Searching for Sterile Neutrinos at the MINOS Experiment

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(on behalf of the MINOS and MINOS+ collaborations)

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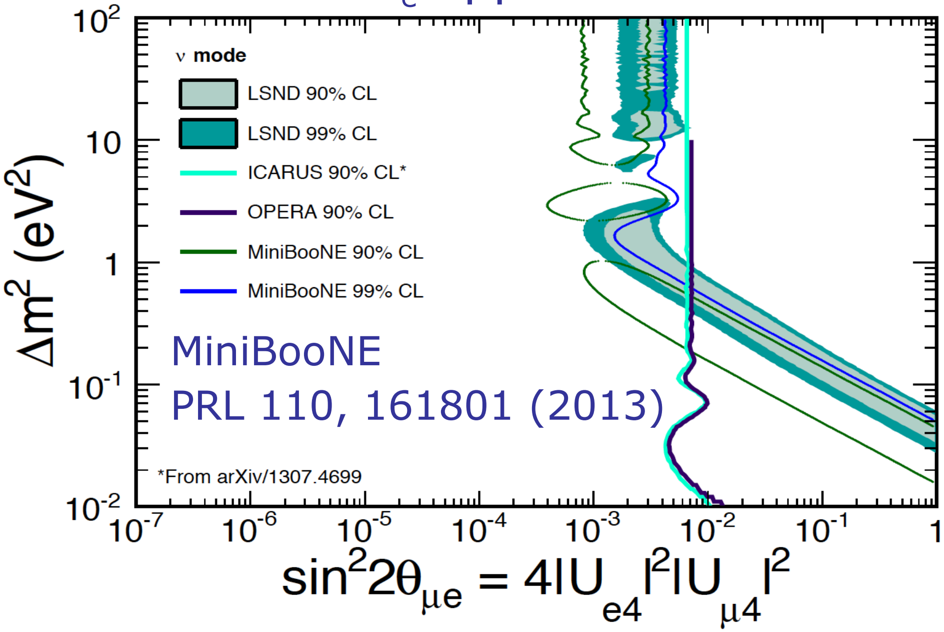
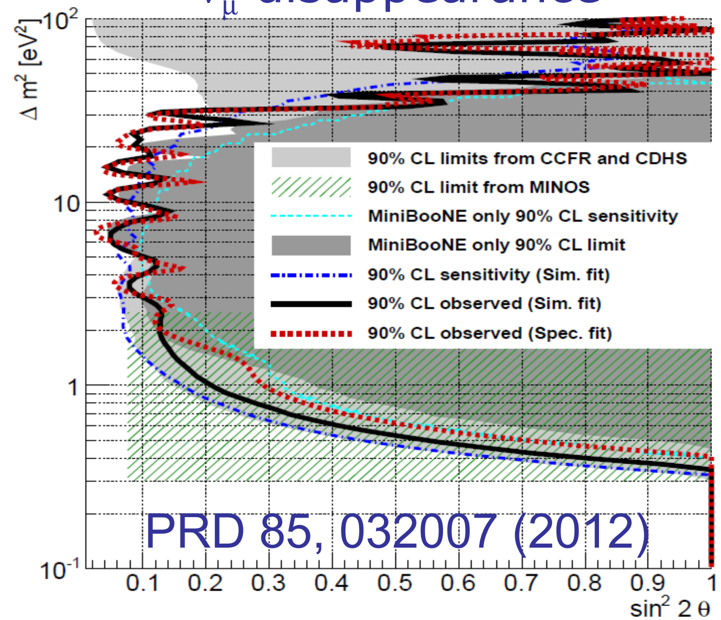
Overview

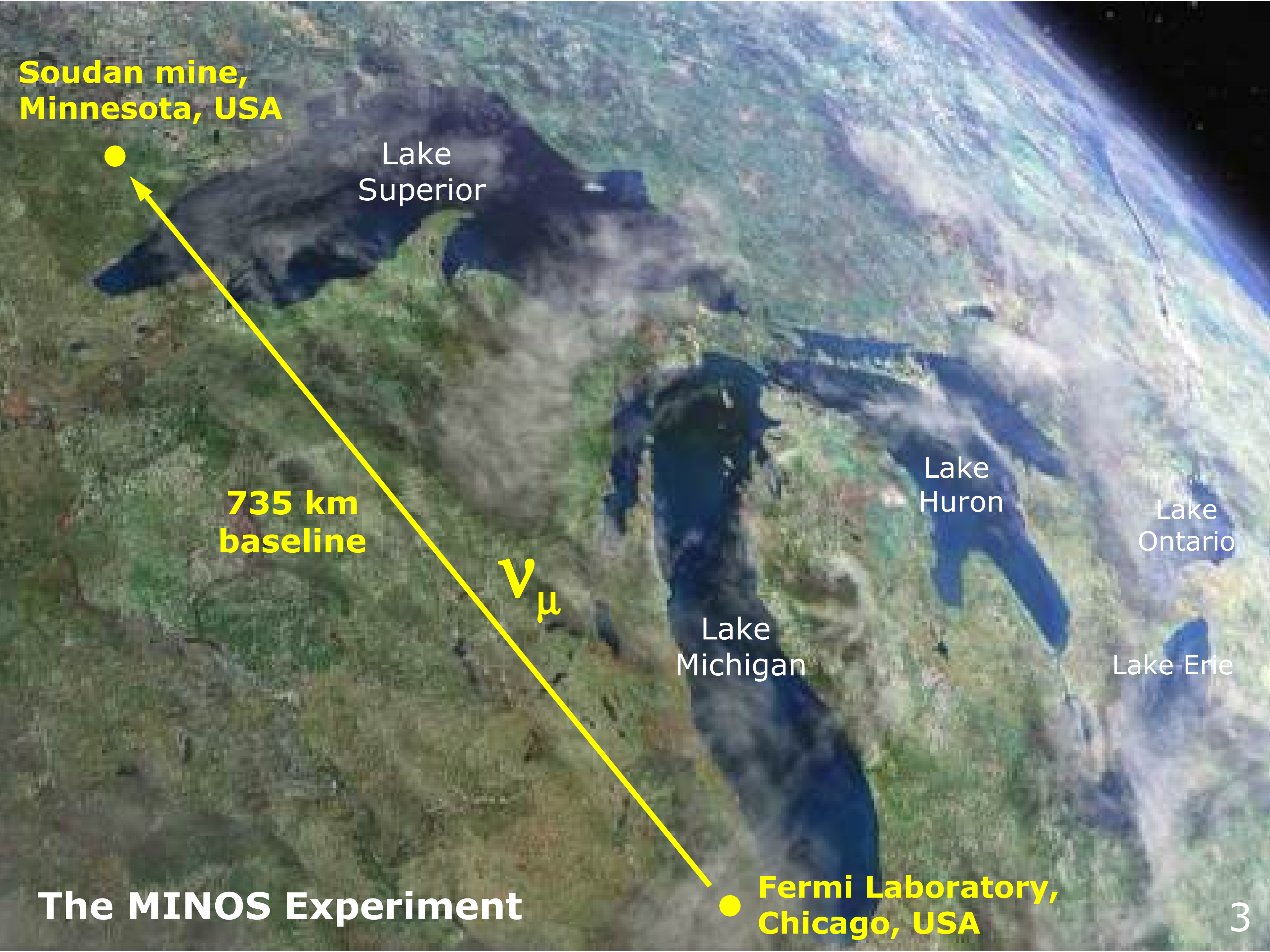
- Oscillations into light sterile neutrinos may explain anomalies in short-baseline, reactor and radiochemical experiments.
- However, the evidence remains inconclusive due to tension between appearance and disappearance measurements
- The MINOS long-baseline experiment offers a complementary probe of sterile neutrino mixing using ν_μ disappearance.

ν_e appearance



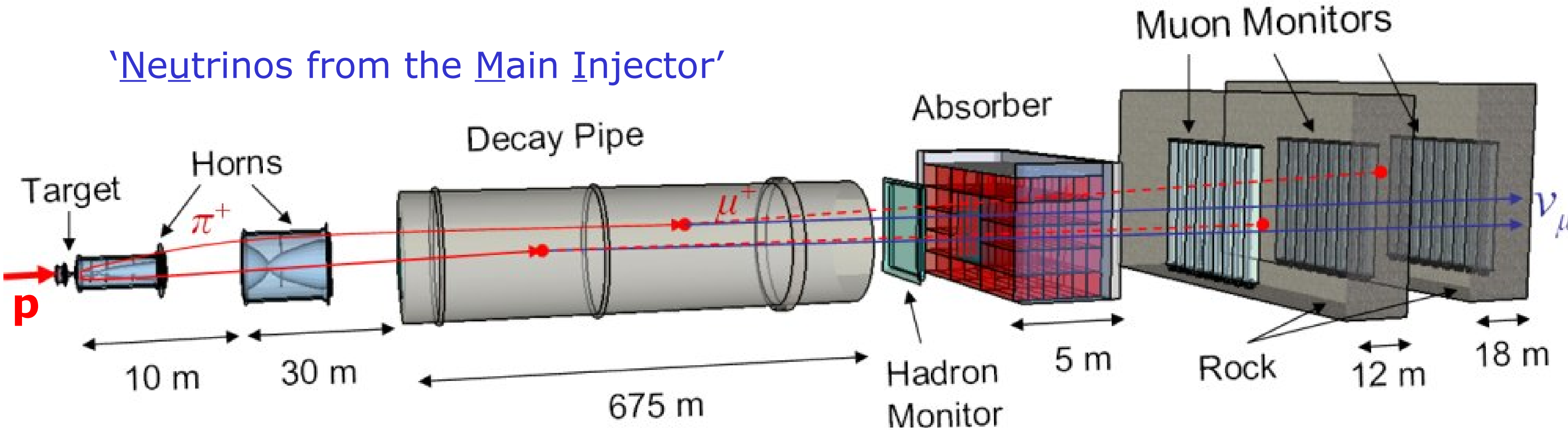
ν_μ disappearance



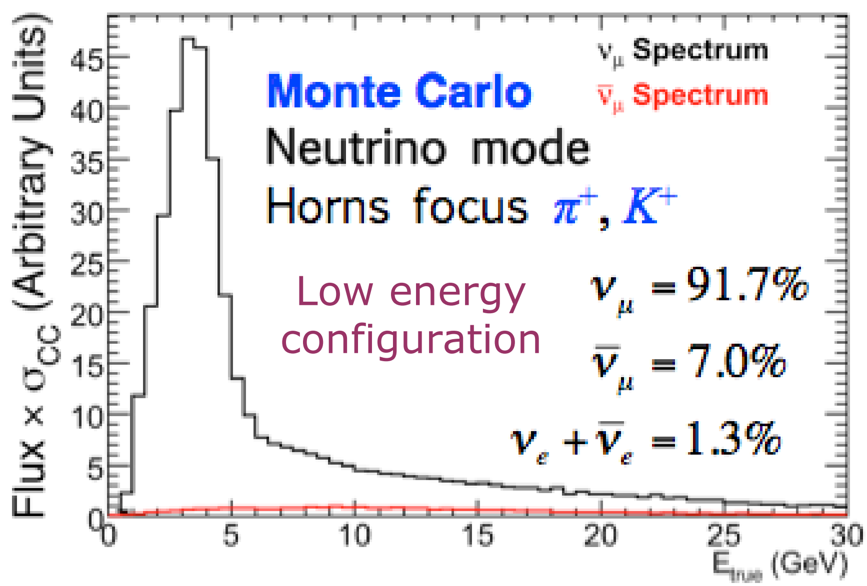

Soudan mine,
Minnesota, USA
Lake
Superior
735 km
baseline
ν_μ
Lake
Huron
Lake
Ontario
Lake
Michigan
Lake Erie
Fermi Laboratory,
Chicago, USA
The MINOS Experiment

The NuMI Accelerator Beam

'Neutrinos from the Main Injector'

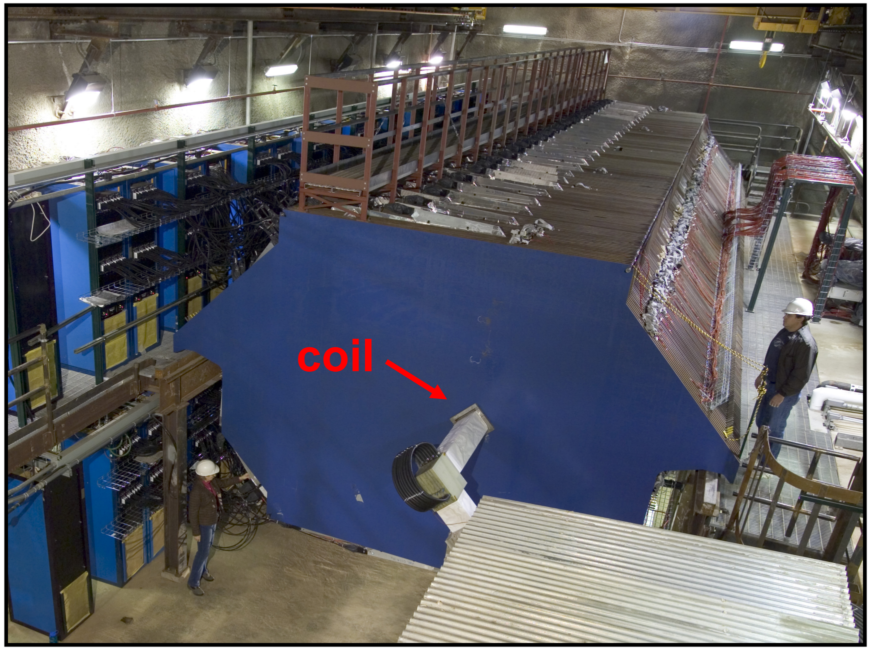


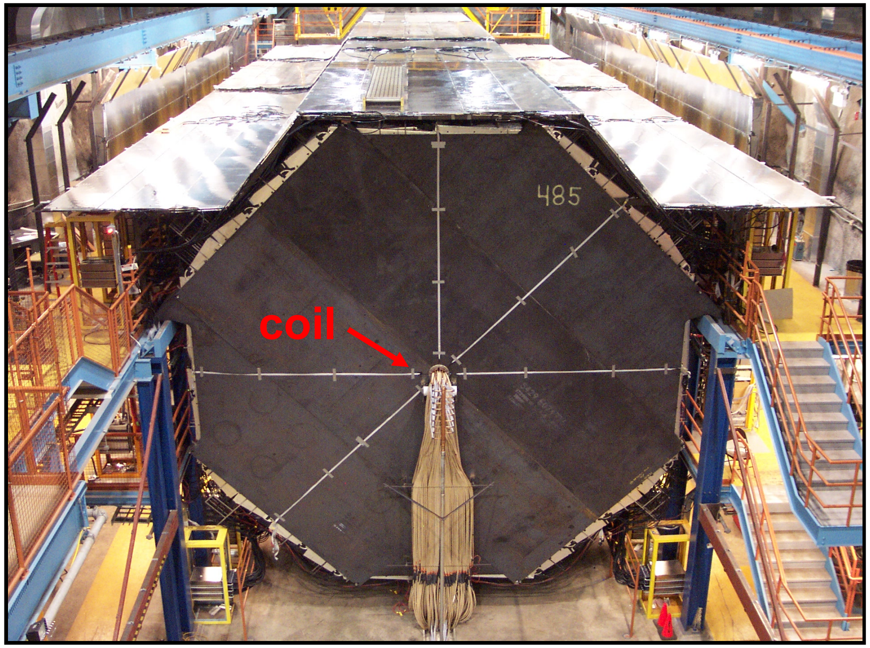
- Operating at Fermilab since 2005.
- Data in both ν_μ and anti-ν_μ modes.
- Analysis described in this talk is based on exposure of 10.56×10^{20} protons on target (POT) using "low energy" ν_μ mode.
- Beam has now begun operating in "medium-energy" ν_μ mode.



The MINOS Detectors

Near Detector	**Far Detector**
(1 kton, 1km from source)	(5.4 kton, 735 km from source)

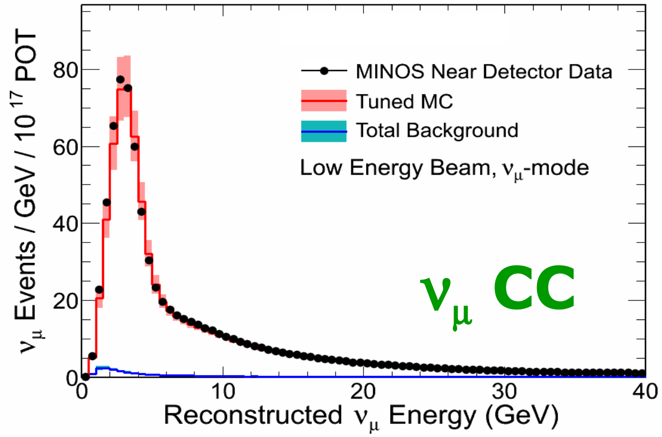




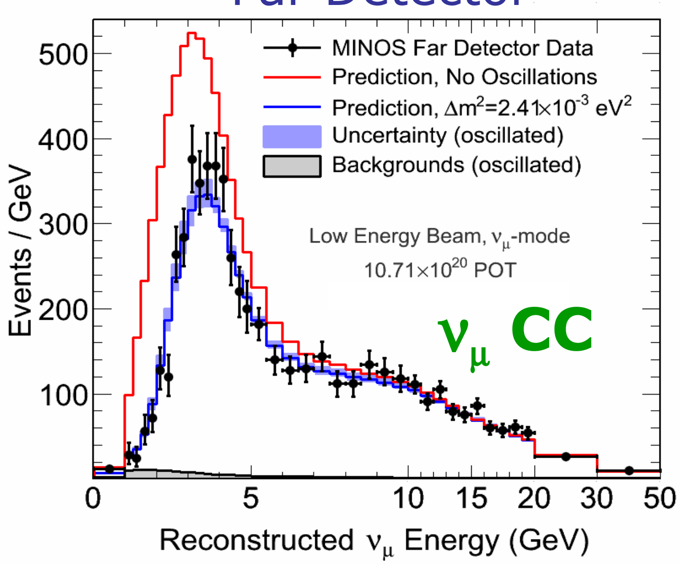
- Functionally similar detectors (steel/scintillator, magnetic field).
- Measure flavour composition and energy spectrum in each detector.
  - ◇ Can separate ν_μ CC, anti-ν_μ CC, ν_e CC, and NC interactions.
- Measure oscillations by combining information from two detectors.

Neutrino Oscillations

Near Detector



Far Detector

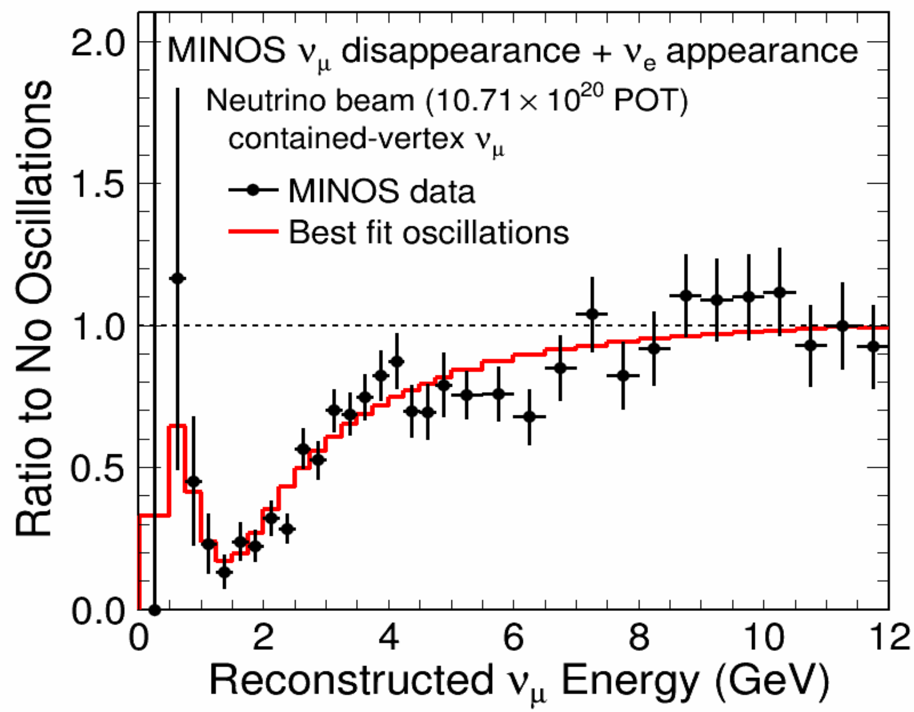


- **MINOS has published measurements of standard oscillation parameters Δm^2_{32}, θ_{23}, θ_{13}:**

  ν_μ disappearance (PRL 110, 251801, 2013)

  $\nu_\mu \rightarrow \nu_e$ appearance (PRL 110, 171801, 2013)

  Combined analysis (PRL 112, 191801, 2014)



Sterile Neutrinos

- **The MINOS disappearance data have now been analysed using 3 + 1 model of sterile neutrinos:**
  - ◇ 3 active flavours (ν_e, ν_μ, ν_τ).
  - ◇ Add 1 sterile flavour (ν_S) and 1 extra mass state (ν_4).

  $\Rightarrow$ 4 $\times$ 4 neutrino mixing matrix.

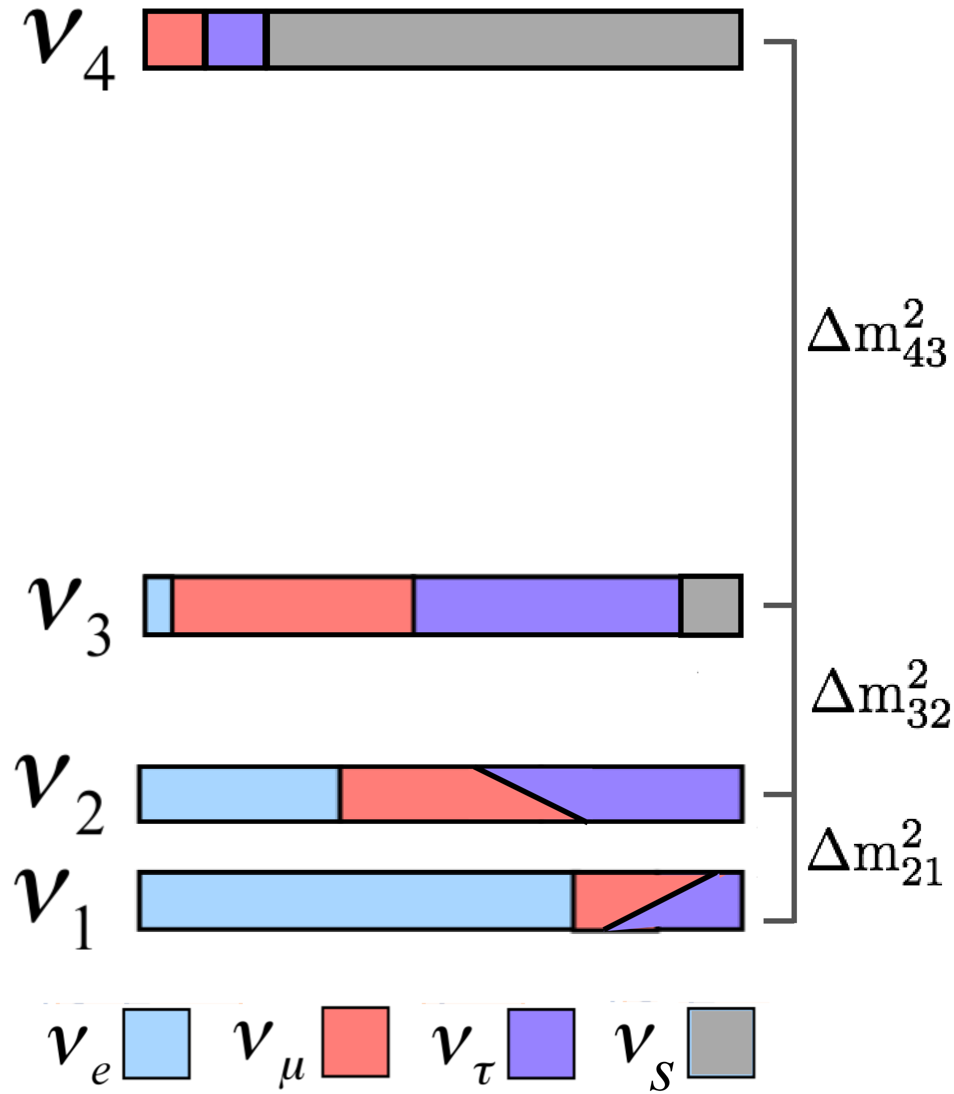
- **Neutrino mixing parameters:**

Standard 3-flavour parameters:

- ◇ Δm^2_{32}, Δm^2_{21}
- ◇ θ_{12}, θ_{23}, θ_{13}, δ_{13}

Additional 4-flavour parameters:

- ◇ Δm^2_{43}
- ◇ θ_{14}, θ_{24}, θ_{34}, δ_{14}, δ_{24}



Sterile Neutrino Signatures

- **Main sterile neutrino signatures in MINOS:**
  - ◇ ν_μ CC spectrum: search for additional oscillations due to presence of third mass splitting Δm^2_{43}.
  - ◇ NC spectrum: search for deficit caused by $\nu_\mu \rightarrow \nu_s$ disappearance, since NC interaction couples to active and not sterile flavours.
- **Mixing parameters and main constraints**: [standard, sterile]

Δm^2_{32}, θ_{23} Δm^2_{43}, θ_{24}	MINOS ν_μ disappearance (ν_μ CC spectrum)
θ_{34}	MINOS $\nu_\mu \rightarrow \nu_s$ disappearance (NC spectrum)
θ_{14}	External reactor data (Bugey)
$\sin^2\theta_{13}=0.024$ $\Delta m^2_{21}=7.59\times10^{-5}\text{eV}^2$ $\sin^2\theta_{12}=0.32$	Fix parameters (external data)
δ_{13}, δ_{14}, δ_{24} = 0	Fix to zero (little sensitivity)

Sterile Neutrino Signatures

- **Sterile neutrino oscillations can occur in both MINOS detectors.**

◇ **Small Δm^2_{43}** ($>\Delta m^2_{32}$) (10^{-3} – 10^{-1} eV^2)

Far Detector: additional oscillations above 3-flavour oscillation maximum

Near Detector: no effect

◇ **Medium Δm^2_{43}** (10^{-1} – 1 eV^2)

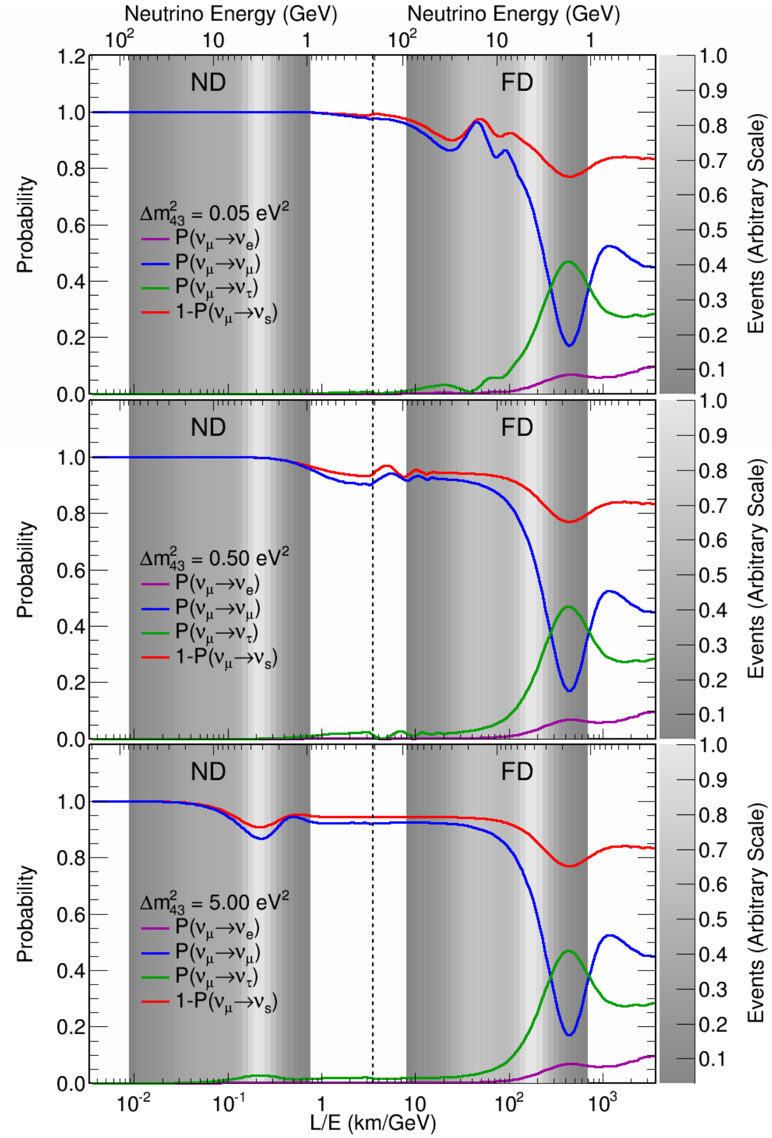
Far Detector: oscillations become rapid and average out, causing a constant depletion (‘counting experiment’).

Near Detector: no effect

◇ **Large Δm^2_{43}** (1 – 10^2 eV^2)

Far Detector: constant depletion.

Near Detector: oscillations.



Far Detector CC and NC Spectra

- **Select CC and NC events based on topology.**
- **Far Detector neutrinos**:
  - ◇ 2721 ν_μ CC events
  - ◇ 1221 NC events

(Right plots show comparisons with three-flavour predictions).

- **Focus on NC event rates**:

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

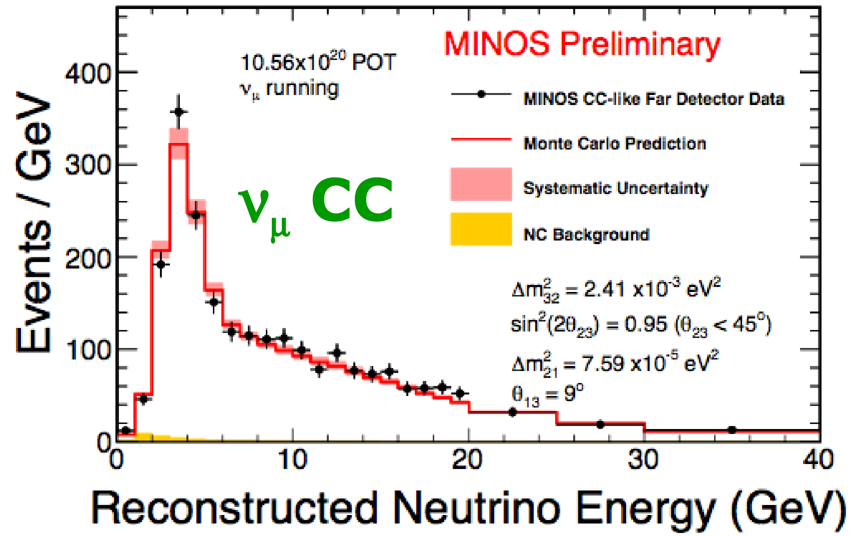
Predicted CC background from all flavors

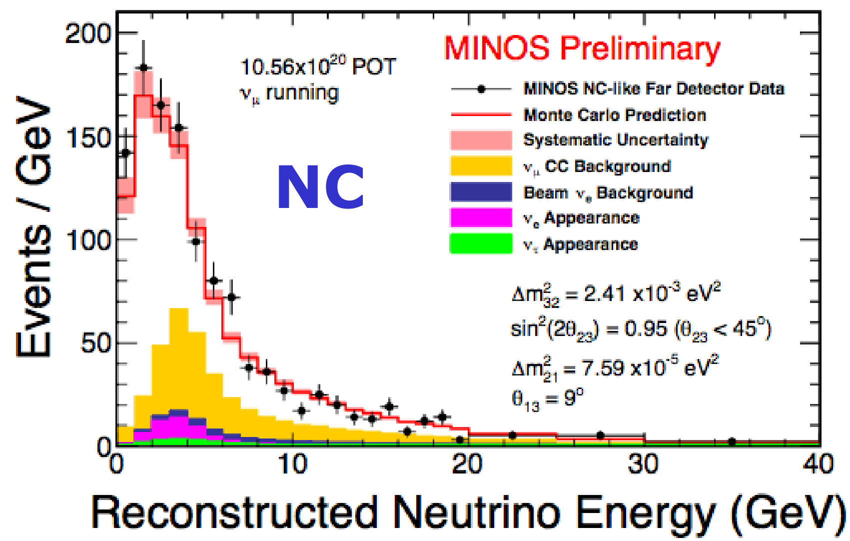
Predicted NC interaction signal

0-200 GeV: $R = 1.049 \pm 0.076$

0-3 GeV: $R = 1.093 \pm 0.097$

- **No evidence for NC deficit.**





Oscillation Analysis

- **Fit the observed FD/ND ratios.**

Data samples:

◇ Use both CC and NC spectra in this analysis [shown right].

Oscillation parameters:

◇ Fit $|\Delta m^2_{43}|$, $|\Delta m^2_{32}|$, θ_{23}, θ_{24}, θ_{34}. (fix all other parameters).

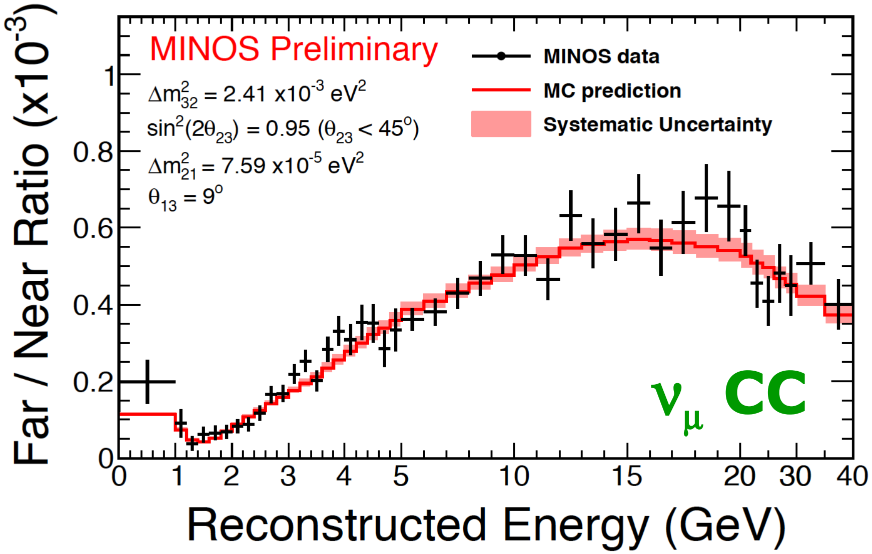
Systematic parameters:

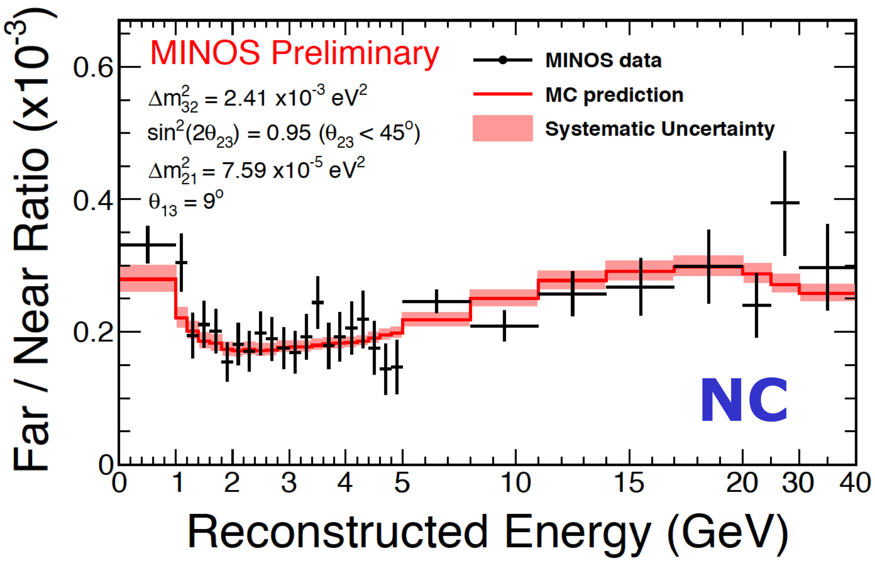
◇ Incorporate systematics into analysis via covariance matrix.

◇ Apply an additional constraint on the overall ND event rate.

Confidence limits:

◇ Use Feldman-Cousins procedure to correct likelihood surfaces.





Systematic Uncertainties

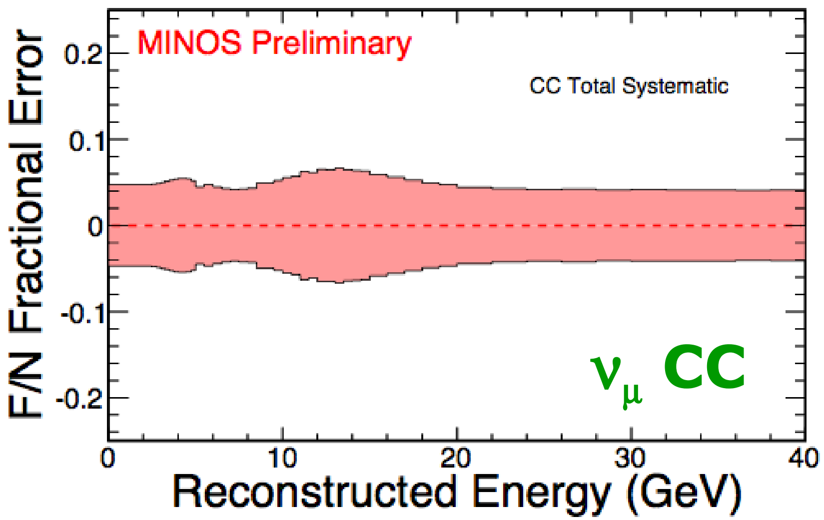
- **26 systematic uncertainties:**
  - ◇ Hadron production, beam optics, cross-sections, detector effects.
- **Incorporate into χ^2 function:**

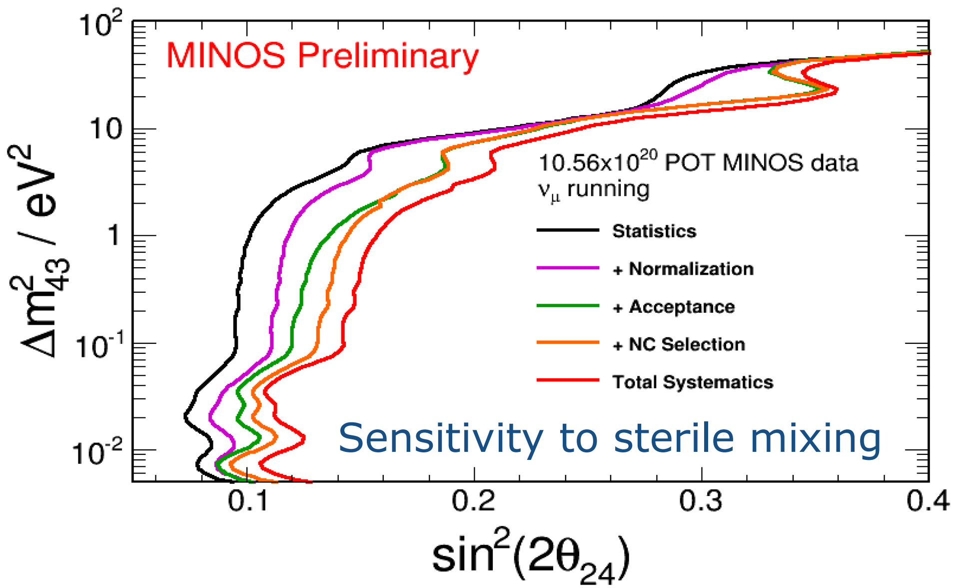
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T[V^{-1}]_{ij}(o_j - e_j)$$

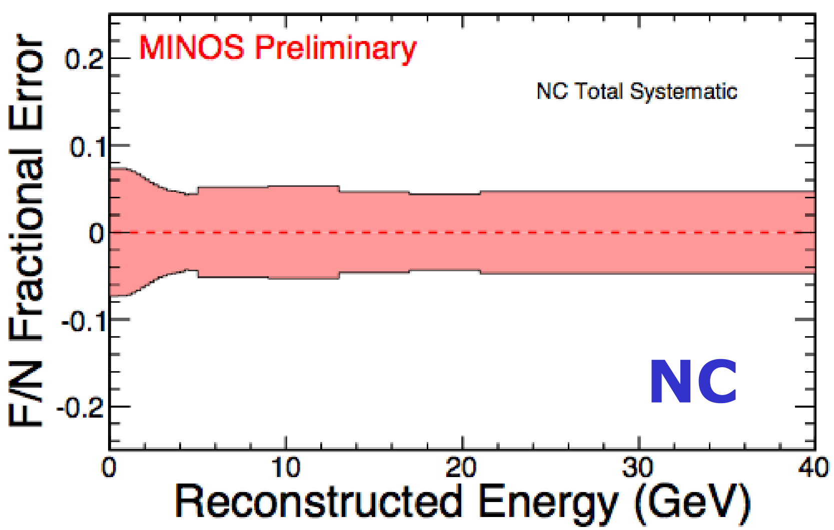
o_i : Observed events in bin i

e_i : Predicted events in bin i

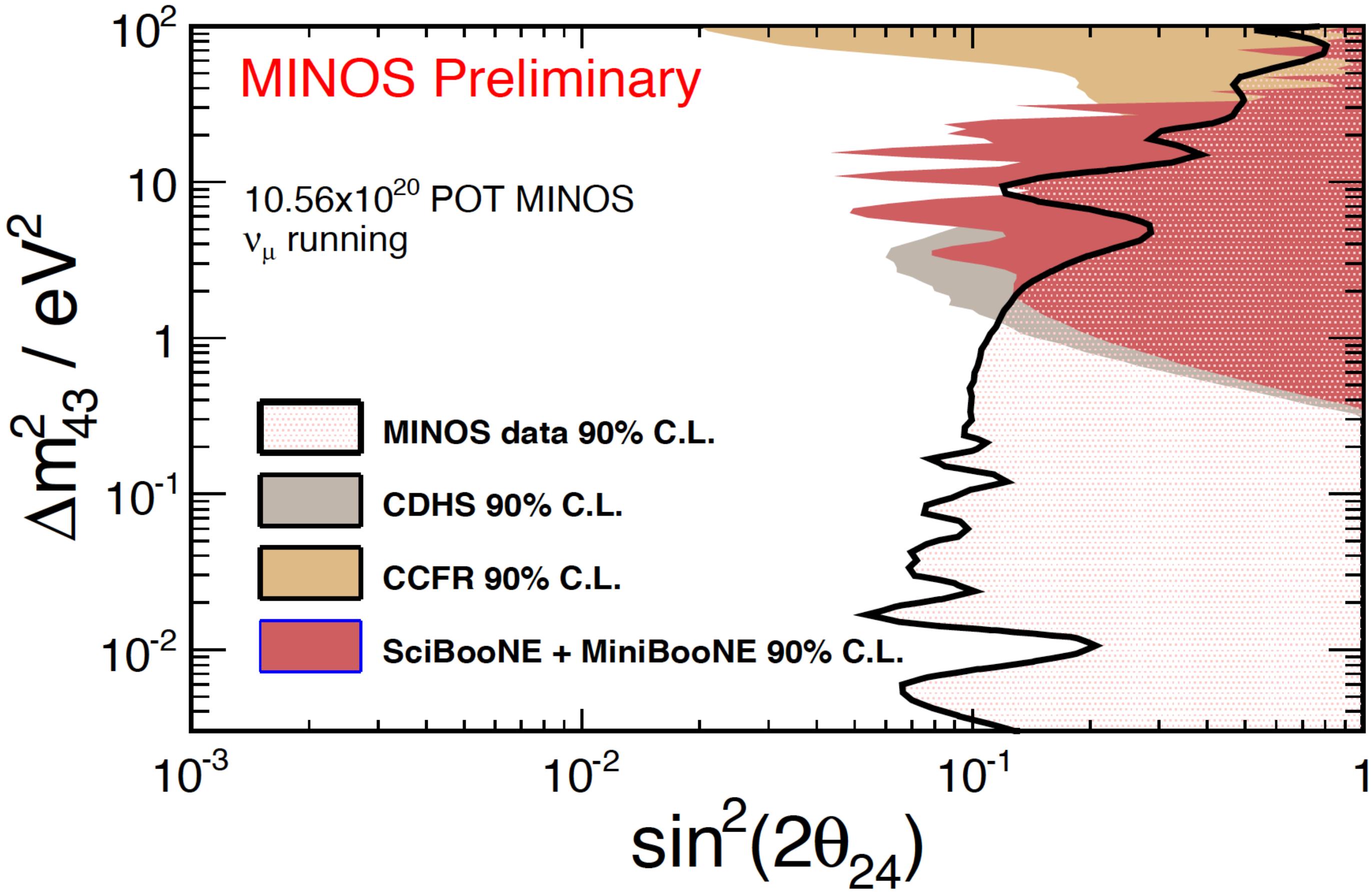
V : Covariance matrix







MINOS ν_μ Disappearance Limits



- MINOS confidence limits on Δm^2_{43} cover four orders of magnitude.
- Strongest constraint on $\nu_\mu \rightarrow \nu_s$ disappearance for $\Delta m^2_{43} < 1$ eV^2.

Currently analysing 3.4×10^{20} POT data collected in antineutrino mode.

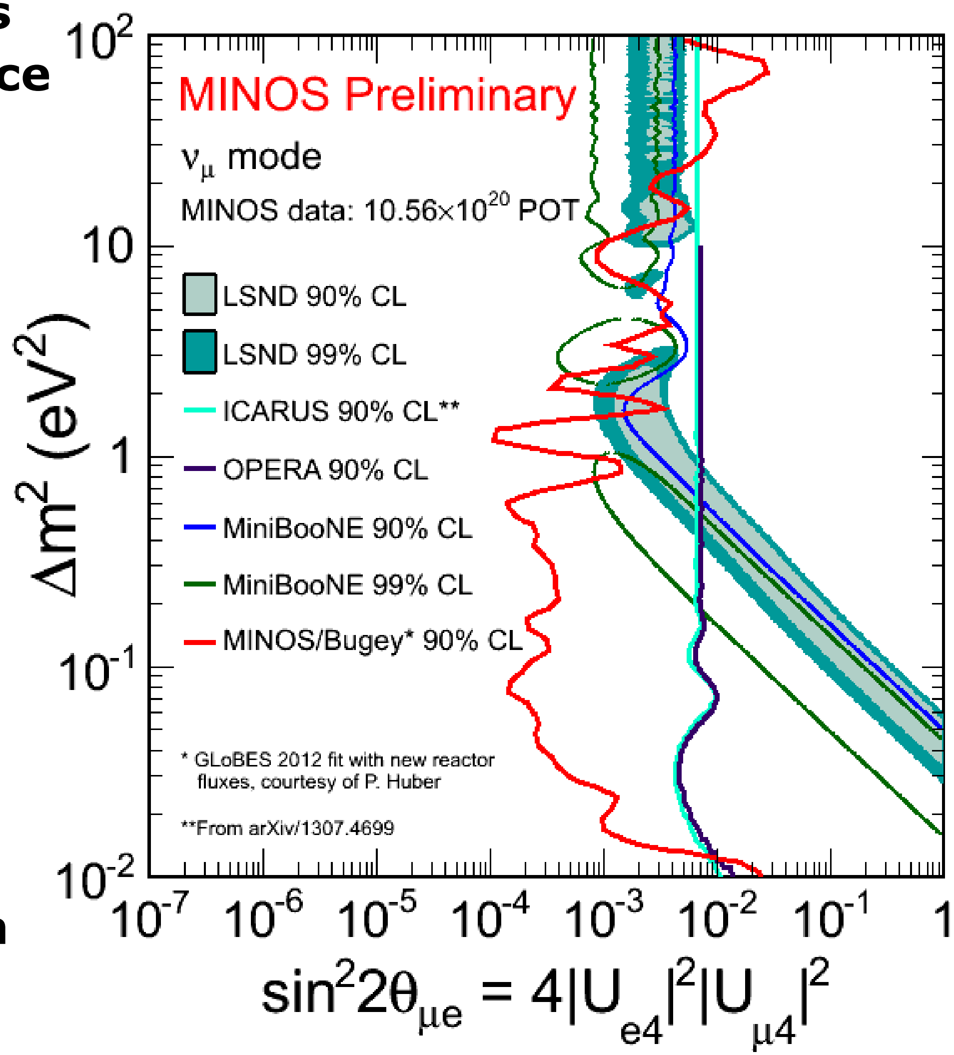
Comparison with ν_e Appearance

- **Combine ν_μ disappearance results from MINOS with ν_e disappearance from Bugey reactor experiment.**
  - ◇ MINOS: 90% C.L. on θ_{24}
  - ◇ Bugey: 90% C.L. on θ_{14}*
  - ◇ Construct combined limit on $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$.

* Bugey limits computed by Patrick Huber using GLoBES 2012 and new reactor fluxes.

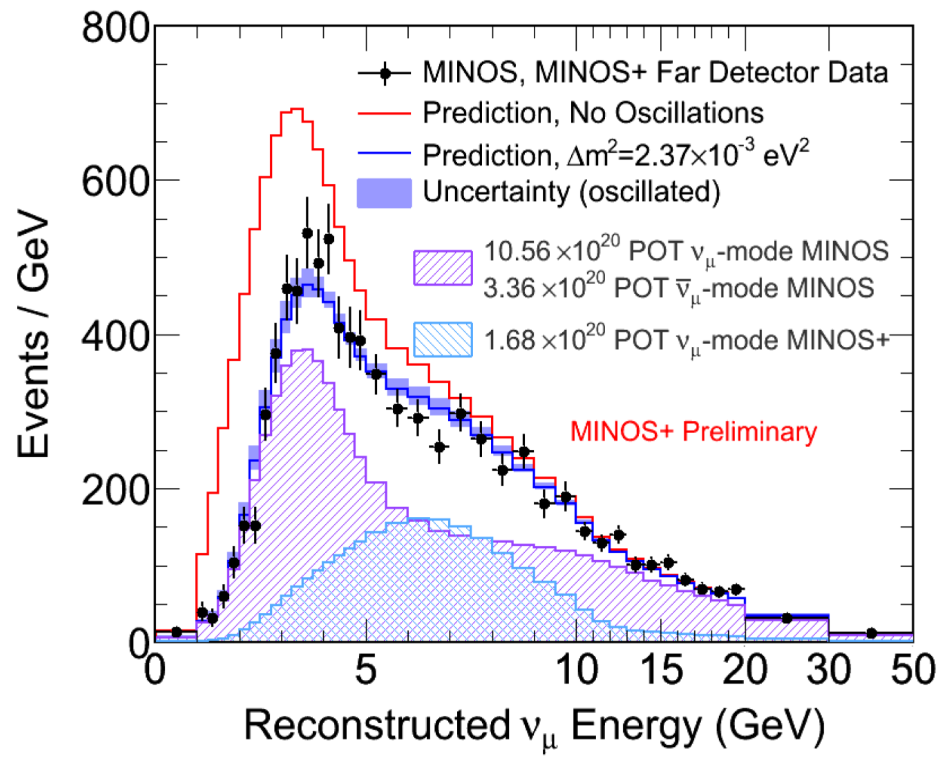
- **<u>Right</u>: comparison of combined limits from MINOS & Bugey with appearance results from MiniBooNE (neutrino-mode), LSND, ICARUS and OPERA.**

- **The MINOS data increase tension between sterile neutrino results for $\Delta m^2_{43} < 1$ eV².**



First Results from MINOS+

- **The MINOS+ experiment began operating in September 2013**
  - ◇ Operate the MINOS detectors in the upgraded NuMI beam.
  - ◇ Higher-energy beam spectrum, with increased beam power.
- **Wide-band spectrum enables precision measurements of oscillation probability curves.**
  - ◇ Measure standard oscillations with increased precision.
  - ◇ Continue searching for new physics e.g. sterile neutrinos.
- **First results released last month, based on 1.7×10^{20} POT exposure.**
  - ◇ Observe 1085 ν_μ CC events.

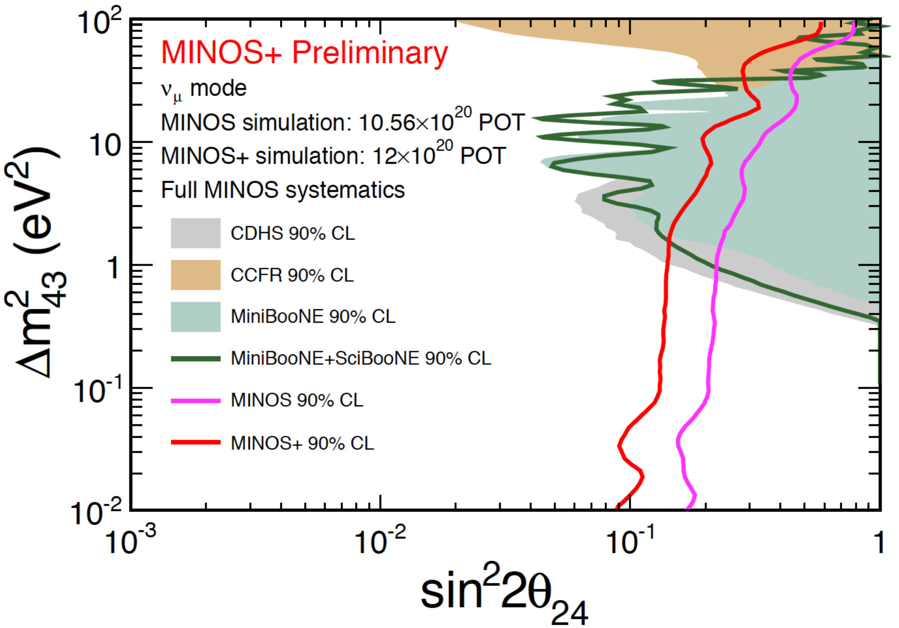


Above: combined spectrum from MINOS & MINOS+.

Enables precision measurement of ν_μ survival probability curve.

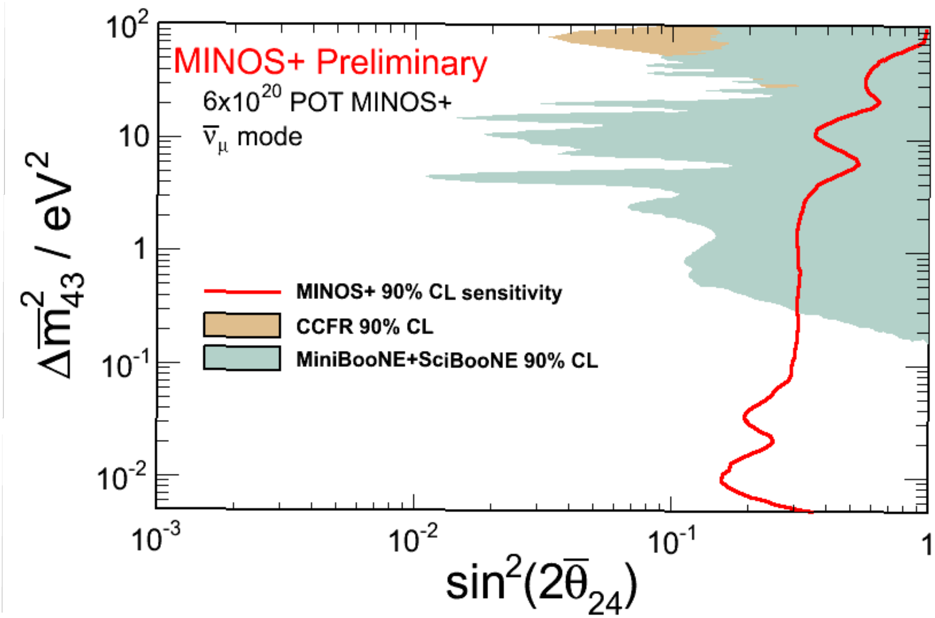
Future Prospects for MINOS+

Neutrino mode



Projected MINOS+ sensitivity by 2016 compared to short-baseline experiments.

Antineutrino mode



Projected MINOS+ sensitivity from 1 year of antineutrino running.

- Also investigating MINOS+ sensitivity to anomalous ν_e appearance above energy of $\nu_\mu \rightarrow \nu_e$ maximum at 735 km.

Summary

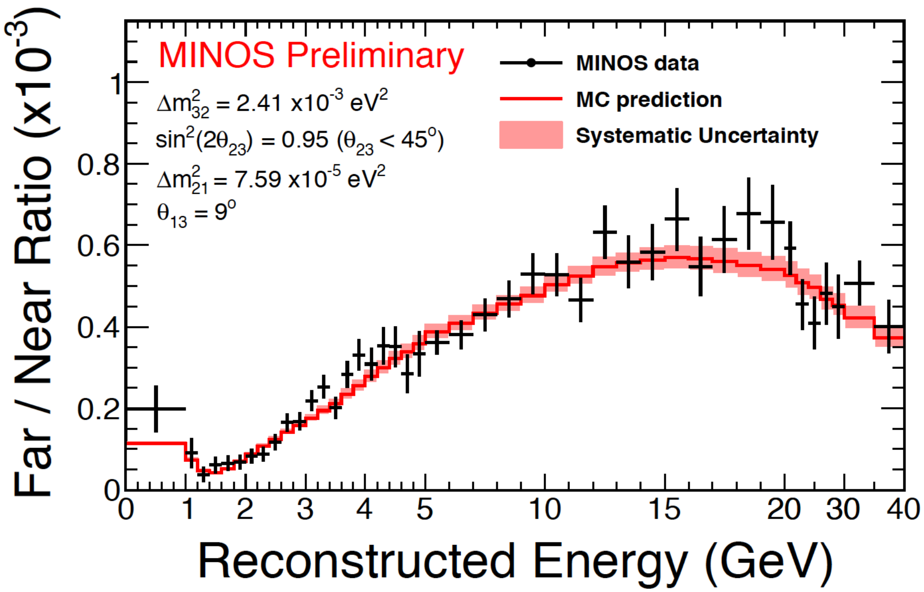
- **MINOS long-baseline experiment has completed a search for sterile neutrinos by measuring ν_μ disappearance.**
  - ◇ No evidence for sterile neutrino oscillations in ν_μ mode.
  - ◇ Confidence limits span four orders of magnitude in Δm^2_{43}. Provides strongest constraints on $\nu_\mu \rightarrow \nu_s$ disappearance for $\Delta m^2_{43} < 1$ eV^2.
  - ◇ Currently analysing MINOS data collected in anti-ν_μ mode.
- **Combination of MINOS and Bugey reactor data yields strong confidence limits on sterile neutrino mixing.**
  - ◇ Increases tension in sterile neutrino data for $\Delta m^2_{43} < 1$ eV^2.
- **The MINOS+ experiment offers improved sensitivity to sterile neutrino mixing.**
  - ◇ MINOS+ has released its first spectrum and sensitivities.
  - ◇ As well as providing high-statistics ν_μ disappearance data, also investigating sensitivity to anomalous ν_e appearance.

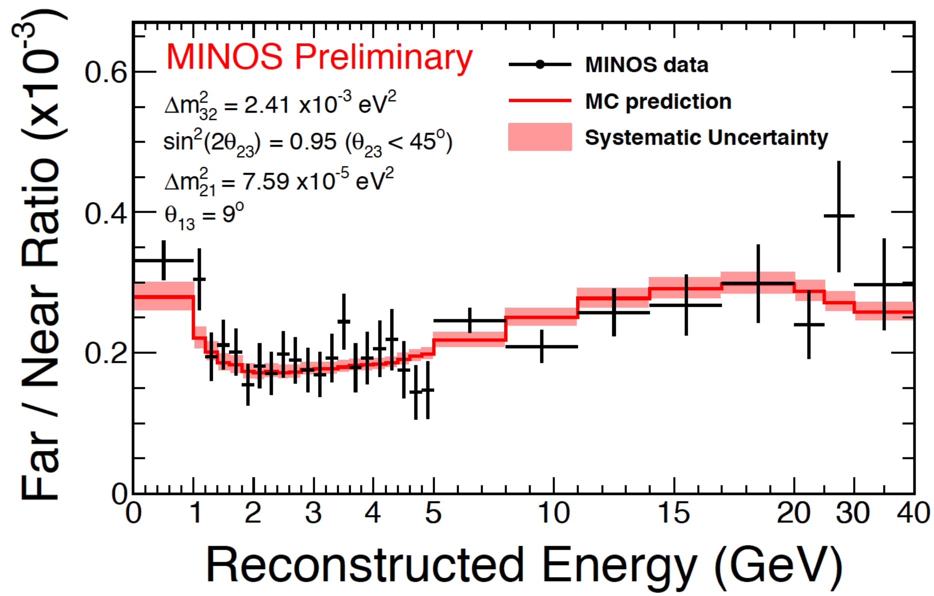
Backup

Oscillation Analysis

Far/Near Ratio

- **The oscillation analysis is based on the observed Far/Near ratio, binned as a function of reconstructed energy:**





(Calculate separate F/N ratios for CC and NC events).

- **Advantages of fitting F/N ratio:**
  - ◇ Enables oscillations from either detector to be incorporated into fit.
  - ◇ Exploits approximate cancellation of systematic uncertainties in ratio.

Oscillation Fit

- **The oscillation fit uses the following chi-squared statistic:**

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

o_i : Observed events in bin i

e_i : Predicted events in bin i

V : Covariance matrix

  - ◇ The covariance matrix V combines both the statistical and systematic uncertainties [see next slide].
  - ◇ An additional penalty term, $(O_{ND}-E_{ND})^2/\sigma_{ND}^2$, is appended to the χ^2 function, where O_{ND} (E_{ND}) is the observed (predicted) total ND rate, and σ_{ND} is the uncertainty on E_{ND} (σ_{ND}=50%).
  - ◇ The binning scheme is chosen such that E_{ND} > 15 events in every bin (for the case of three-flavour oscillations).

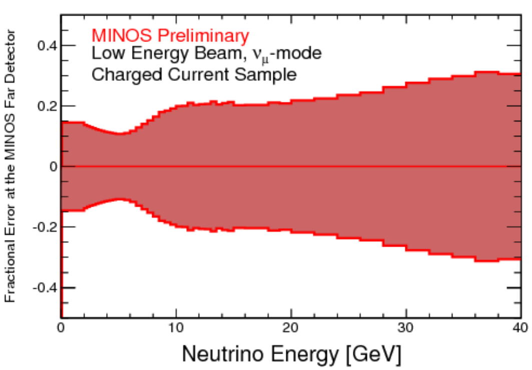
- **This chi-squared statistic is minimised as a function of the five oscillation parameters Δm^2_{43}, Δm^2_{32}, θ_{23}, θ_{24}, θ_{34}.**

Covariance Matrix

- **Covariance matrix is given by:** $$\mathbf{V} = \underbrace{\begin{pmatrix} \sigma^2_{MC_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma^2_{MC_N} \end{pmatrix}}_{\text{stats}} + \underbrace{\sum_{i=1}^{N} \mathbf{M}_i}_{\text{systematics}}$$

  - ◇ The two terms in the sum represent the total statistical and systematic uncertainty in the predicted F/N ratio.
  - ◇ The second term is generated by calculating the bin-to-bin covariances for each systematic effect, and then summing over all the systematics.
  - ◇ The bin-to-bin covariances are calculated using uncertainty envelopes in the F/N ratio, which are obtained by varying the Near and Far simulations according to the $\pm 1\sigma$ uncertainties.

Far Detector Uncertainty



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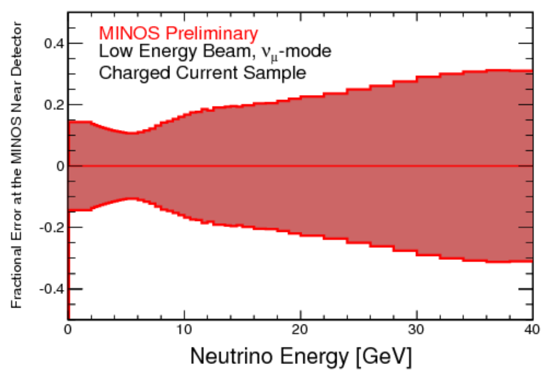
Near Detector Uncertainty



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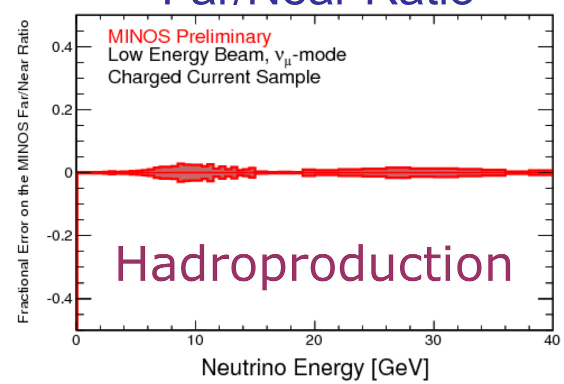
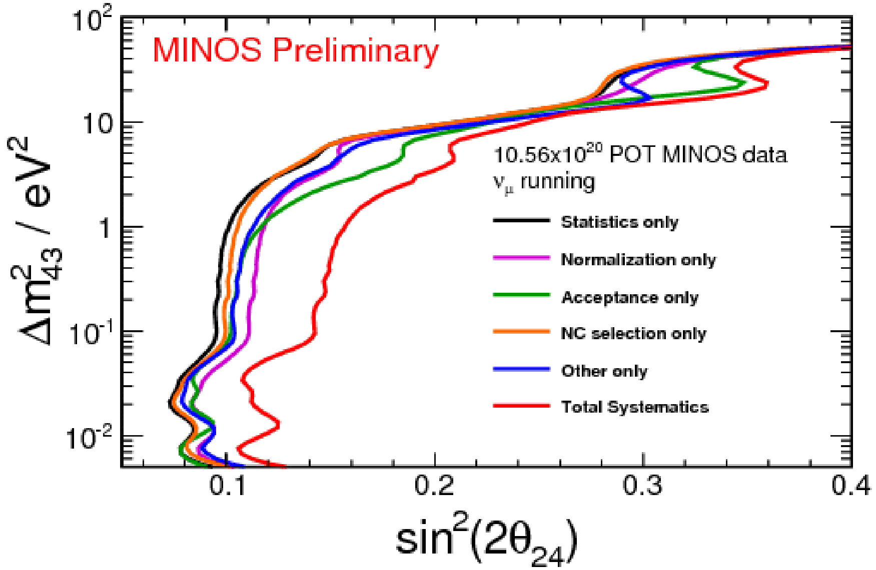
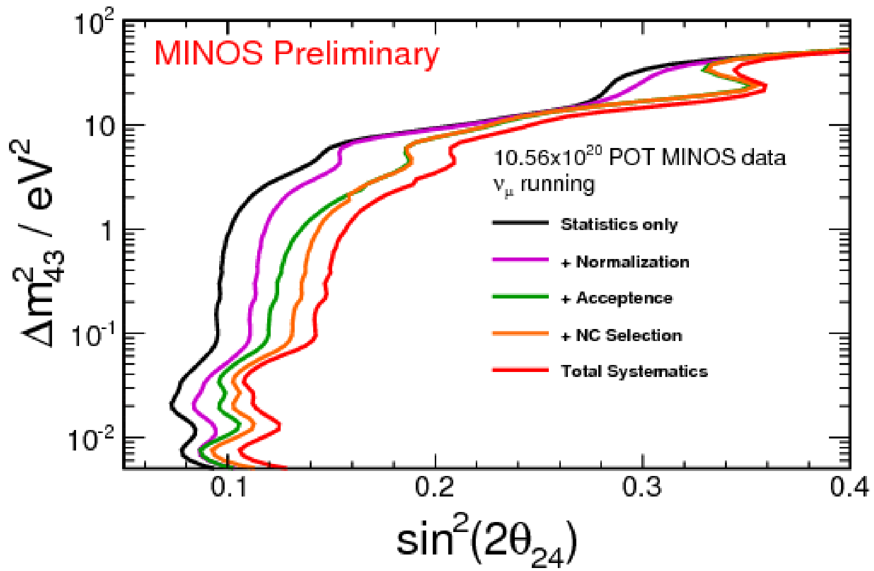
Far/Near Ratio



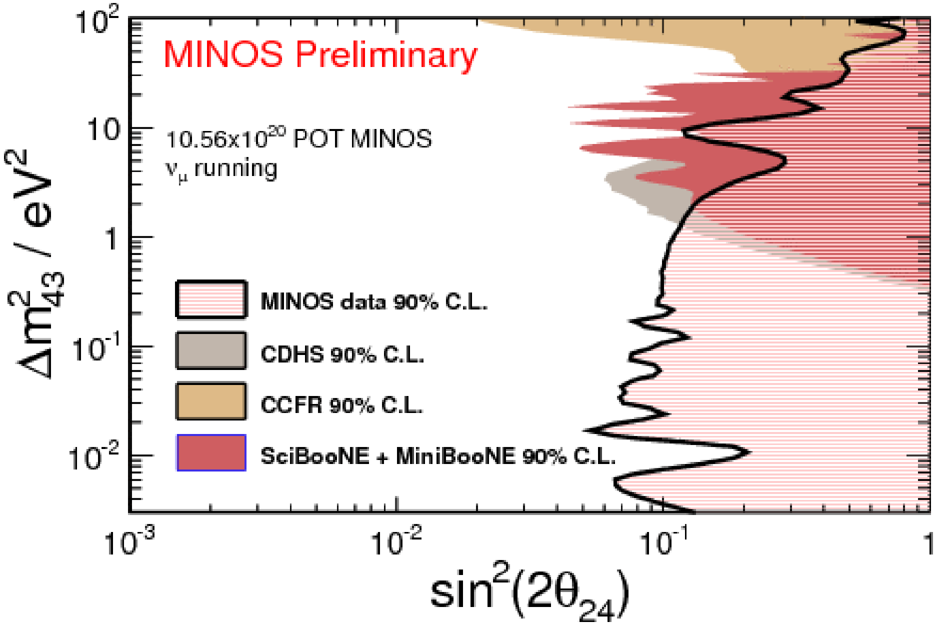
Systematics

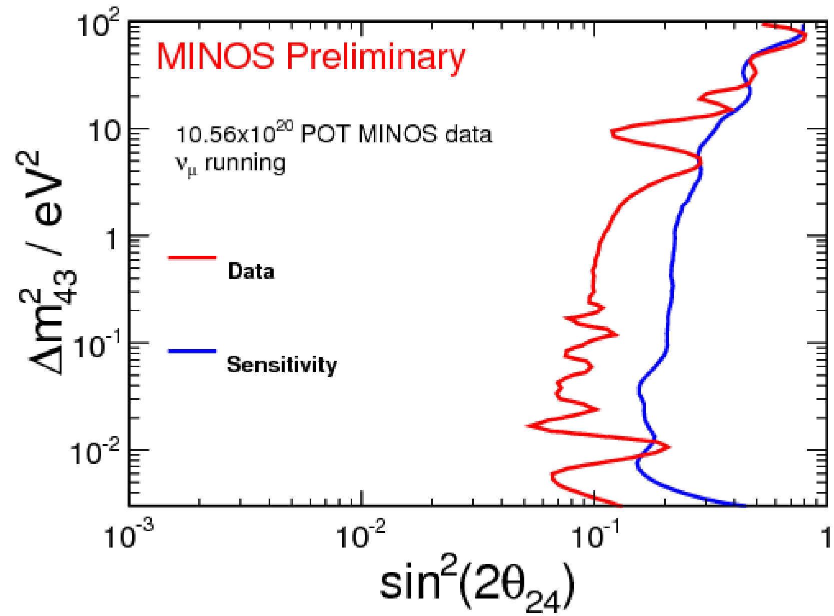
- **Beam Systematics**:
  - ◇ Hadroproduction
  - ◇ Beam optics
- **Detector Effects**:
  - ◇ Fiducial Volumes
  - ◇ Acceptances
  - ◇ Event Selection
  - ◇ Energy Scales
  - ◇ Backgrounds
- **Cross-sections**:
  - ◇ Overall cross-section
  - ◇ Resonance-DIS transition
  - ◇ Resonance axial mass
  - ◇ CC QE axial mass

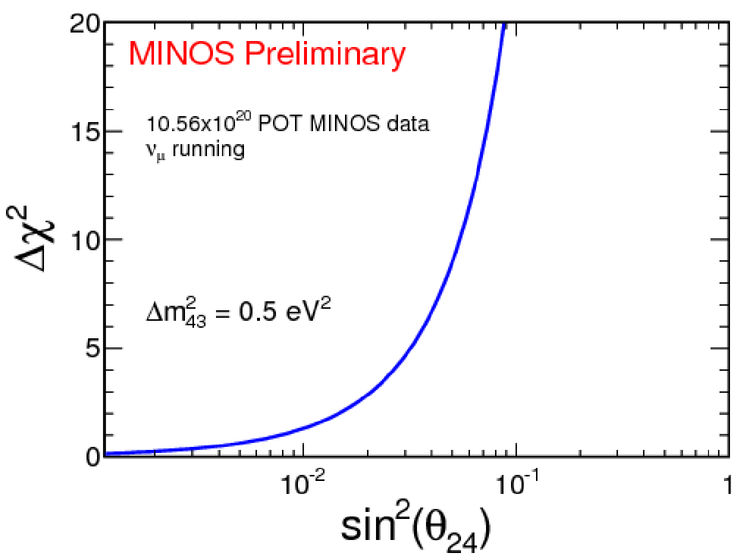


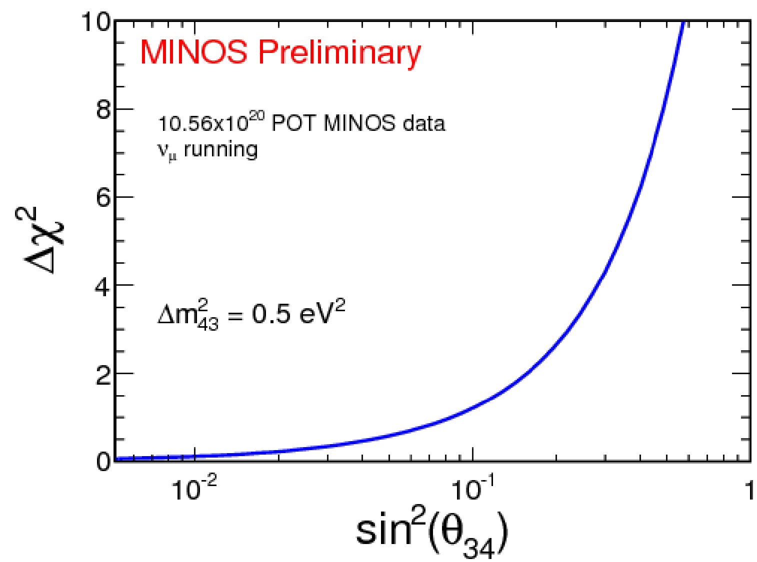


ν_μ Disappearance Results



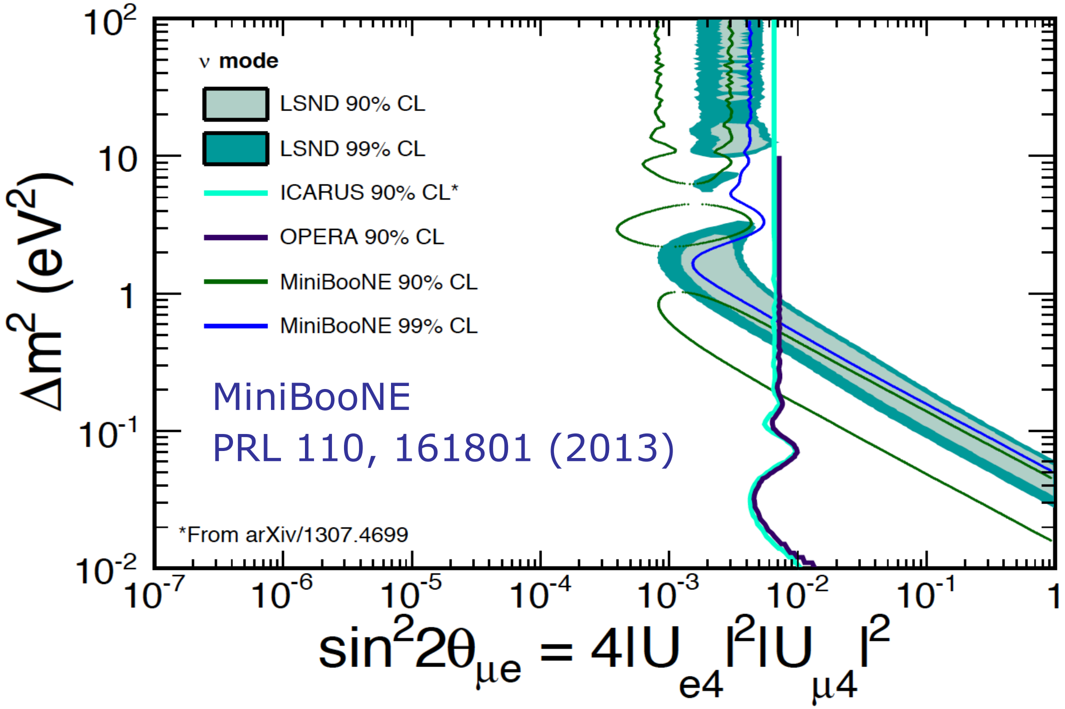






Comparison with ν_e Appearance

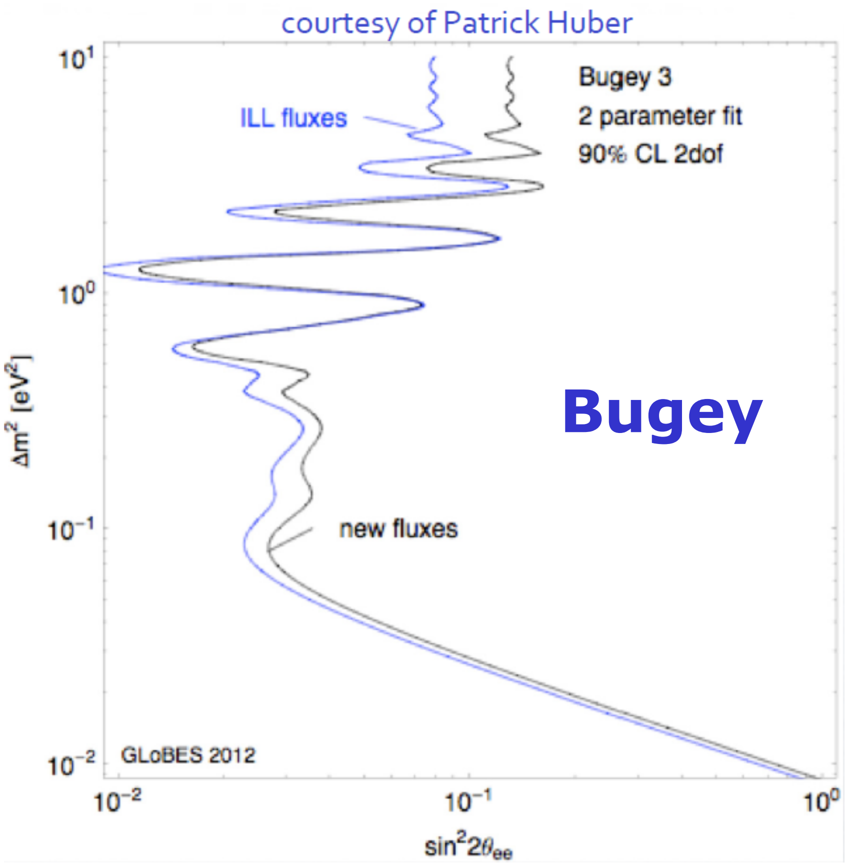
- By applying unitarity constraints, can combine experimental results on ν_μ disappearance (MINOS) and ν_e disappearance (reactor data) to place constraints on MiniBooNE and LSND appearance signal.



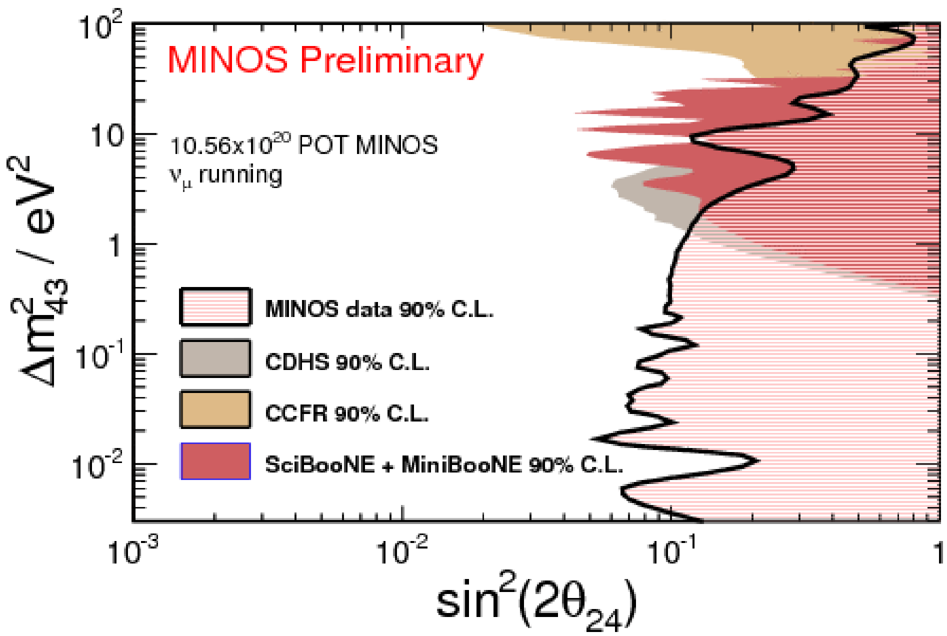
$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \quad \begin{cases} |U_{e4}|^2 = \sin^2\theta_{14} \\ |U_{\mu 4}|^2 = \cos^2\theta_{14}\sin^2\theta_{24} \end{cases}$$

$$\Rightarrow \sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$$

Combination with Bugey



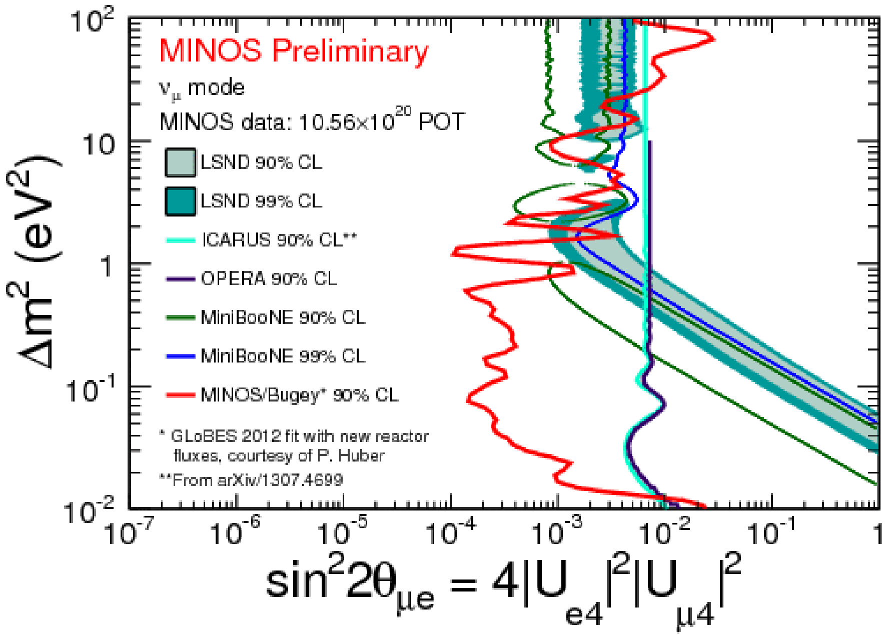
Bugey likelihood surface computed using GLoBES 2012 and new reactor fluxes



Δm^2 vs **$\sin^2 2\theta_{14}$**

Δm^2 vs **$\sin^2 2\theta_{24}$**

Combination with Bugey



- The Bugey χ^2 surface is a function of Δm^2 and $\sin^2 2\theta_{14}$.
- The MINOS χ^2 surface is a function of Δm^2 and $\sin^2 2\theta_{24}$.
  (corrected using FC procedure).
- Can calculate a combined surface in Δm^2 vs $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$.

Method:

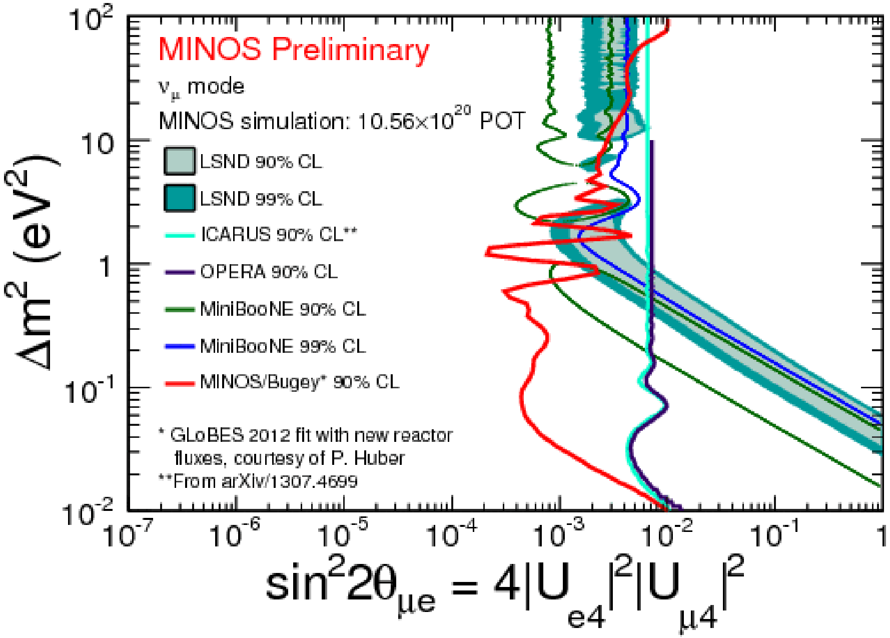
◇ For a given Δm^2, consider all combinations of MINOS and Bugey points and calculate $\sin^2 2\theta_{\mu e}$ and summed χ^2 for each combination.

◇ Each value of $\sin^2 2\theta_{\mu e}$ can occur at different $\sin^2 2\theta_{14}$ and $\sin^2 2\theta_{24}$, so the summed χ^2 values are not a unique function of $\sin^2 2\theta_{\mu e}$.

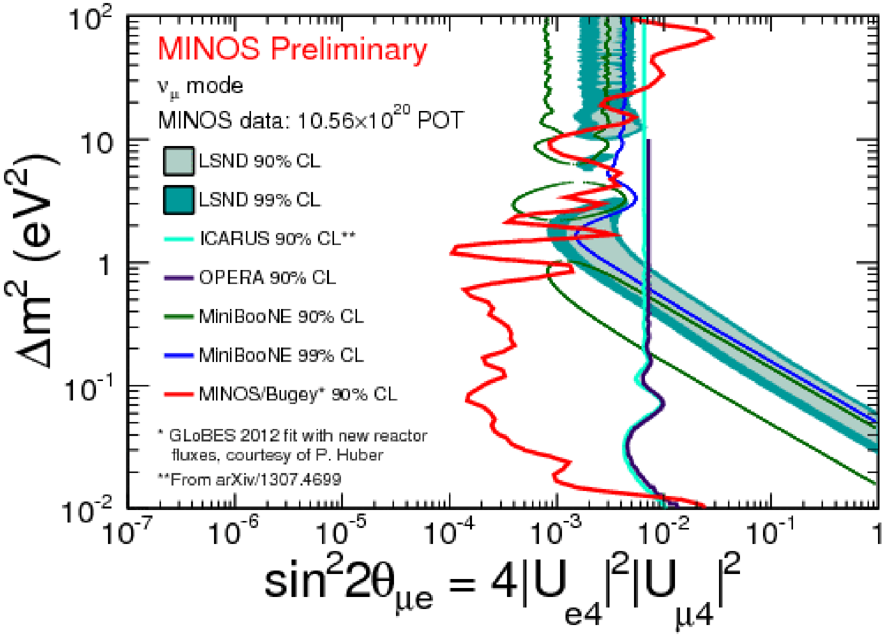
◇ Combined limit is taken to be the largest value of $\sin^2 2\theta_{\mu e}$ within the specified confidence interval (e.g. $\Delta\chi^2 < 4.61$).

Comparison with ν_e Appearance

Monte Carlo Simulation

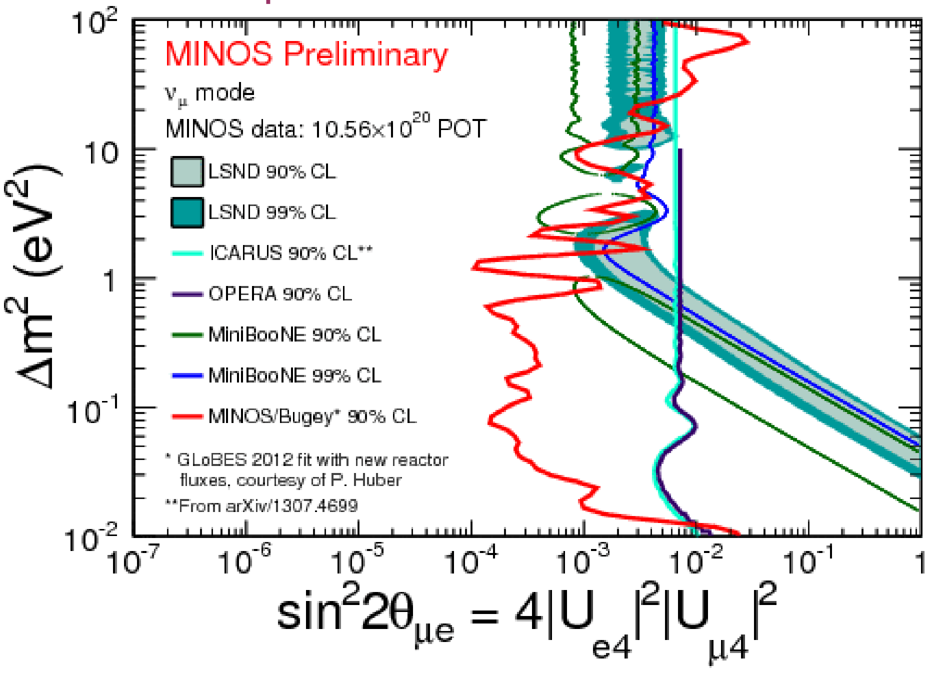


Observed Data

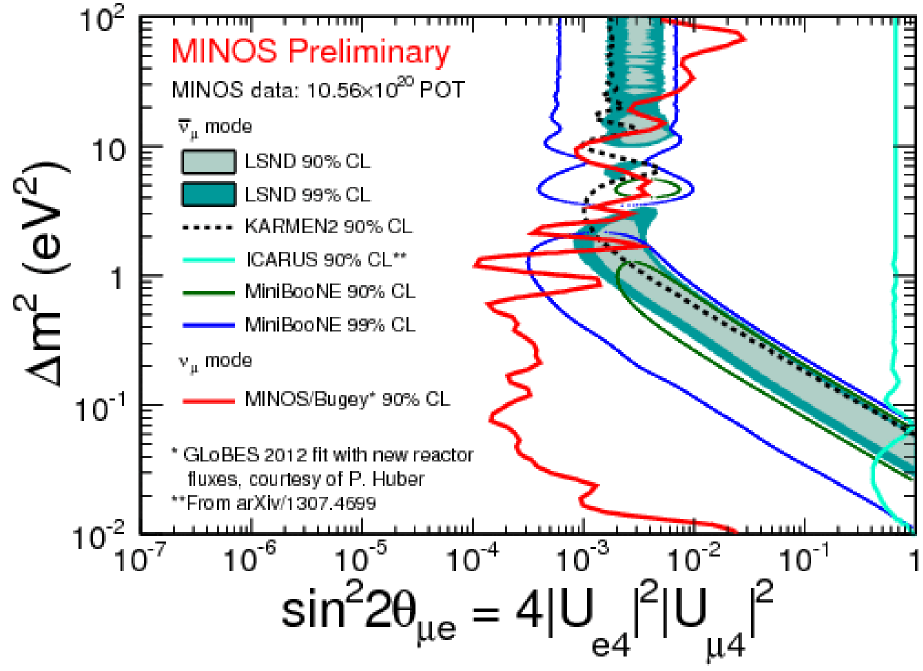


Comparison with ν_e Appearance

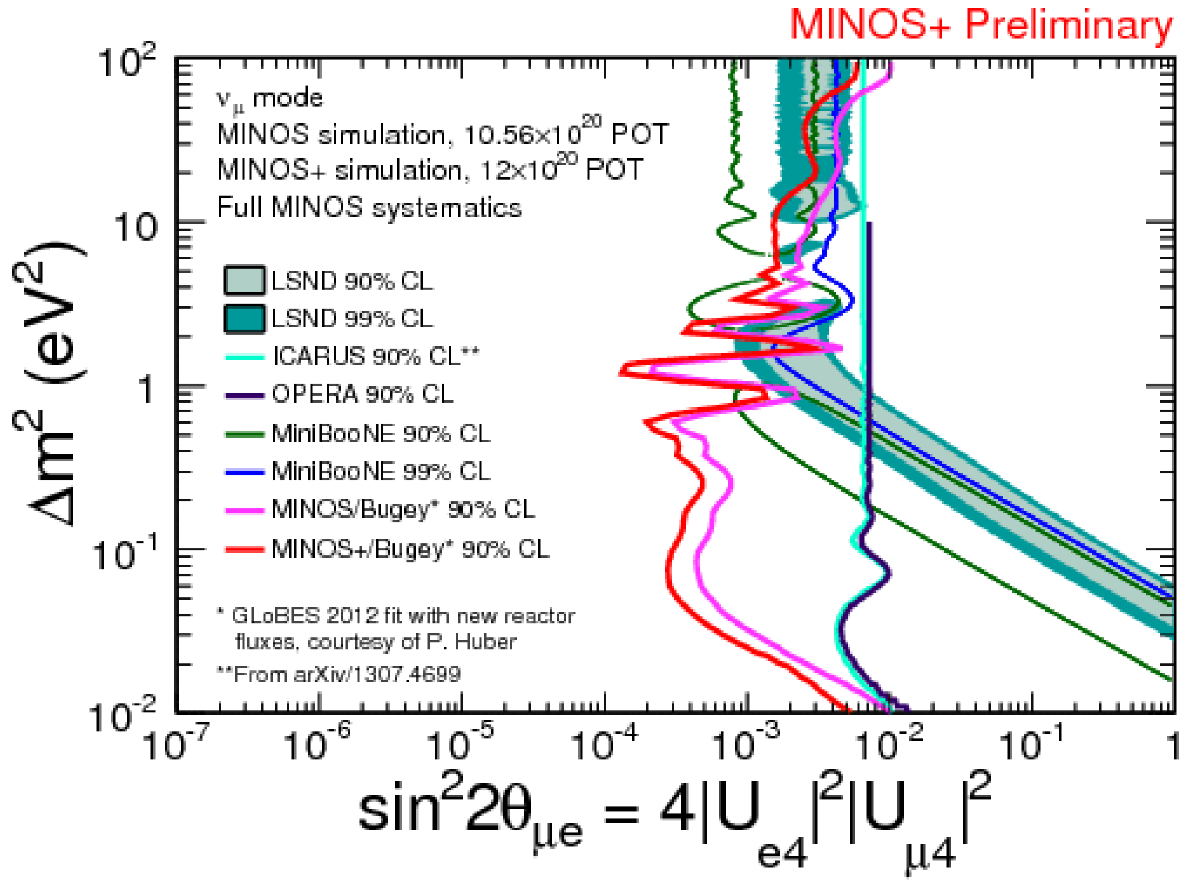
Comparison with neutrino results



Comparison with antineutrino results



Future Prospects: MINOS+

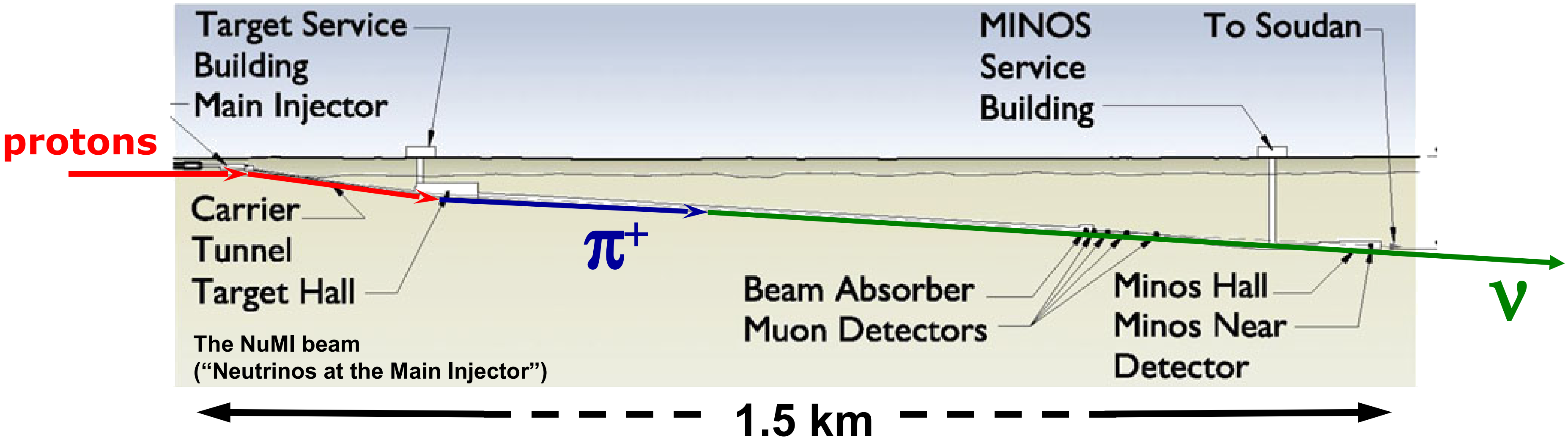


<u>Potential improvements</u>:

Improved systematic uncertainties, improved fitting techniques, inclusion of reactor data from other experiments.

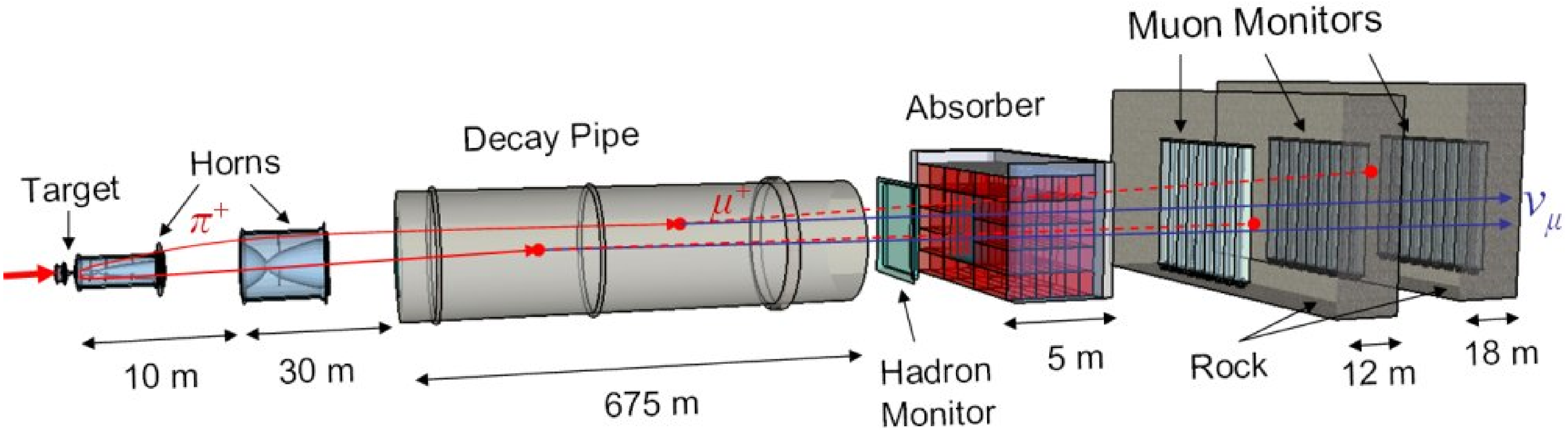
Production and Detection of Neutrinos

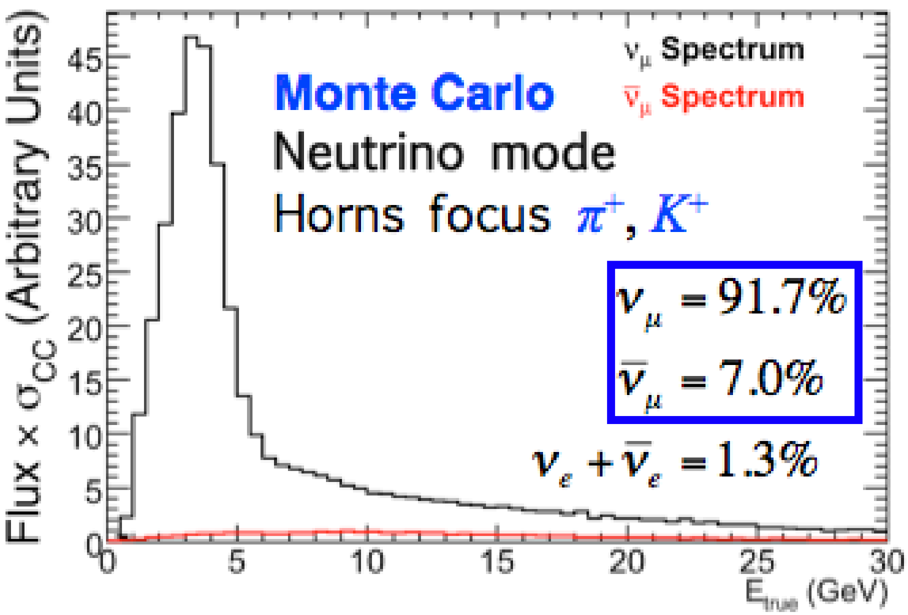
The NuMI Beam

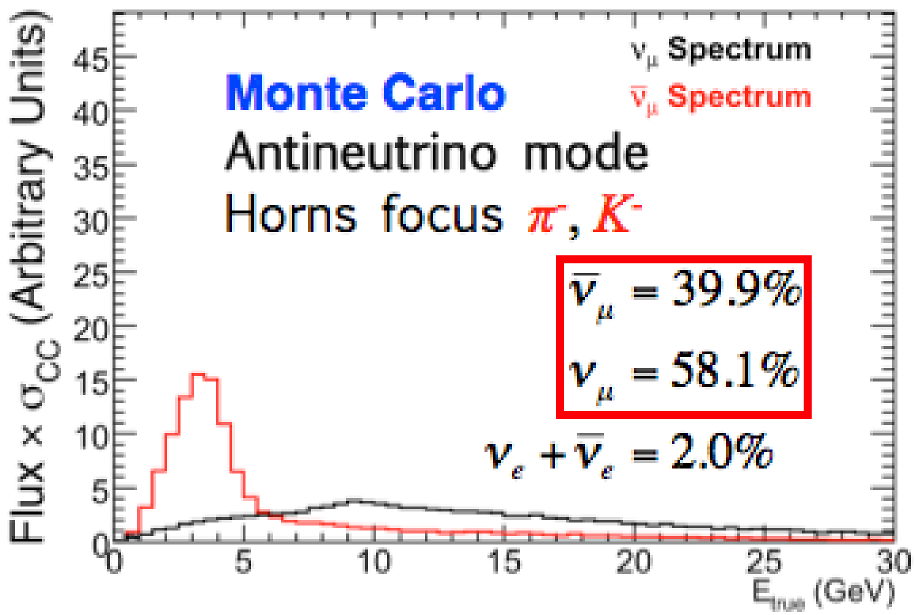


- **Direct protons onto 50g segmented graphite target.**
  - produces an intense flux of secondary pions and kaons.
- **Focus π+/κ+ into tight beam using magnetic focusing.**
  - requires two 200kA parabolic electromagnets (act as lenses).
- **Direct π^+/κ^+ into 675m evacuated decay pipe.**
  - need to point the beam 3 degrees into earth to reach Soudan!
  - π^+/κ^+ decay in pipe to produce μ^+/ν_μ (and ~1% e^+/ν_e).
- **Absorb μ in 200m rock to leave pure neutrino beam.**
  - produce ~1 neutrino for each proton on target.

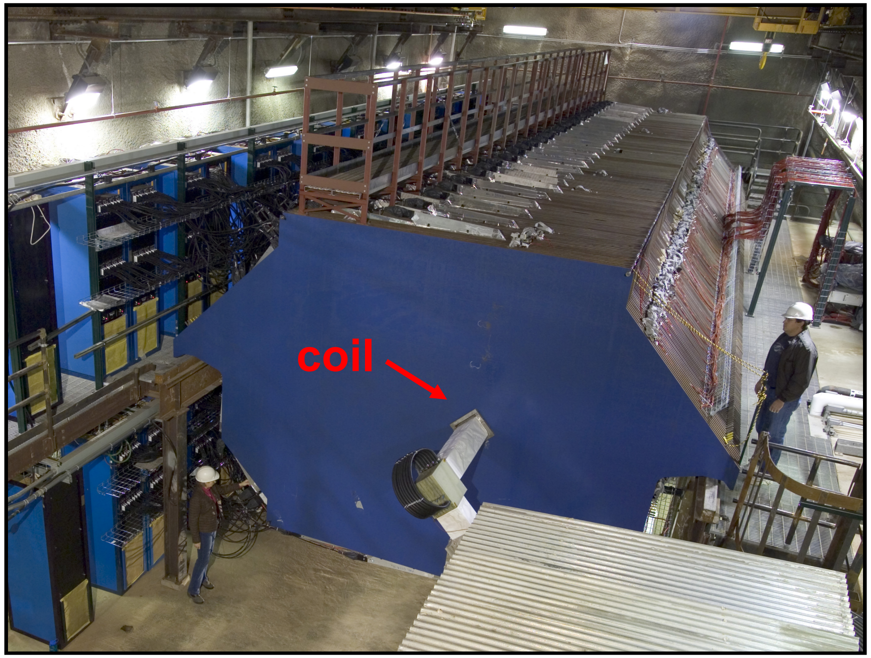
The NuMI Beam

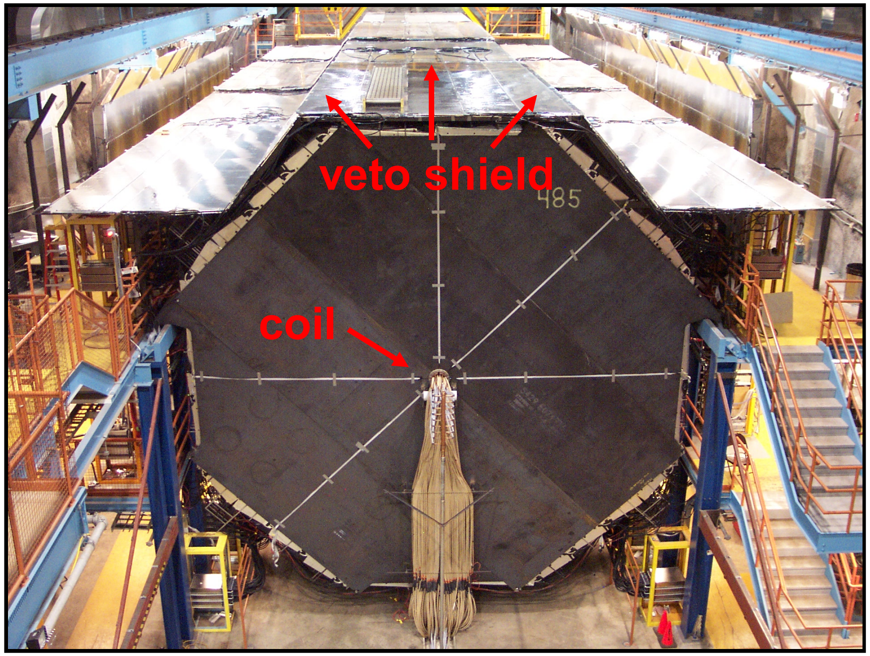






The MINOS Detectors





Near Detector

1 kt mass
1 km from target
282 steel planes
153 scintillator planes
100m underground

Functionally Identical Detectors!

Both are steel/scintillator tracking detectors.

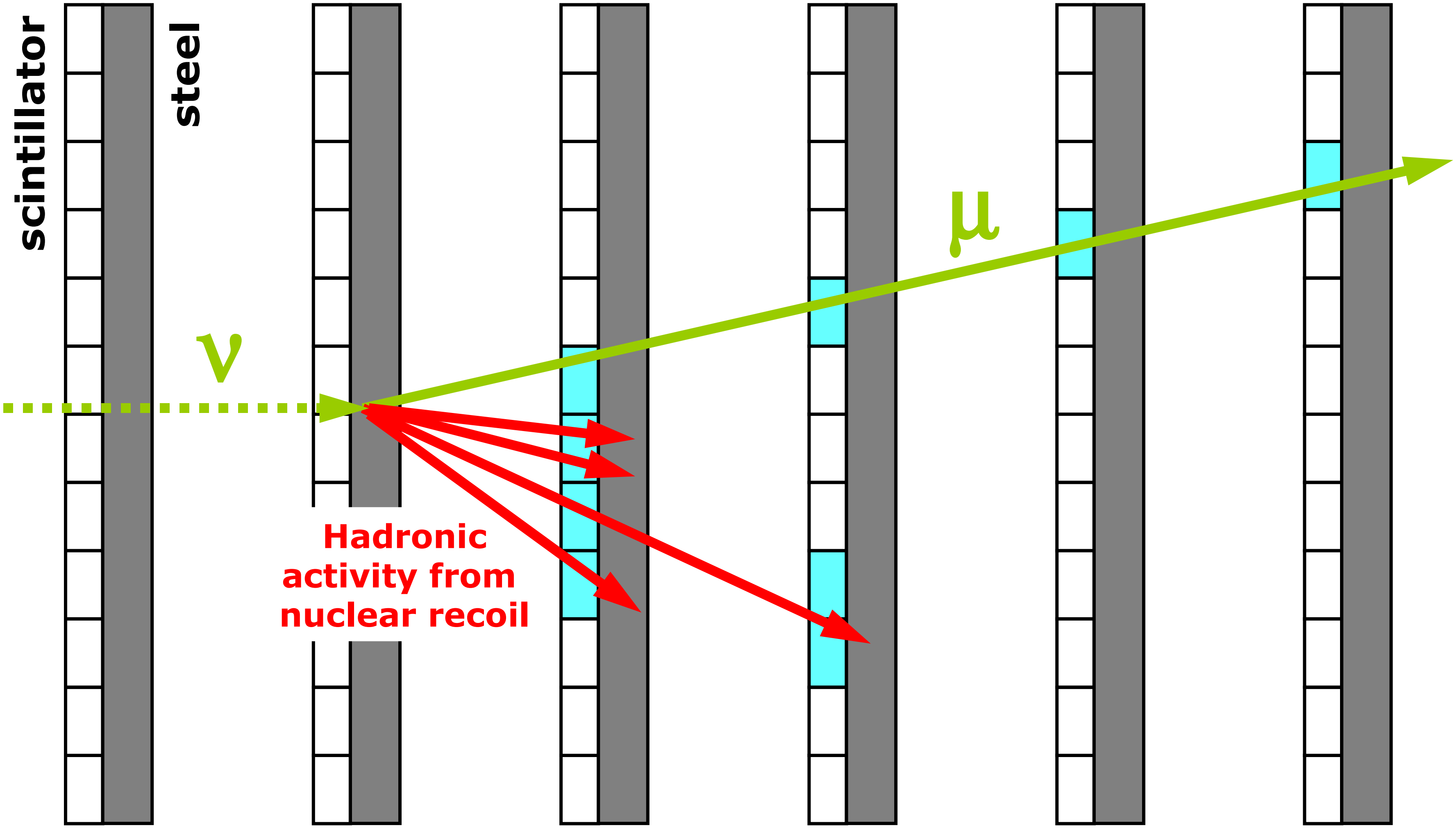
Magnetized steel (B ~1.3T).

GPS synchronization.

Far Detector

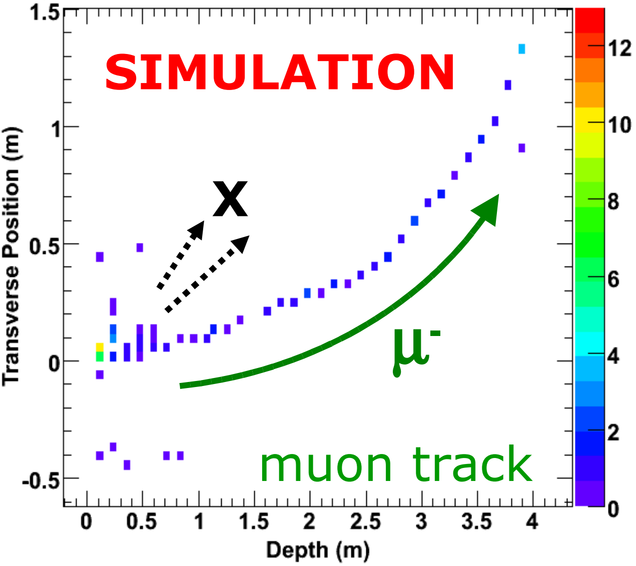
5.4 kt mass
735 km from target
486 steel planes
484 scintillator planes
700m underground

Neutrino Interactions

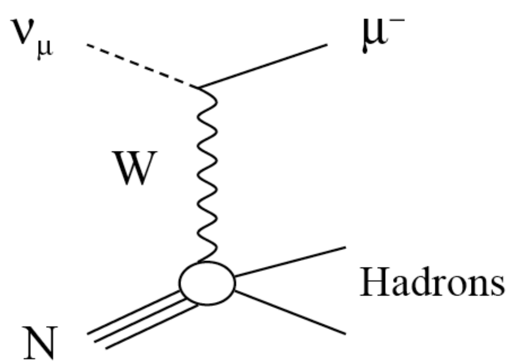


Neutrino Interactions

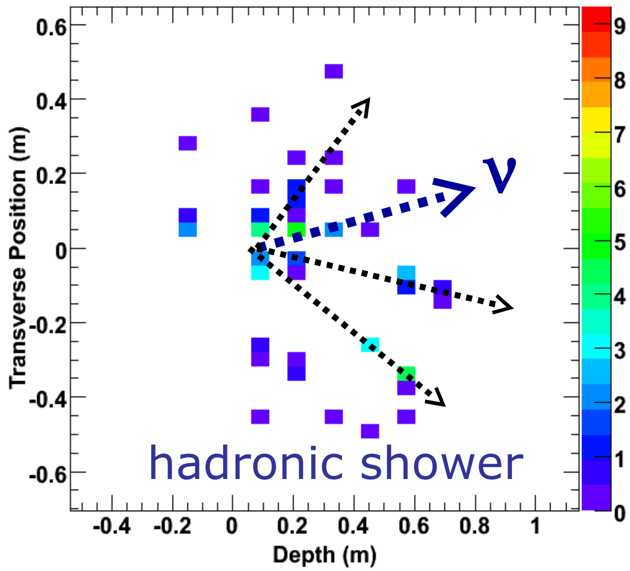
ν_μ Charged Current (CC)



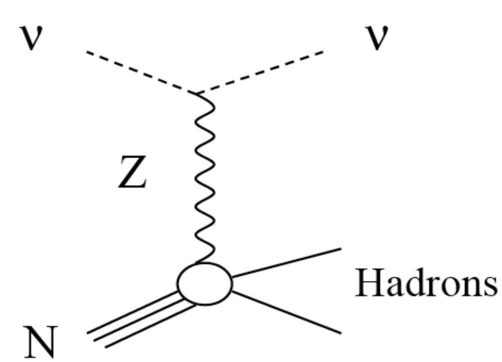
$$\nu_\mu + N \rightarrow \mu^- + X$$



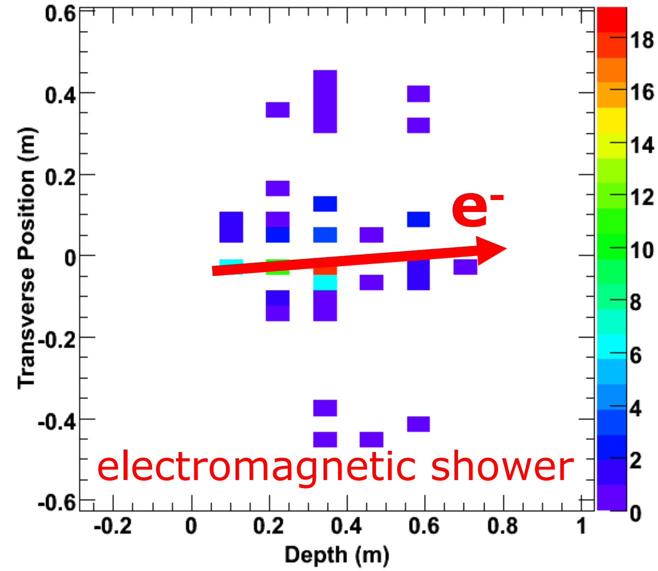
Neutral Current (NC)



$$\nu + N \rightarrow \nu + X$$



ν_e Charged Current (CC)



$$\nu_e + N \rightarrow e^- + X$$