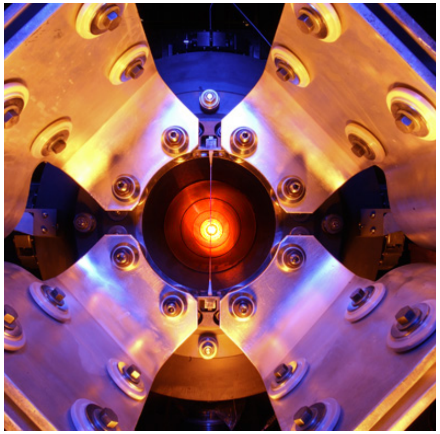
+

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$\nu_\mu \rightarrow \nu_\tau$$

$$\nu_\mu \rightarrow \nu_s$$



MINOS:

New Results and First MINOS+ Data

Ruth Toner
Harvard University
LLWI 2015

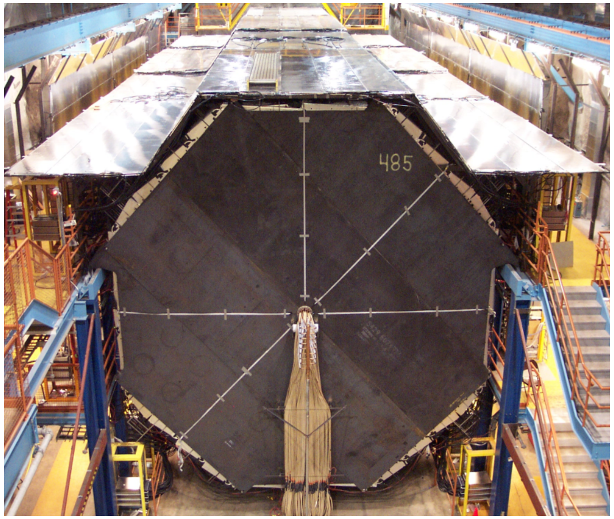
+ MINOS and MINOS+: An Introduction

MINOS = **M**ain **I**njector **N**eutrino **O**scillation **S**earch

- Long-baseline neutrino oscillation experiment, utilizing the Fermilab NUMI muon neutrino beam
- Two magnetized tracking calorimeter detectors to study this neutrino flux
- **Aim = study the oscillation of neutrinos between the two detectors**

This talk:

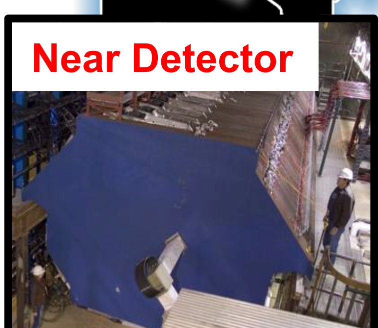
- Newest **science results** from MINOS
- Discussion of the status of our newest stage, **MINOS+**, and plans for the future

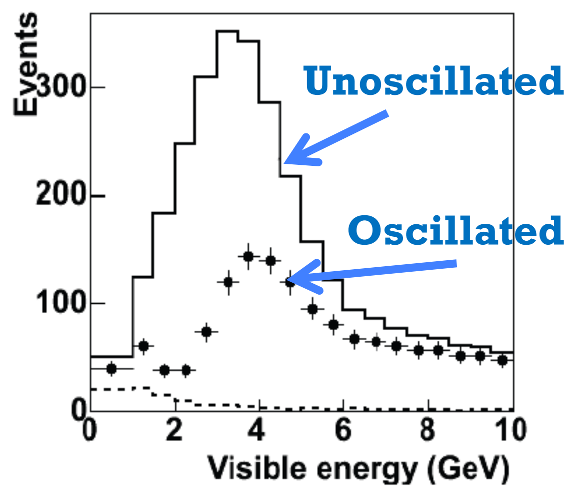


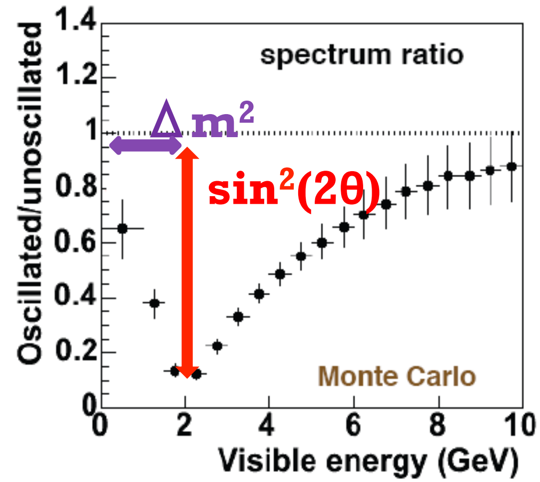
+ The MINOS Concept

- **Beam:** NuMI on-axis beam (formerly peaked at 3.3 GeV)
- **Detectors:** Functionally equivalent; steel and solid scintillator
  - One **Near Detector** (0.029 kT fiducial), one **Far Detector** (4.0 kT fiducial at depth of 700 m) at distance of 735 km
- **Intended Goal:** look for disappearance of muon neutrinos:

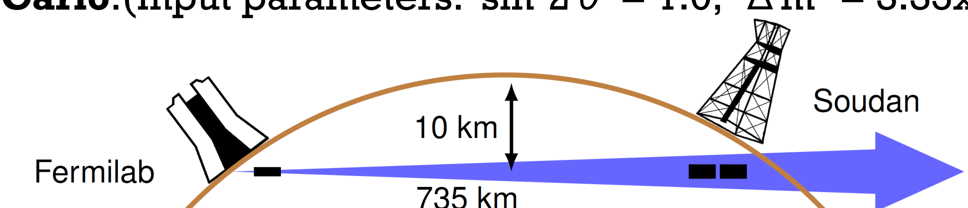
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32} L/E)$$





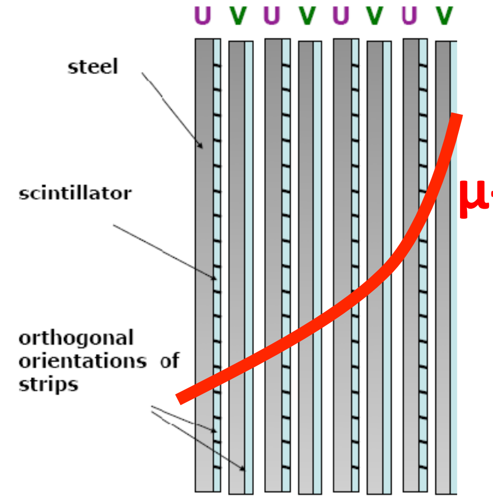


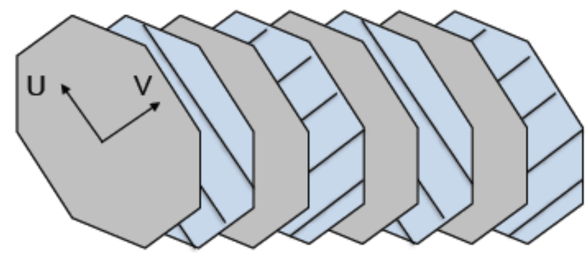
Monte Carlo:(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\text{x}10^{-3}\ \text{eV}^2$)

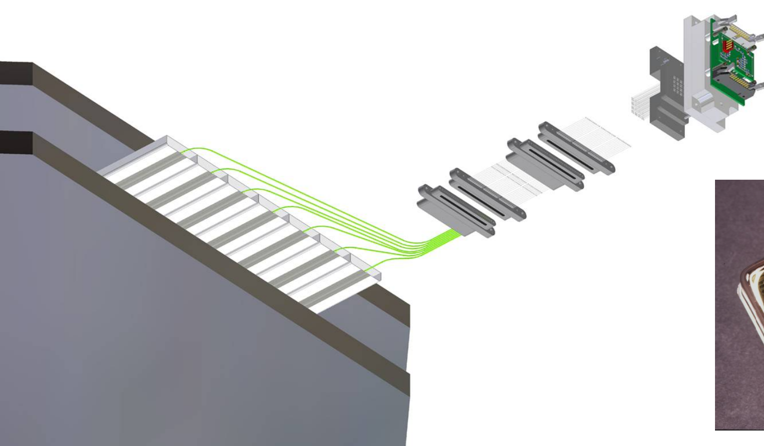


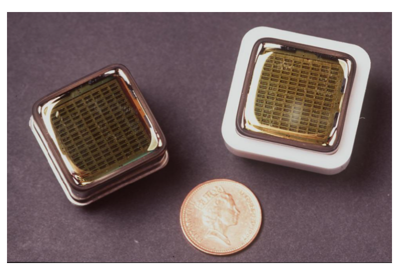
Detectors

- **Both MINOS detectors consist of a series of octagonal planes through which the neutrino beam passes and interacts**
  - Designed primarily to study μ+/μ- tracks
- **Each plane contains:**
  - Layer of 1" steel – **target mass**
  - Layer of 1 cm thick / 4.1 cm wide strips of plastic scintillator – **photons**
- **Detectors are magnetized (~1.3 T)** to allow discrimination between neutrino and antineutrinos









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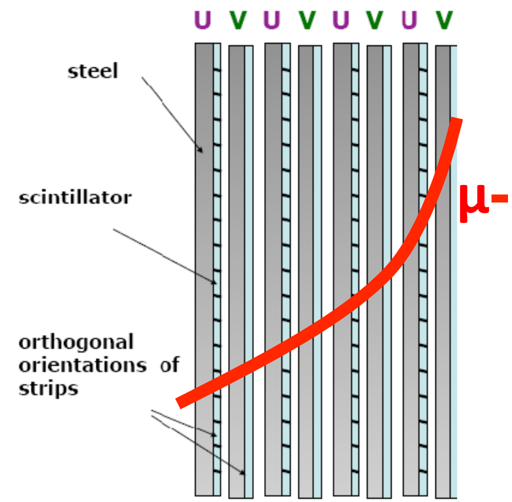
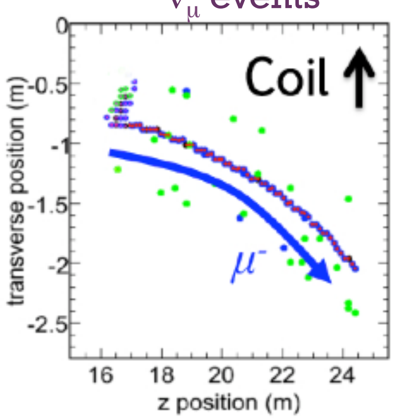
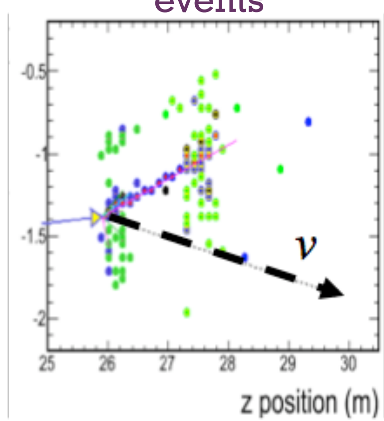


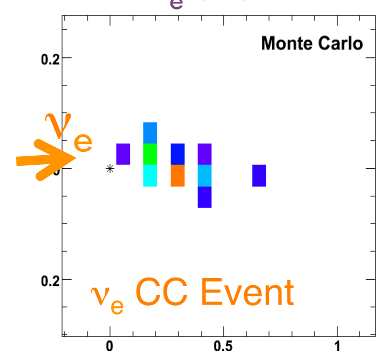
Charged current ν_μ events



Neutral current events



Charged current ν_e events



+ NuMI Beamline

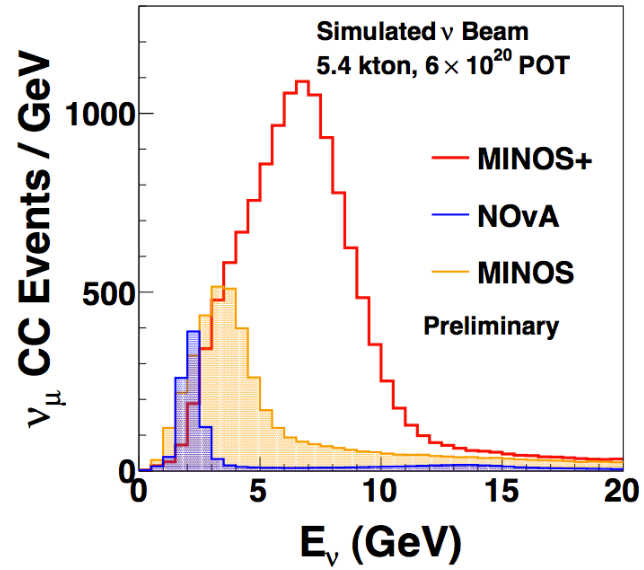
Production: 120 GeV p+ from Main Injector collides with graphite target to produce hadrons

Focusing:

- Focus pi+/K+ for neutrino beam
- Focus pi-/K- for antineutrino beam

Decay: Hadrons decay in 675 m long decay pipe

➢**End = on-axis wide-band muon neutrino beam**

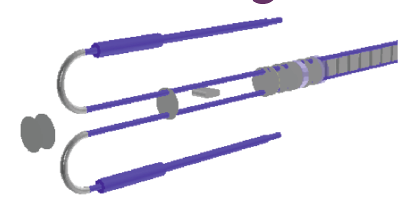


MINOS+: Takes advantage of new Medium Energy (ME) beam setting (for NOvA)

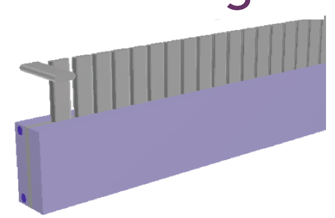
- New target and new Horn 1
- Horn 2 moved 10 m downstream
- Future Proton Improvement Plan → 700 kw beam

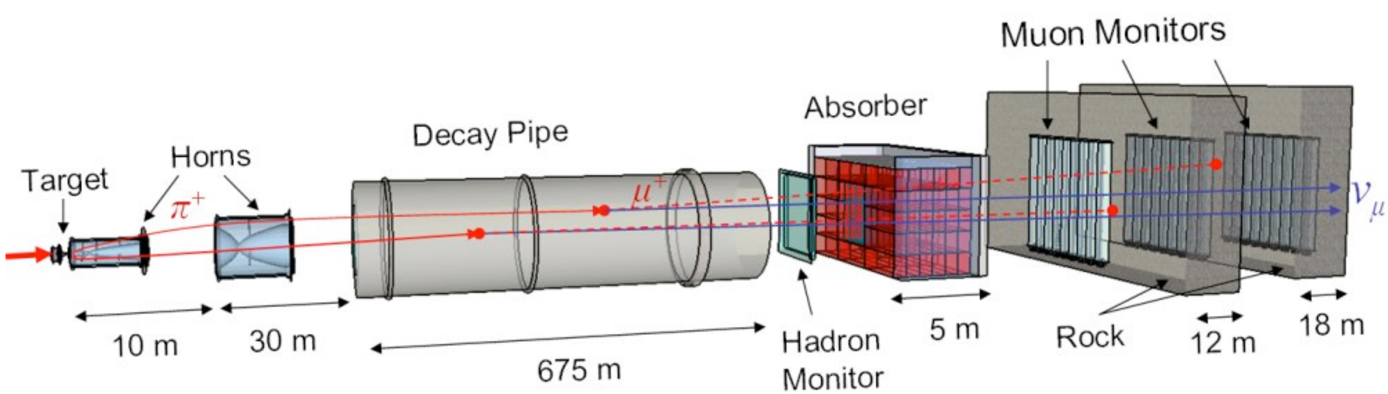
Result = Higher intensity, higher energy beam

Old target



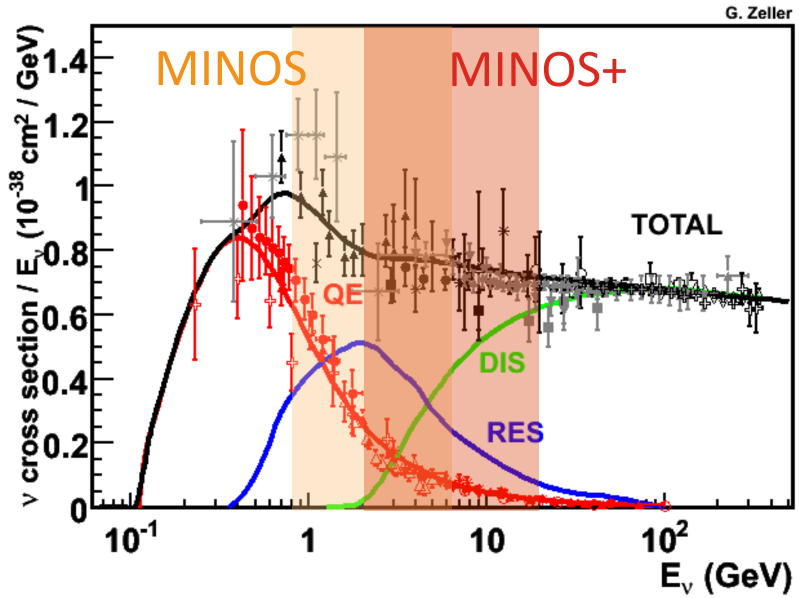
New target





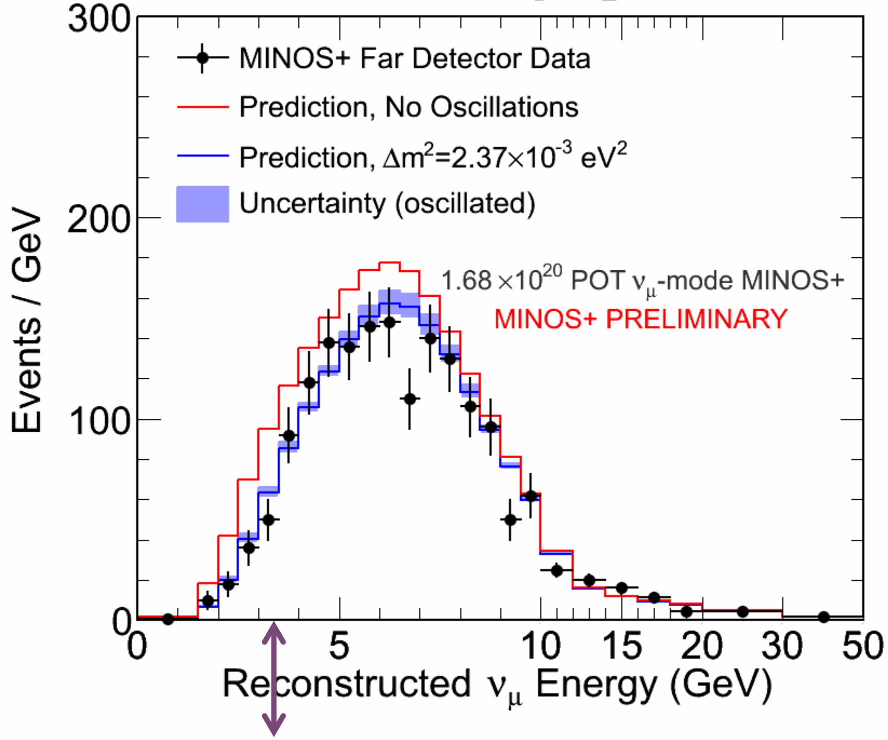
+ Why MINOS+?

- **Higher Energy:** Can cross-check existing results in higher energy region, using new beam and cross-section systematics
- **Higher Statistics:** Extend our analyses with an expected ~4000 events/year at the Far Detector
- **New Physics?:** Only wide band beam neutrino experiment this generation!



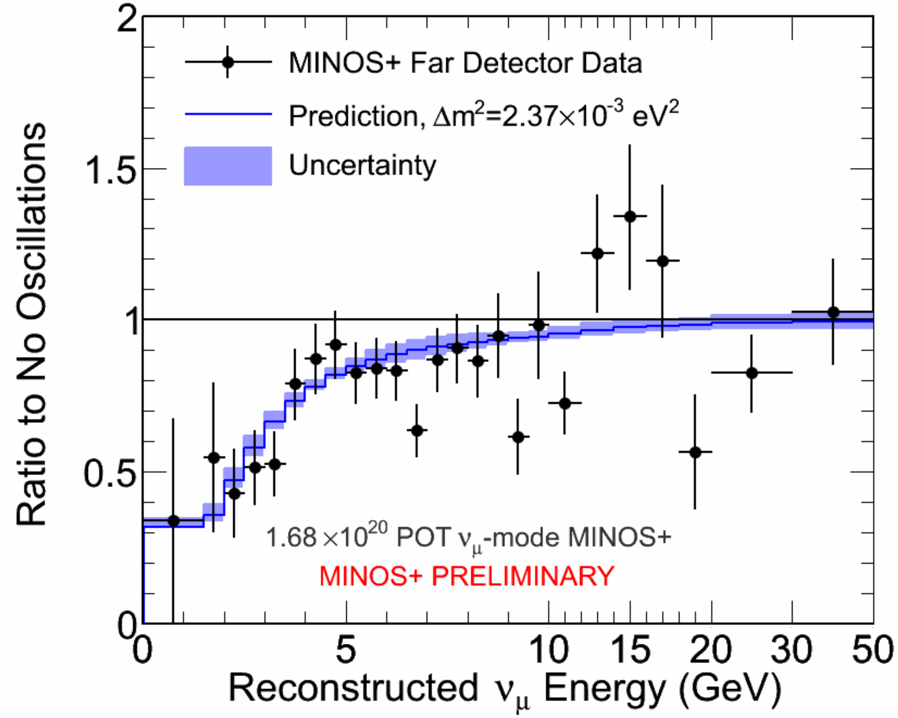
+ First MINOS+ Data!

MINOS+ only Spectra



Previous MINOS Peak

MINOS+ only Ratio

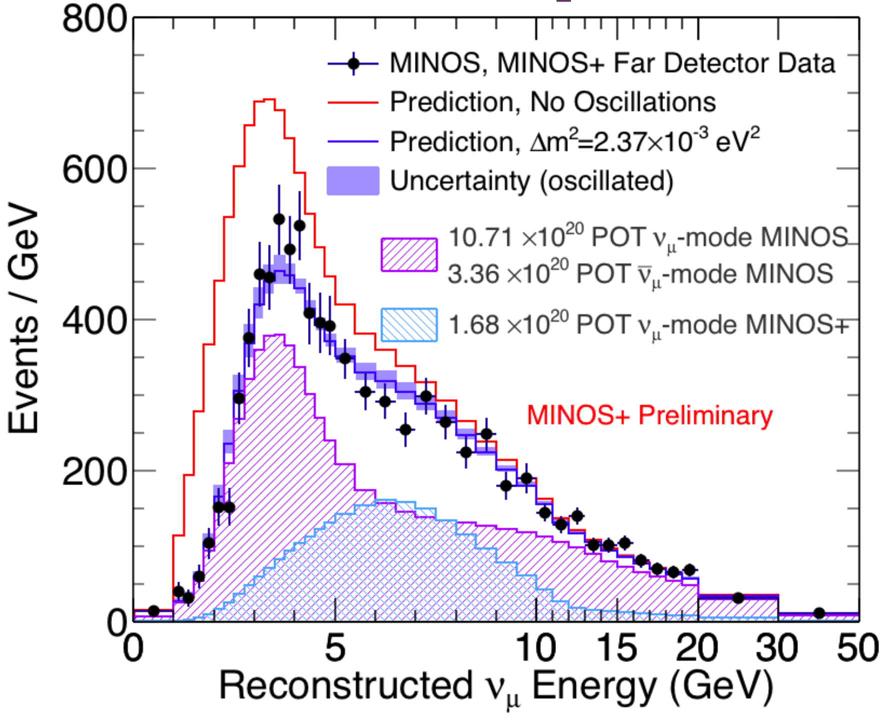


- So far, prediction matches data for muon neutrino survival
- Will publish combined MINOS/ MINOS+ fit in the near future

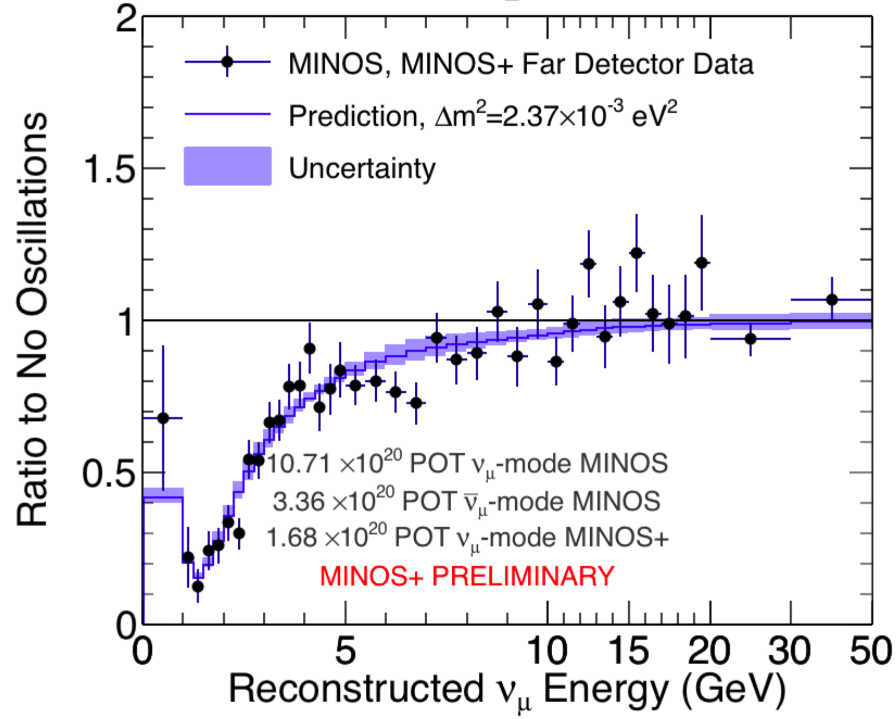
New MINOS+ nus	μ^-	μ^+
Unoscillated Prediction	1254.8	52.0
Oscillated Prediction	1087.7	47.2
Data	1037	48

+ First MINOS+ Data!

Combined Spectra



Combined Spectra Ratio



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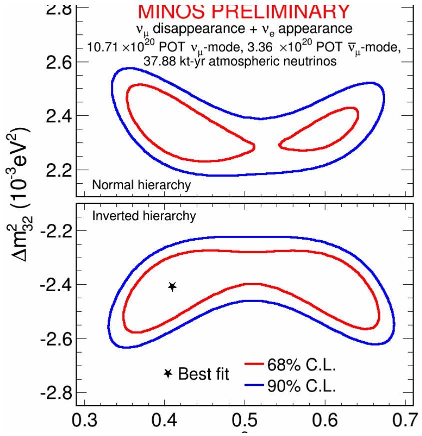
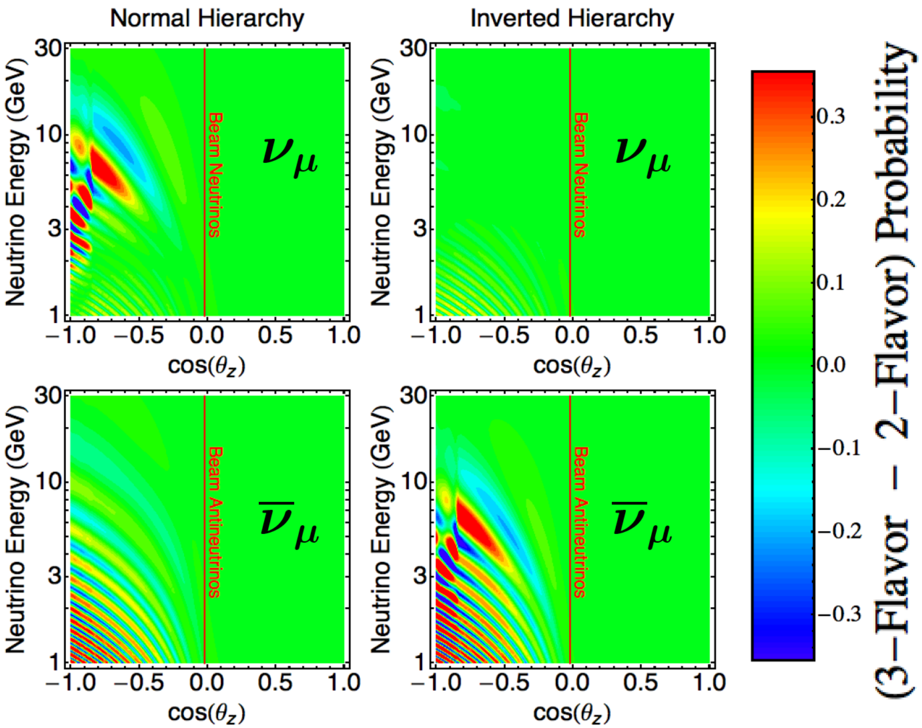
Physics Results

MINOS Data, and Future MINOS+ Prospects



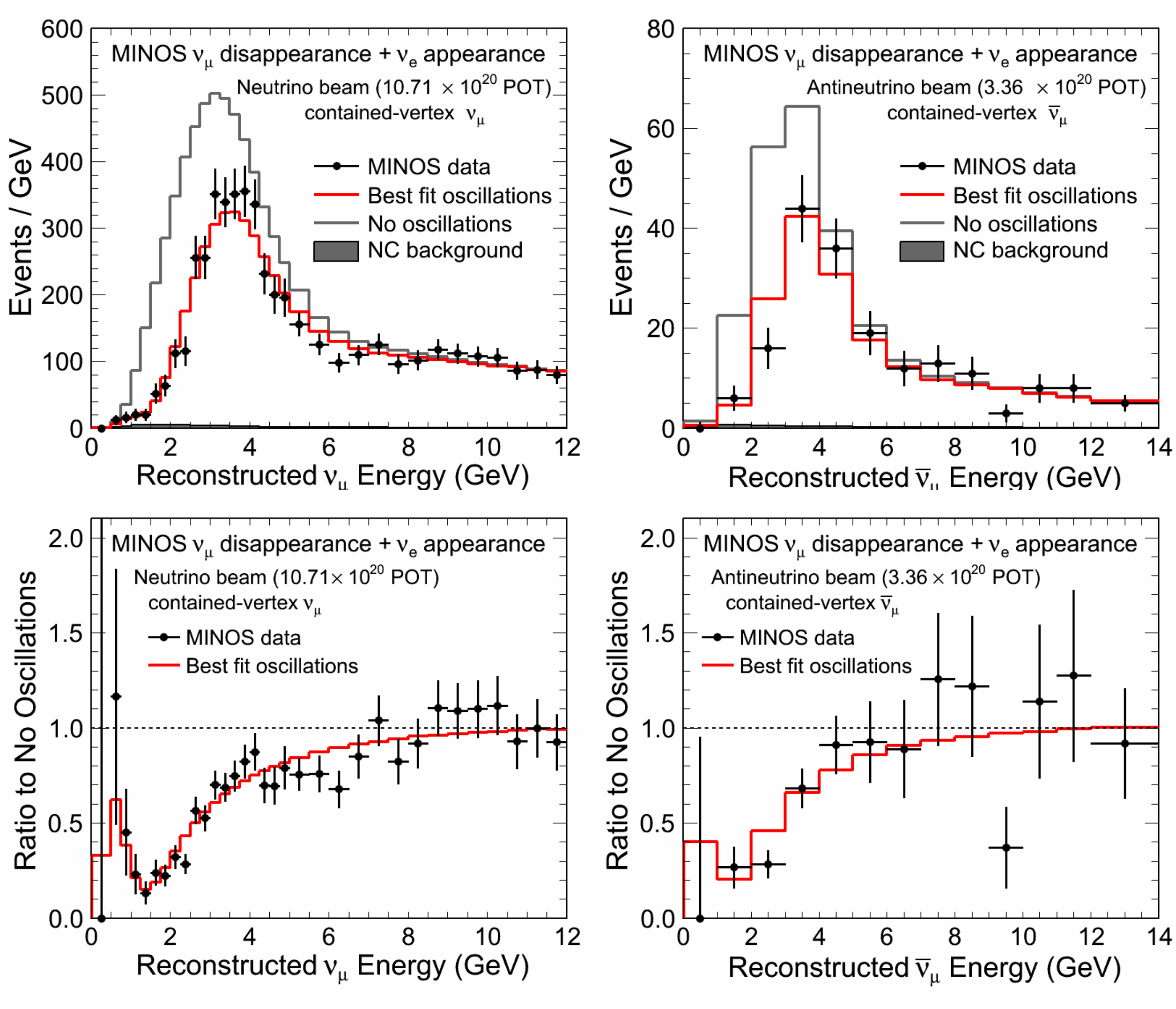
+ 3-Flavor Neutrino Oscillations

- Unlike previous disappearance results, can get a much more full picture of standard Near→Far oscillations by fitting three separate samples:
  - Full MINOS ν_μ-CC and $\bar{\nu}_\mu$-CC disappearance sample
  - Full ν_e-CC and $\bar{\nu}_e$-CC appearance sample
  - Full MINOS and **new MINOS+ atmospheric neutrino sample**



Relevant published results:
- ν_μ disappearance (PRL 110, 251801, 2013)
- $\nu_\mu \rightarrow \nu_e$ appearance (PRL 110, 171801, 2013)
- Combined analysis (PRL 112, 191801, 2014)

MINOS Beam Disappearance Data



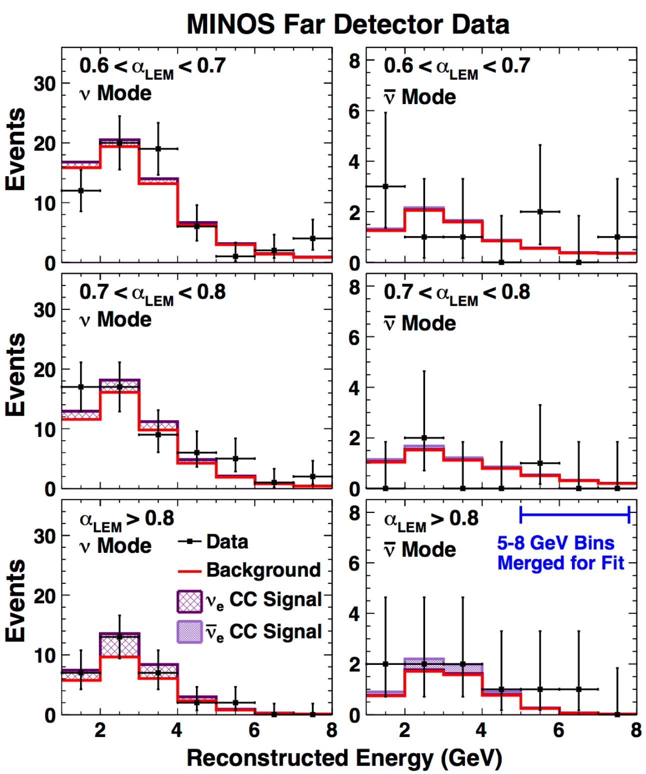
- Use Near Detector spectrum to predict un-oscillated Far Detector Spectrum
- Compare data to prediction and look for disappearance of muon neutrinos
- MINOS data: analysis optimized for previous Low Energy Beam Peak

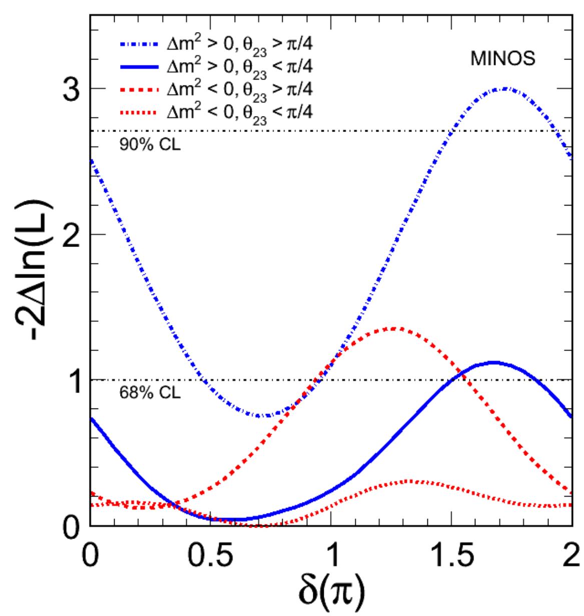
Published Result:
PRL 110, 251801, 2013

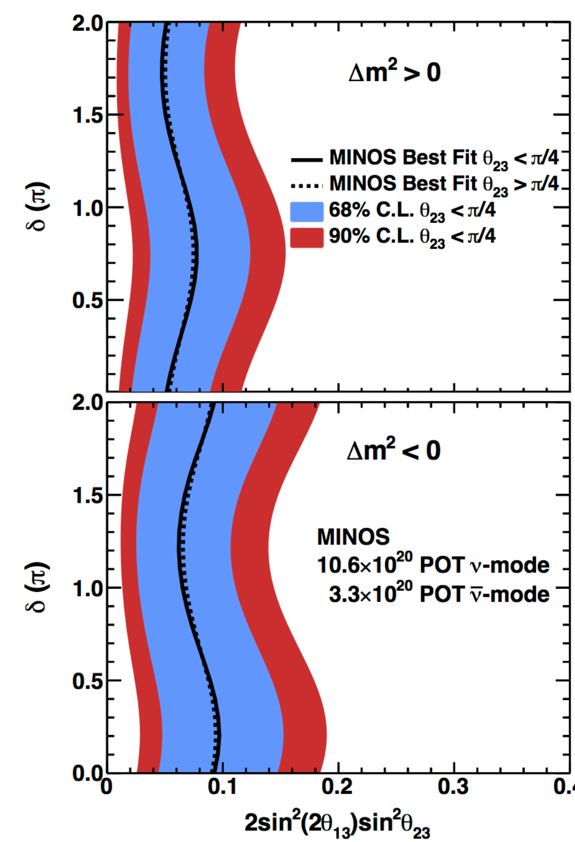
MINOS ν_e Appearance Data

- ν_e sample provides sensitivity to θ_{13}, θ_{23} octant, mass hierarchy, and δ_{CP}
- Analysis separates electron neutrino candidates from NC background using the Library Event Matching (LEM) particle ID method
- Extrapolate Near Detector to Far Detector Prediction
- Compare with reactor limits (Daya Bay, etc.) for sensitivity to hierarchy and δ_{CP}

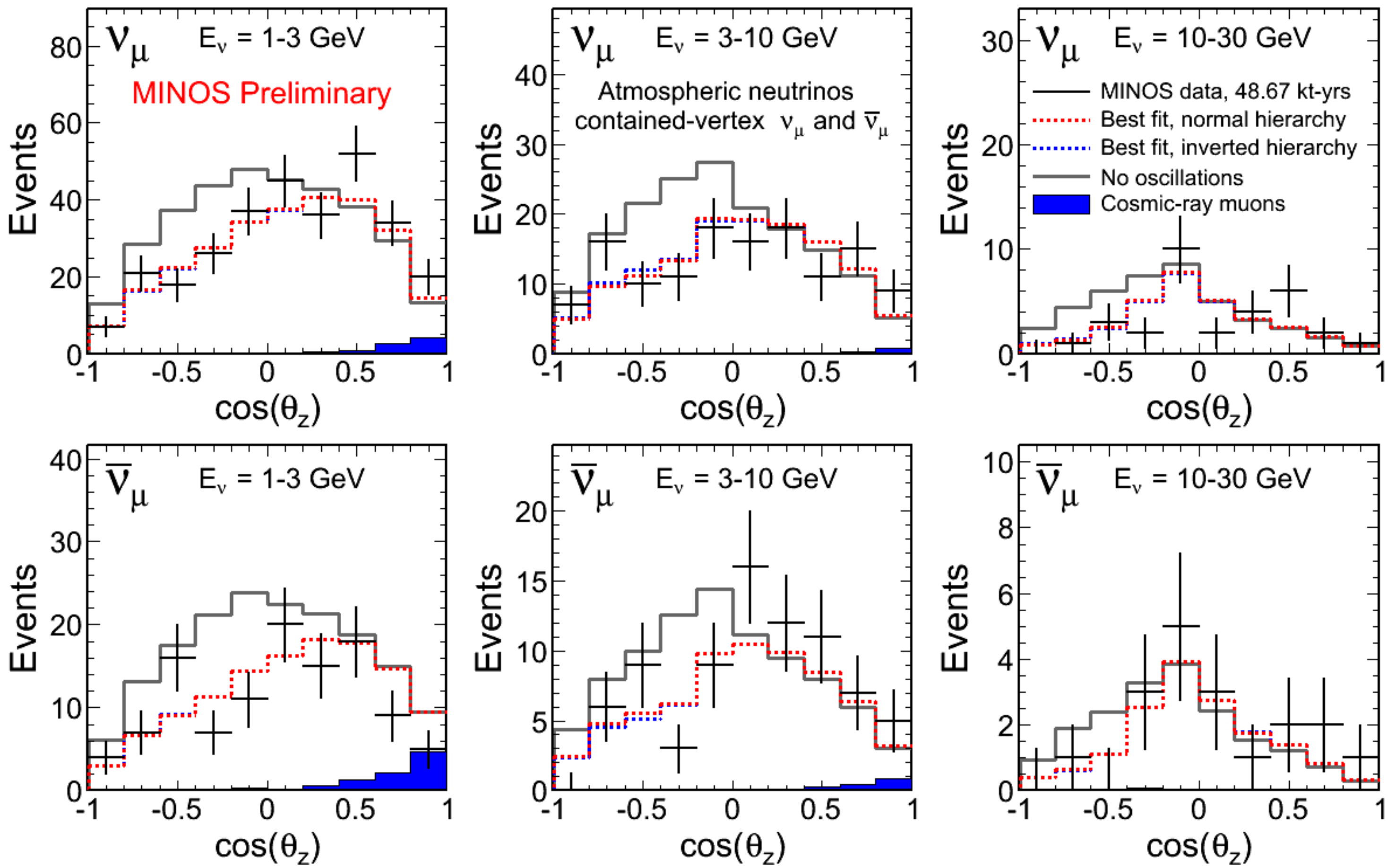
Published Result: PRL 110, 171801, 2013





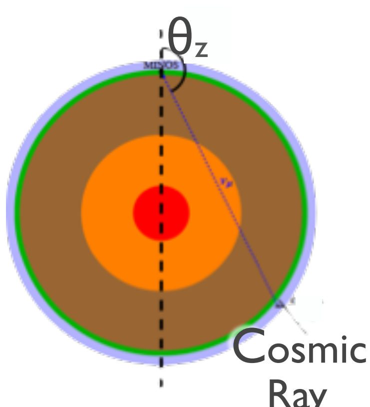


+ MINOS and MINOS+ Atmospheric Data



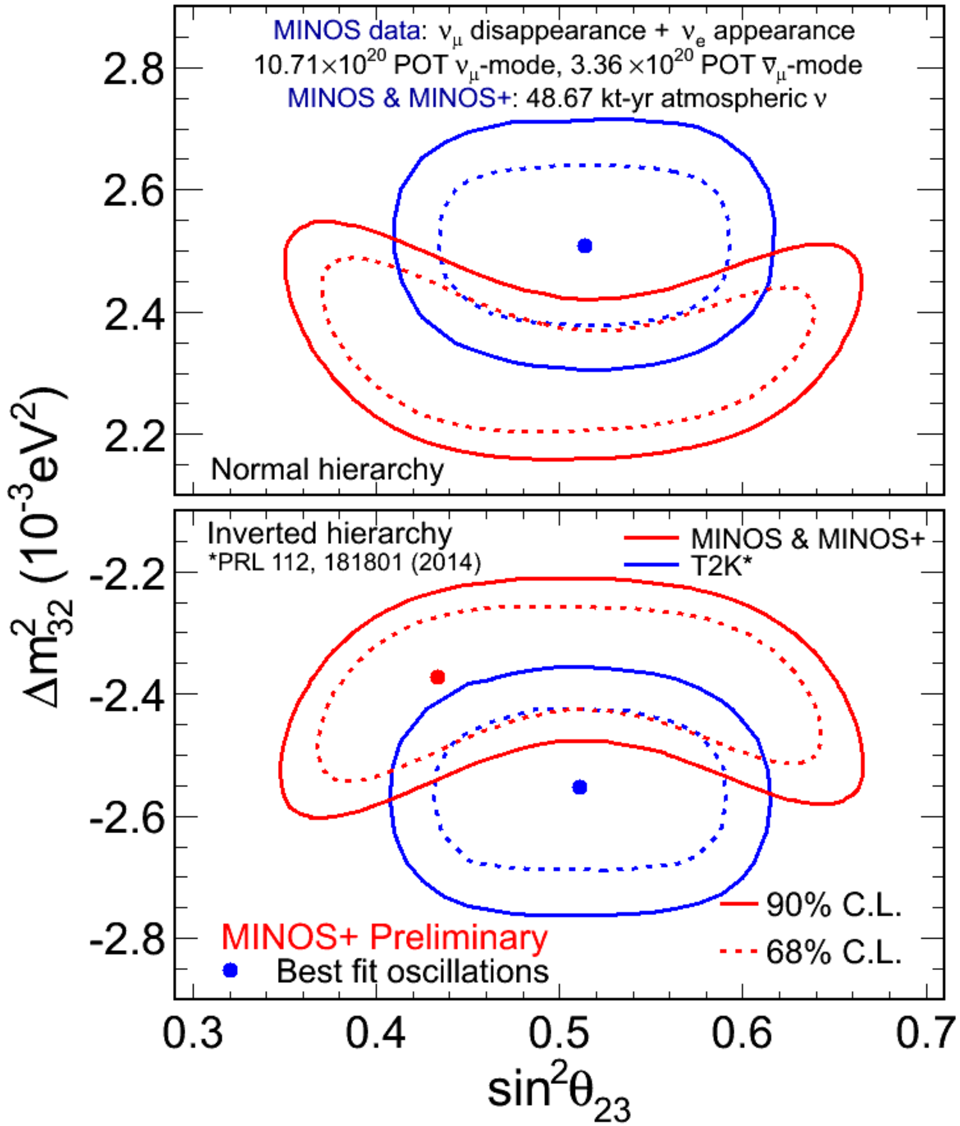
Neutrinos

Anti-Neutrinos



- Impact of matter effects seen in multi-GeV upward going muons
- MINOS: can separate events into neutrinos and anti-neutrinos using charge separation → additional information on mass hierarchy!

+ Combined Fit



New Three-Flavor Oscillation Best Fit:

Inverted Hierarchy

$$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$$

$$0.36 < \sin^2\theta_{23} < 0.65 \text{ (90\% C.L.)}$$

Normal Hierarchy

$$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$$

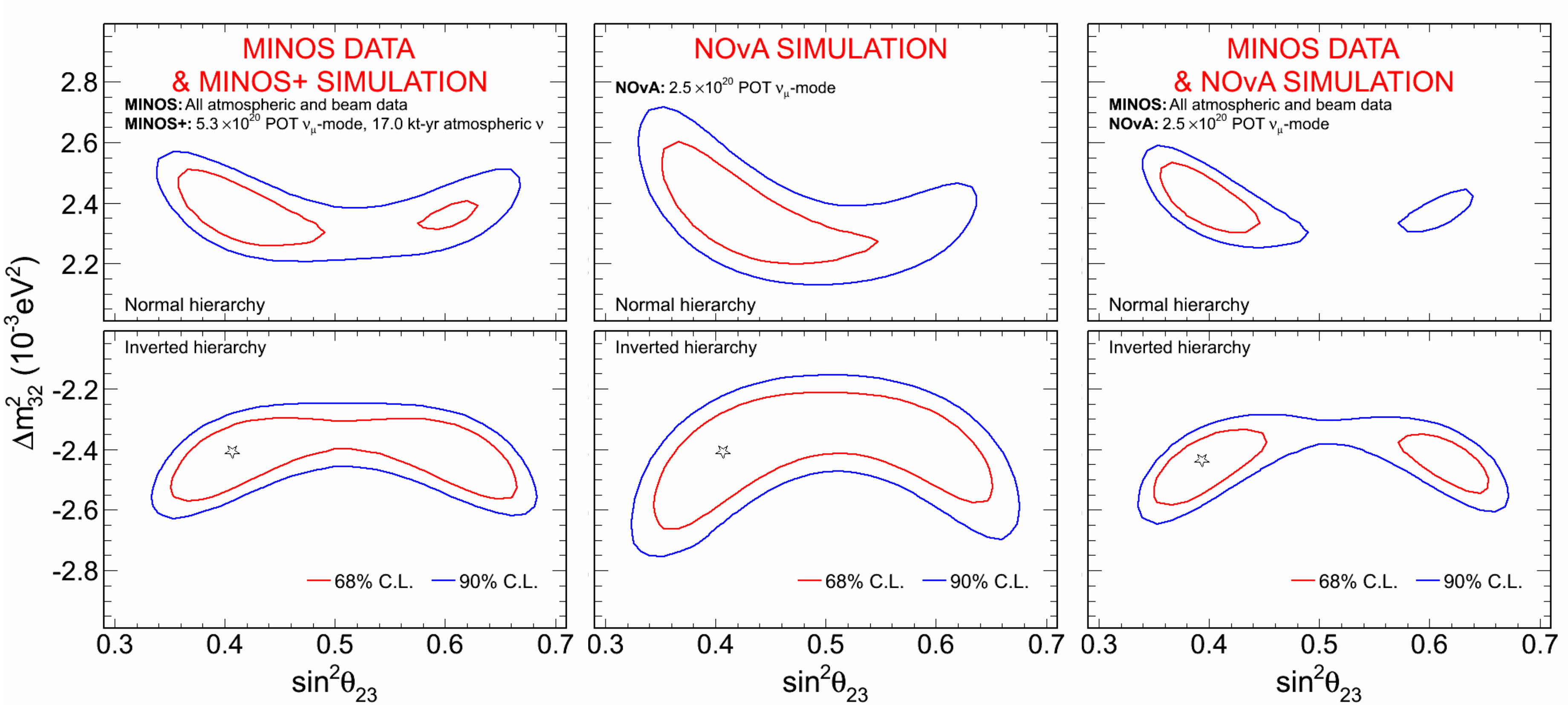
$$0.37 < \sin^2\theta_{23} < 0.64 \text{ (90\% C.L.)}$$

- Most precise measurement of $|\Delta m^2_{32}|$ to date!
- We are still consistent with maximal mixing

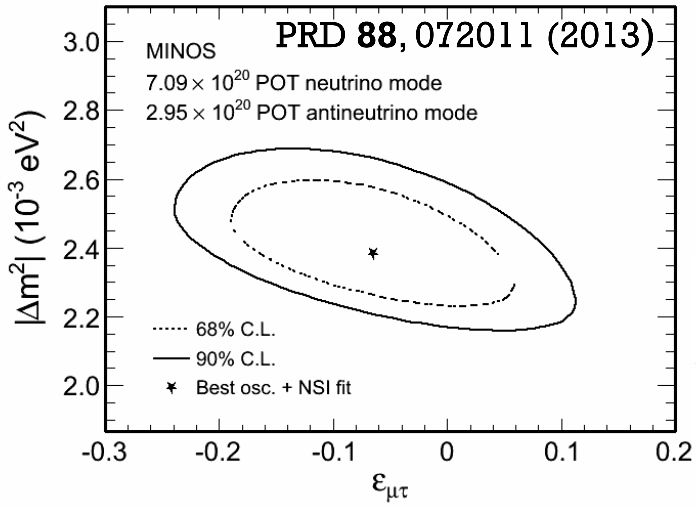
Published Result: PRL 112, 191801, 2014

+ MINOS+ Sensitivity

- NOvA and MINOS+ running at same time → can combine results to get best possible three-flavor oscillation fit
- Contours projected by 2015 FNAL shutdown, assuming same best fit parameters as earlier MINOS result:



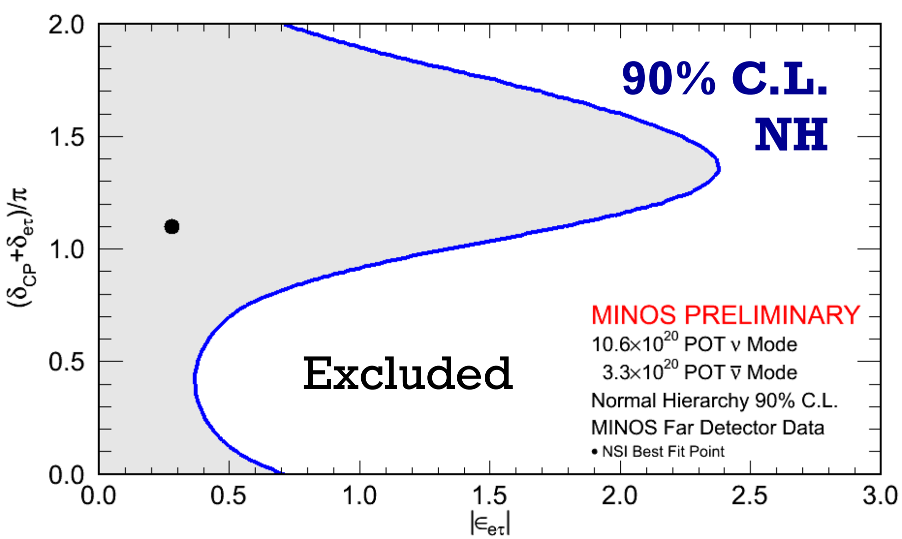
+ Non-Standard Interactions

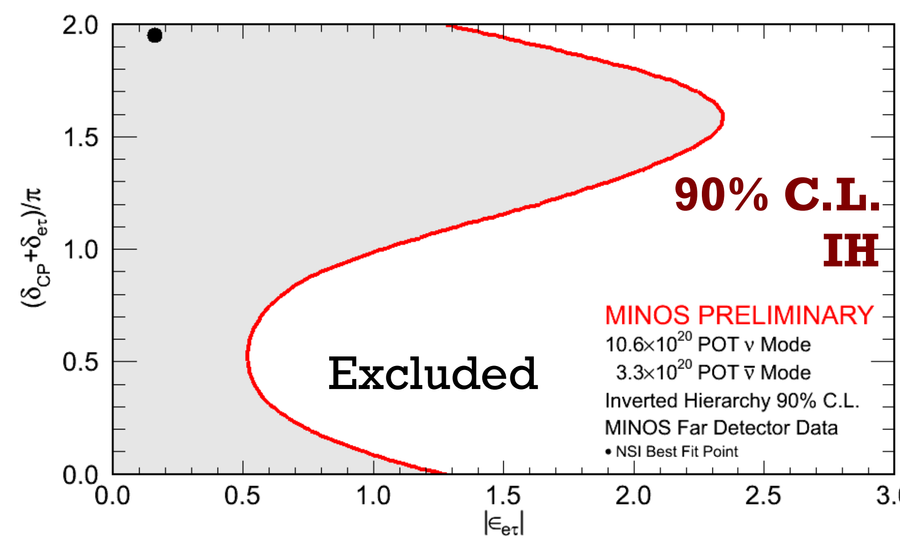


- Oscillations could **exhibit non-standard behavior**:
  - Friedland, Lunardini, Maltoni, PRD 70, 111301(2004)
  - Coelho, Kafka, Mann, Schneps, Altinok, PRD 86, 113015 (2012)

$$H = U_{PMNS}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger_{PMNS} + \sqrt{2}G_F n_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^\star_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}$$

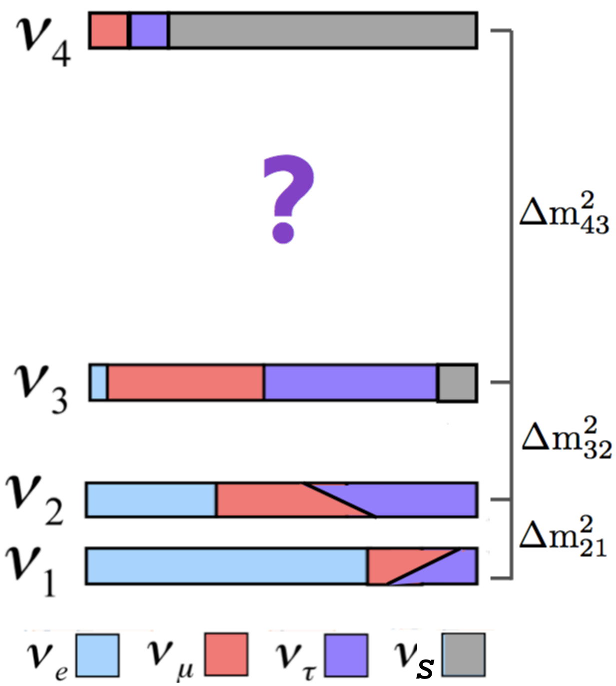
- Sensitive to two parameters: $\boldsymbol{\varepsilon_{\mu\tau}}$ (through ν_μ, $\bar{\nu}_\mu$ disappearance) and $\boldsymbol{\varepsilon_{e\tau}}$ (through ν_e, $\bar{\nu}_e$ appearance)
- Previously measured $\boldsymbol{\varepsilon_{\mu\tau}}$; have now measured $\boldsymbol{\varepsilon_{e\tau}}$ as well!

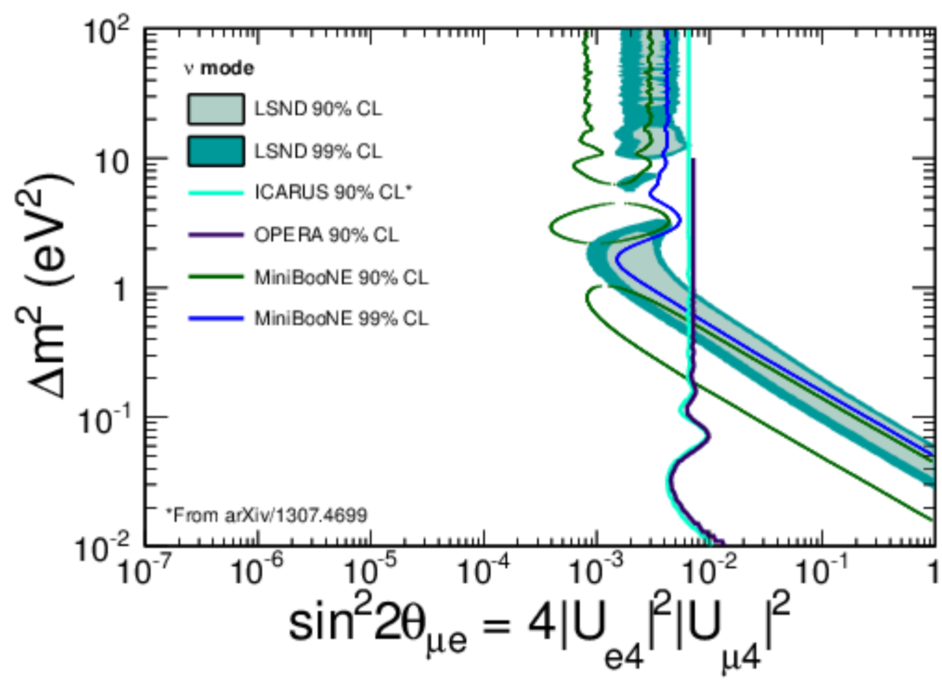




Sterile Neutrino Search

- Possibility of one (or more) additional light sterile neutrino states
- **Anomalies** seen in:
  - Short baseline neutrino experiments
  - Radiochemical experiments
  - Reactor measurements
- Neutrino experiments looking for sterile disappearance = no evidence
- MINOS can further check for the existence of these sterile oscillations





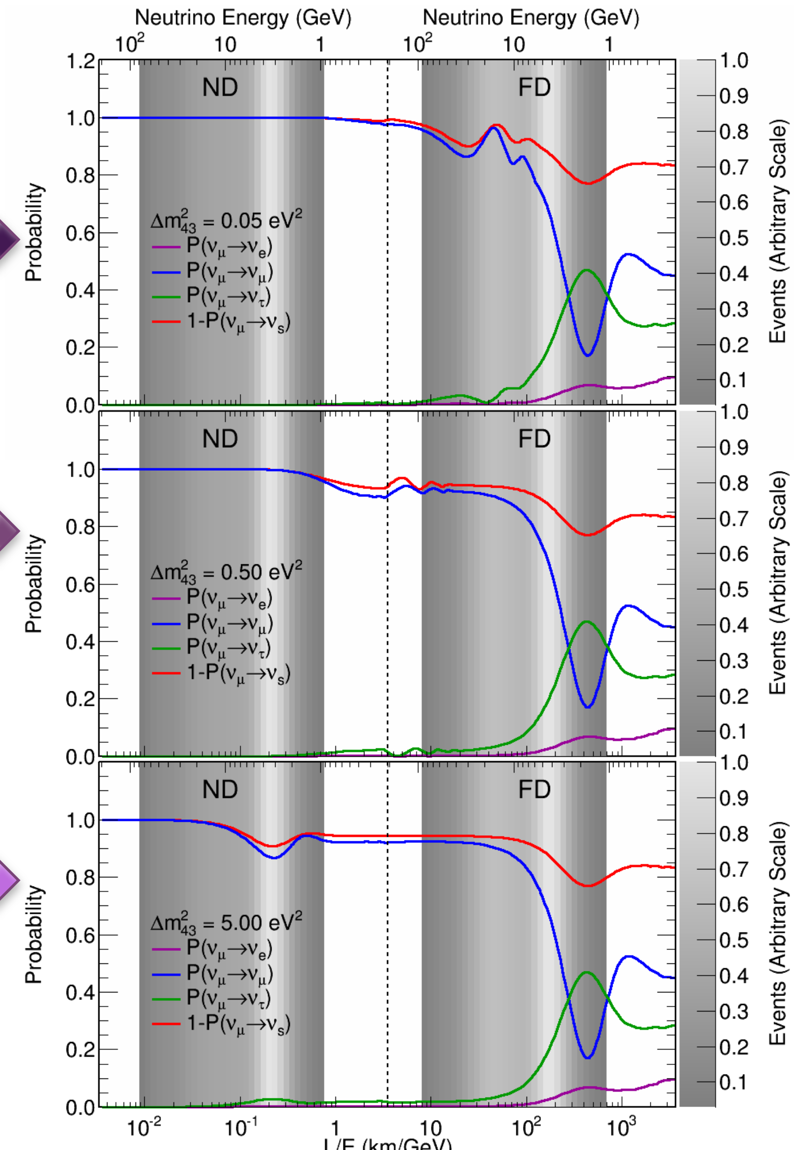
Sterile Oscillations in MINOS

- Oscillation to sterile neutrinos will be seen as energy-dependent depletion in both NC and ν_μ–CC energy spectra
  - Potentially both Far and Near detectors!

- **Small Δm^2_{43} ($\Delta m^2_{43} > \Delta m^2_{32}$)** **~ 0.05 eV^2**
  - ND unaffected; distortion of FD spectrum shape above standard max

- **Medium Δm^2_{43}** **~ 0.5 eV^2**
  - ND unaffected; rapid oscillations in FD average out, so can perform counting experiment

- **Large Δm^2_{43}** **~ 5.0 eV^2**
  - ND spectrum distorted; rapid oscillations in FD average out
  - Must account for ND oscillations in extrapolation to Far Detector!

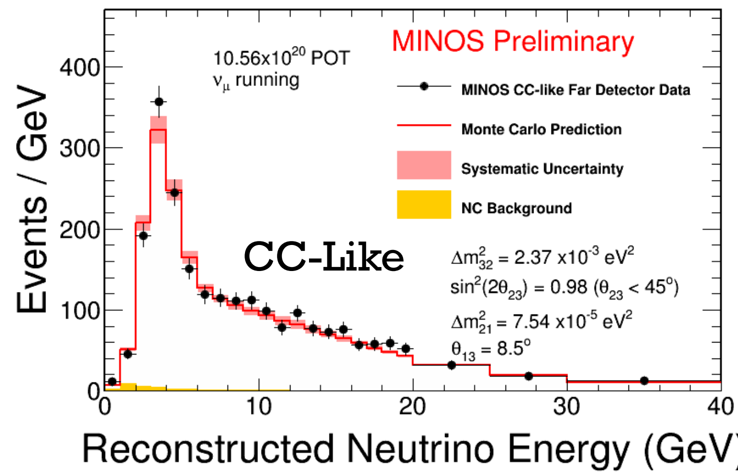


+ How to do a 4-Flavor Analysis

- Two ways of looking for sterile neutrinos:

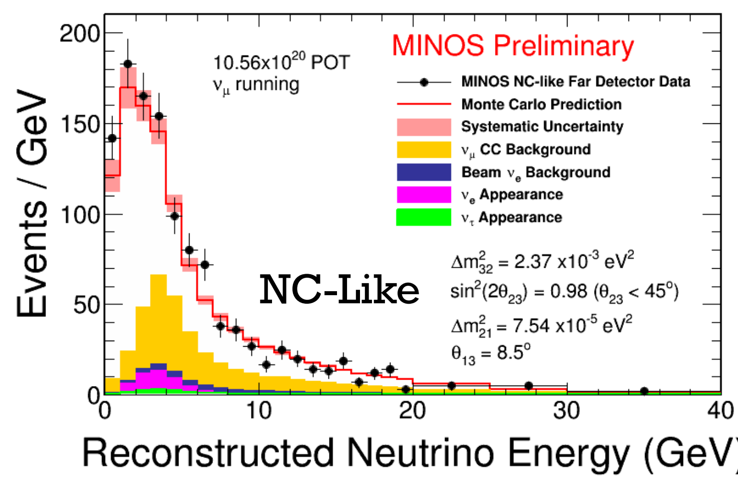
1) Traditional Near to Far extrapolation: looking for evidence of deficit of Far Detector neutrino events in NC sample

- No-ND-oscillation case ($\Delta m^2_{43} < \sim 0.5$ eV^2)
- **No evidence** for NC deficit, i.e. any FD events oscillating away to sterile state



2) **New analysis:** simultaneous Far/Near fit

- Assume 3+1 sterile mixing model
- Apply osc. to both Far and Near sims
- Compare **F/N oscillated ratio** to **F/N data ratio** for CC-like and NC-like events
  - Fit for $|\Delta m^2_{32}|, \theta_{23}, |\Delta m^2_{43}|, \theta_{24}, \theta_{34}$
  - Constrain Near Detector rate
  - Re-evaluate systematic errors, especially those for **beam flux**
  - Correct log-likelihoods with Feldman-Cousins method



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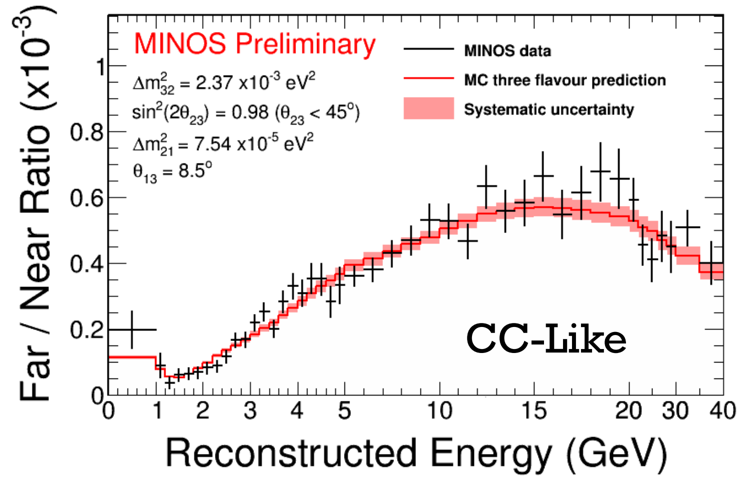
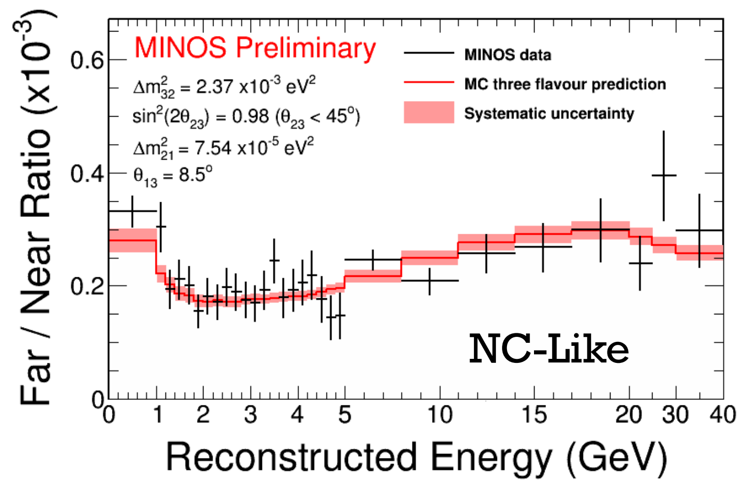
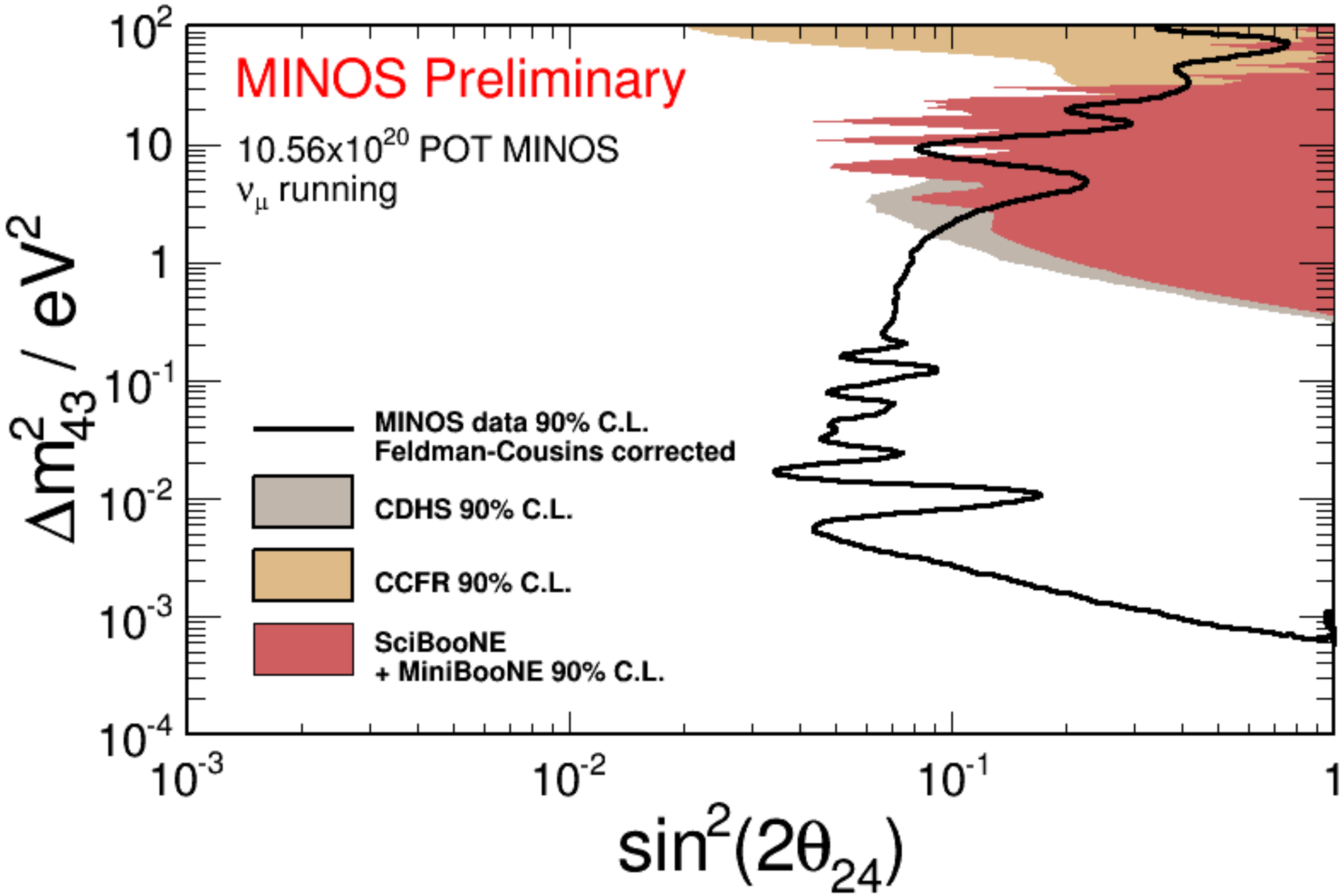




+ Disappearance Results



- Resulting Feldman-Cousins-corrected limits for F/N ratio method!

+ Comparison with Appearance

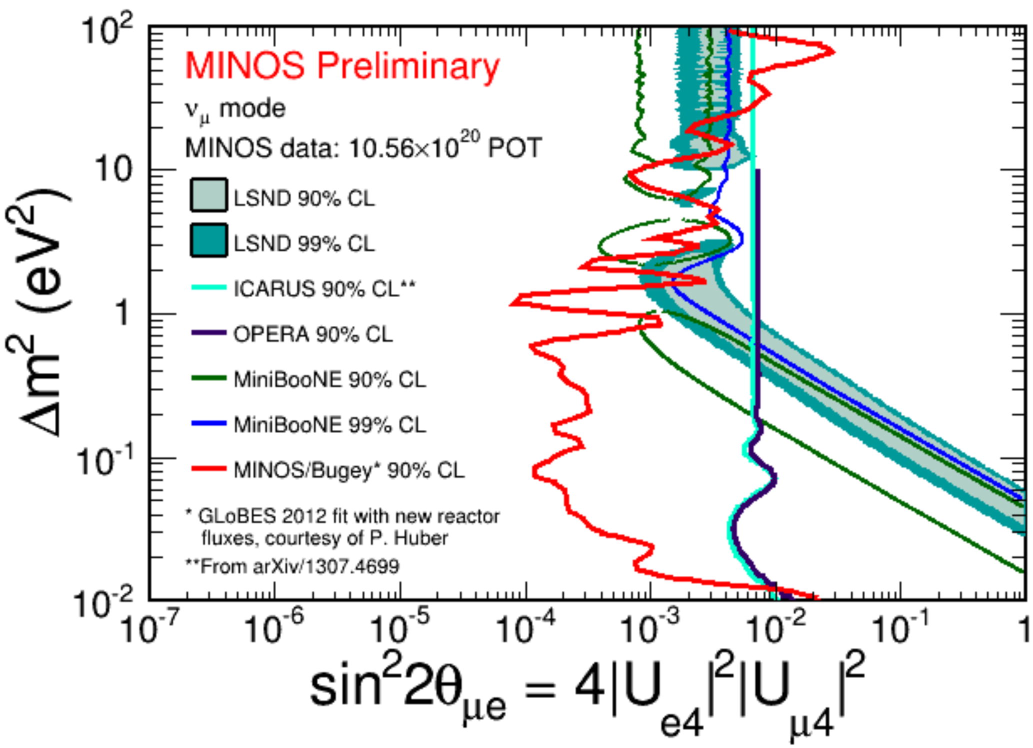
- Can combine with other data to compare to appearance results:
  - Point of comparison:

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

  - MINOS: 90% C.L. on θ_{24}
  - Bugey: 90% C.L. on θ_{14}
  - Assume 3+1 model and CPT conservation

- Increased tension between results in $\Delta m^2_{43} < 1\,\mathrm{eV}^2$ regime
- **Future MINOS plans:**
  - Sterile neutrino search using 3.4×10^{20} POT of MINOS antineutrino-running data
  - Combination with Daya Bay results

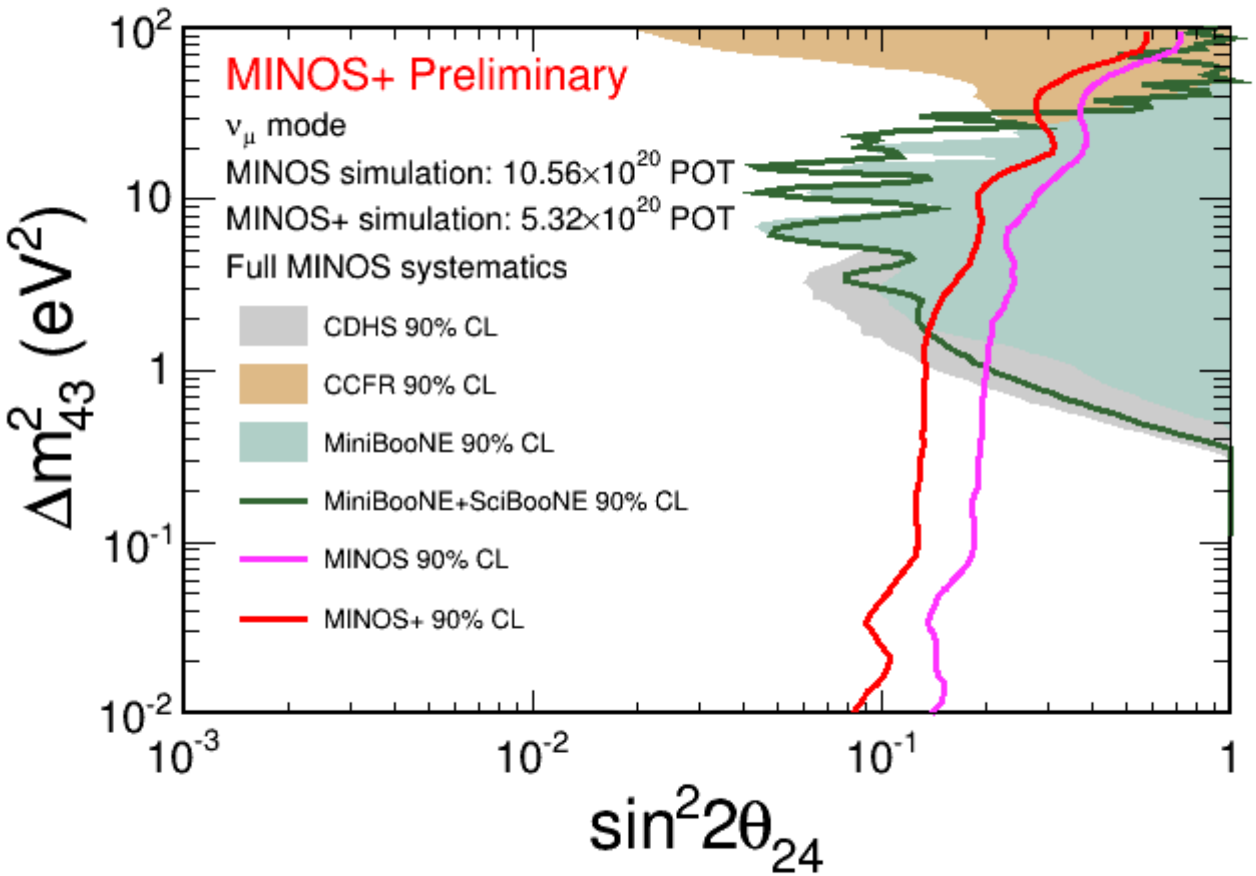
MiniBooNE Neutrino Mode:



Bugey limits: from P. Huber, using GLoBES 2012 and new reactor fluxes

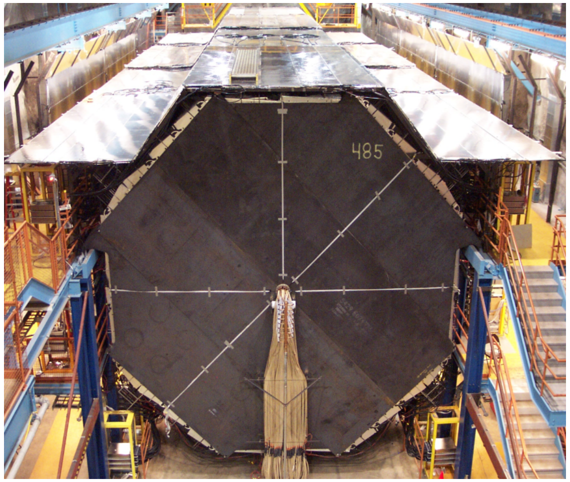
+ MINOS+ Reach

- MINOS/MINOS+ disappearance limits by 2016, w/ 5.32×10^{20} POT MINOS+



+ Conclusions

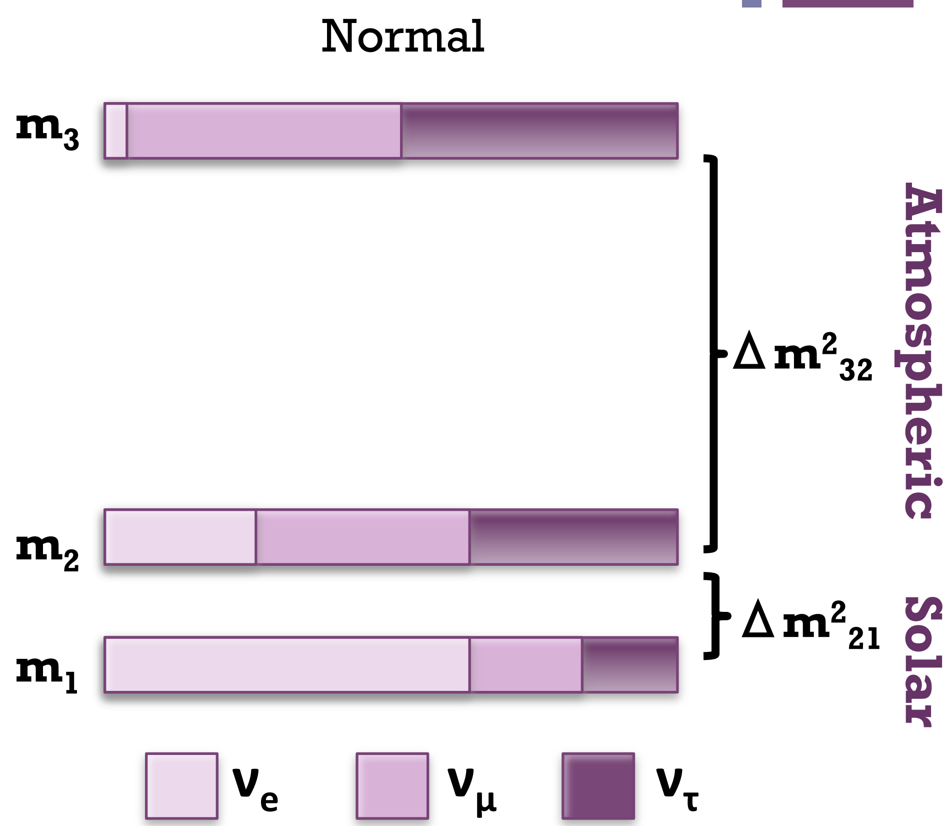
- Almost 10 years later, MINOS is still running strong!
- Strong set of new physics results:
  - 3-flavor Standard Oscillations
  - Non-standard interactions
  - Search for Sterile Neutrinos
- We are now in the MINOS+ era, which will allow us to make more precise measurements than ever
  - New era = new physics?



Thank you!

+ Outstanding Questions

- ~~What is the **value of θ_{13}**~~?
  - This is measured with best precision of any mixing angle!
- What is **the sign of Δm^2_{32}?** Is the **mass hierarchy** "Inverted" or "Normal"?
- Do neutrinos exhibit **CP violation**? What the size of phase δ_{CP}?
- Is **θ_{23} exactly 45°** (i.e., what is its "octant"?)
- Do sterile neutrinos exist (mostly short-baseline)?



$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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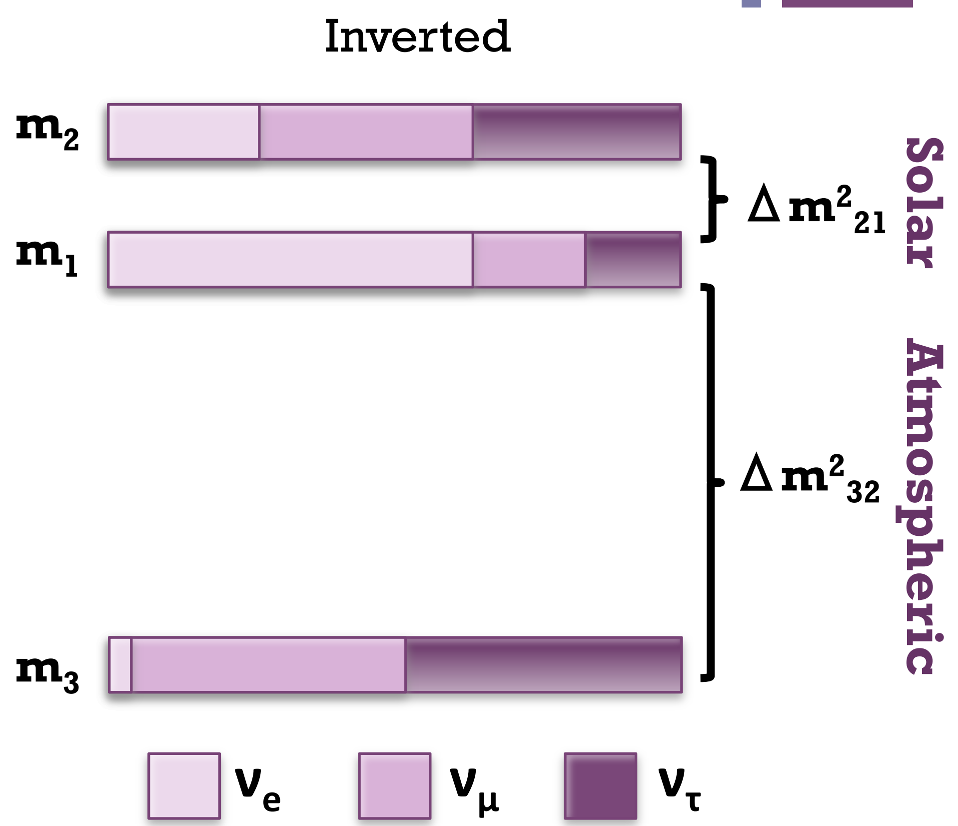

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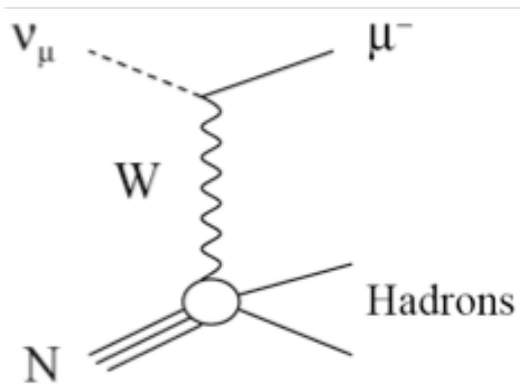
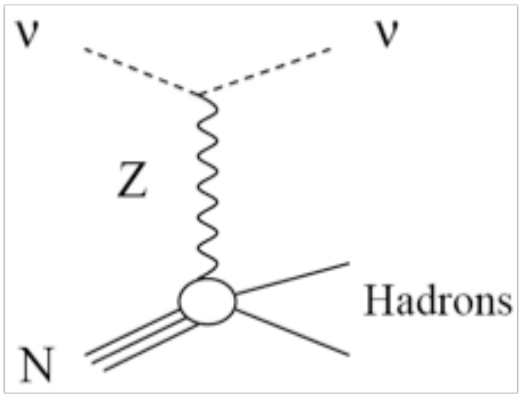
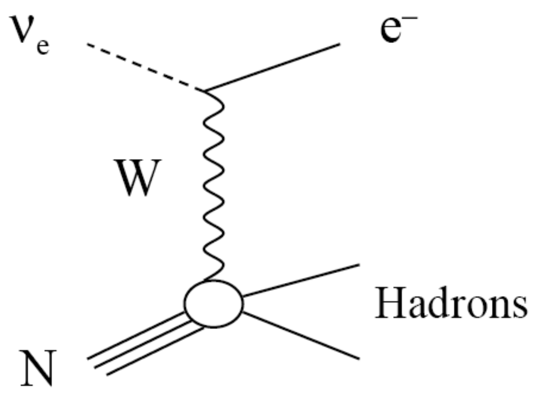
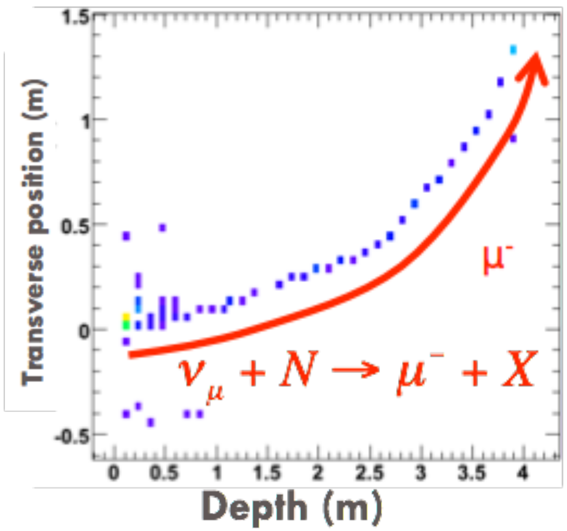
+ Event Topologies

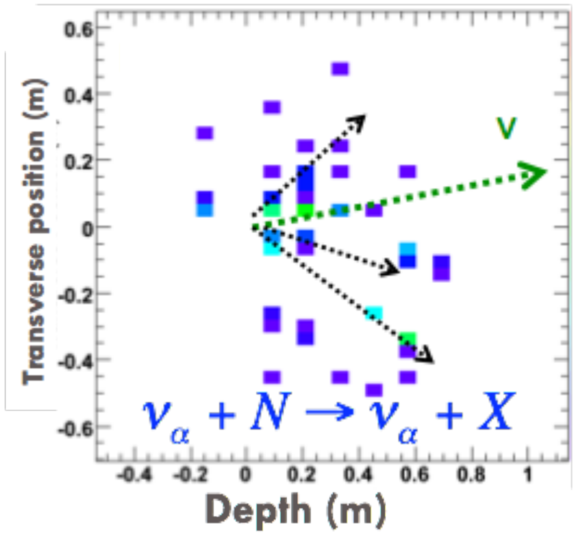
ν_μ Charged Current (CC)	**Neutral Current (NC)**	**ν_e Charged Current (CC)**

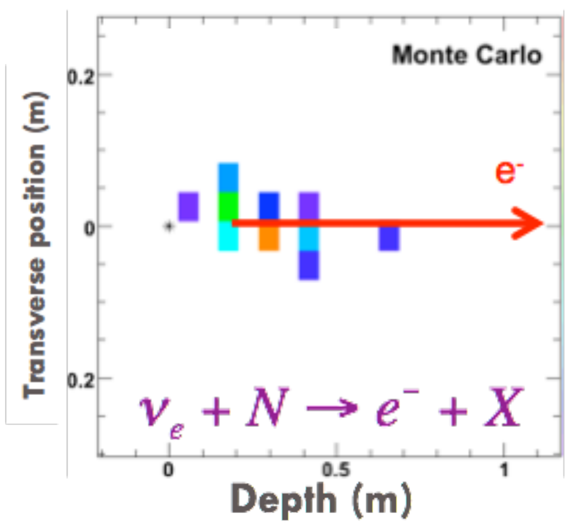






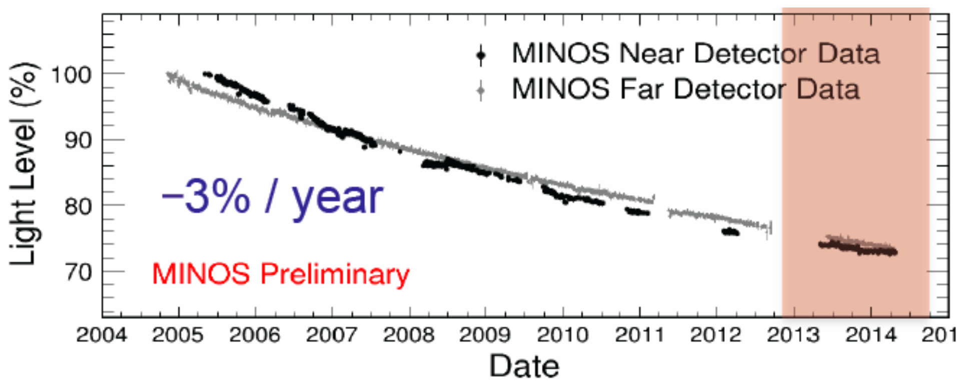




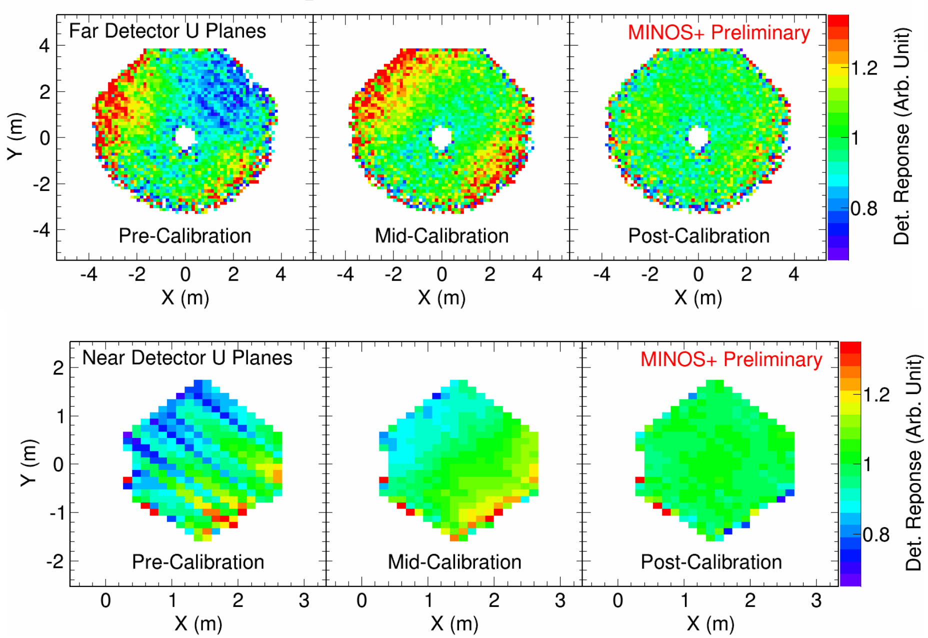


Calibration and Stability

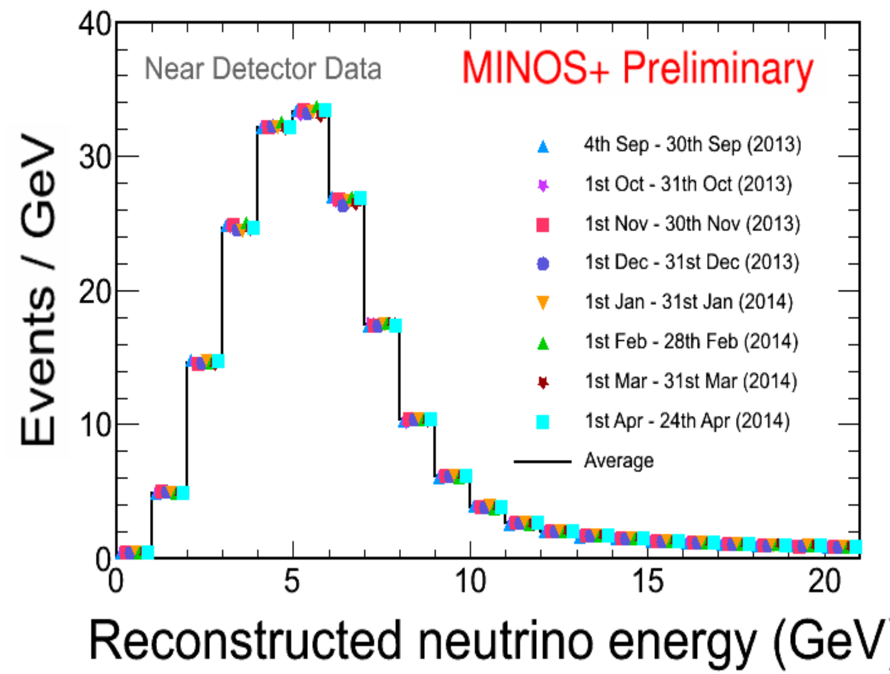
Light Level vs time:



Uniformity across detector face:

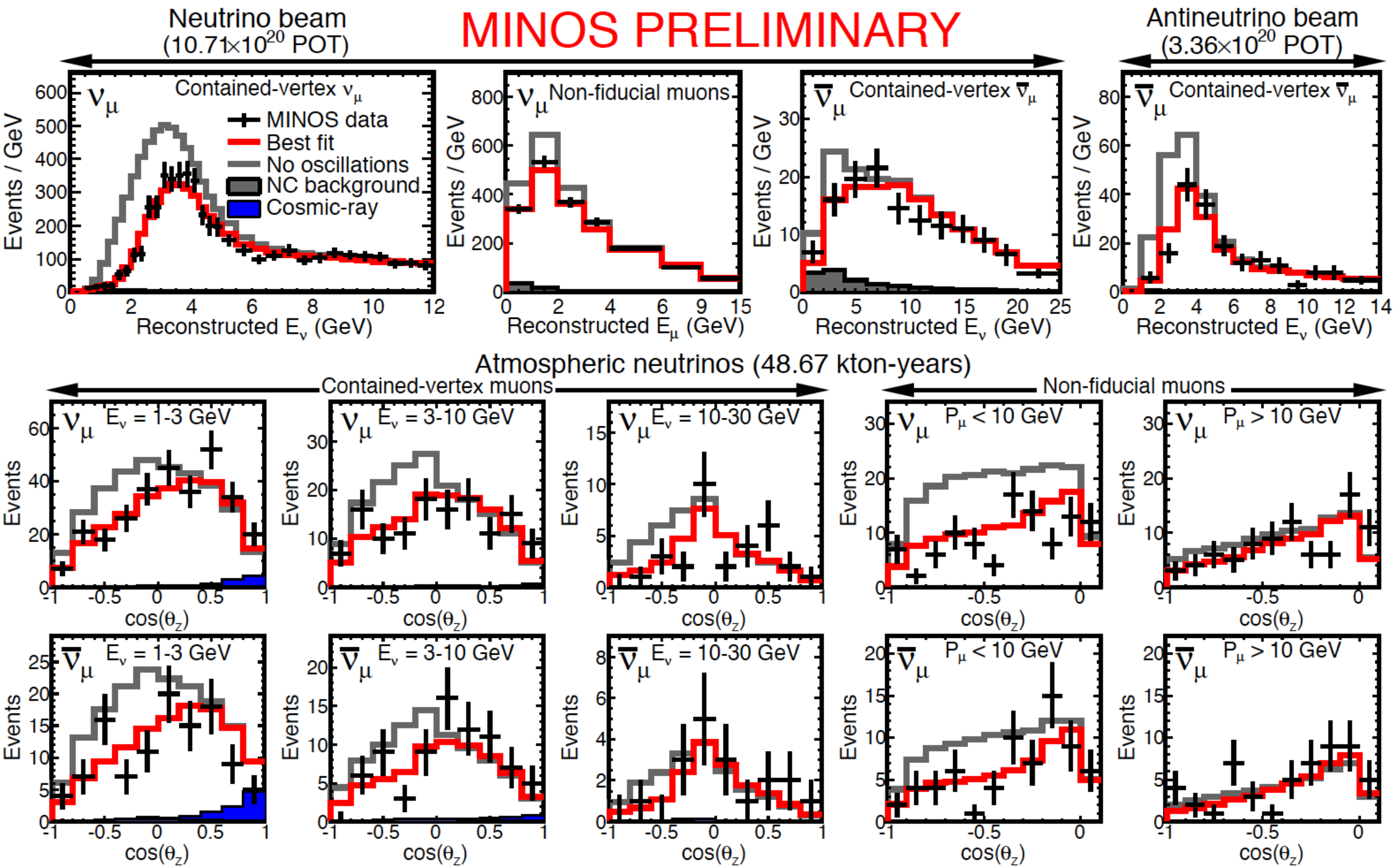


Spectrum vs. Time:

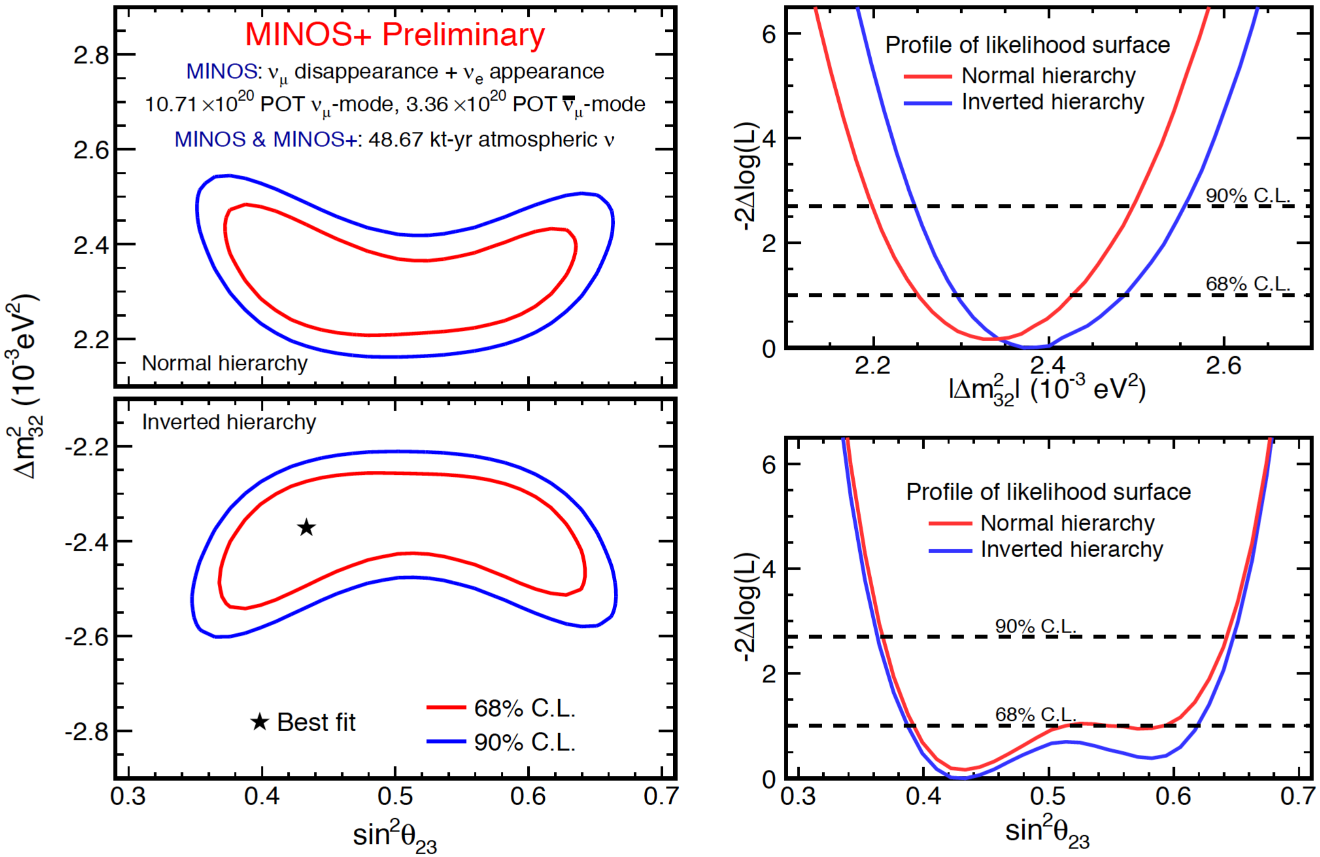


>95% Live-time!

3-Flavor Complete Dataset



Combined Fit Details



- **Solar mixing parameters**: fixed to $\Delta m^2_{21} = 7.54\times10^{-5}$ eV^2 and $\sin^2\theta_{12} = 0.307$
- **Nue appearance**: θ_{13} used as nuisance parameter, with range of reactor results: $\sin^2\theta_{13} = 0.0242 \pm 0.0025$ (θ_{13}=8.95°) from Fogli et al., PRD **86**, 013012 (2012)
- **Other parameters:** δ_{CP} , θ_{23}, Δm^2_{32} unconstrained
- **Systematic errors**: 19 systematic uncertainties (4 for beam+15 for atmospherics) included as nuisance parameters

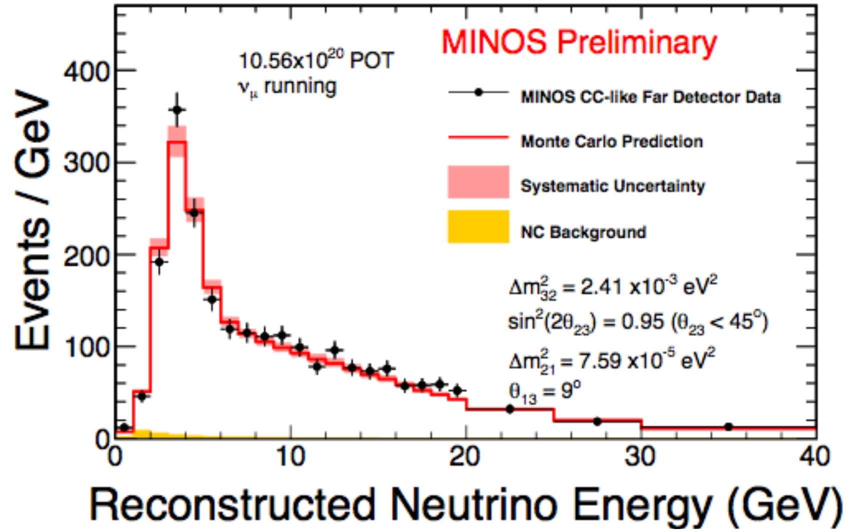
Disappearance NC Analysis

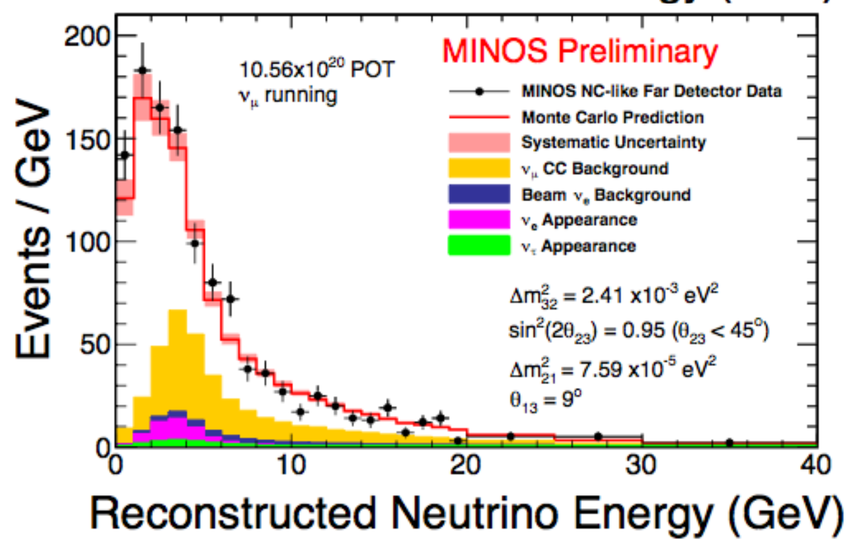
- 2721 ν_μ-CC-like events in FD
- 1221 NC-like events in FD

Predicted CC background from all flavors

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

Predicted NC interaction signal



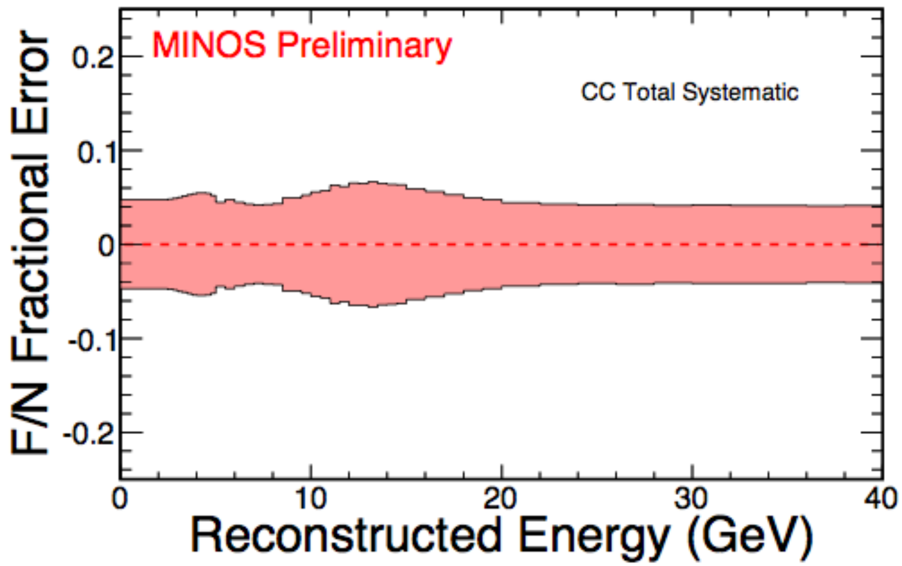


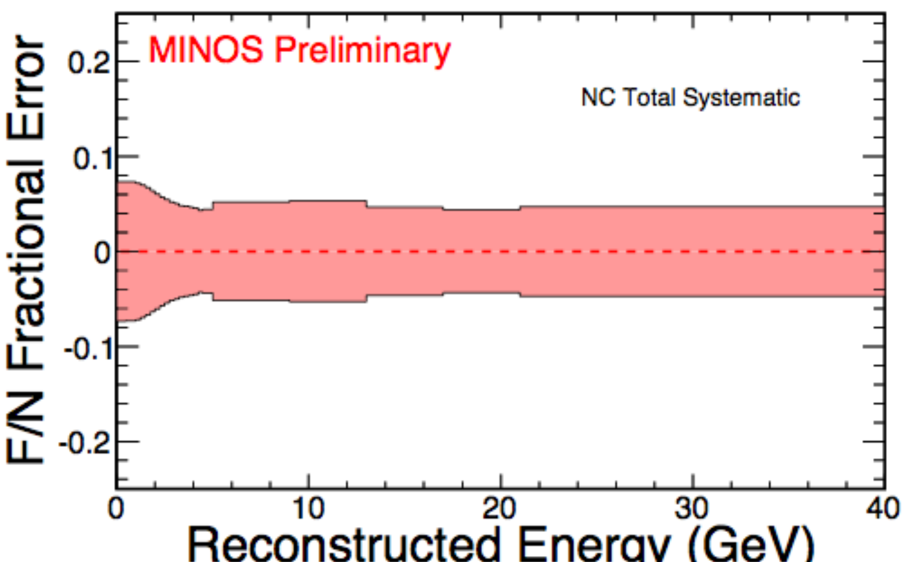
+ Disappearance NC Analysis

Energy Range (GeV)	R Value	stats +/-	sys +/-	total +/-
~~0 - 200~~				
0 - 40	1.075	0.047	0.096	0.107
0 - 3	1.109	0.062	0.073	0.096
3 - 40	1.043	0.070	0.130	0.148

No evidence for Sterile Oscillations

+ Sterile Fit Systematic Errors





- 26 systematic uncert., including:
  - Normalization
  - Detector acceptance
  - NC selection
  - Hadron production, beam optics, cross sections, energy scale, and backgrounds
- Incorporate via 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

e_i : Predicted events in bin i

V : Covariance matrix