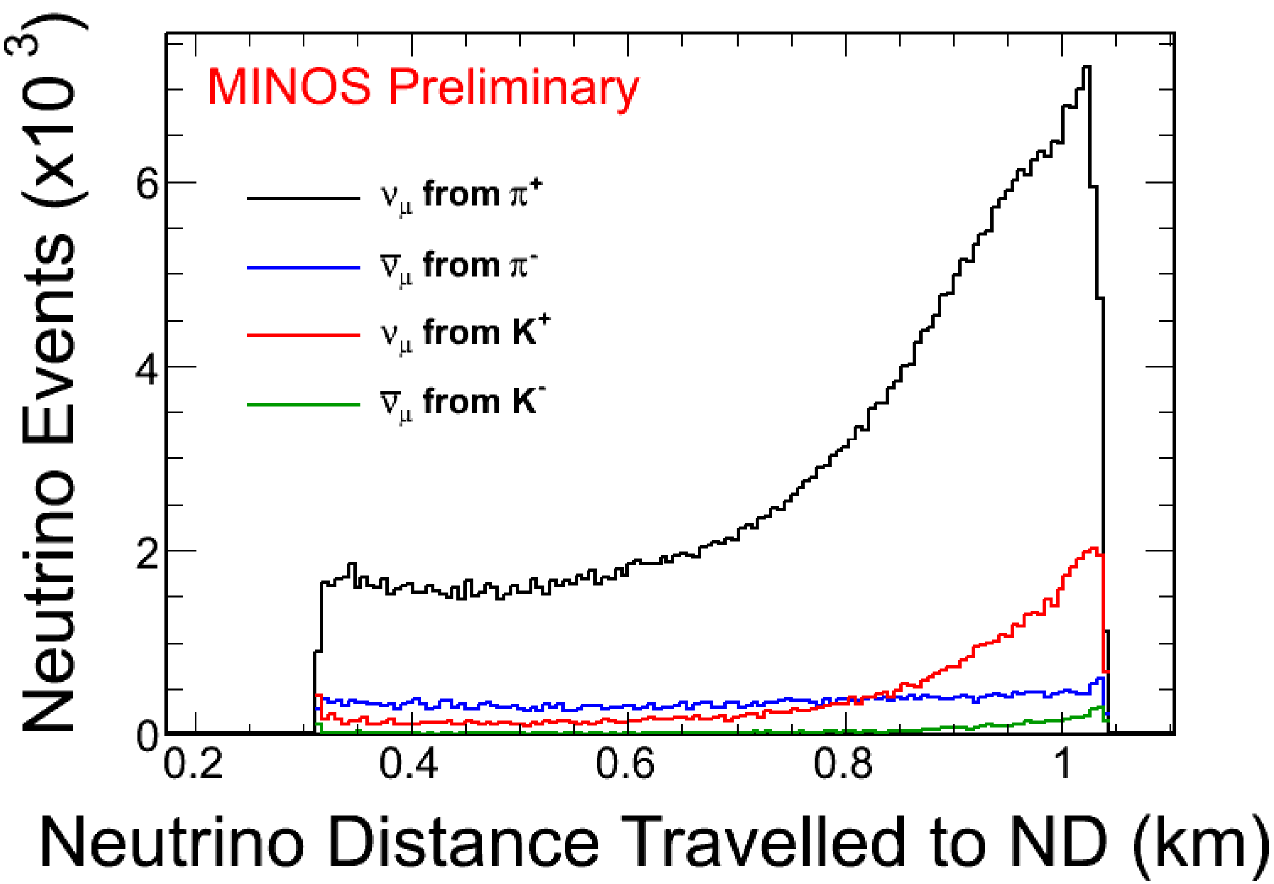


MINOS 4-Flavor Analysis Strategy

- Assume 3+1 model
  - One additional sterile neutrino and an additional neutrino mass scale.
  - Extend mixing matrix with extra angles and phases.
- For simplicity, fix parameters MINOS is not sensitive to (δ_1, δ_2, δ_3, and θ_{14}) to zero.
- Fit both the NC and CC spectra to determine θ_{23}, θ_{24}, θ_{34}, Δm^2_{32} and Δm^2_{41}.
- To account for ND oscillations, fit oscillated F/N MC ratio directly to F/N data ratio.
  - Include a constraint on ND rate.
- Move to a covariance matrix based likelihood function to allow for an increased number of systematic uncertainties.



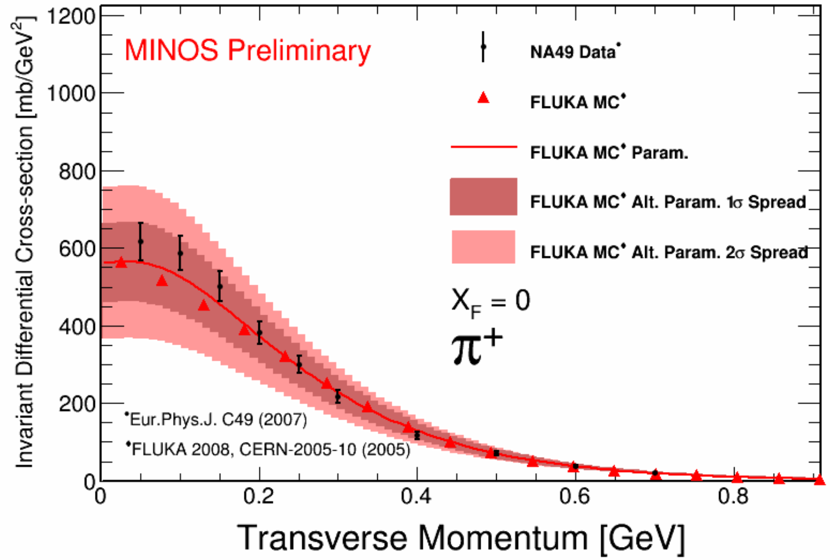
Varying Baseline

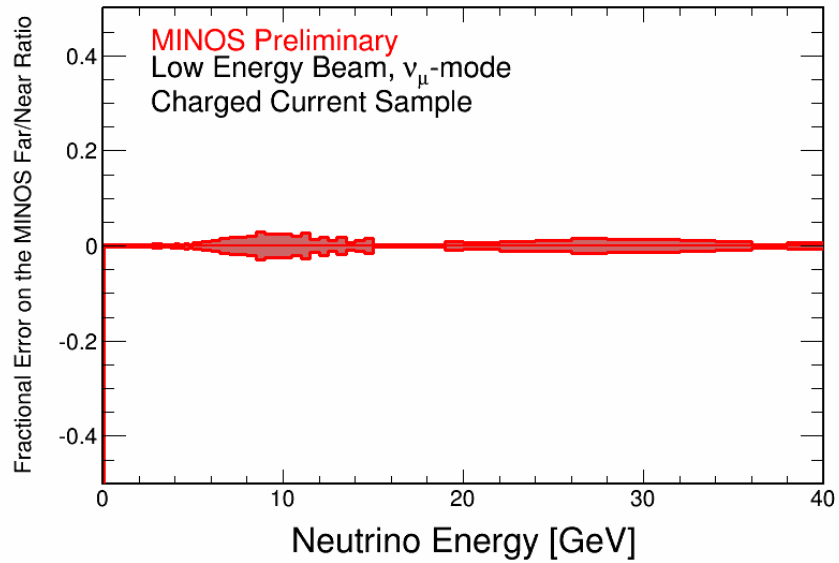


Because we now allow for short-baseline oscillations, it is crucial that we account for the baseline varying due to the distribution of hadron decay points within the decay pipe.

Beam Systematics

- Due to ND oscillations, it is not possible to constrain the beam flux using a fit to ND data.
  - Need to reassess beam systematics.
- Fit a FLUKA simulation 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.
- Use this collection of alternate parametrizations to reweight the ND and FD neutrino spectra and create a covariance matrix.
- The resulting error band on the F/N ratio is small.





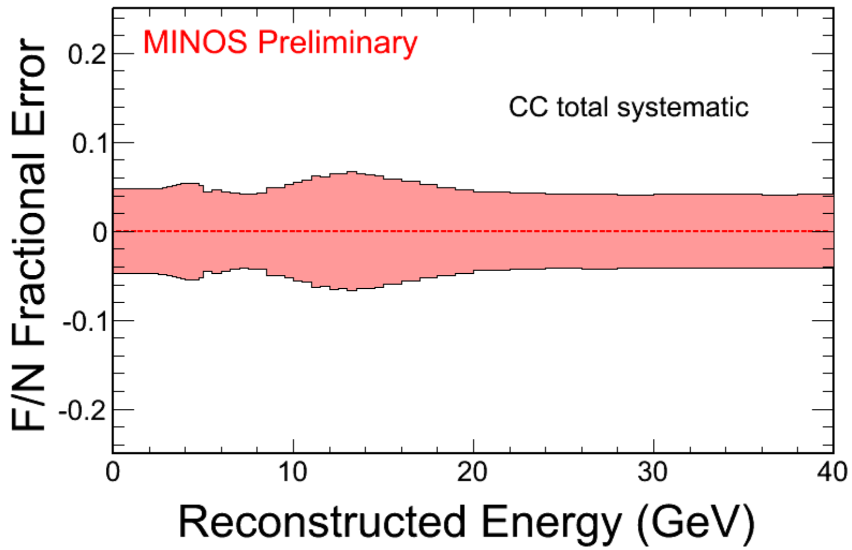
ND Acceptance Systematics

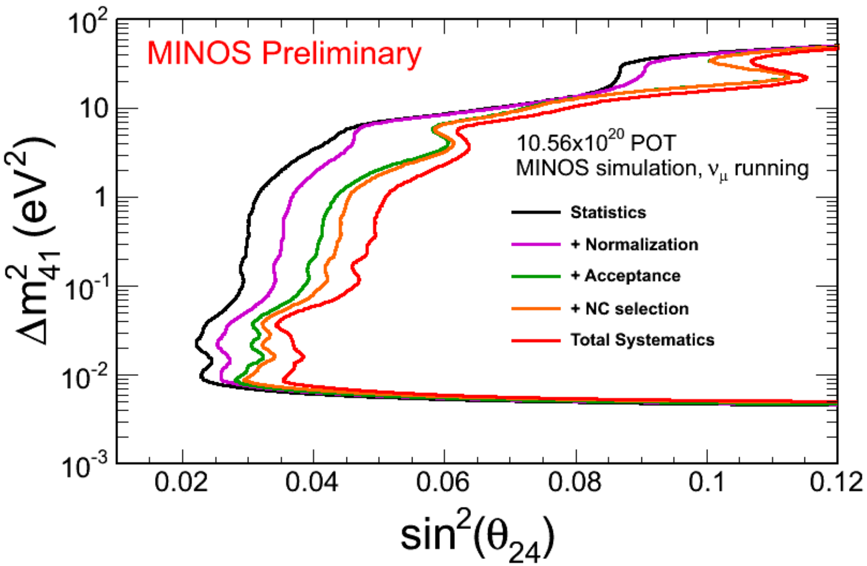
- Acceptance uncertainties are determined by comparing the effect of varying cuts on data/MC at the ND compared to the nominal cuts.
- Examined the effect of:
  - Varying the fiducial volume.
  - Varying the containment criteria.
  - Excluding tracks ending near the join between the calorimeter and spectrometer.
  - Varying how close tracks can come to the coil hole.
- Together, these have the largest effect on our sensitivity.

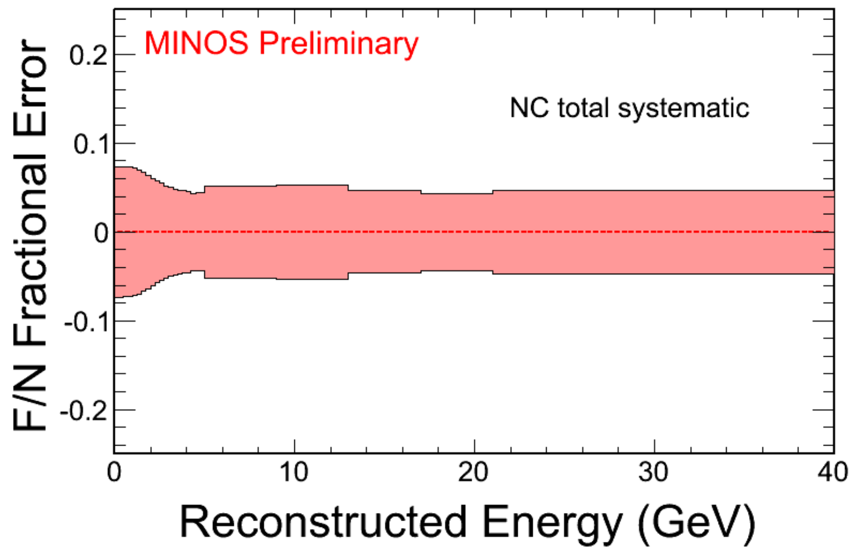
Total Systematics

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

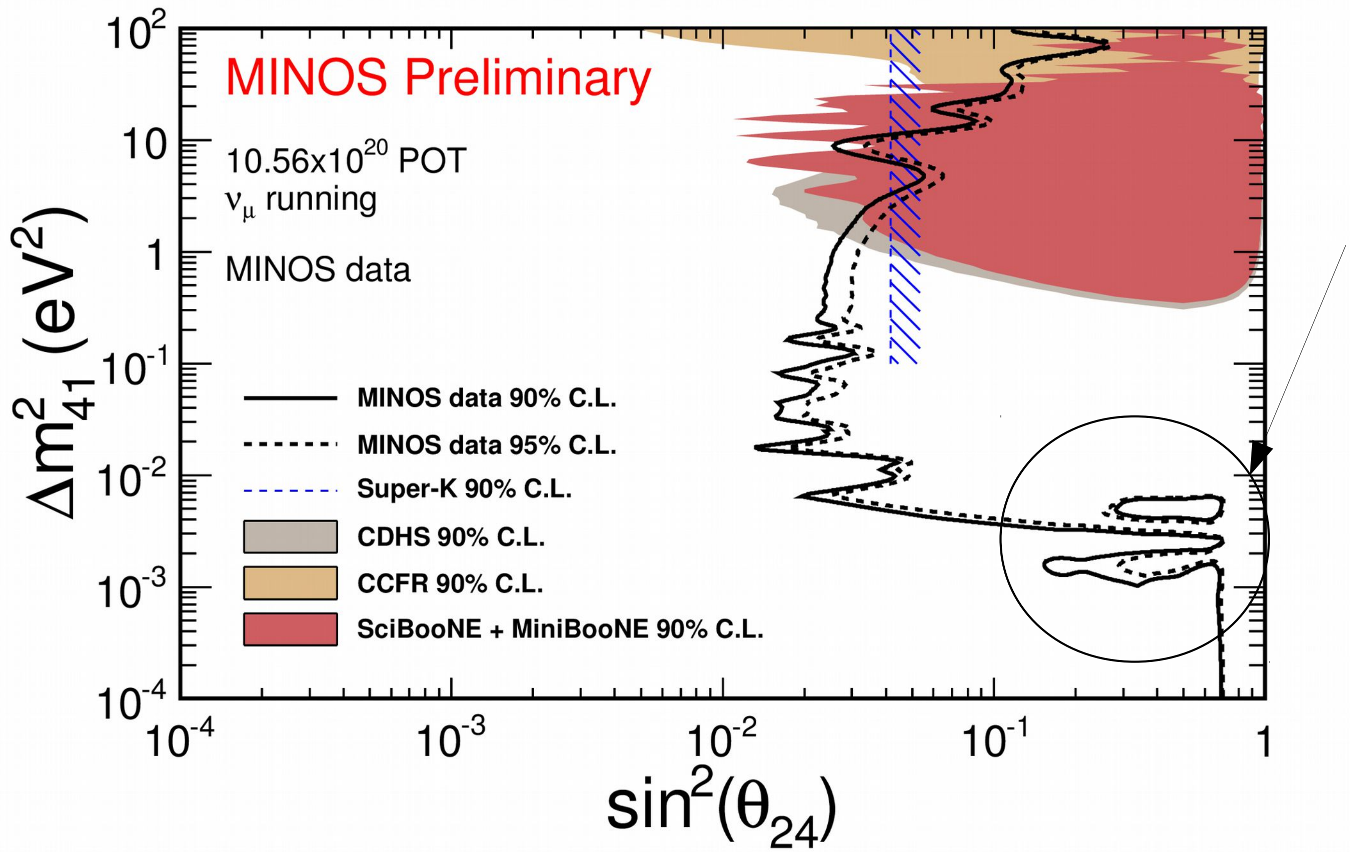
o_i = Observed events in bin i
e_i = Expected events in bin I
V = Covariance matrix







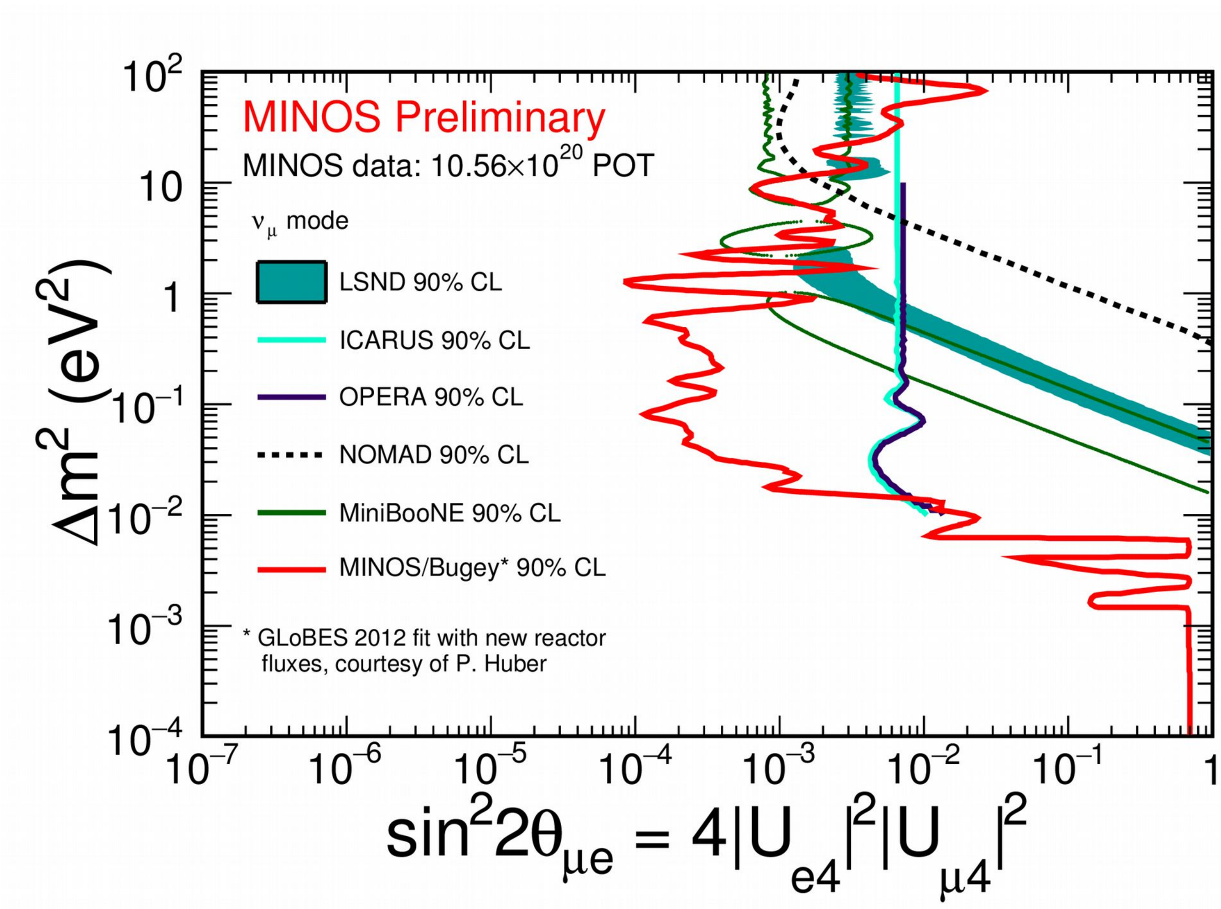
MINOS Disappearance Limit



Internal non-excluded region due to degenerate solutions where $\Delta m^2_{32} \sim \Delta m^2_{41}$, $\theta_{23} \sim \pi/2$, $\theta_{24} \sim \pi/4$, and $\theta_{34} \sim \pi/2$

MINOS 90% C.L. exclusion limit ranges over 6 orders of magnitude and is the strongest constraint on ν_μ disappearance into ν_s for $\Delta m^2_{41} < 1\ \mathrm{eV}^2$

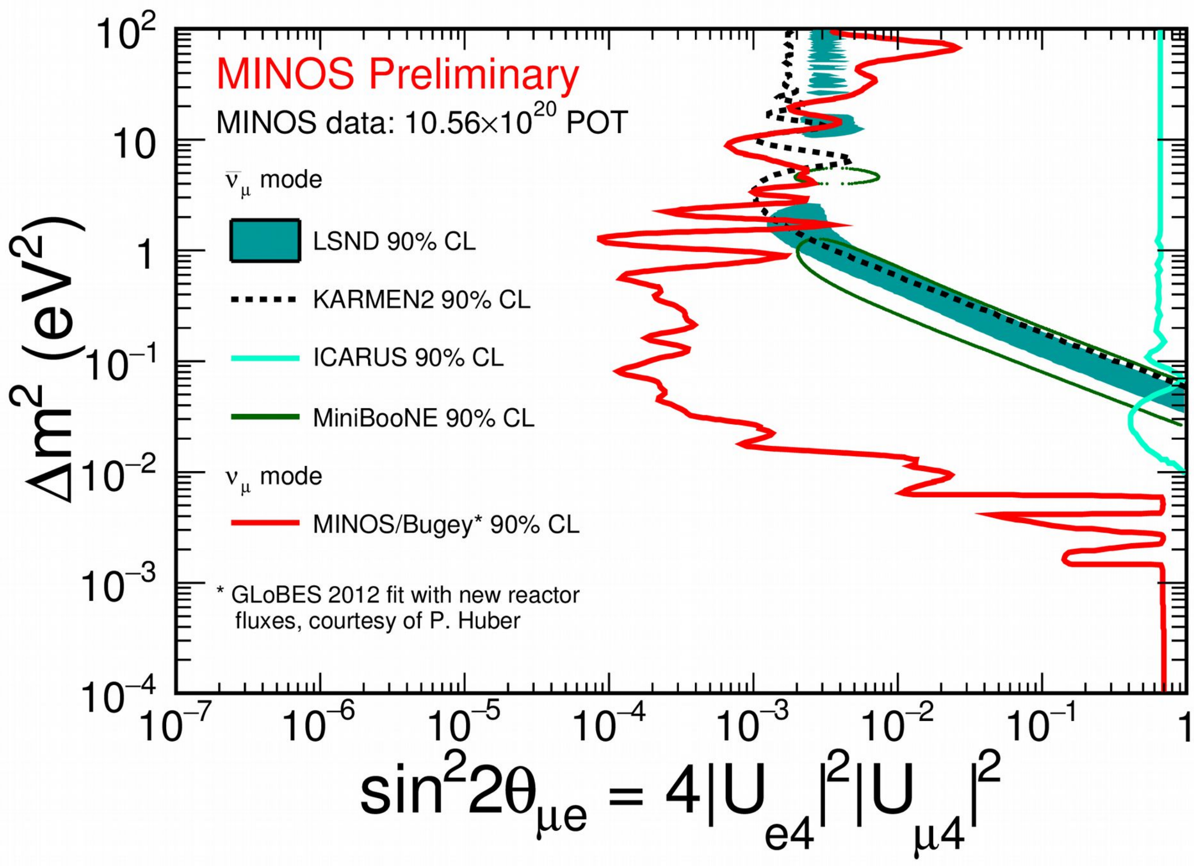
Comparison to Appearance Results



Working with Daya Bay to produce a MINOS/Daya Bay combined limit.

- With MiniBooNE neutrino mode.
- Assuming the 3+1 model, an accelerator-based disappearance result (θ_{24}) can be combined with a reactor based disappearance results (θ_{14}) to compare with appearance results.
- Combined MINOS with a Bugey limit, provided by Patrick Huber, computed with GLoBES 2012 using new reactor fluxes.
- Increases tension between null and signal results for $\Delta m^2 < 1$ eV^2.

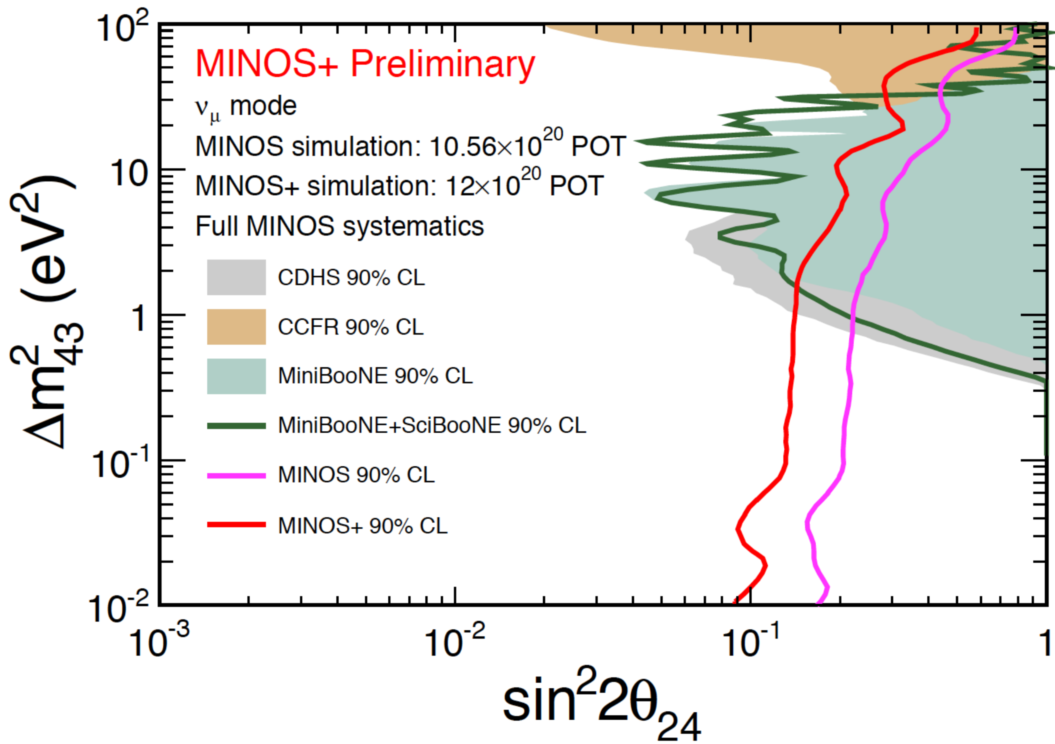
Comparison to Appearance Results



Working on a sterile search using MINOS antineutrino running and MINOS/MINOS+ antineutrino contamination during neutrino running

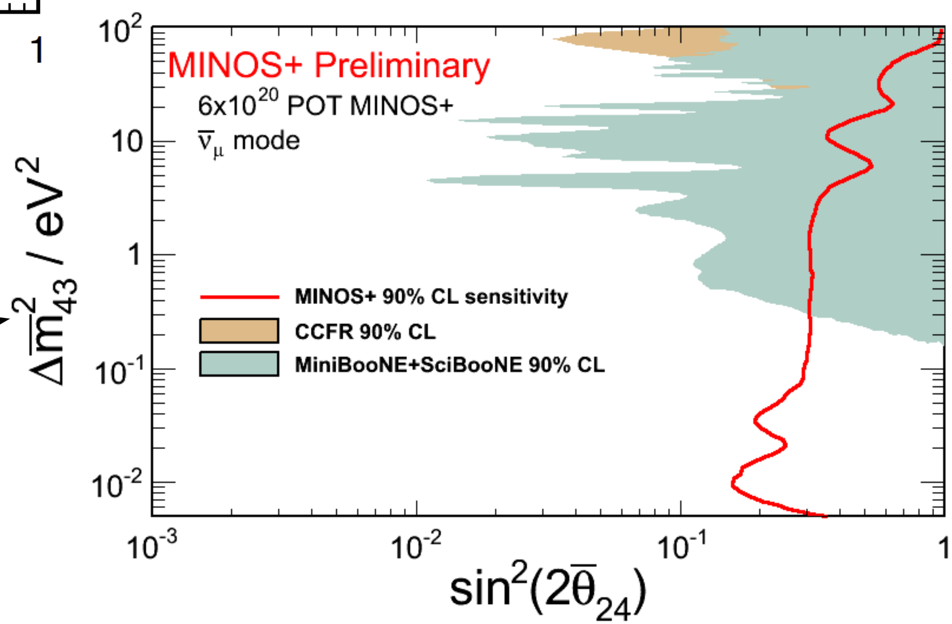
- With MiniBooNE antineutrino mode.
- Assuming the 3+1 model, and CPT conservations, SBL neutrino and antineutrino oscillations are identical.
- Combined MINOS with a Bugey limit, provided by Patrick Huber, computed with GLoBES 2012 using new reactor fluxes.
- Increases tension between null and signal results for $\Delta m^2 < 1$ eV^2.

The Future



Comparison of MINOS+ reach by the end of 2016 to MINOS.

Projected MINOS+ sensitivity to sterile neutrino oscillations with one year of antineutrino running.



Conclusions

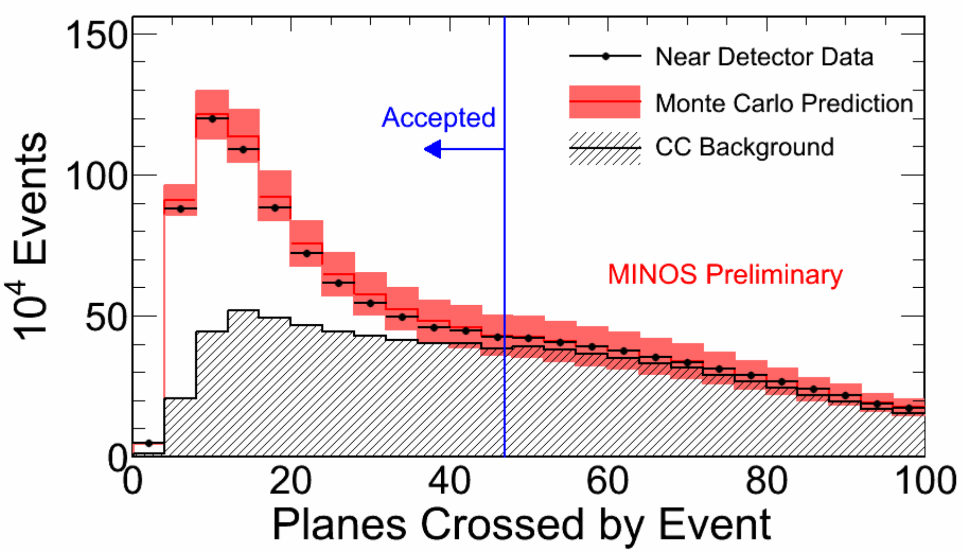
- Searches for sterile neutrinos at long-baselines are complementary to short-baseline searches.
  - Test a region of parameter short-baseline searches are less sensitive to.
- Accounting for ND oscillations, improving systematic uncertainties, and careful handling of 4-flavor degeneracies has allowed us to extend the MINOS 90% C.L. exclusion limit over 6 orders of magnitude in Δm^2_{41}.
  - Strongest constraint on ν_μ disappearance to ν_s for $\Delta m^2_{41} < 1$ eV^2.
- Combined these results with Bugey to allow for comparison with short-baseline appearance experiments.
  - Increases the tension between signal and null results for $\Delta m^2_{41} < 1$ eV^2.
  - Working with Daya Bay to produce a MINOS/Daya Bay combination as well.
- Currently working to extend these results using MINOS+ data and to search for sterile neutrinos using antineutrinos in MINOS/MINOS+ data for the first time.

Thank You!

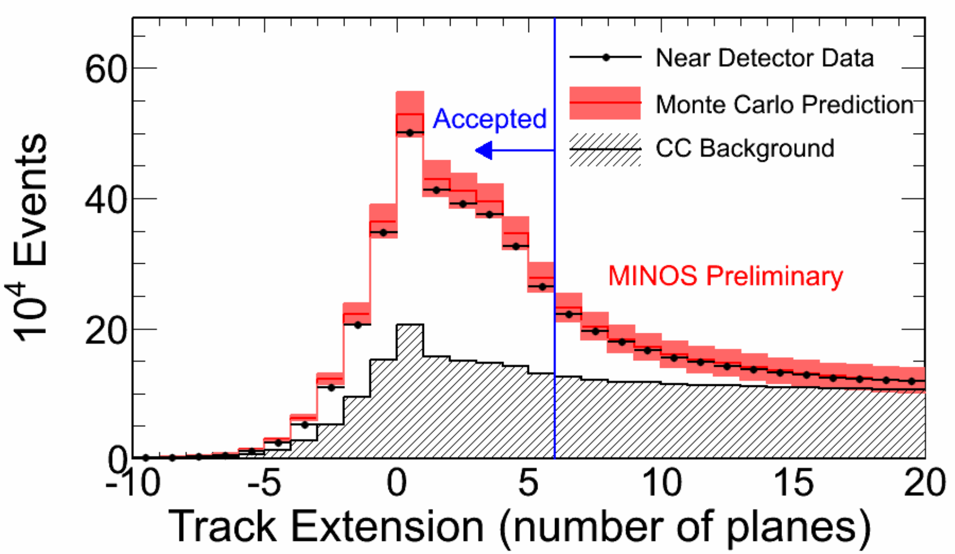
Backup

NC Event Selection

NC/CC event separation achieved via cuts on topological variables.



Discard events with length > 47 planes



Discard events with track > 6 planes longer than the shower

- Same selection applied to data and MC in the FD
- CC events are selected from events failing NC selection

CC Event Selection

- CC and NC events are separated using a 4 variable kNN.
  - Number of scintillator planes in a track.
  - Mean pulse height of all track hits.
  - Ratio of low pulse height to high pulse height hits.
  - Ratio of pulse height on the track to all hits.