Recent Results from MINOS and MINOS+

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Outline

- Introduction to MINOS and MINOS+
- MINOS+ ν_μ disappearance analysis
- MINOS sterile neutrino analysis
- Other results and prospects for MINOS+
- Summary

The MINOS+ Experiment

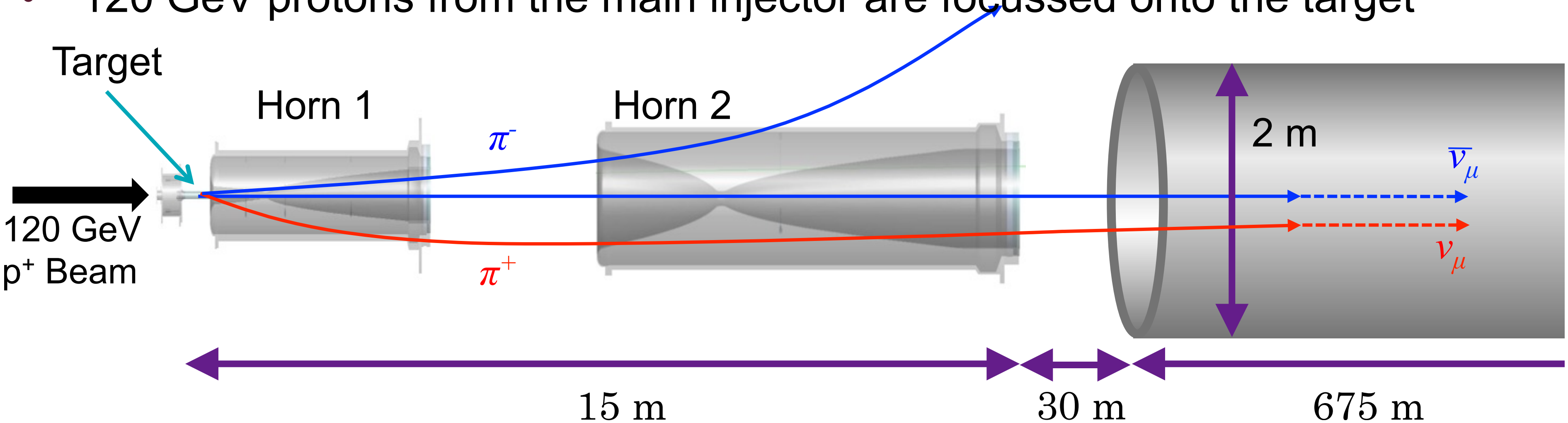
- MINOS+ is a long-baseline neutrino oscillation experiment
  - Continuation of MINOS in the NOvA era
- Exposed by the NuMI beam from Fermilab
- Two detectors: Near and Far
  - Detectors are both magnetised steel / scintillator sampling calorimeters
- Compare event spectra between the two detectors to study neutrino oscillations
- Can run in neutrino or anti-neutrino modes

Far Detector (FD)
735km from source
5.4kt

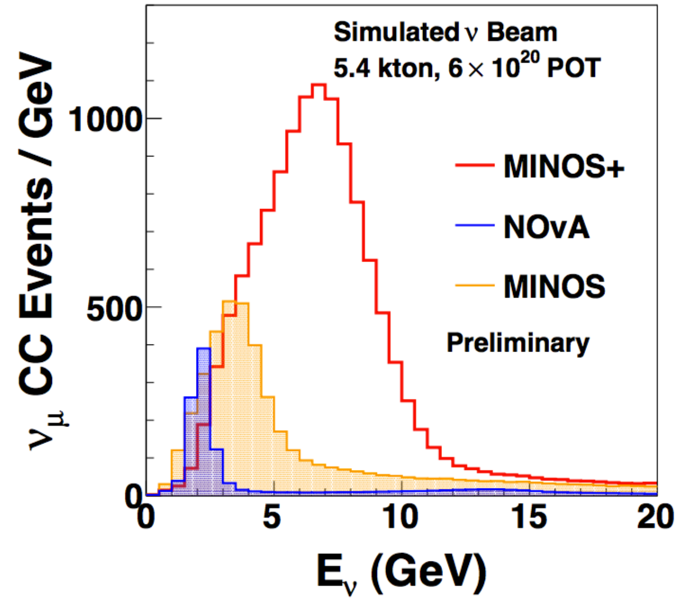
Near Detector (ND)
1km from source
1kt

The FNAL NuMI

- 120 GeV protons from the main injector are focussed onto the target

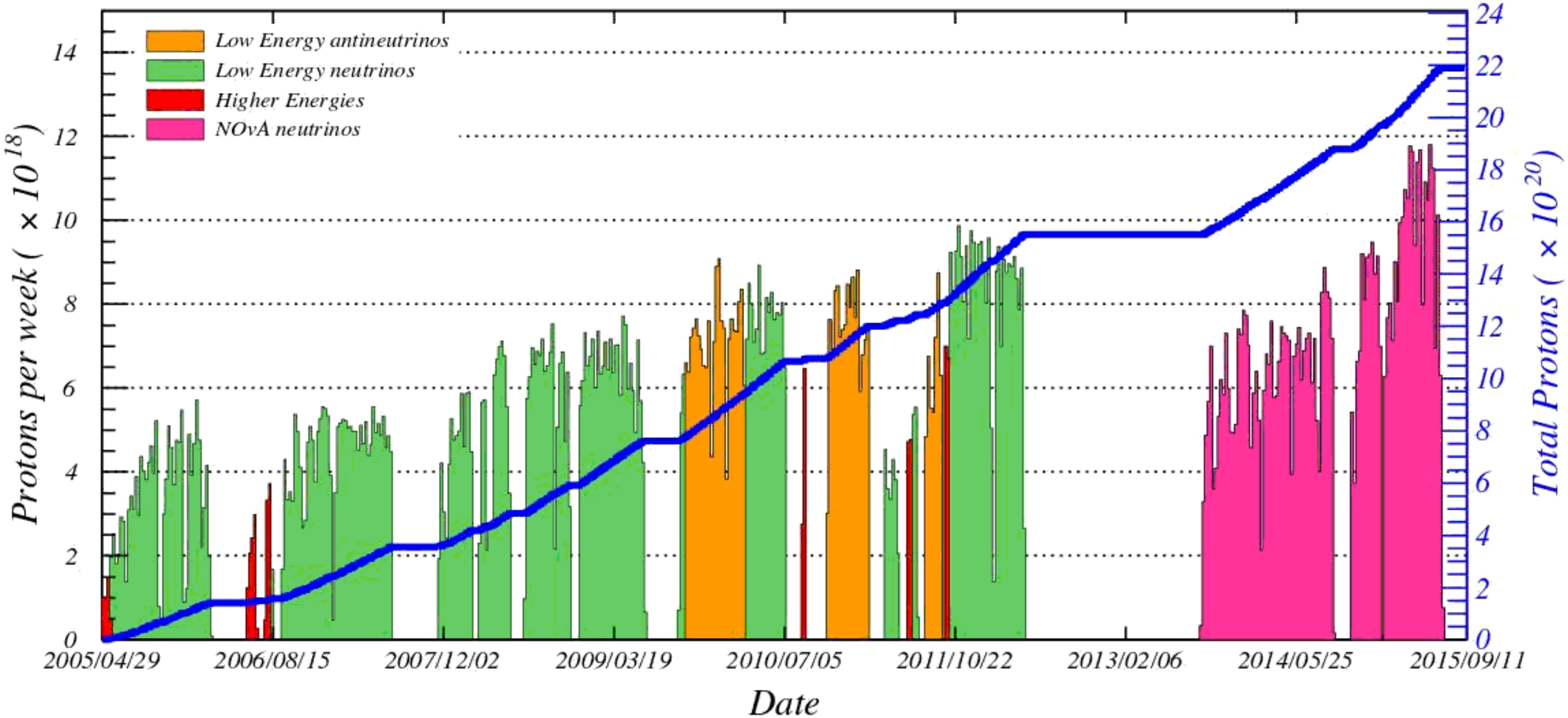


- Horns and target positioned for the medium energy tune.
  - MINOS+ on axis with a wide energy peak.
  - NOvA has a very narrow peak since it is off-axis from the beam.



NuMI Beam Performance

- The upgraded NuMI beam has been running since September 2013.
  - Upgraded to provide the NOvA beam in medium energy mode.

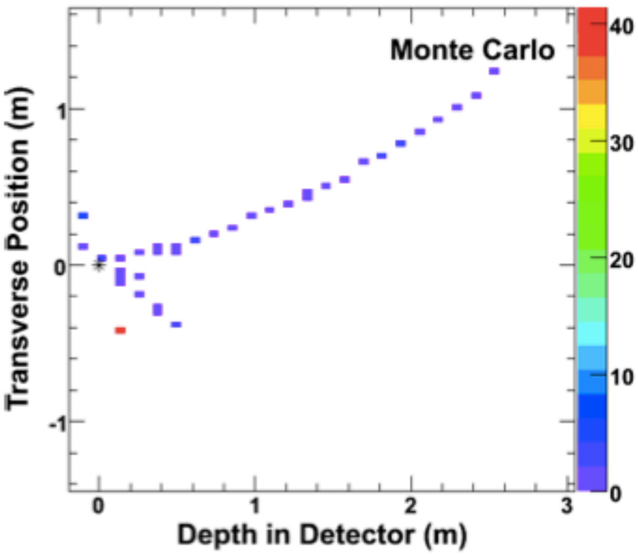


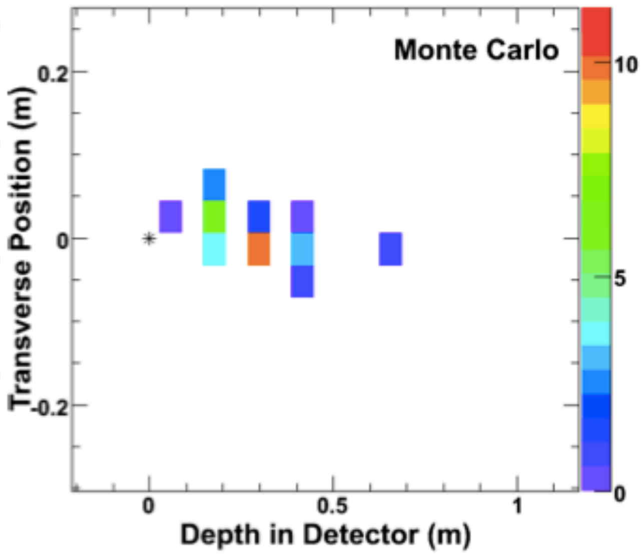
- With MINOS, in the low energy beam configuration, collected:
  - 10.71×10^{20} POT neutrino mode.
  - 3.36×10^{20} POT anti-neutrino mode.

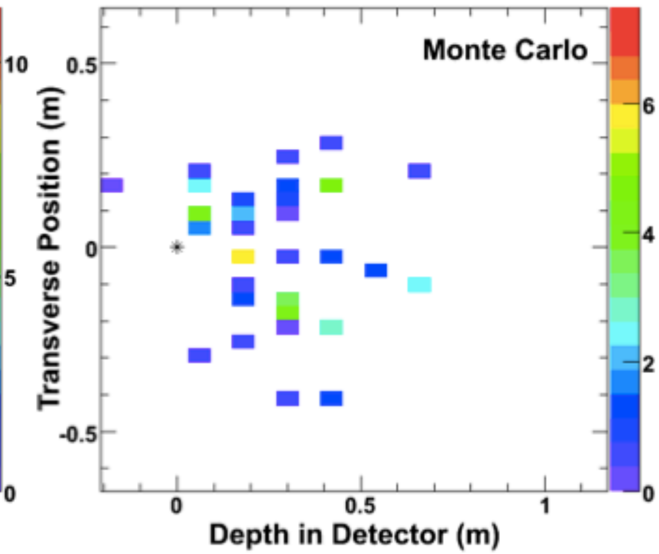
Over 6×10^{20} POT collected for MINOS+ and counting!

Event Topologies

- Expect three classes of events inside the detectors.







CC ν_μ

Identify muon track and use curvature to measure the sign.

Momentum comes from range or curvature (if not contained).

CC ν_e

Compact electro-magnetic shower.

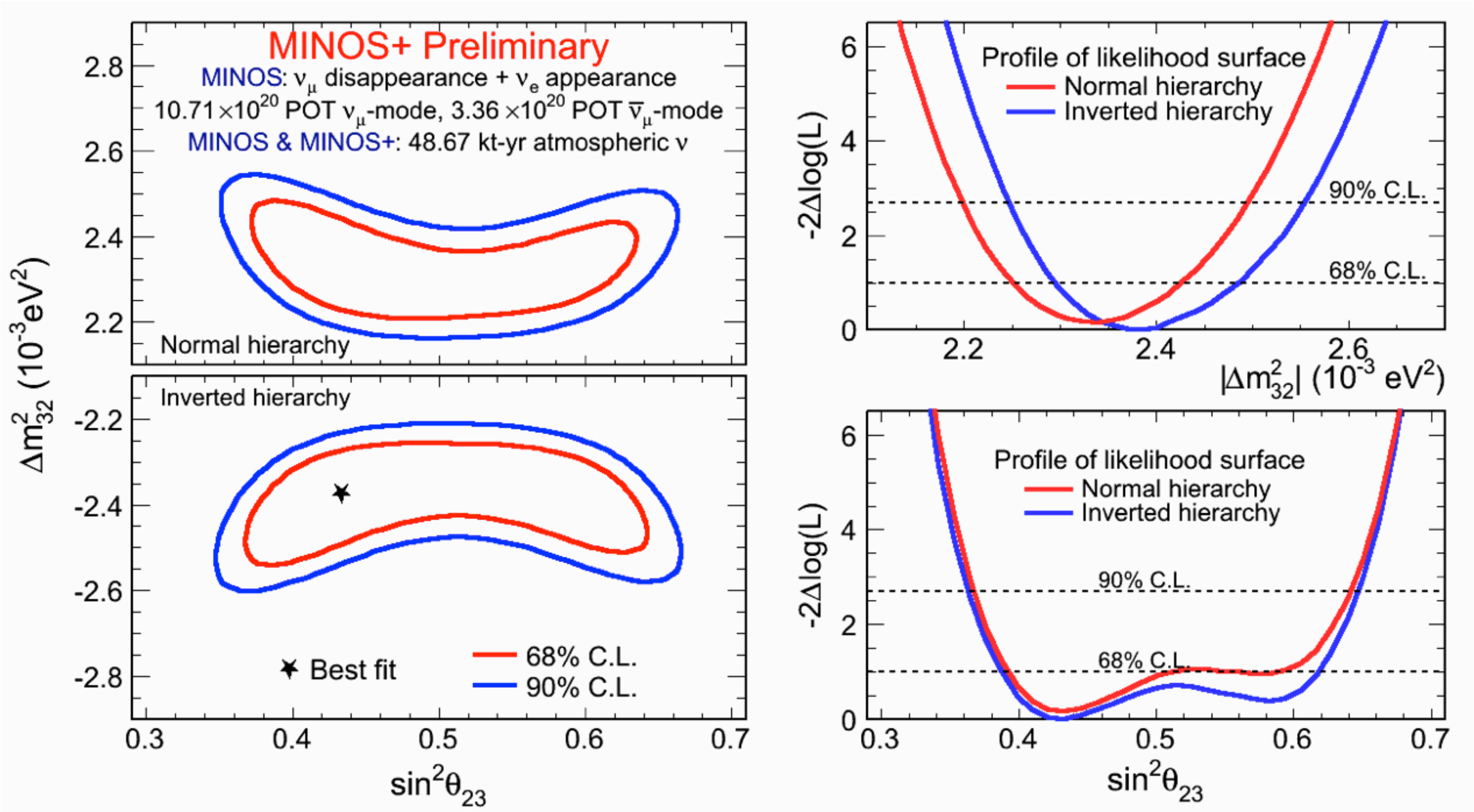
NC ν_x

Disperse hadronic shower energy deposits.

MINOS+ ν_μ Disappearance Analysis

MINOS / MINOS+ Recap

- Last year we showed the final MINOS combined result combined with additional MINOS+ atmospheric data.

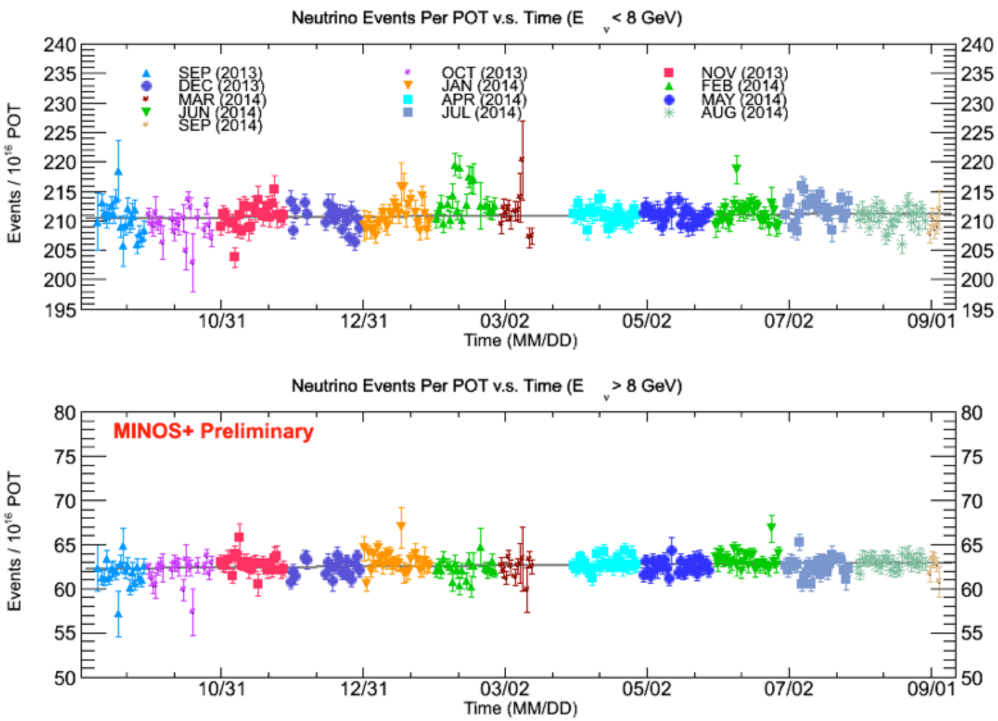


- We have now processed the first 2.99×10^{20} POT of MINOS+ beam data.

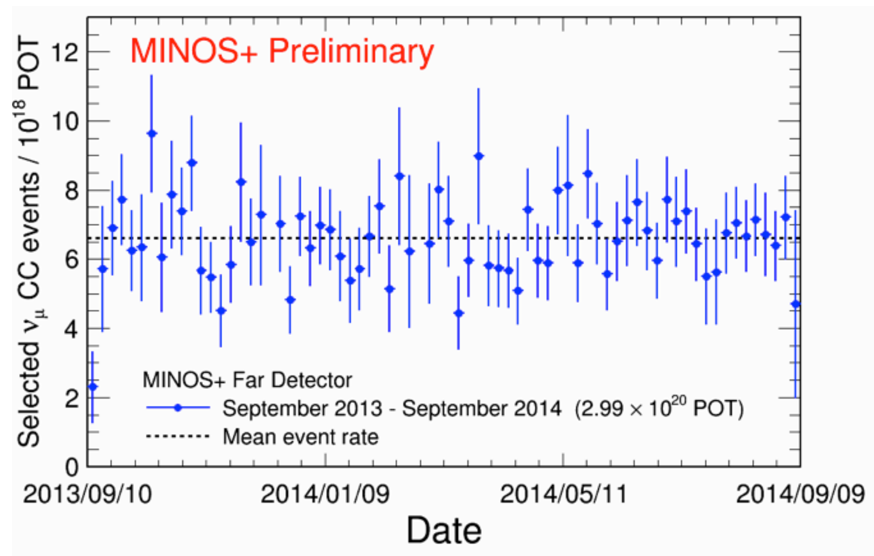
MINOS+ ν_μ Disappearance Analysis

- Data sample corresponds to the first year of MINOS+ running.
  - 2.99×10^{20} POT

Near Detector



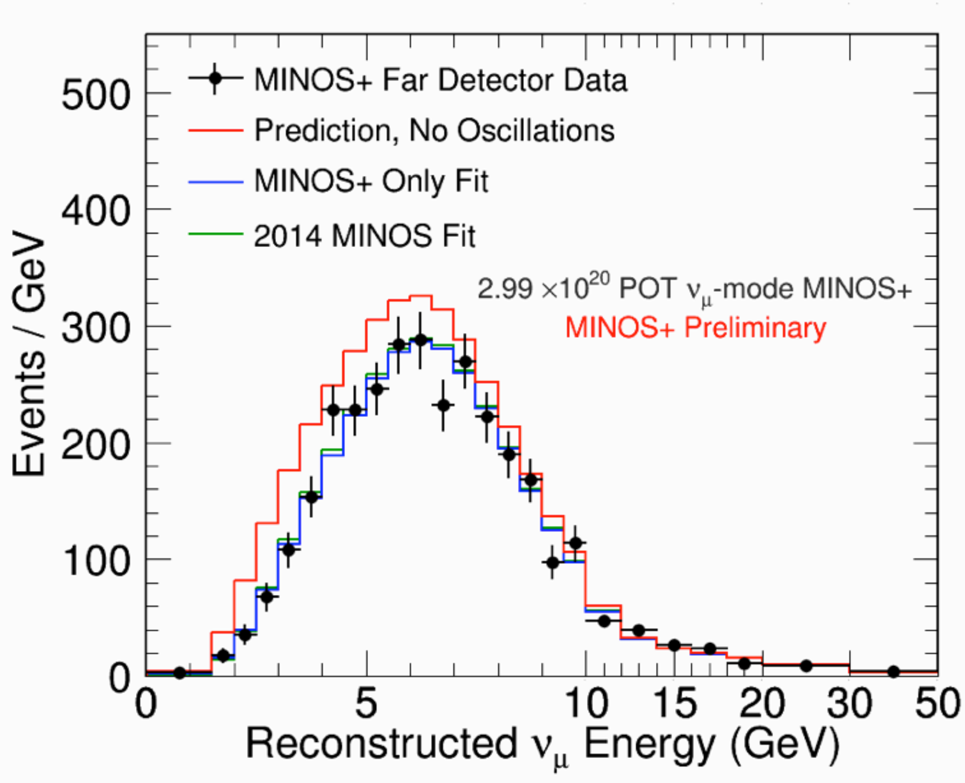
Far Detector

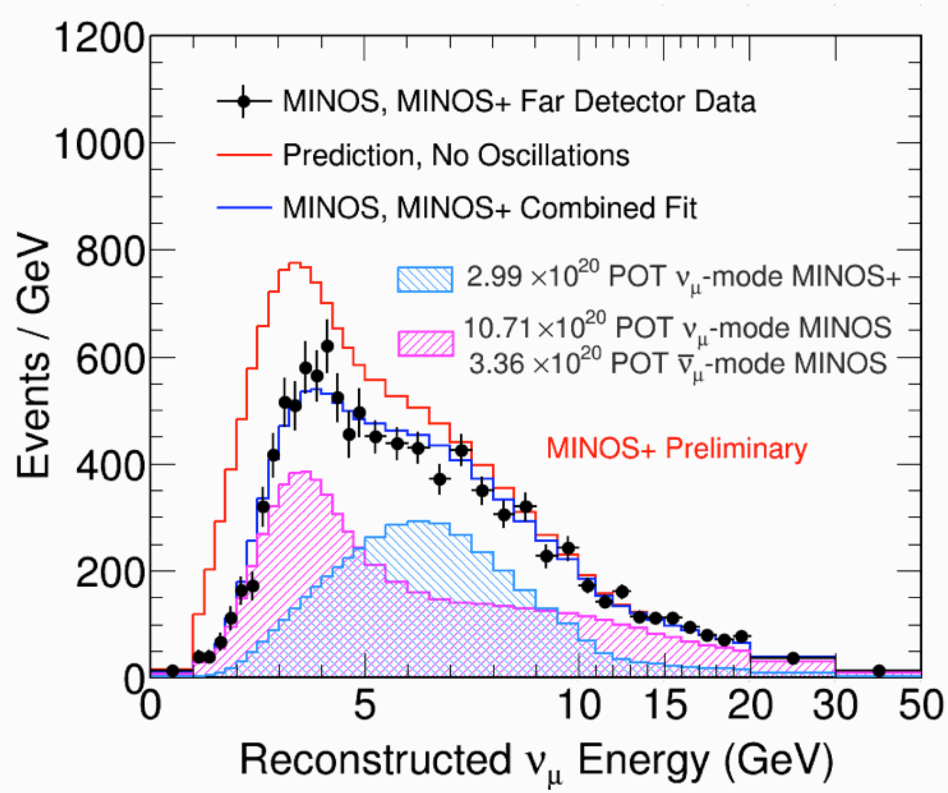


- Measure the beam in the ND, then extrapolate to predict what should be seen at the FD.

MINOS+ Disappearance Analysis

- Fitted the first year of MINOS+ beam data and compared the result to that from the final MINOS fit.

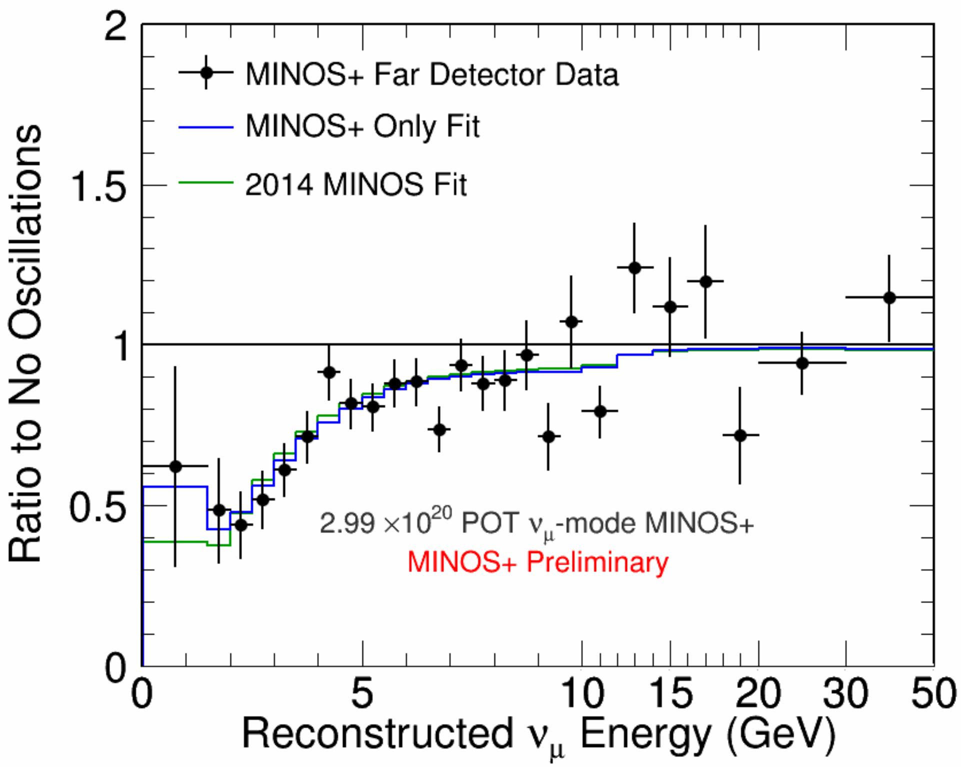


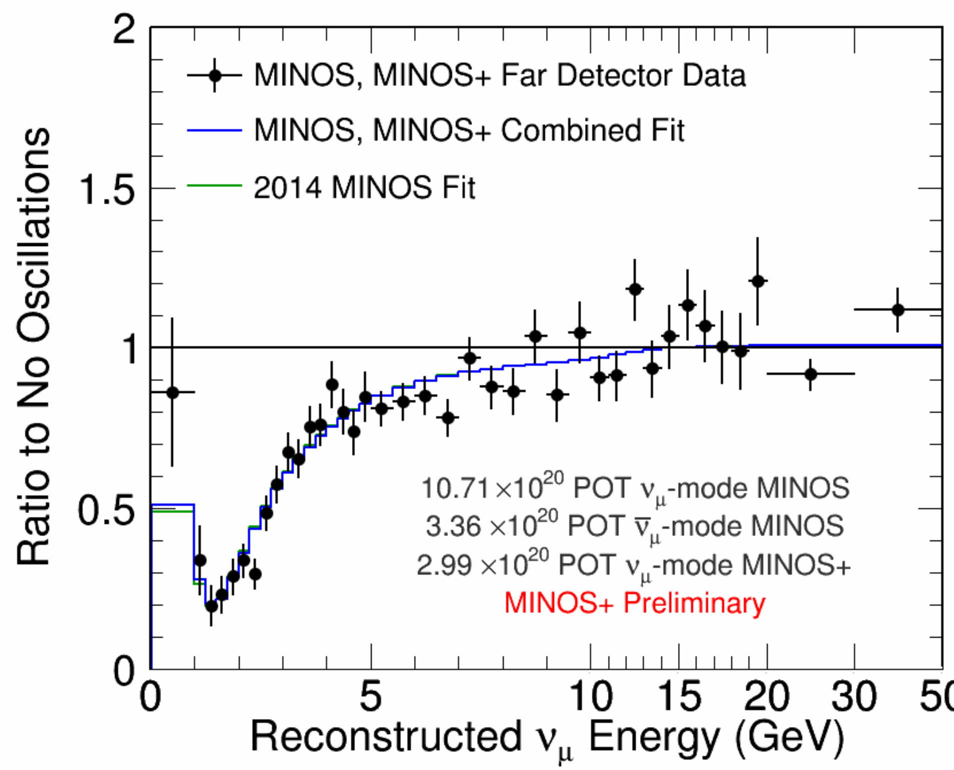


- Clear to see that the MINOS best fit describes the MINOS+ data.
  - Strong test of the oscillation paradigm away from the maximum.

MINOS+ Disappearance Analysis

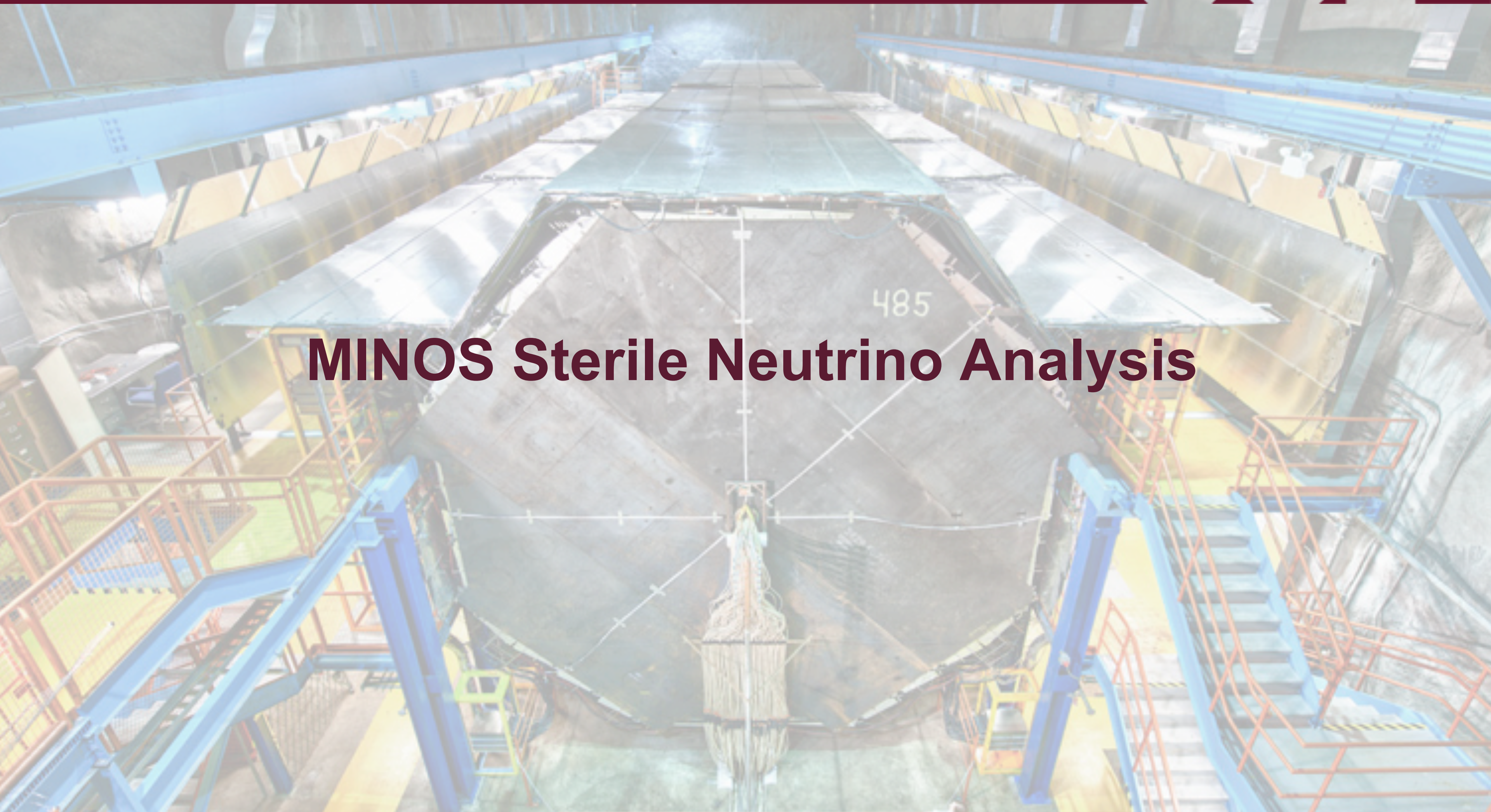
- Fitted the MINOS+ beam data and compared the result to that from the final MINOS fit.





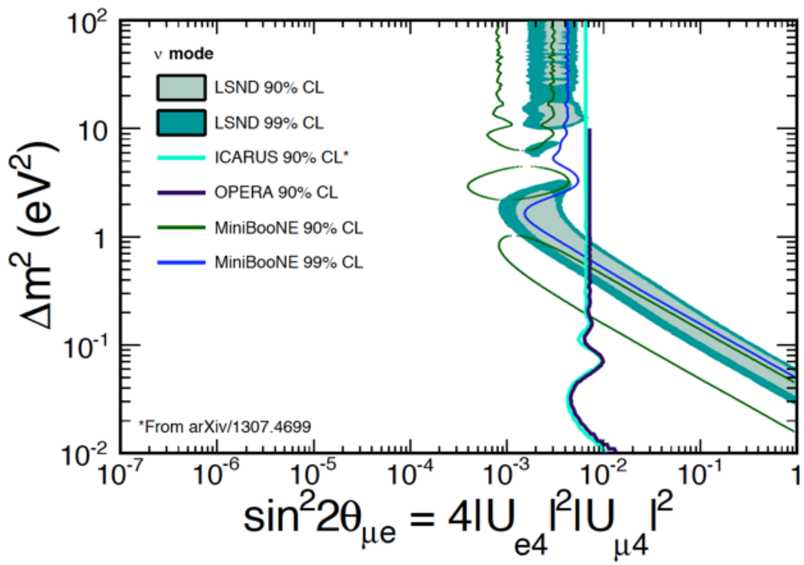
- Clear to see that the MINOS best fit describes the MINOS+ data.
  - Only a difference of 1.3 chi-square units between the two best fit points.

MINOS Sterile Neutrino Analysis

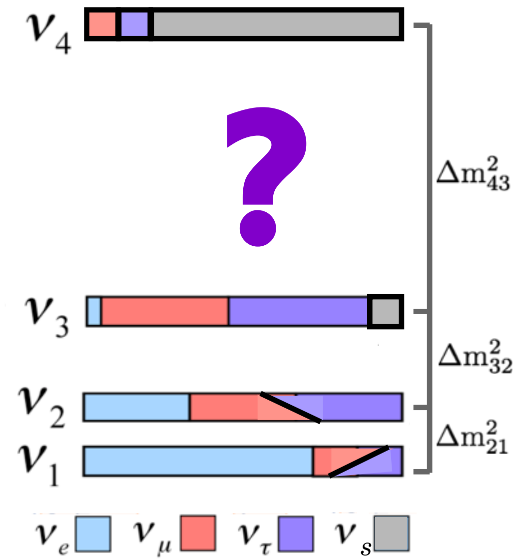


Sterile Neutrinos

- There have been anomalous results in various low energy short baseline appearance and reactor experiments
  - Look with long-baseline: Higher energy and different systematics
- Oscillations to a 4th light neutrino could explain results
- A sterile neutrino would be seen in MINOS as an energy dependent reduction in event rate
  - In both neutral-current (NC) and charged-current (CC) channels
- MINOS mostly sensitive to Δm^2_{43} and θ_{24}, but also to θ_{34}

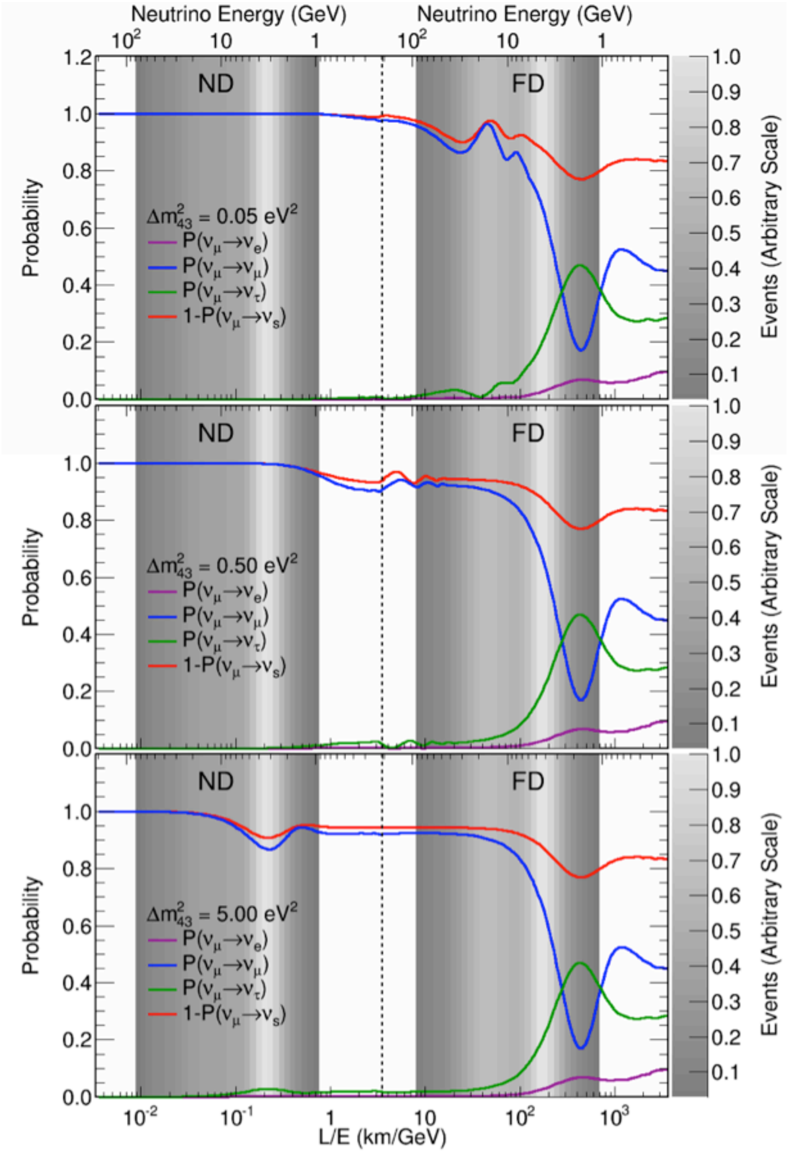


MiniBooNE, PRL 110, 161801(2013)



Sterile Neutrinos in MINOS

- Think of potential oscillations in categories:
- Small Δm^2_{43}
  - Expect spectral distortions in the FD in the high energy tail
  - No ND effects
- Medium Δm^2_{43}
  - Rapid oscillations in the FD average out
  - No ND effects
  - Counting experiment
- Large Δm^2_{43}
  - Rapid oscillations in the FD average out
  - Spectral distortions in the ND
  - Simple extrapolation no longer works



Sterile Neutrinos in MINOS

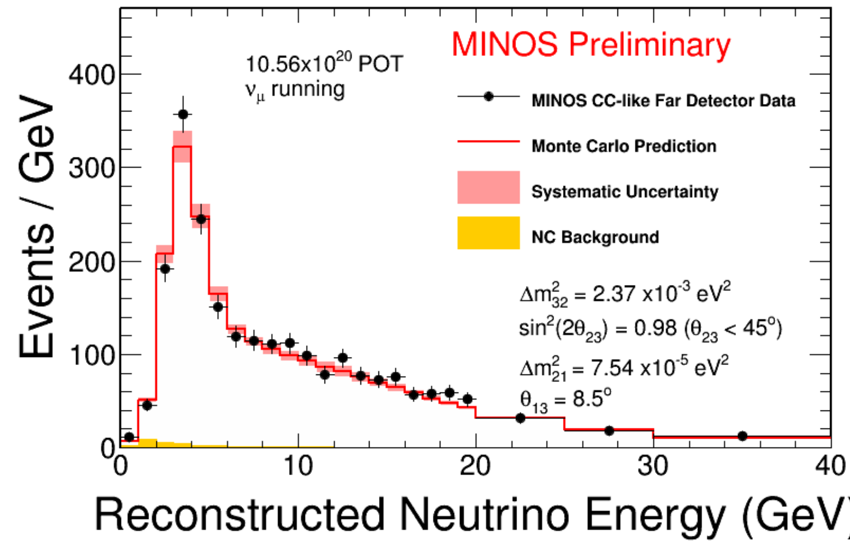
- Perform combined fit of the NC and CC samples
  - 2712 ν_μ-CC-like events in FD
  - 1221 NC-like events in FD
- For NC selection, define test statistic

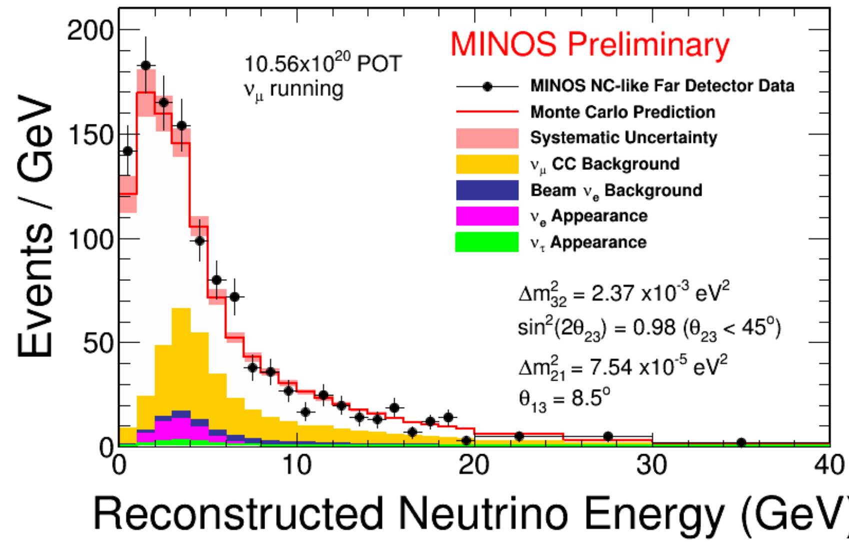
Predicted Background

$$R = \frac{N_{data} - N_{bkg}}{S_{NC}}$$

Predicted Signal

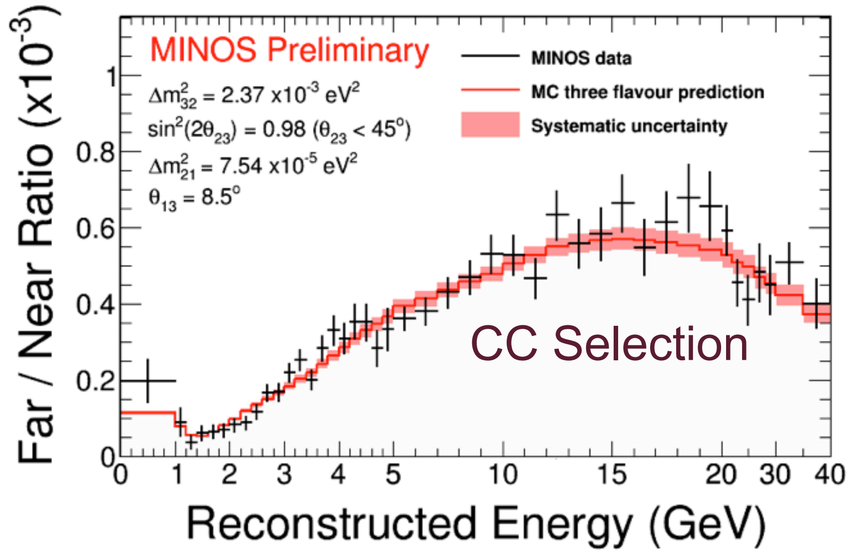
  - 0 – 40 GeV: $R = 1.075 \pm 0.107$
  - 0 – 3 GeV $R = 1.109 \pm 0.096$
- No evidence for a sterile neutrino at $\Delta m^2_{43} \approx 0.5\ \mathrm{eV}^2$

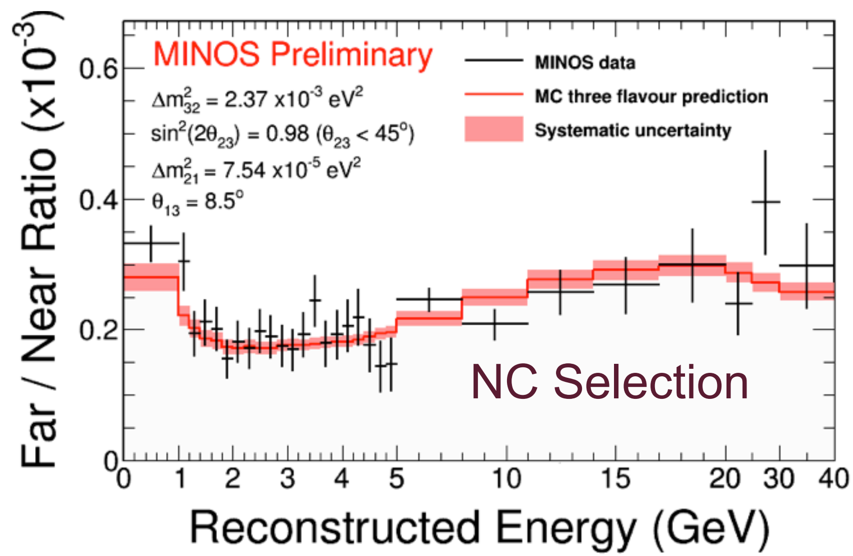




Full Four Flavour Fit

- Assume 3+1 scenario
  - Apply oscillations for ND and FD
  - Account for meson decay position
  - Fit for $|\Delta m^2_{32}|$, θ_{23}, $|\Delta m^2_{43}|$, θ_{24}, θ_{34}
- Due to potential ND oscillations, fit expected F/N ratio to data F/N ratio
  - Standard extrapolation technique not applicable in this case
  - Additional constraint on ND rate
- Use Feldman-Cousins method to obtain the confidence limits
- Careful study of systematics in the high energy tail





Systematic Uncertainties

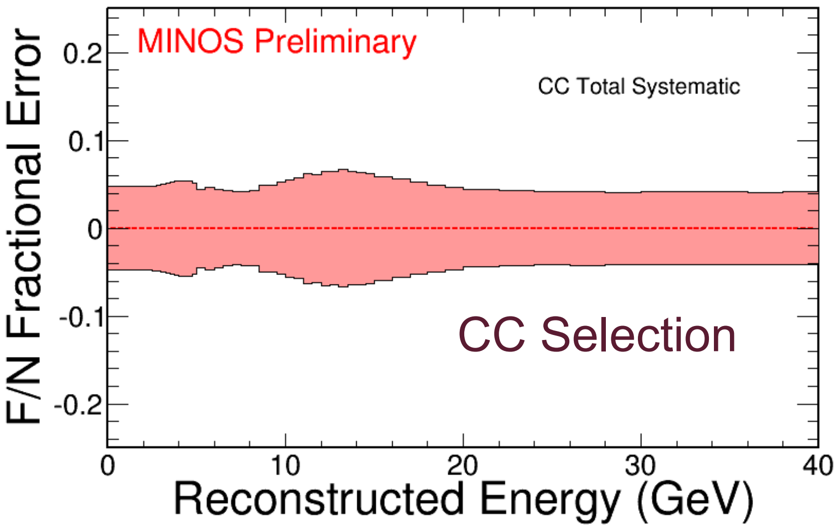
- 26 systematic uncertainties included in the fit via a covariance matrix

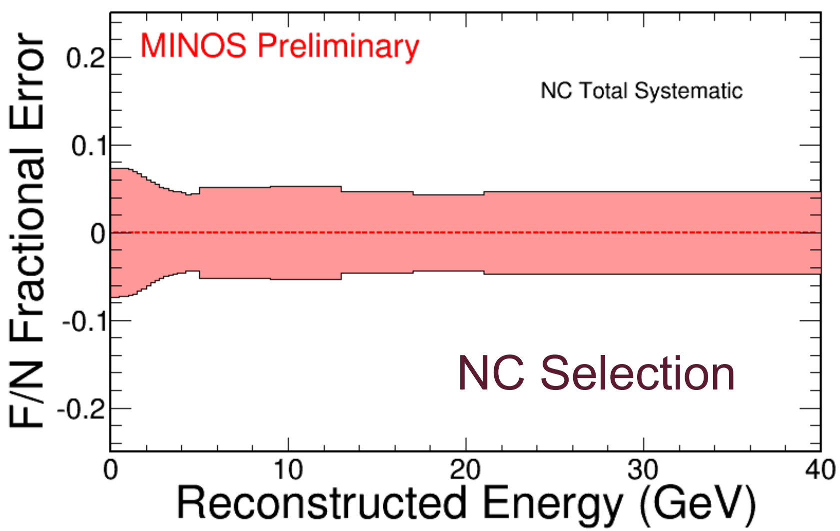
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T[V^{-1}]_{ij}(o_j - e_j)$$

o_i : Observed events in bin i $\quad V$: Covariance matrix

e_i : Predicted events in bin i

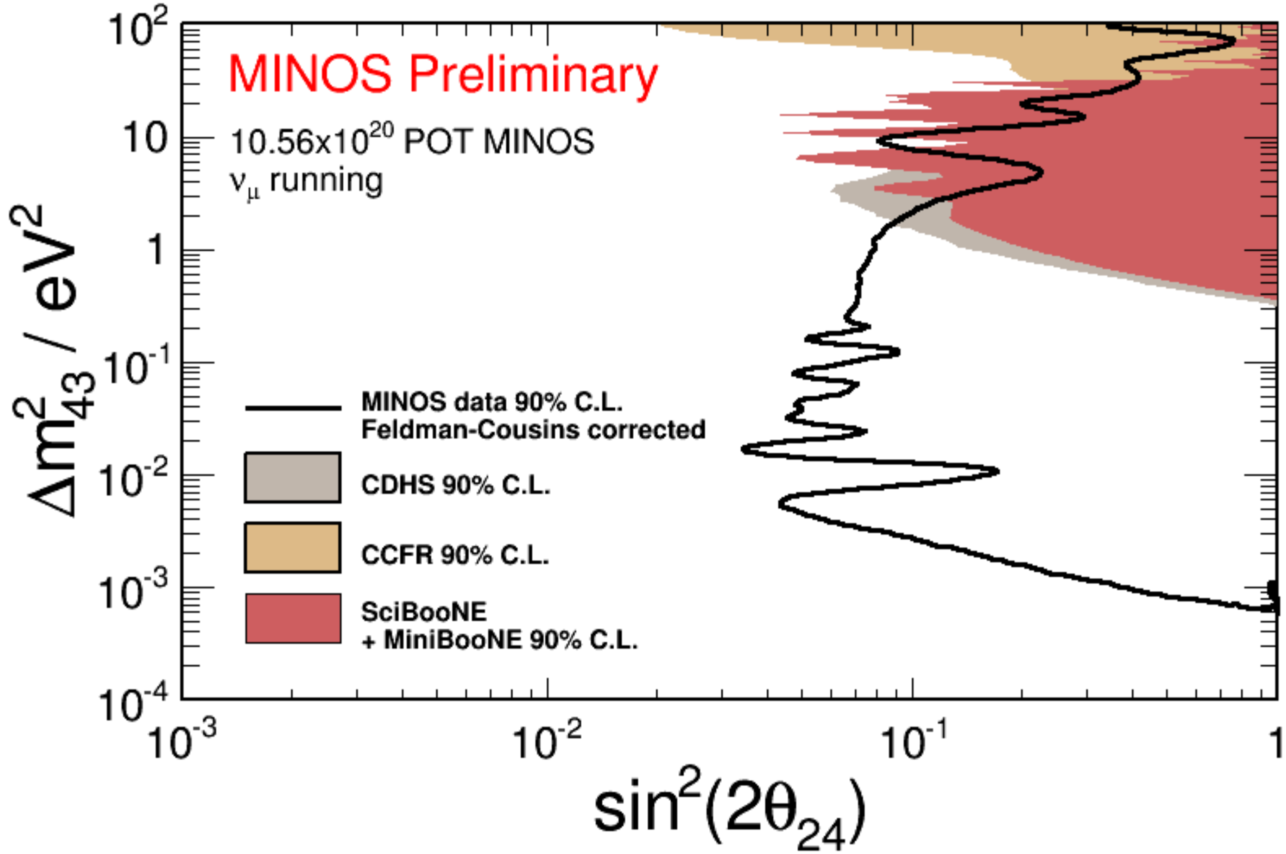
- Systematics come from both CC and NC selections.
  - Many sources: selection, energy scale cross-sections, normalistion, beam flux etc





MINOS Sterile Neutrino Result

- Comparison of the MINOS result with disappearance searches in $|\Delta m^2_{43}|$, θ_{24} space.



- MINOS limit stretches over 5 orders of magnitude in $|\Delta m^2_{43}|$
  - For values $|\Delta m^2_{43}| < 1.0\text{eV}^2$, strongest limit on ν_μ to ν_s disappearance

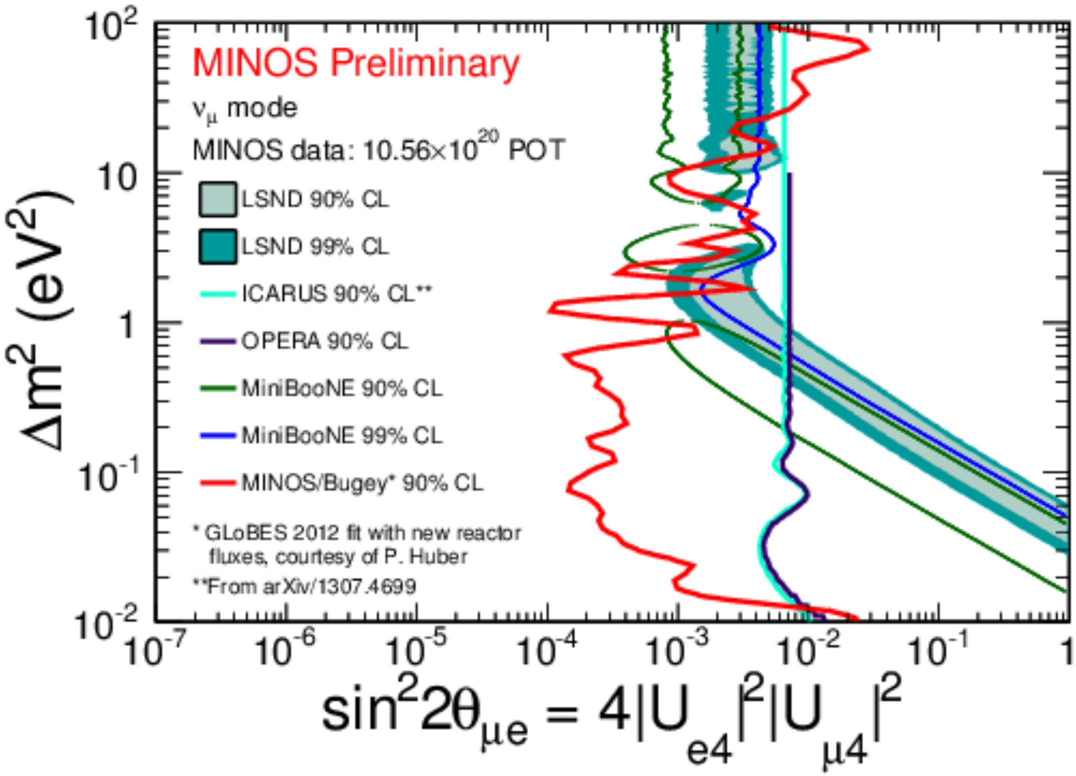
MINOS Sterile Neutrino Result

- To compare the MINOS result with appearance searches, can combine with Bugey, a reactor disappearance experiment.

- MINOS measures $|U_{\mu 4}|$
- Bugey measured $|U_{e4}|$

- Bugey contour is that calculated by P. Huber with updated reactor fluxes.

- Systematics assumed to be orthogonal between the experiments.



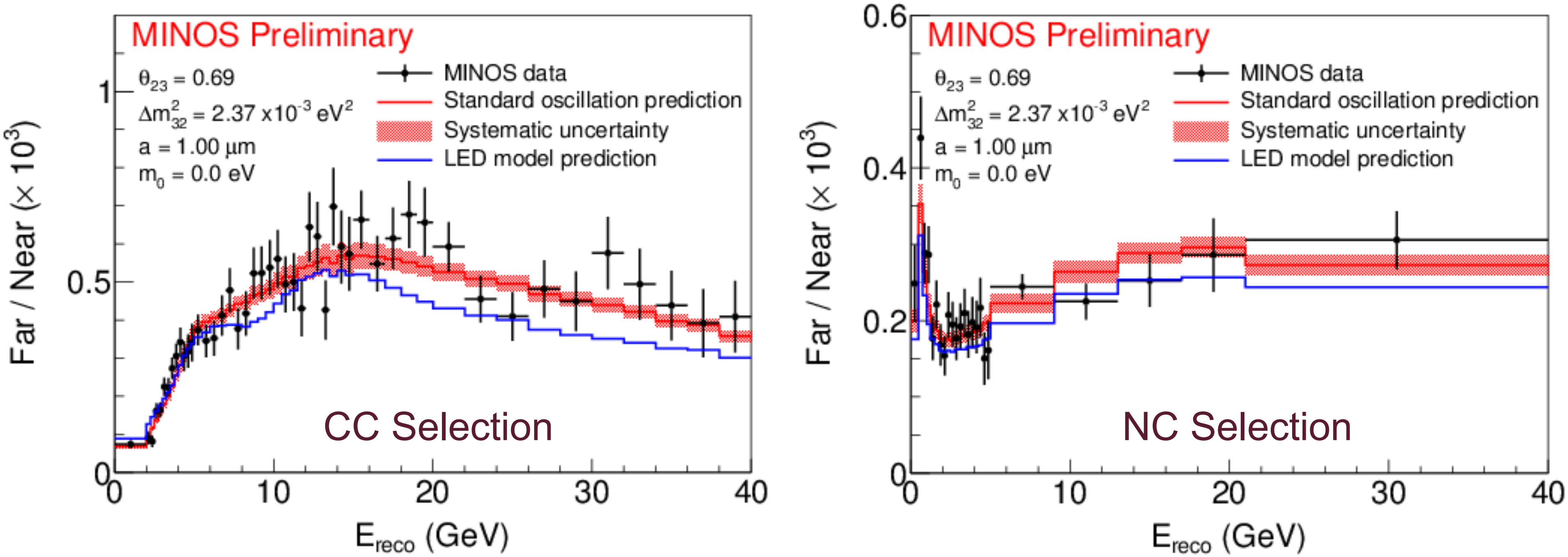
- Tension between the disappearance and appearance experiments.

Other Results and Prospects

MINOS Large Extra Dimensions

- We can use the MINOS sterile neutrino selection to search for extra dimensions.
  - Model by N. Arkani-Hamed et al[1].
- Two additional parameters:
  - Size of the extra dimension, a.
  - Mass of the lightest neutrino state, m_0.

[1] N. Arkani-Hamed et al. , Phys. Lett. B 429, 263 (1998):



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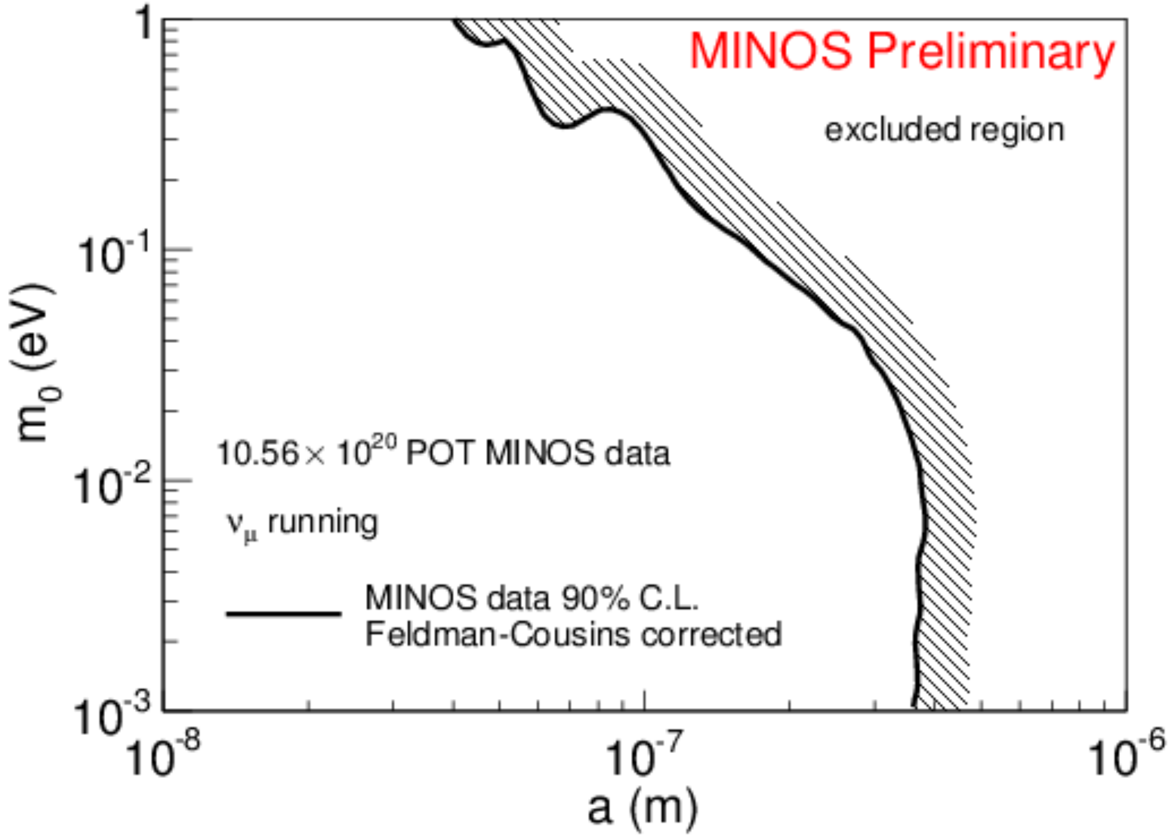
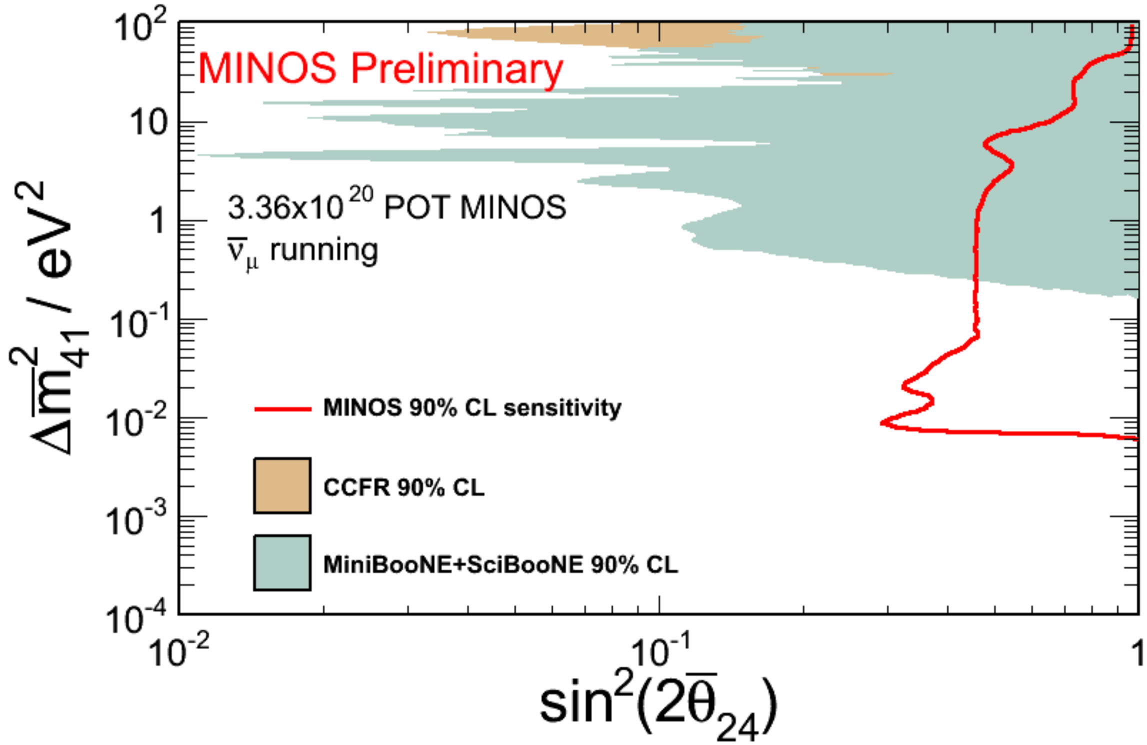


- Strongest limit on this LED model from neutrino oscillation experiments.
- In the limit of $m_0 = 0$, size of LED must be less than 0.35μm

MINOS Sterile Anti-Neutrinos

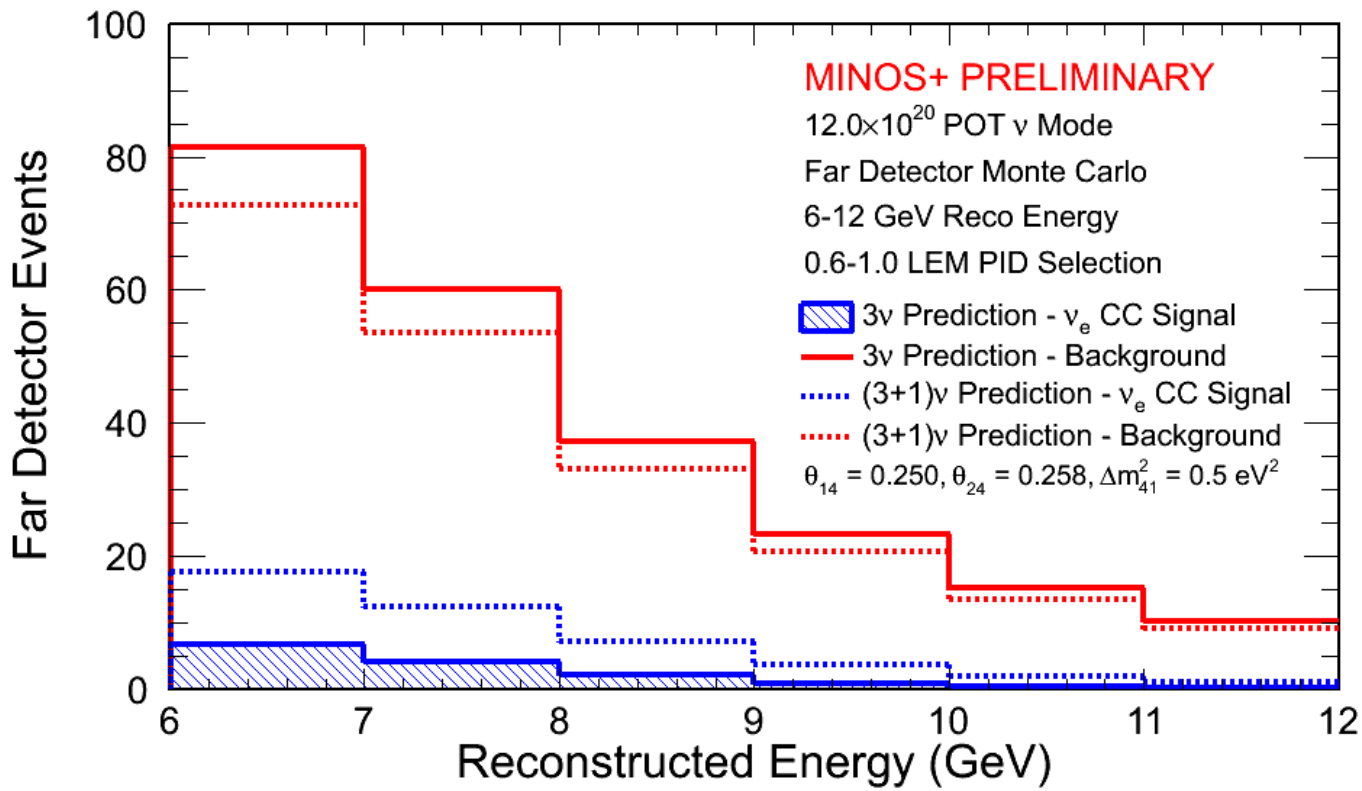
- We're also working on an antineutrino sterile neutrino search.
  - Sensitivity shown only includes the CC anti-neutrino sample.



- Expect improvements from two samples:
  - NC sample from the anti-neutrino beam configuration.
  - CC anti-neutrinos selected from the neutrino beam mode.

MINOS+ Sterile ν_e Appearance

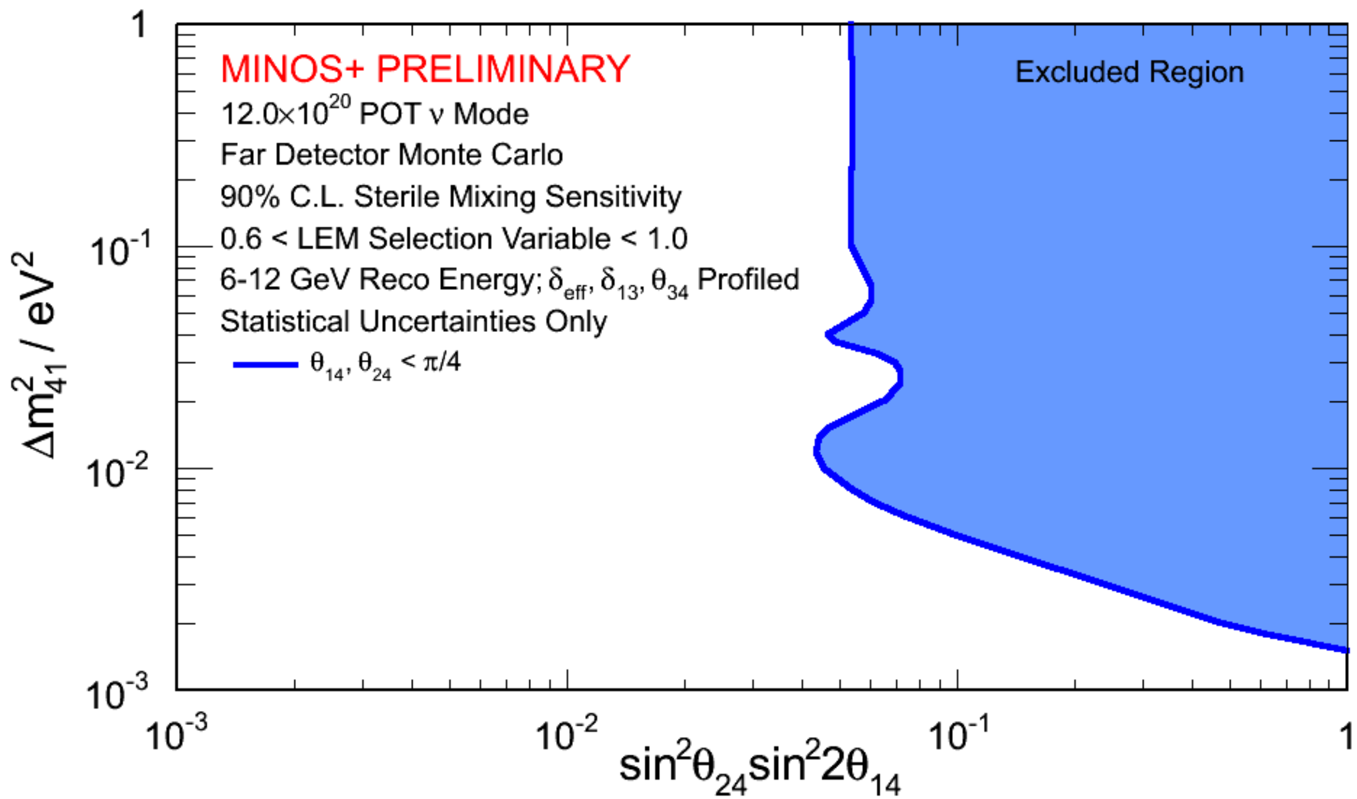
- Take advantage of the higher energy spectrum to search for enhanced appearance signals arising from a sterile neutrino.



- Look above 6 GeV where the background is reduced.
  - Expect a fairly large enhancement compared to the 3-flavour signal.

MINOS+ Sterile ν_e Appearance

- Sensitive to θ_{24} and θ_{14}, hence directly comparable to LSND and MiniBooNE.



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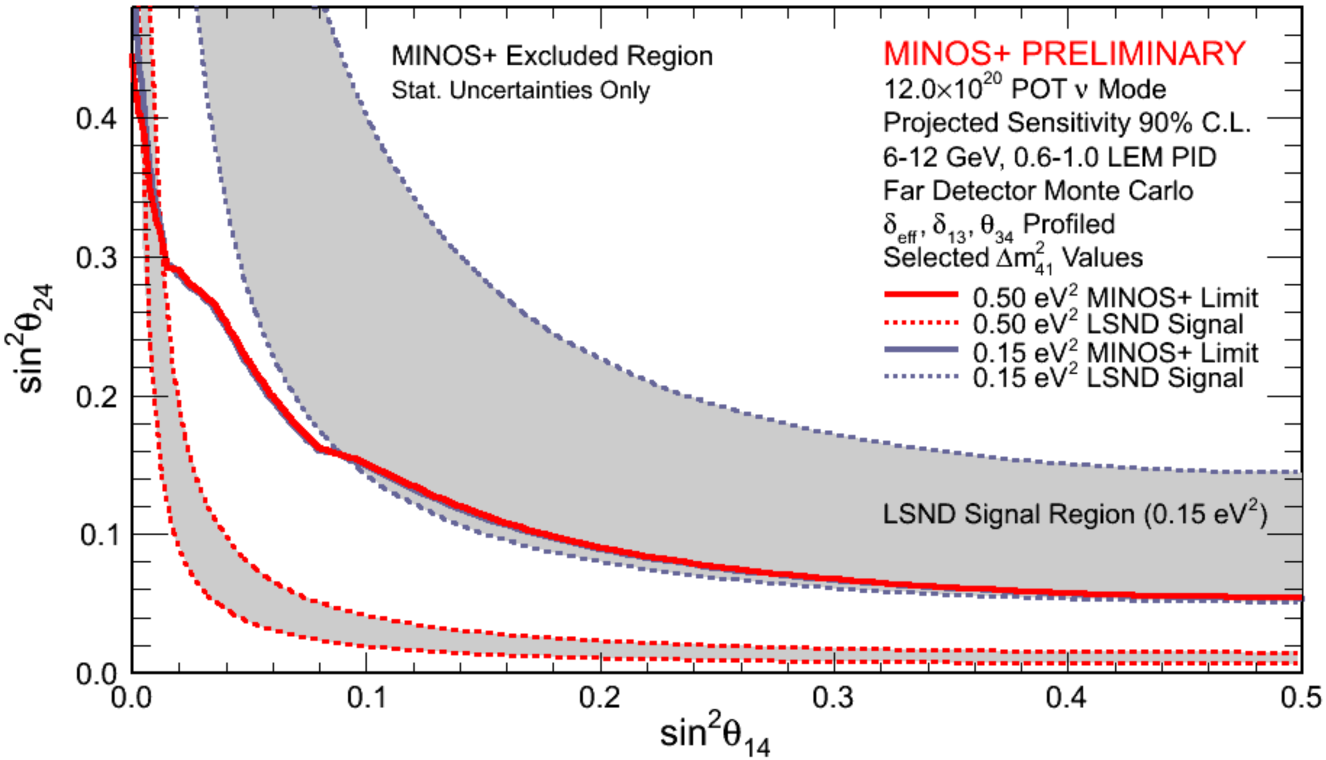


- Sensitivity to exclude the LSND signal region below 0.15eV^2 at 90% C.L.

Summary

- MINOS+ disappearance search in good agreement with the values fitted by MINOS.
  - MINOS still holds the best atmospheric mass-splitting measurement (but coming under increasing pressure!).

- Very strong limits on sterile neutrinos below 1eV^2

- Still data being analysed from MINOS:
  - MINOS sterile anti-neutrinos

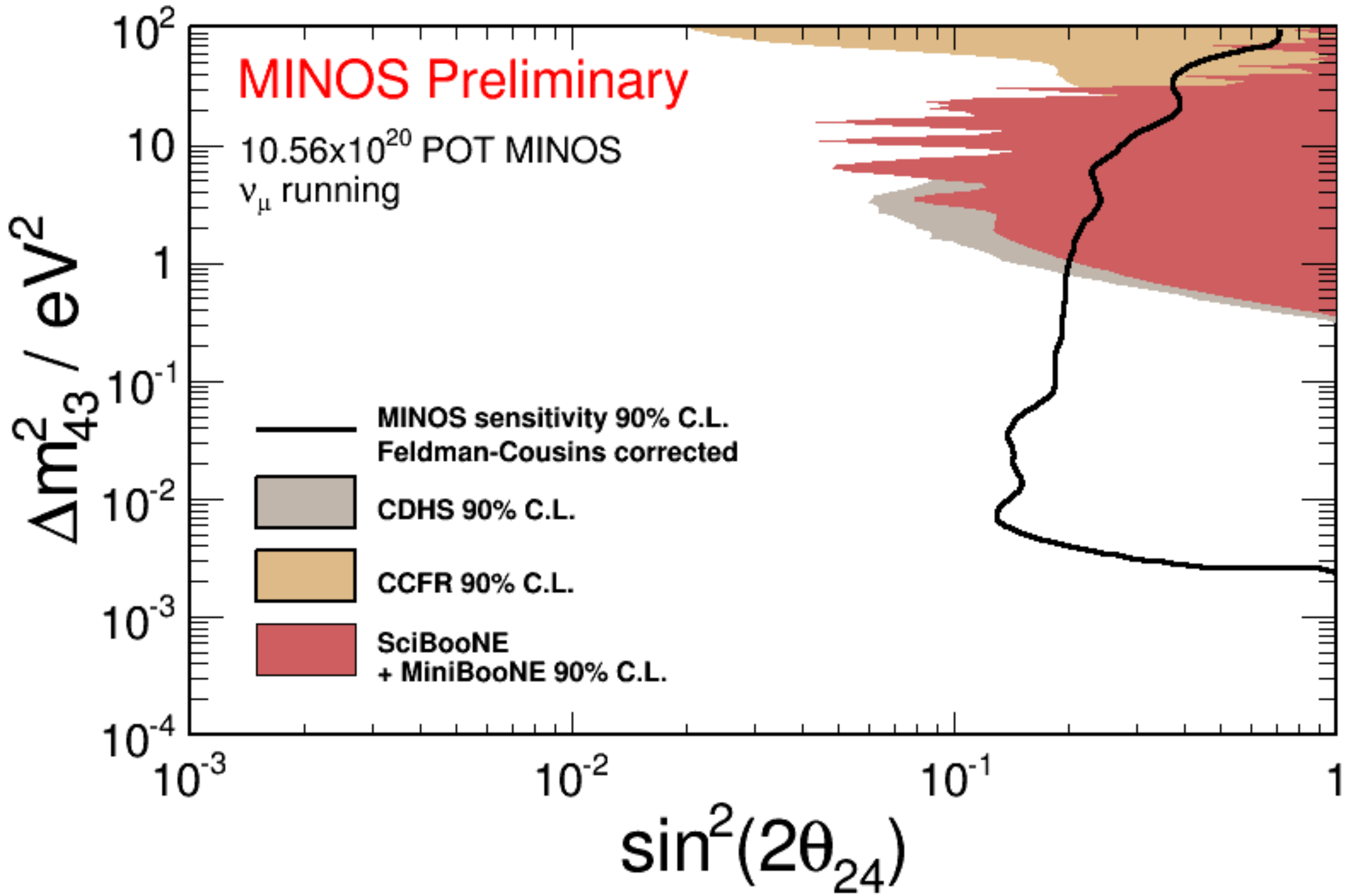
- More exciting prospects to come with the full MINOS+ data sample:
  - Combined MINOS and MINOS+ disappearance measurement
    - At least an extra year of data on top of what was shown here
  - Sterile disappearance and appearance search
  - Large extra dimensions
  - Non-standard interactions

Thank You

Backup Slides

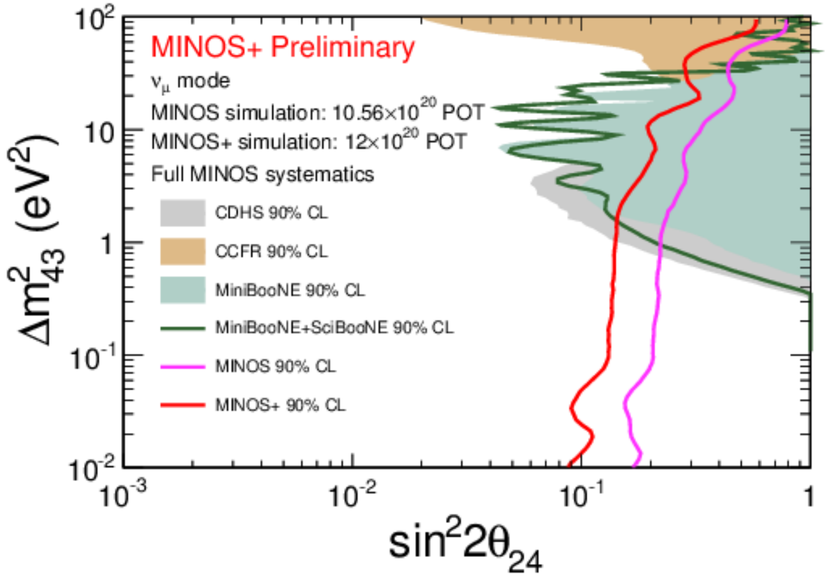
MINOS Sterile Sensitivity

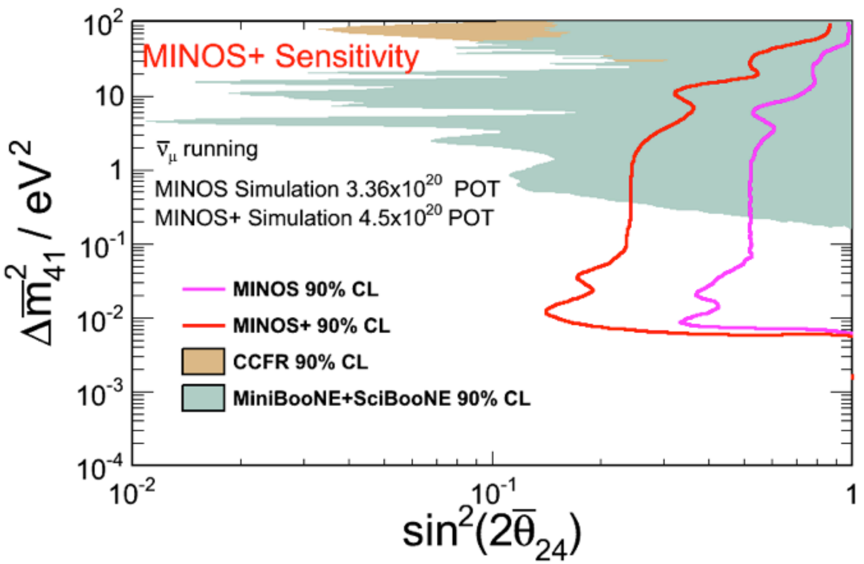
- The sensitivity expected from the simulation:



MINOS+ Sterile Sensitivities

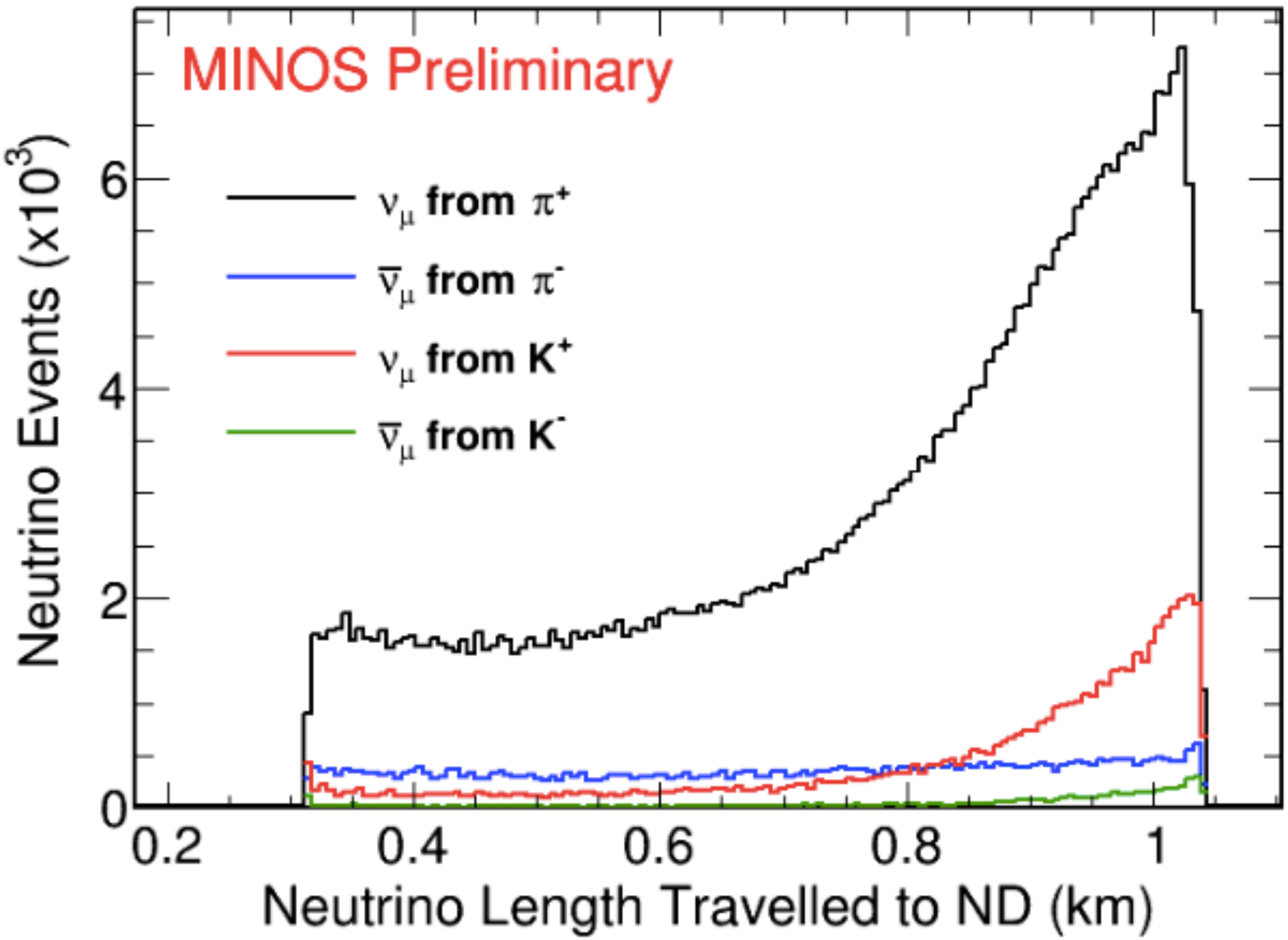
- Can expect a good improvement over the MINOS limits:





MINOS Sterile Analysis: Meson Decay

- Mesons decay at varying points along the decay pipe. This has a large effect on the ND in terms of the baseline.

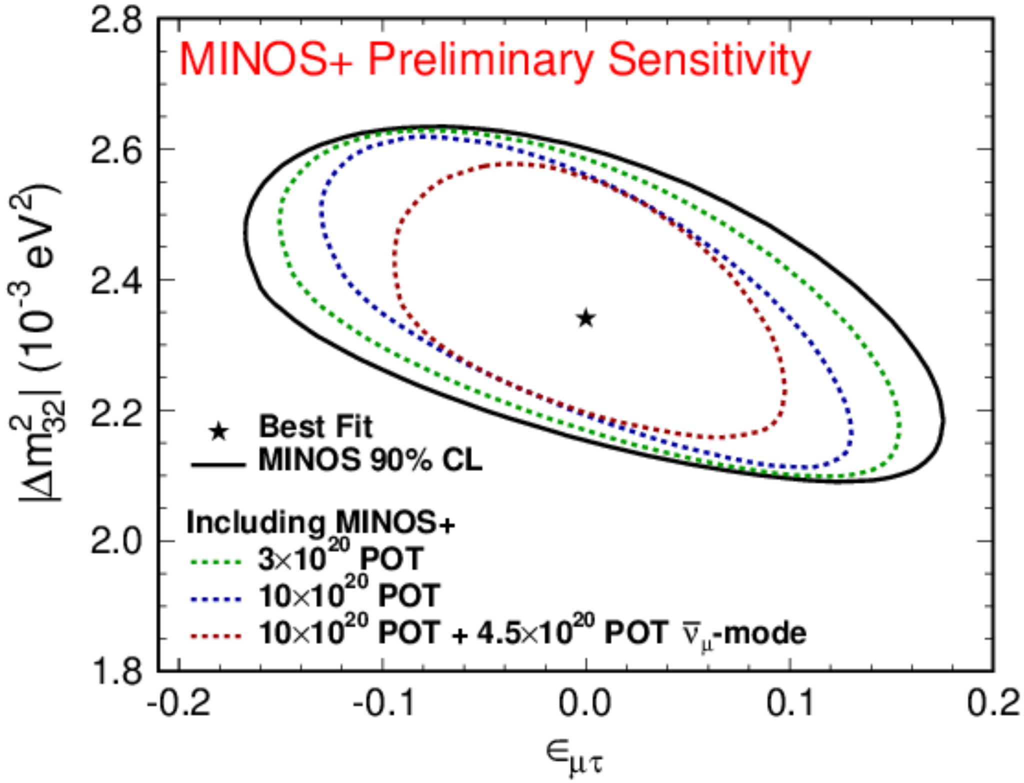


MINOS+ NSI Sensitivity

- Non-standard interactions provide a framework to accommodate deviations from standard oscillations

$$H = U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{bmatrix} U_{PMNS}^{\dagger} + \sqrt{2} G_F n_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^{\star} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^{*} & \epsilon_{\mu\tau}^{*} & \epsilon_{\tau\tau} \end{bmatrix}$$

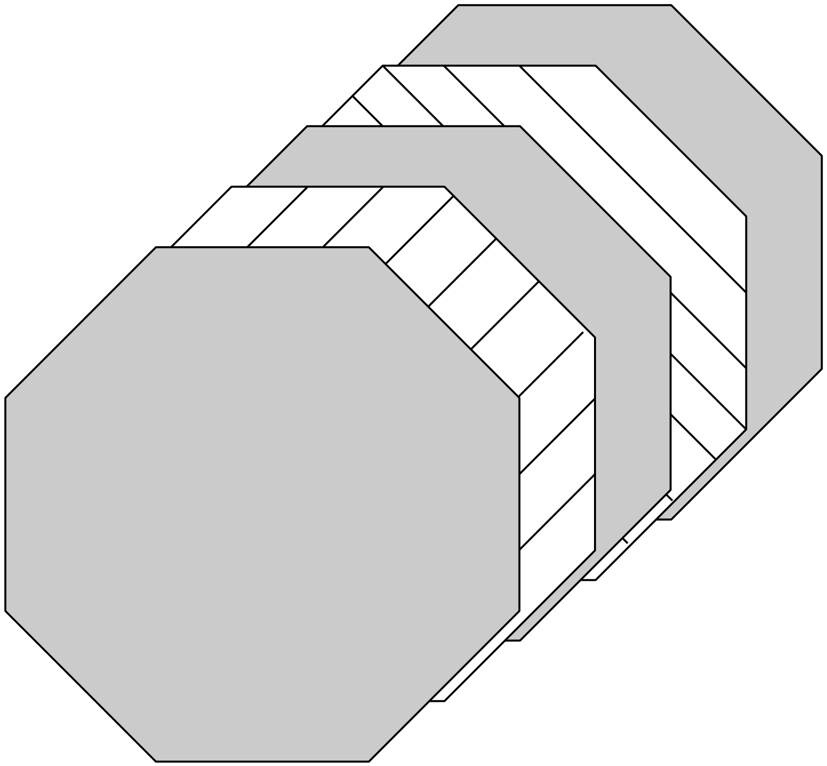
  - MINOS+ sensitive to $\varepsilon_{\mu\tau}$ from ν_μ disappearance



- MINOS+ anti-neutrino data would give a real boost.
- Even with just neutrinos, a decent improvement is expected.

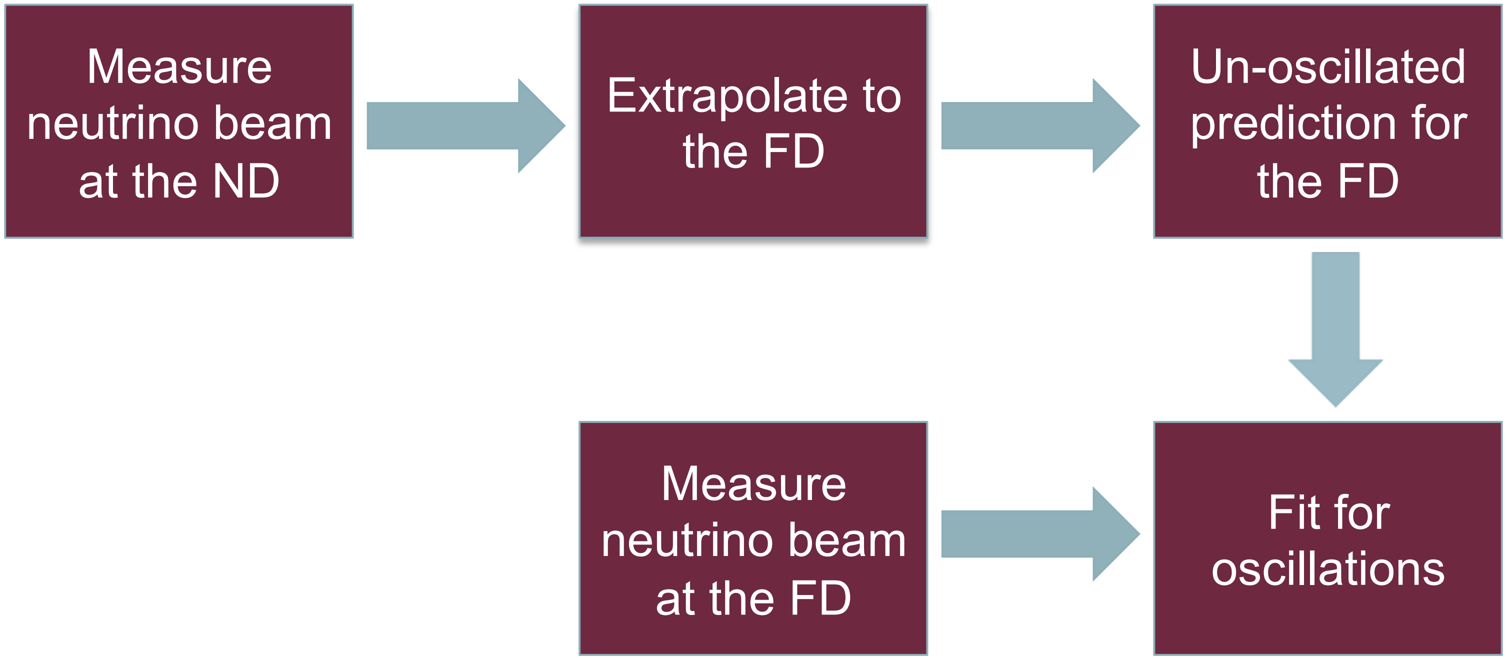
Detector Technology

- Detectors built from alternating planes:
  - 2.54cm steel absorber ~1.4 X_0
  - 1cm thick scintillator.
- Scintillator planes:
  - Made from plastic scintillator bars, each 4.1cm wide.
  - Read out by multi-anode PMTs via WLS fibres.
  - Alternating layers have bars in orthogonal directions views, U and V
- Magnetic field allows for charge separation.
  - Both detectors have average field of 1.3T



Three Flavour Analysis – Methodology I

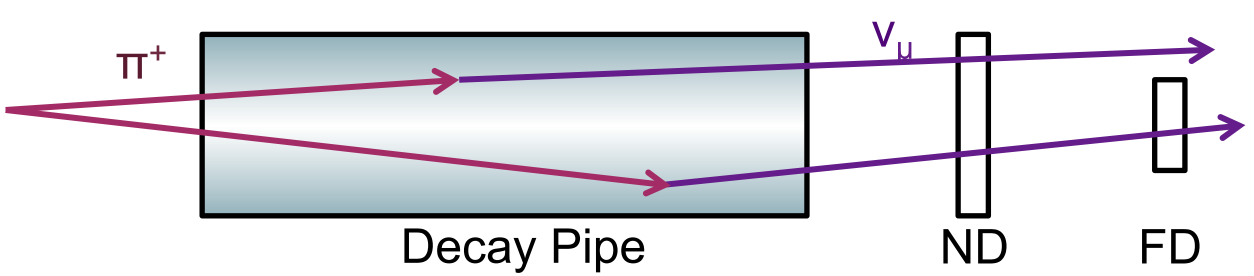
- Use the ND to predict the FD un-oscillated spectrum



- The extrapolation to the FD requires a few steps…

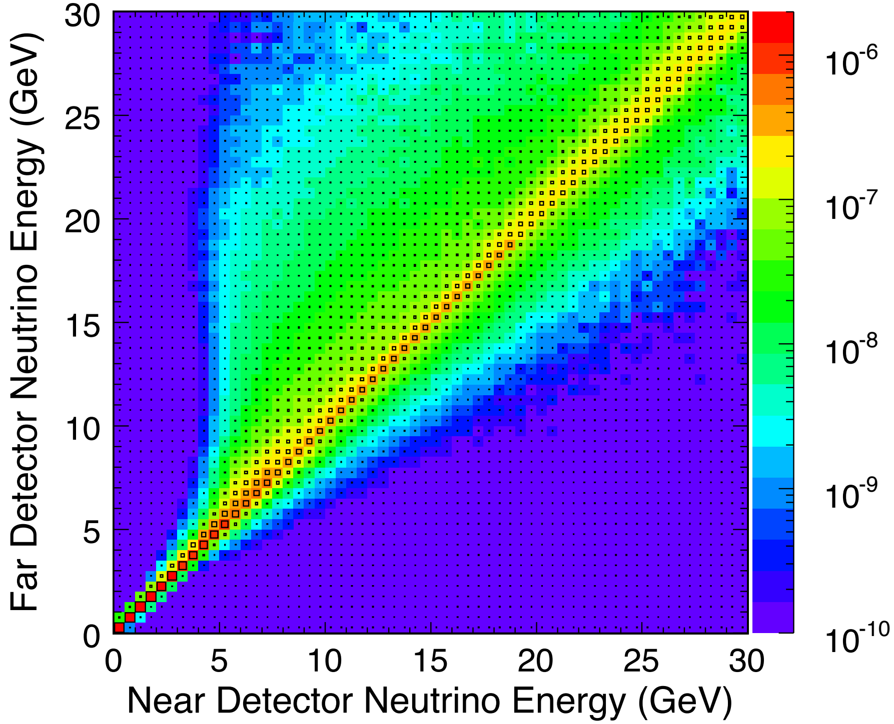
Three Flavour Analysis – Methodology II

- Starting with the ND data:
  - Correct for ND purity and efficiency and apply reco-true matrix
  - Account for cross-sections, POT and ND mass
- Need to account for beam differences now
  - The energy spectrum differs between the two detectors
    - Different angular acceptances
    - Low energy pions decay upstream in the decay pipe.
  - FD sees a point source
  - ND sees an extended source



Three Flavour Analysis – Methodology III

- Apply the beam matrix to extrapolate to the FD.



- Then apply the FD specific corrections.
  - These are the analogues to those shown previously for the ND

- Provides the un-oscillated prediction at the FD