First MINOS+ Data and New Results from MINOS

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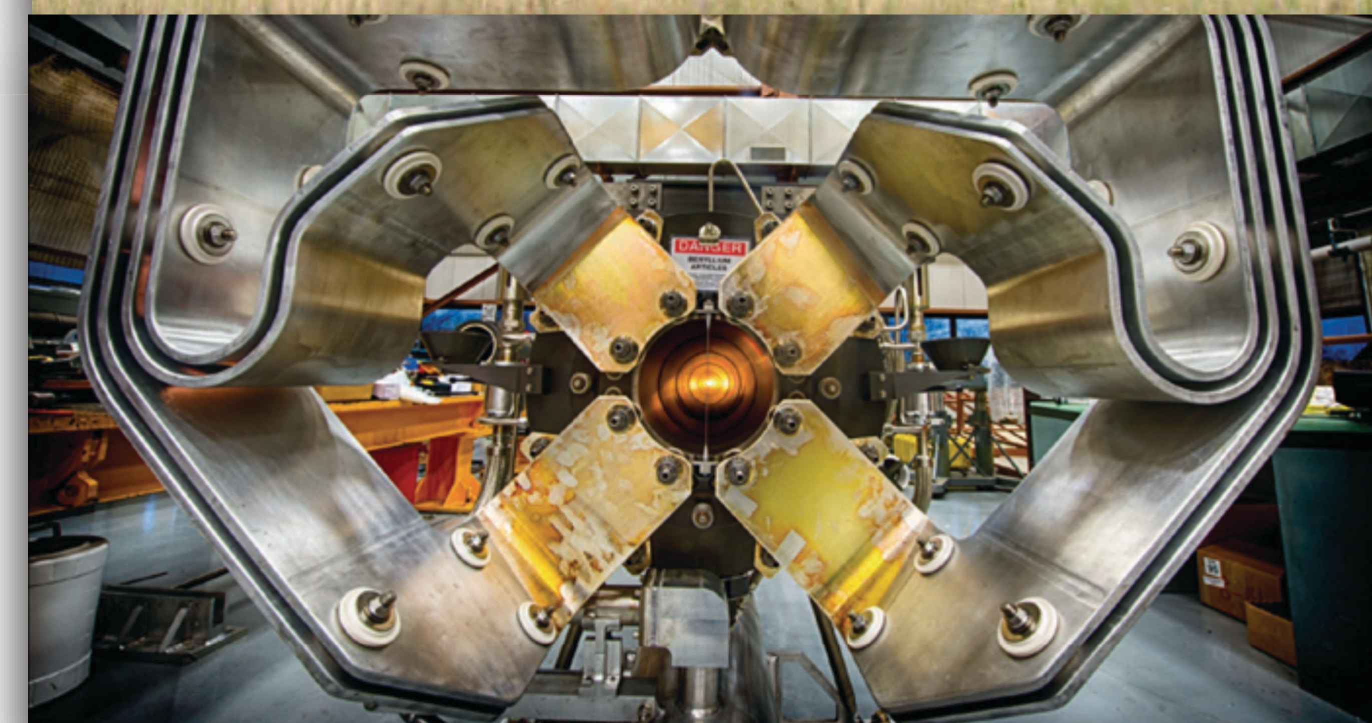
Outline

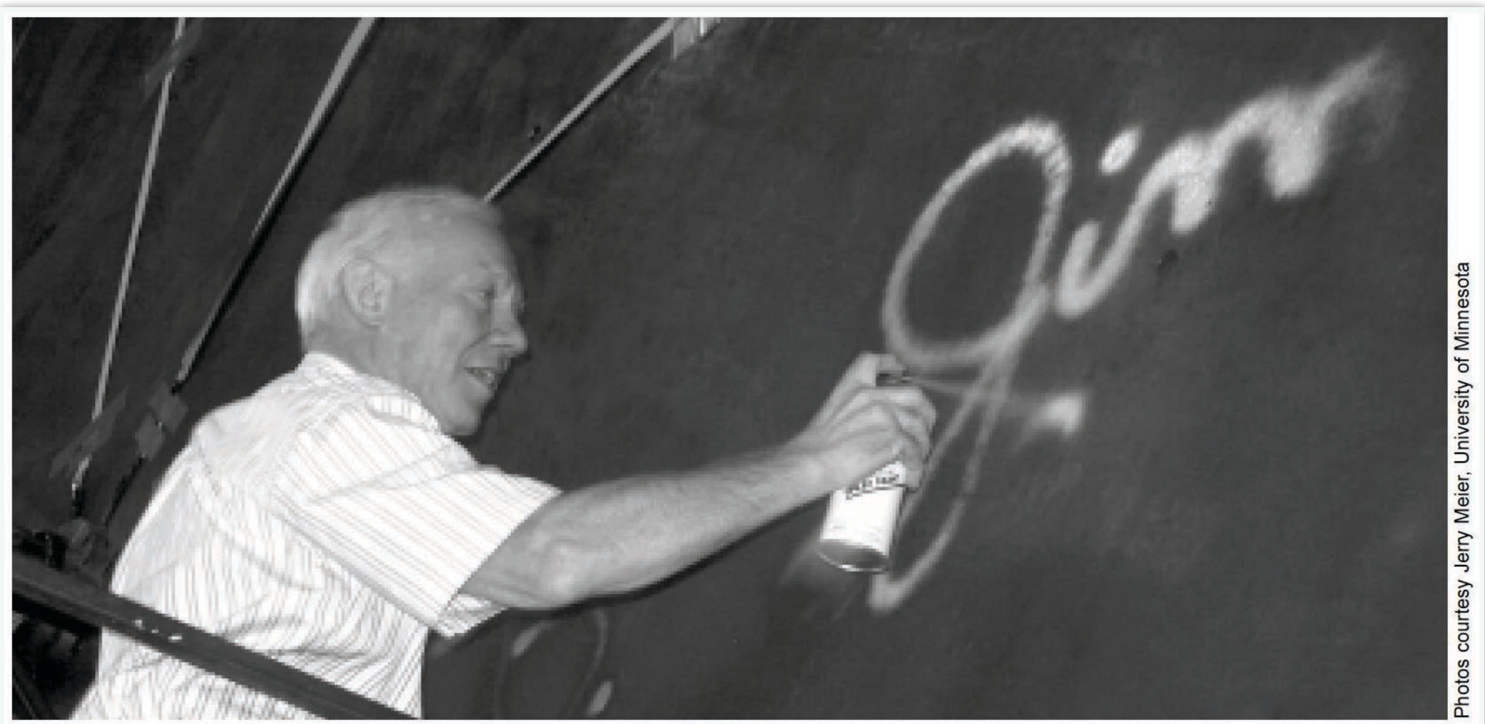
- Introduction to MINOS+
- First MINOS+ Data
  - Measurement of Three-Flavor Neutrino Oscillations
- New Results from MINOS
  - Non-Standard Interactions
  - Search for Sterile Neutrinos
- Summary



In Memoriam

James L. "Jim" Oberstar (1934-2014)

US Representative, Minnesota's 8th Congressional District (1975-2011)



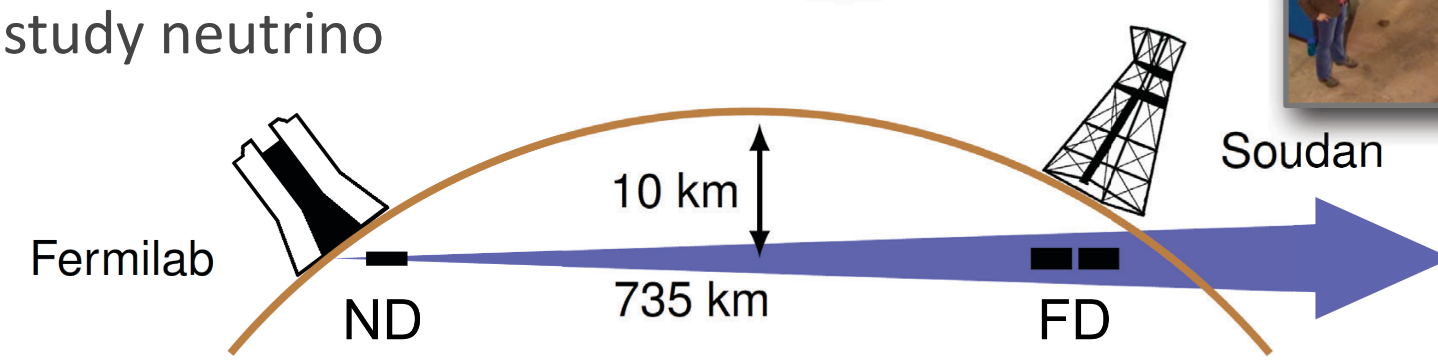
"The MINOS project (…) is a bold, visionary initiative which will have profound implications for our understanding of the structure and evolution of the universe."

- Jim Oberstar, NuMI/MINOS Dedication Ceremony, Fermilab, March 4, 2005

The MINOS+ Concept

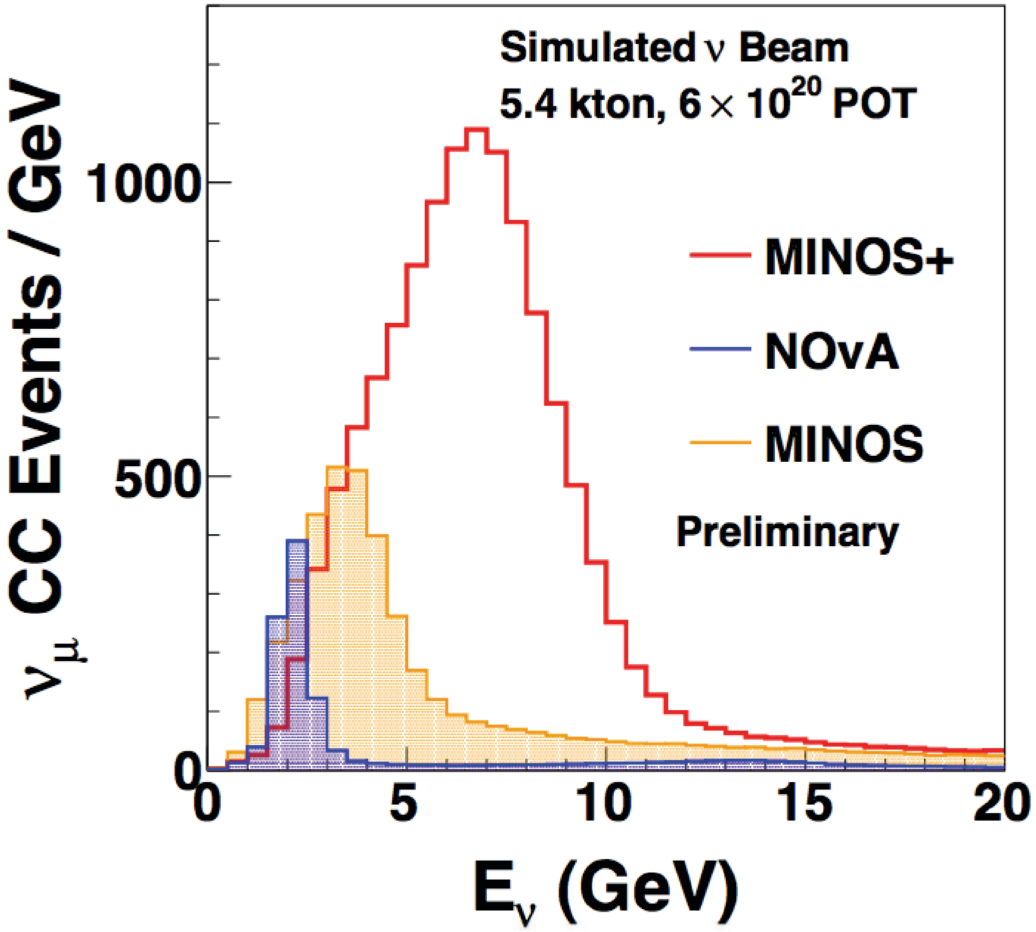
- Long-baseline neutrino oscillation experiment
- Measure NuMI Neutrino beam energy and flavor composition with two detectors over 735 km
    - L/E ~ 500 km/GeV

- Near Detector at Fermilab
- Far Detector at Soudan Underground Lab, MN
- Compare Near and Far measurements to study neutrino mixing



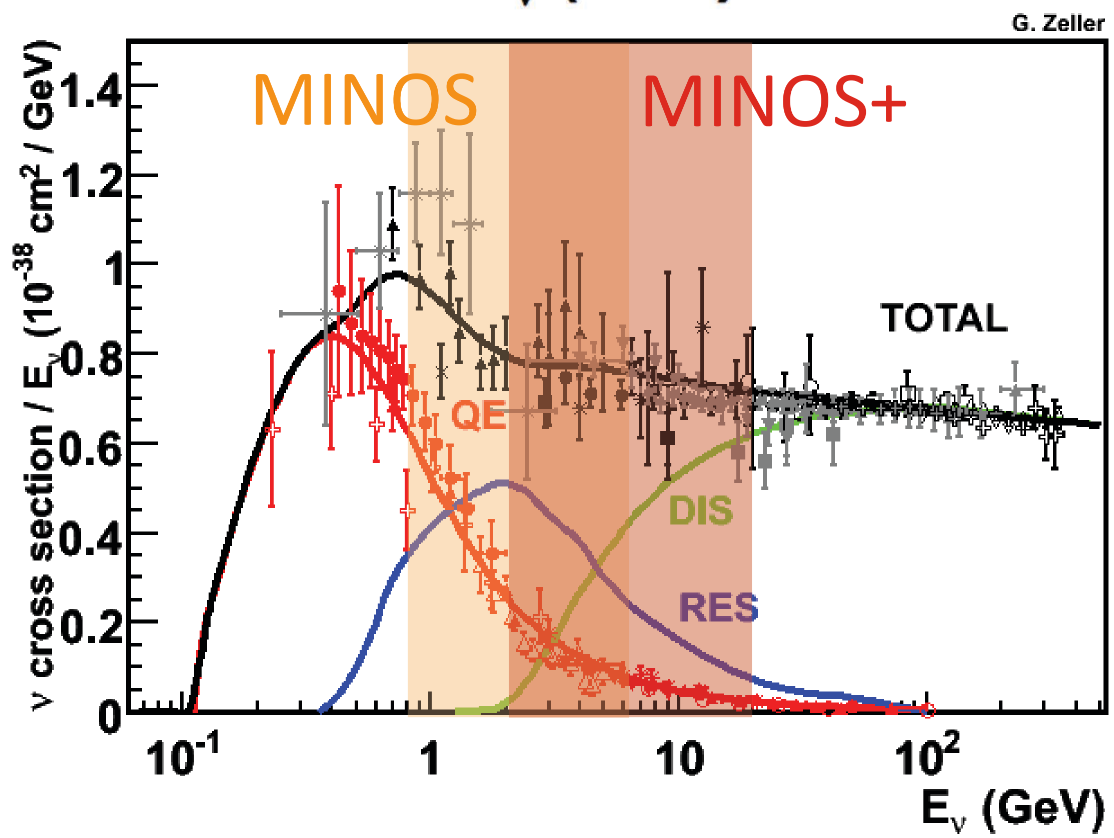
The MINOS+ Concept

- + ⟹ **New Neutrino Beam**
  - Run the MINOS detectors concurrently with NOvA operations with updated NuMI beam



- + ⟹ **More Statistics**
  - Expect ~4000 ν_μ CC events/year at the FD

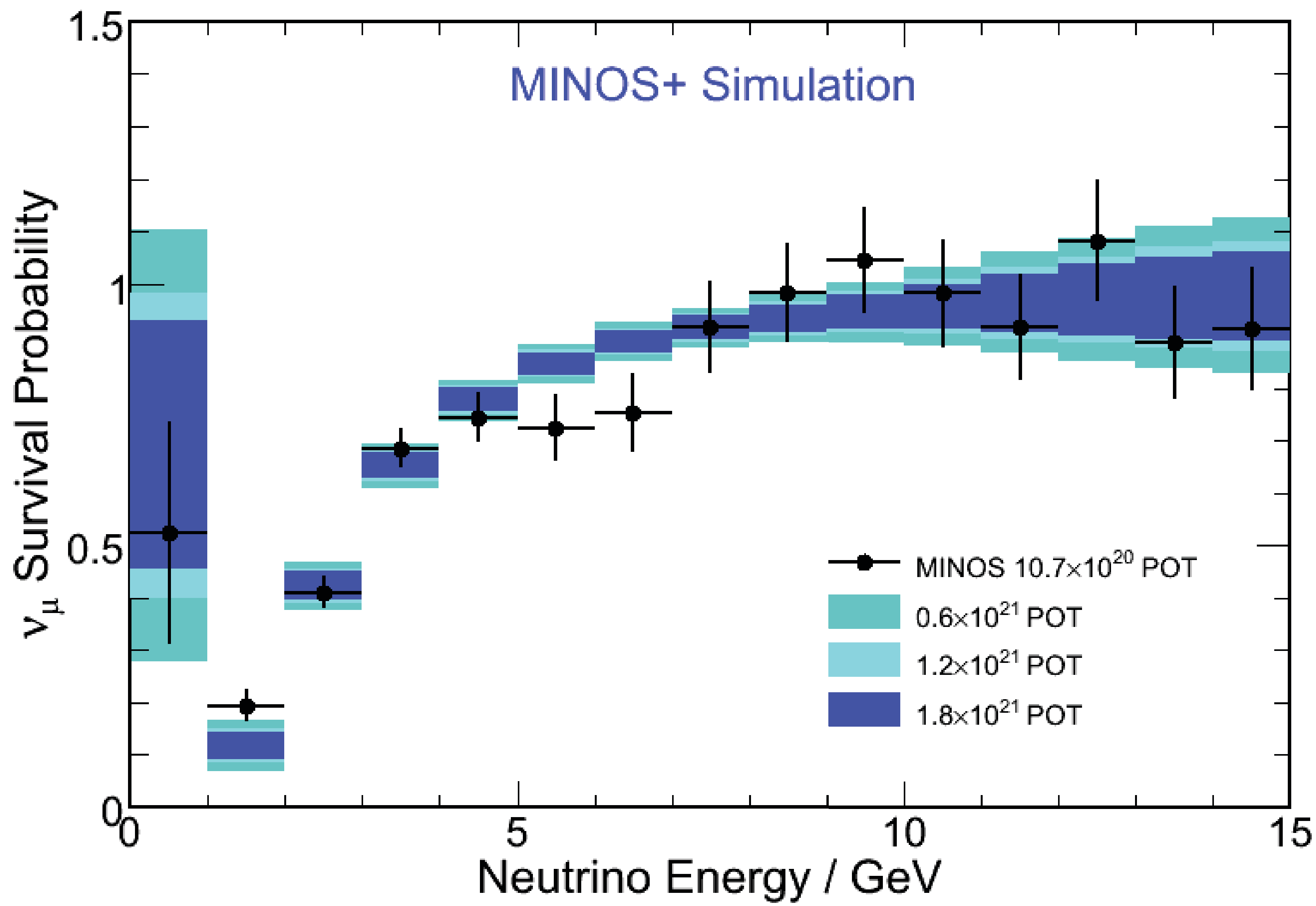
- + ⟹ **Higher Energy**
  - Cross-check MINOS in different energy region
  - With different beam and cross section systematics



- + ⟹ **More Physics**
  - Only wide-band beam long-baseline experiment in operation during this decade
  - **Look for new physics!**

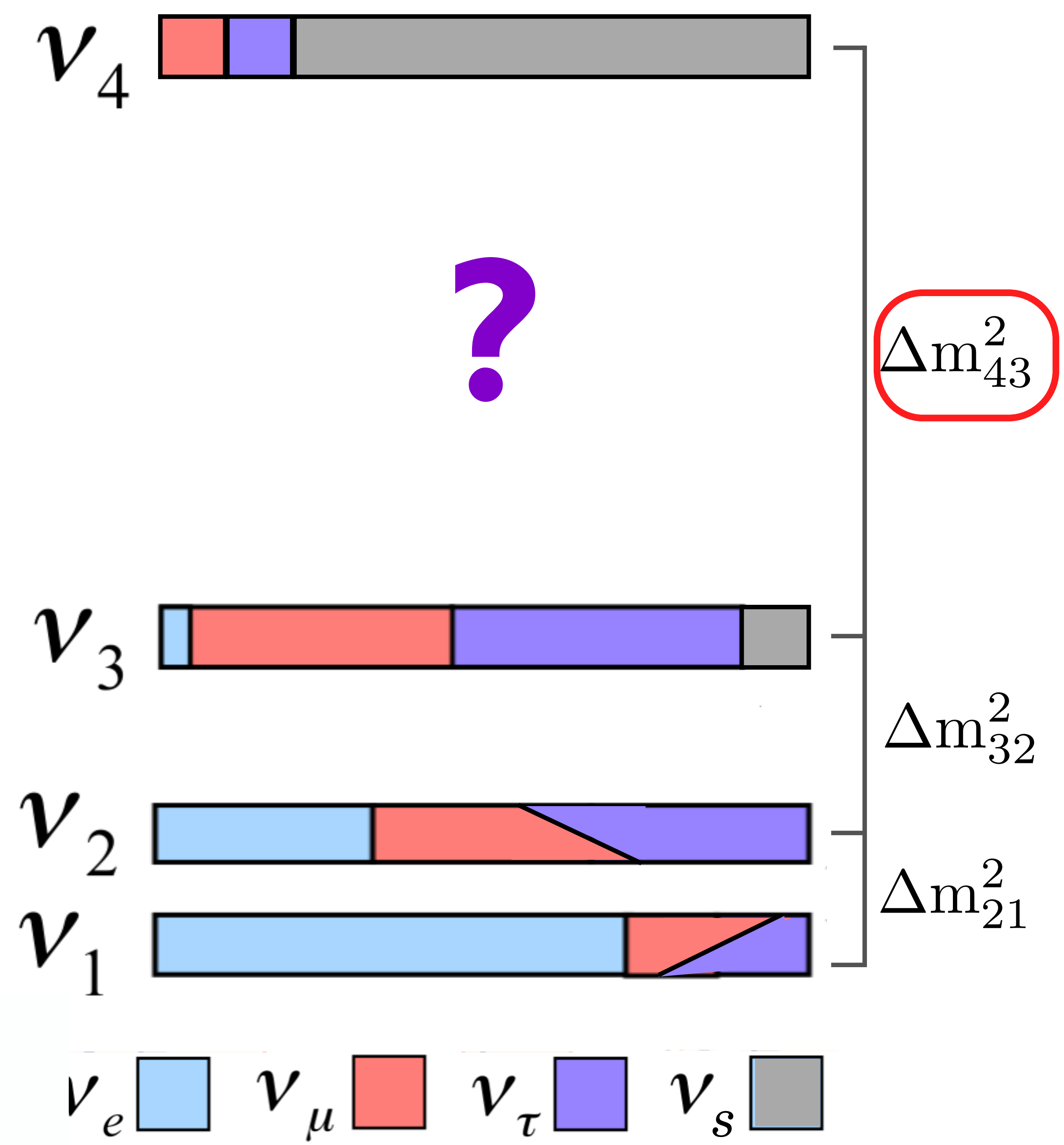
MINOS+ Physics

- Precision test of three-neutrino oscillation scenario



MINOS+ Physics

- Precision test of three-neutrino oscillation scenario
- Search for exotic phenomena
  - **Sterile neutrino mixing**
  - Non-standard interactions
  - Large extra-dimensions
  - Decoherence
  - Decay



MINOS+ Physics

- Precision test of three-neutrino oscillation scenario
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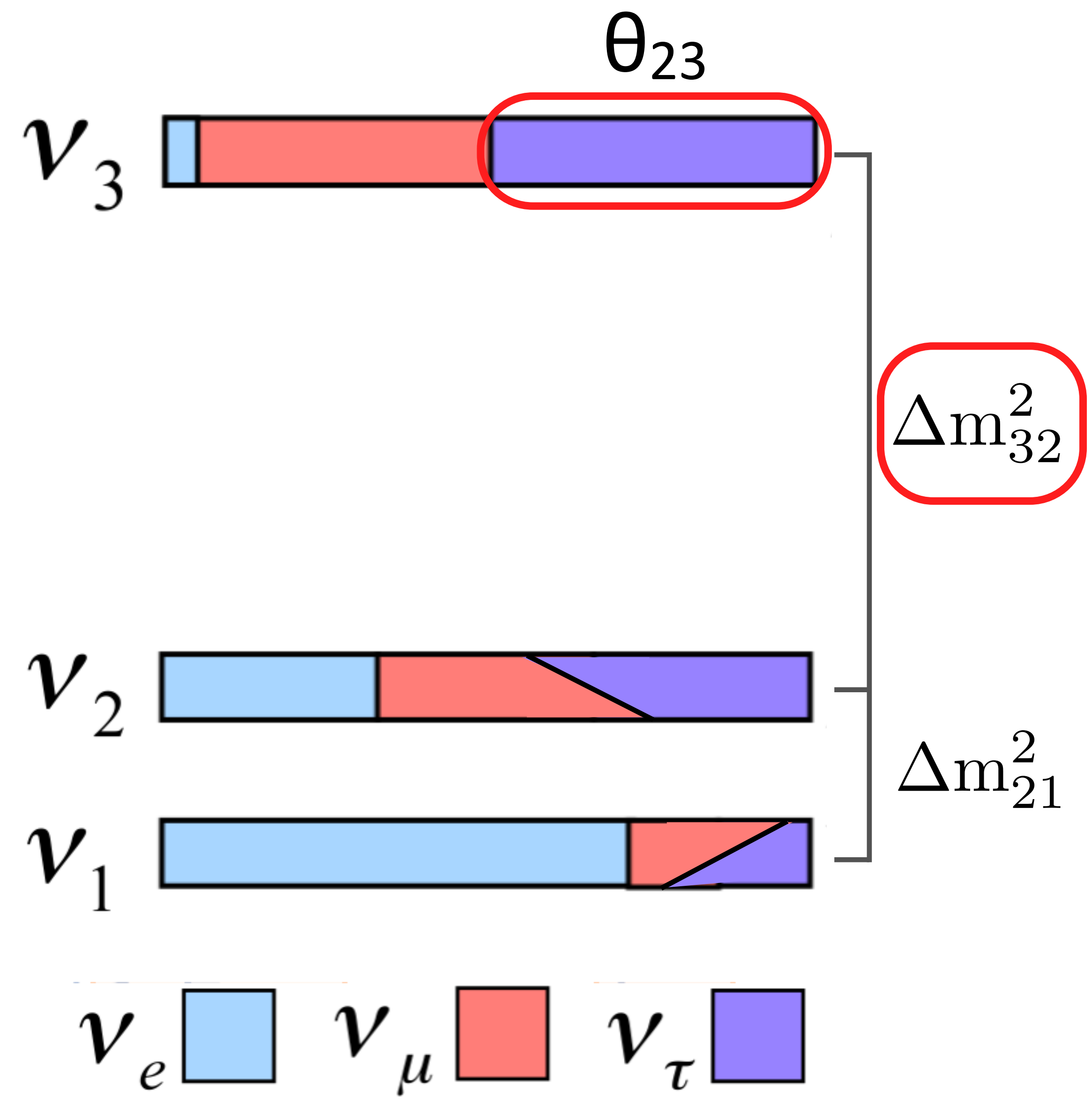
  - Decay
- Improve precision measurements of atmospheric sector oscillations



MINOS+ Physics

- Precision test of three-neutrino oscillation scenario
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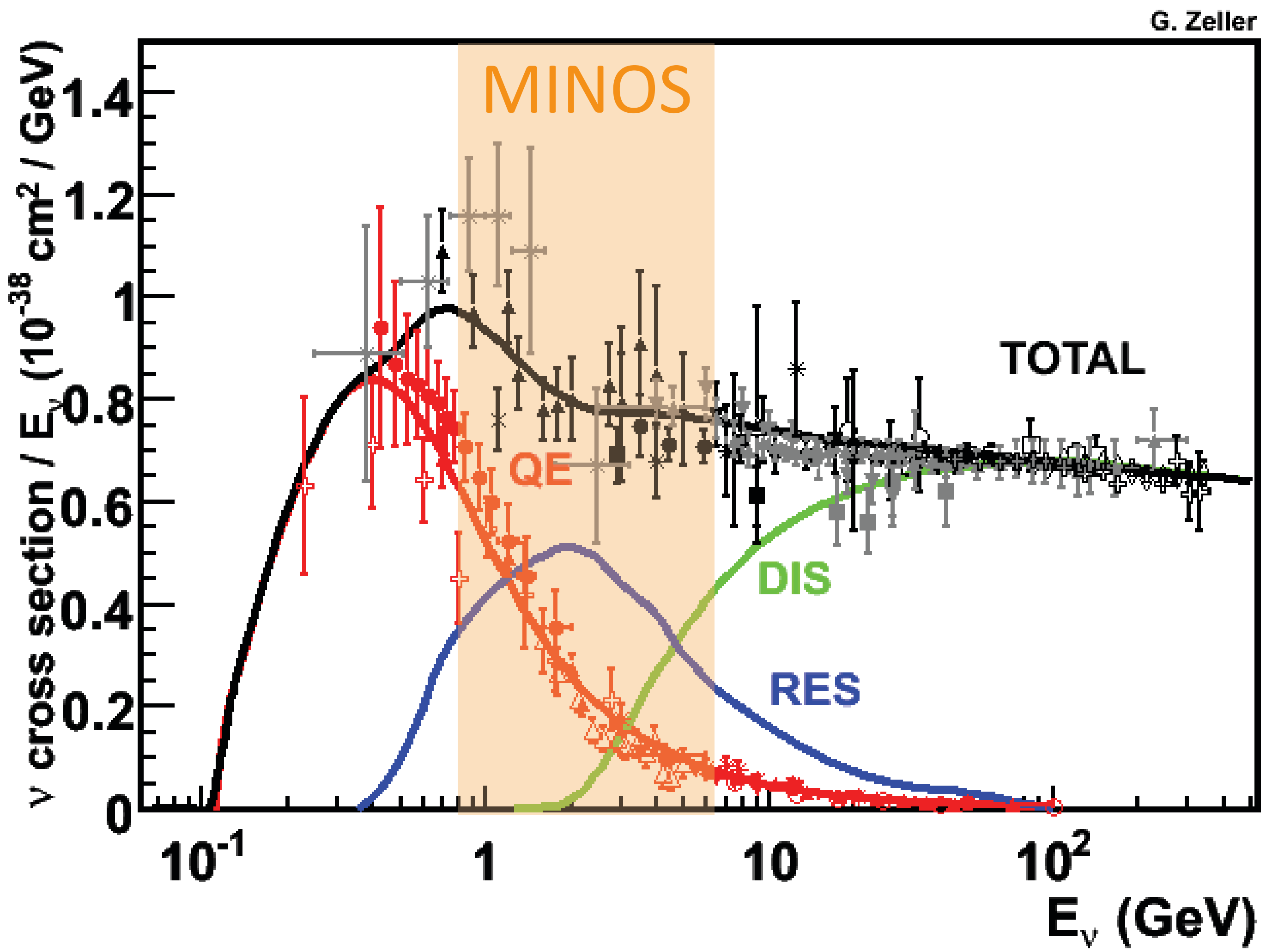
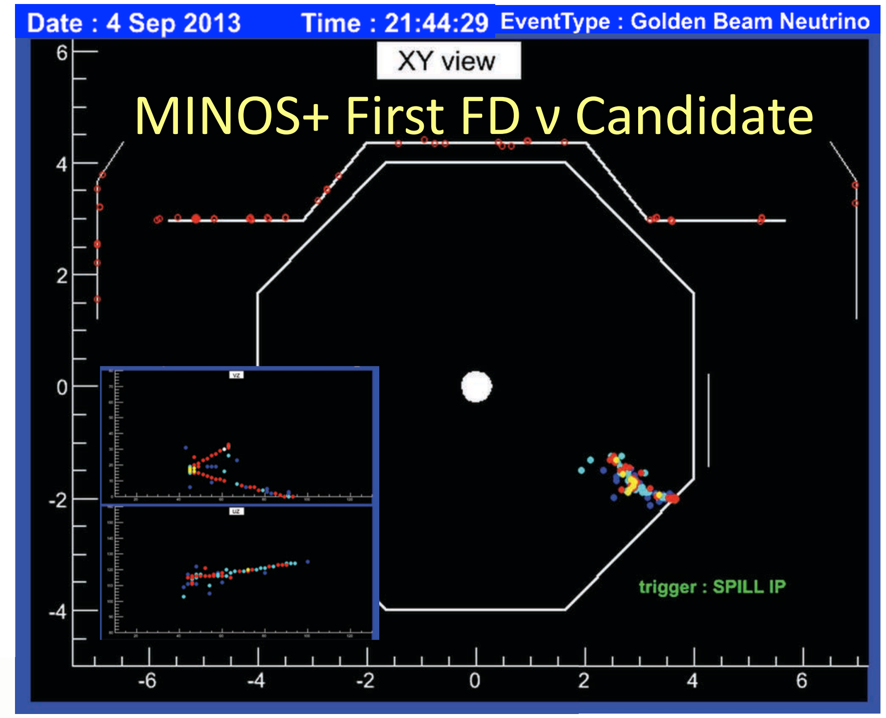
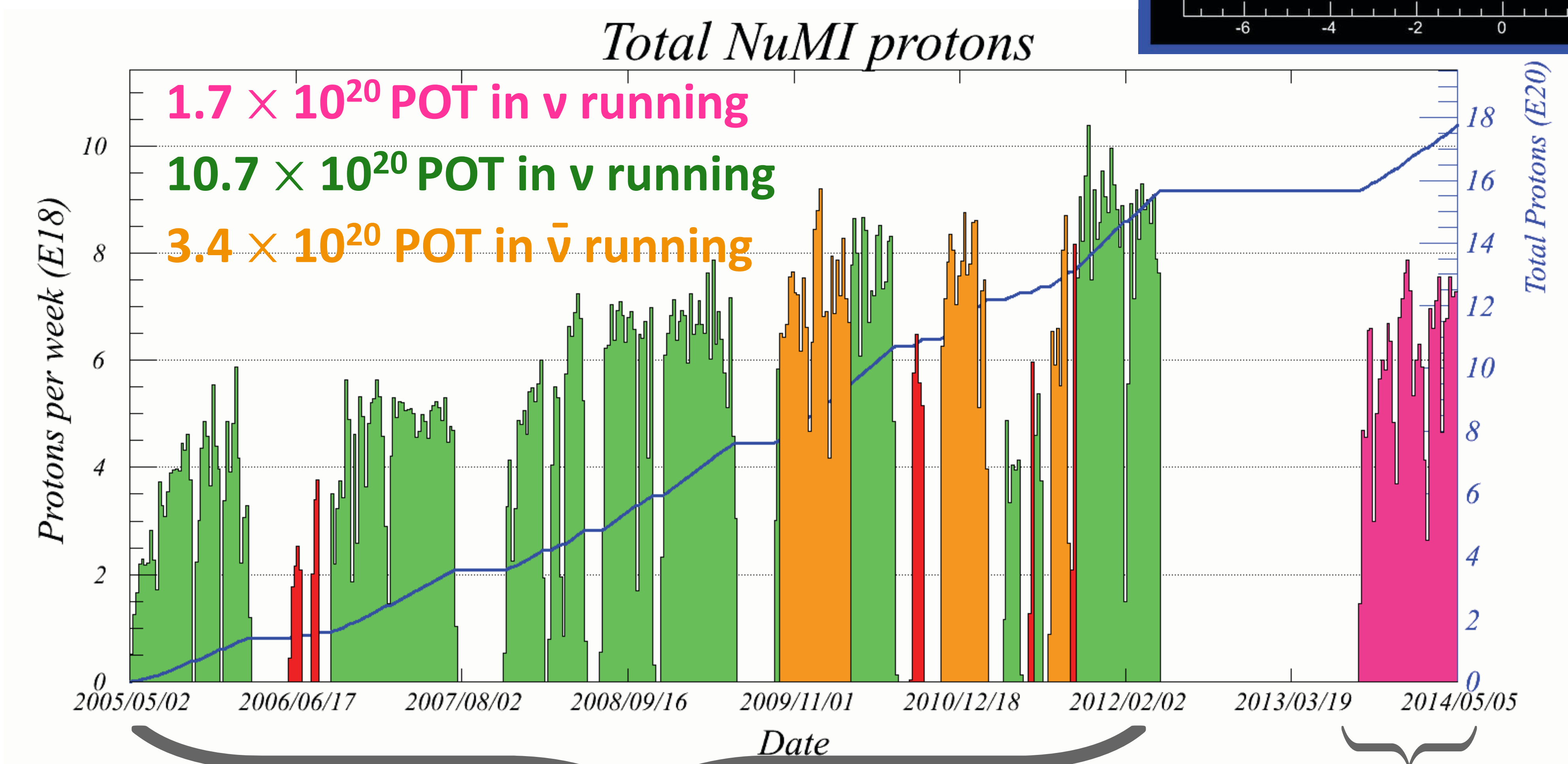


- **Cross-sections of neutrino interactions**, cosmic ray studies, Lorentz invariance tests,…

First MINOS+ Beam Data

- Upgraded NuMI beam returned in Sept. 4, 2013
  - Current (**Design**) beam running
  - 2.4×10^{13} (**5×10^{13}**) protons/pulse
  - 280 kW (**700 kW**) beam power
  - Beam spill every 1.7 s (**1.33 s**)



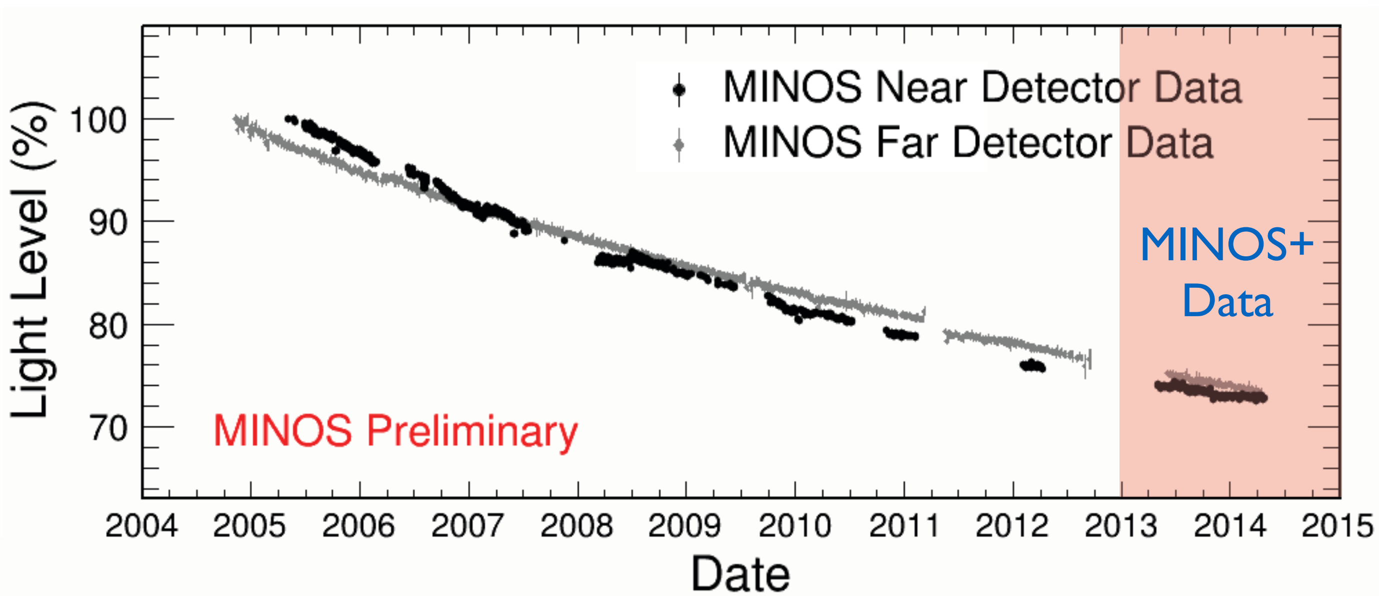


MINOS (2005-2012)

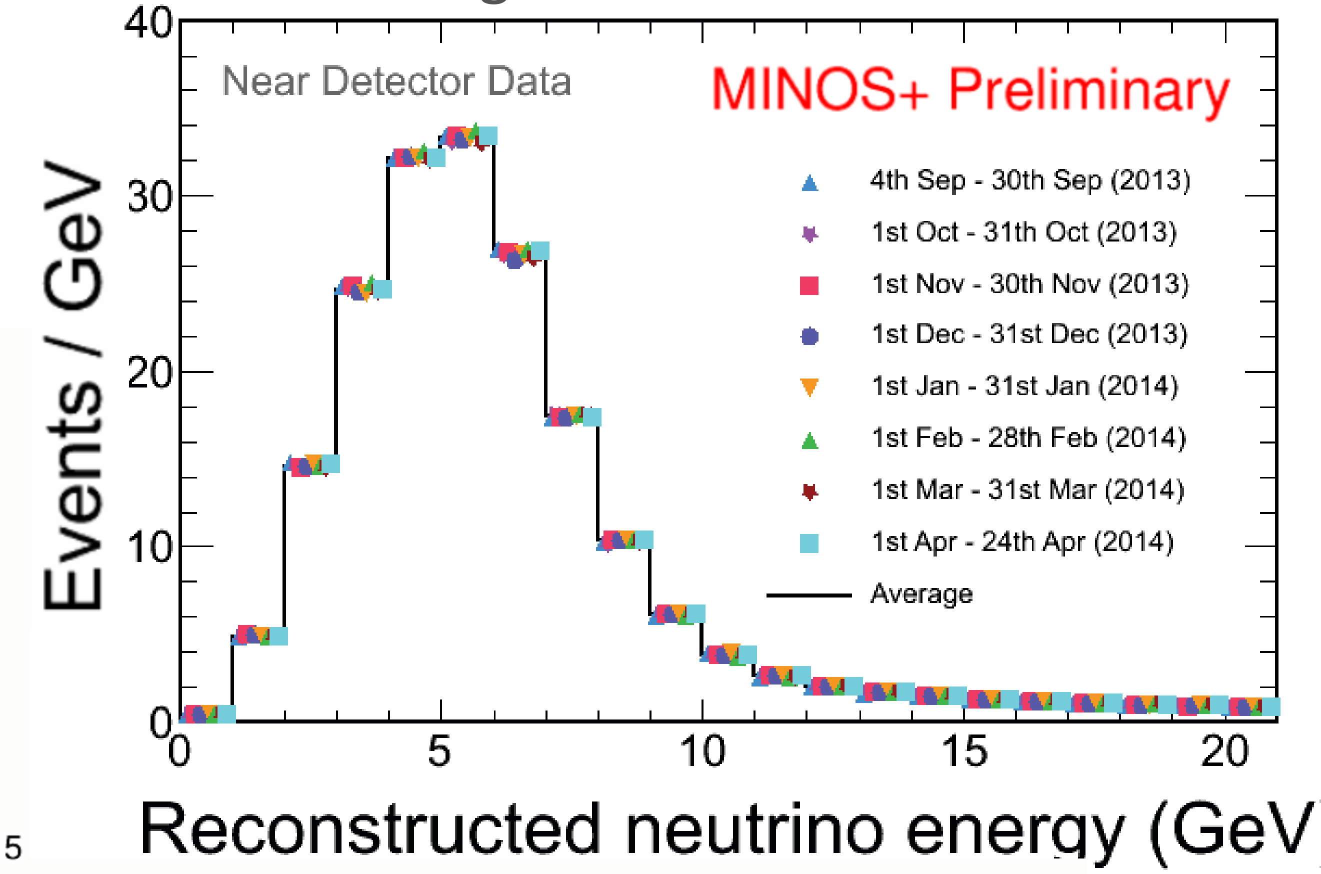
MINOS+

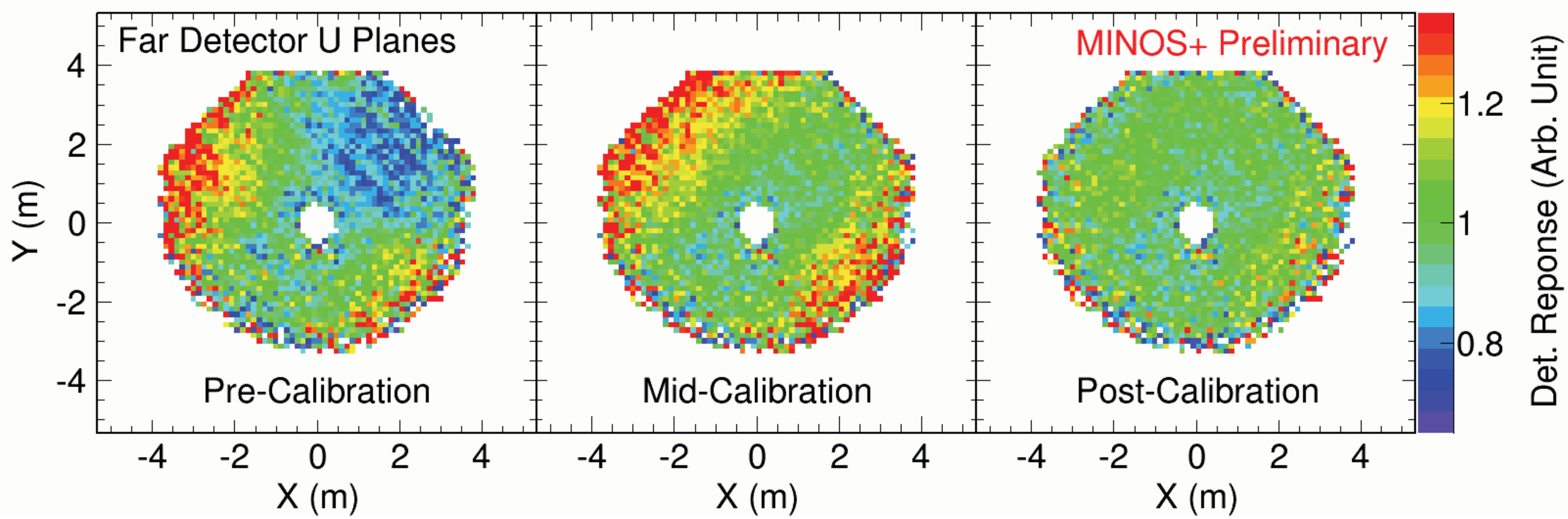
Data Calibration and Stability

- Detector response calibrated using light injection and cosmic ray muons
- ND CC-like energy spectrum stable over MINOS+ running



ND Charged-Current Event Selection



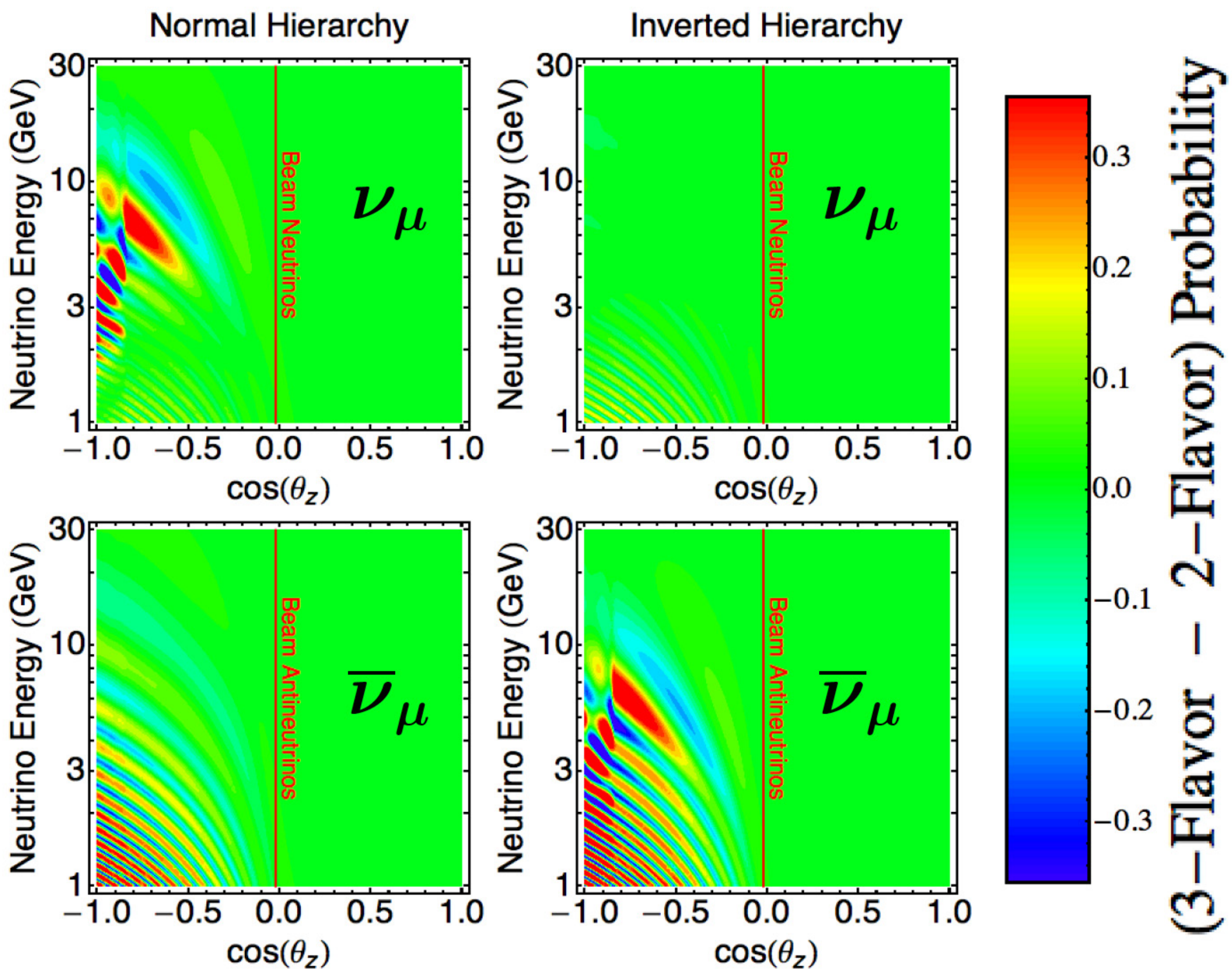


Three-Flavor Oscillation Measurement
-Update-

Three-Flavor Oscillation Analysis

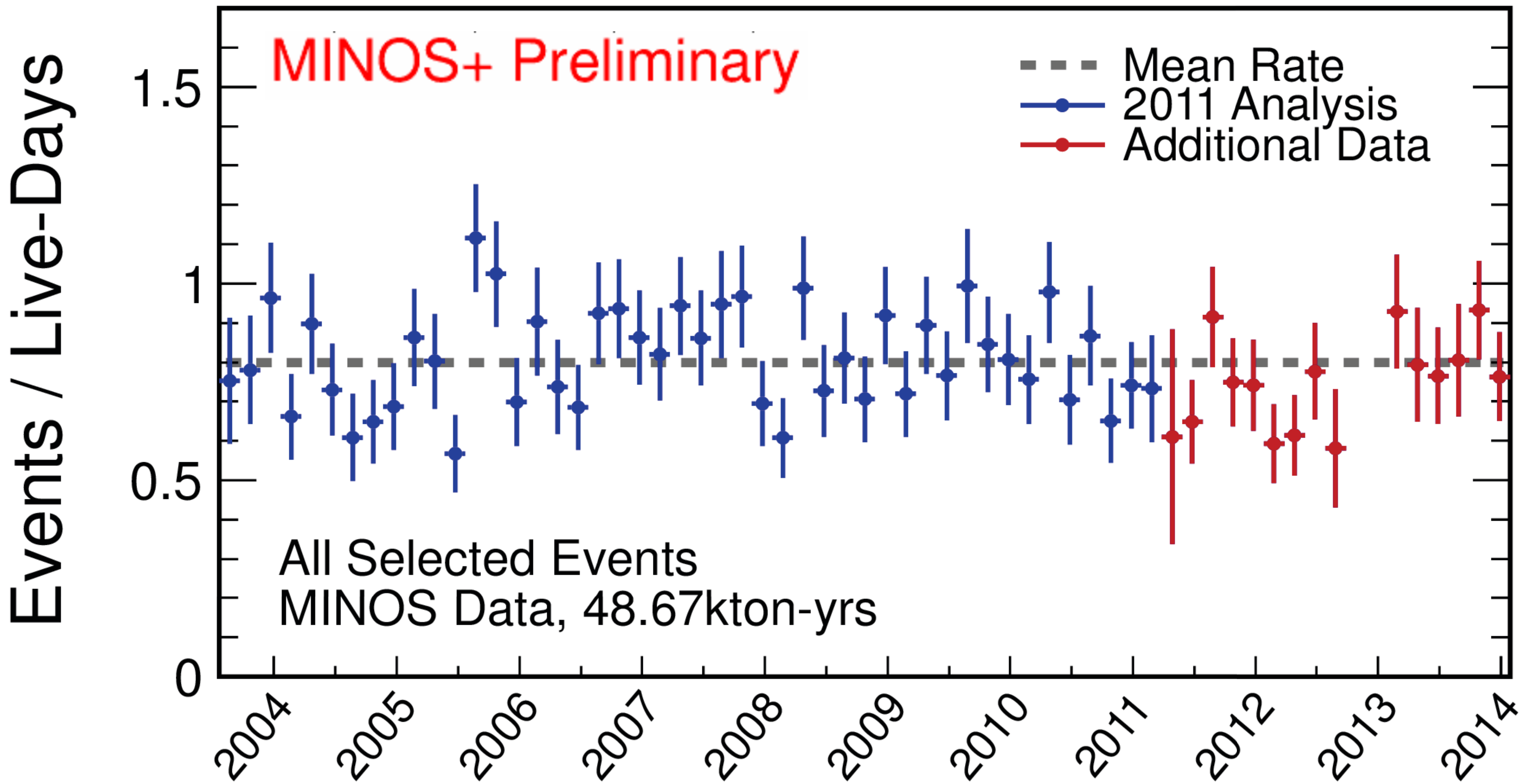
- Analysis combines:
  - Full MINOS ν_μ-CC and $\bar{\nu}_\mu$-CC disappearance sample - *PRL* ***112****, 191801 (2014)*
  - Full ν_e-CC, $\bar{\nu}_e$-CC appearance sample, described in *PRL* ***110*** *171801 (2013)*
  - Full MINOS and **new MINOS+ atmospheric neutrino samples**

- Sensitive to θ_{13}, θ_{23} octant, mass hierarchy, and δ_{CP} from ν_e sample
- Sensitivity enhanced by atmospherics:
  - Matter effects in multi-GeV, upward-going events
  - Effect seen in neutrinos or antineutrinos, depending on hierarchy
- MINOS first to probe effect with event-by-event charge separation



Atmospheric Neutrinos

- Including data taken during MINOS+ running, have accumulated 48.7 kton-years of atmospheric neutrinos in Far Detector between 2003 and 2014

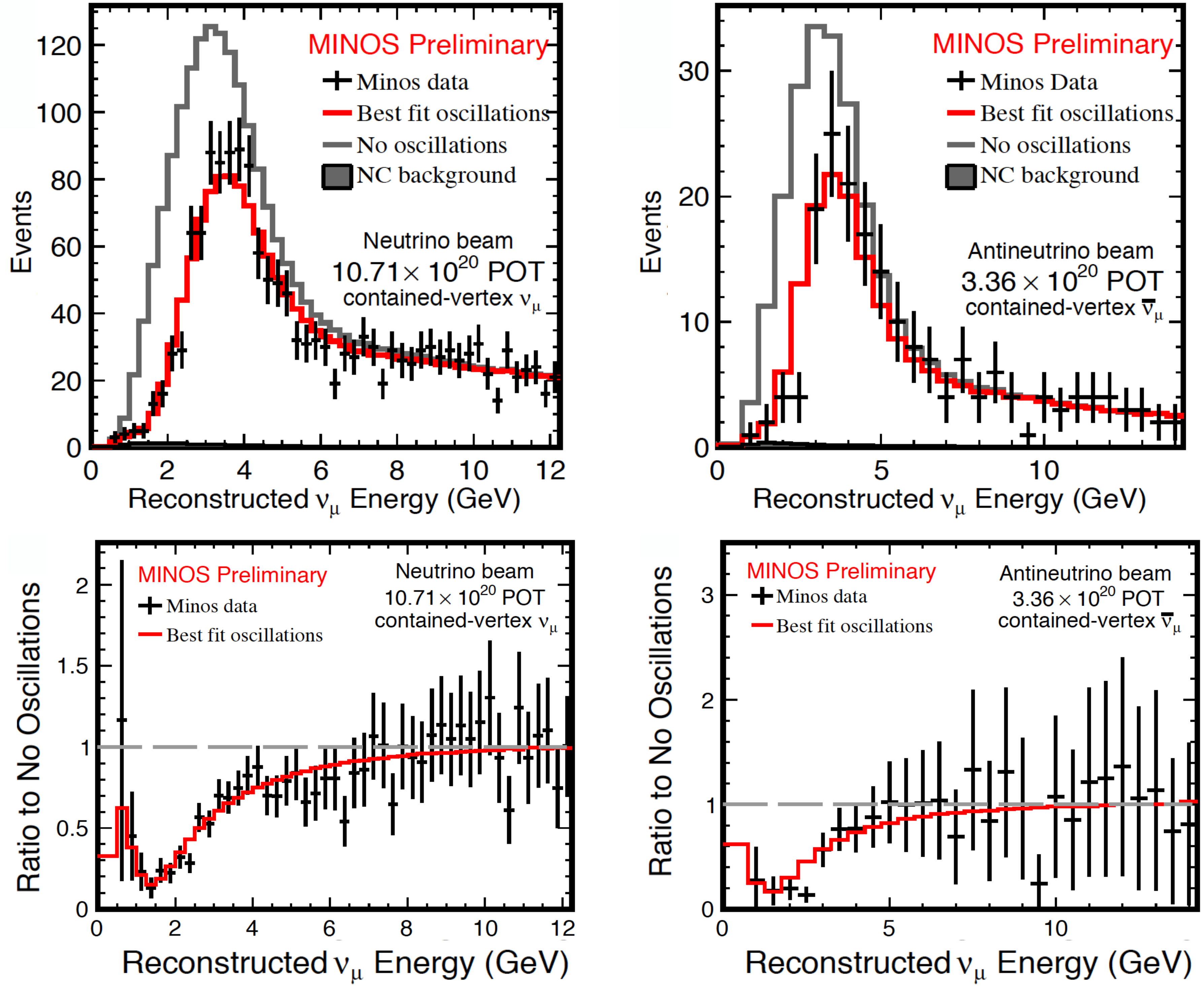


- Updating oscillation parameter measurement with increased atmospherics statistics
  - Additional 10.8 kton-year (+28%) over previous beam+atmospherics combined analysis [*PRL* ***112****, 191801 (2014)*]

MINOS FD Beam Data

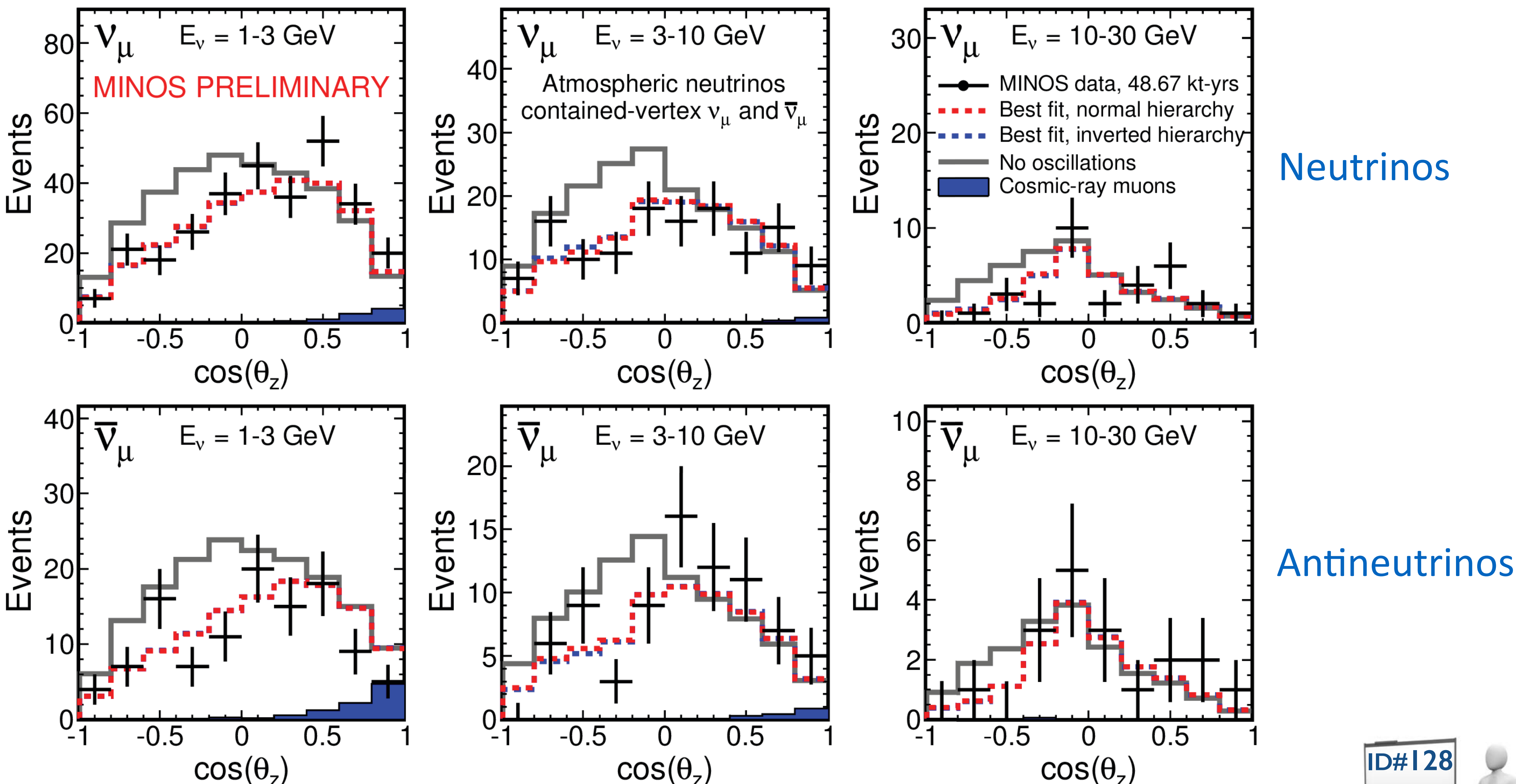
- Showing three-flavor oscillations fit to FD disappearance beam data

Neutrinos | Antineutrinos



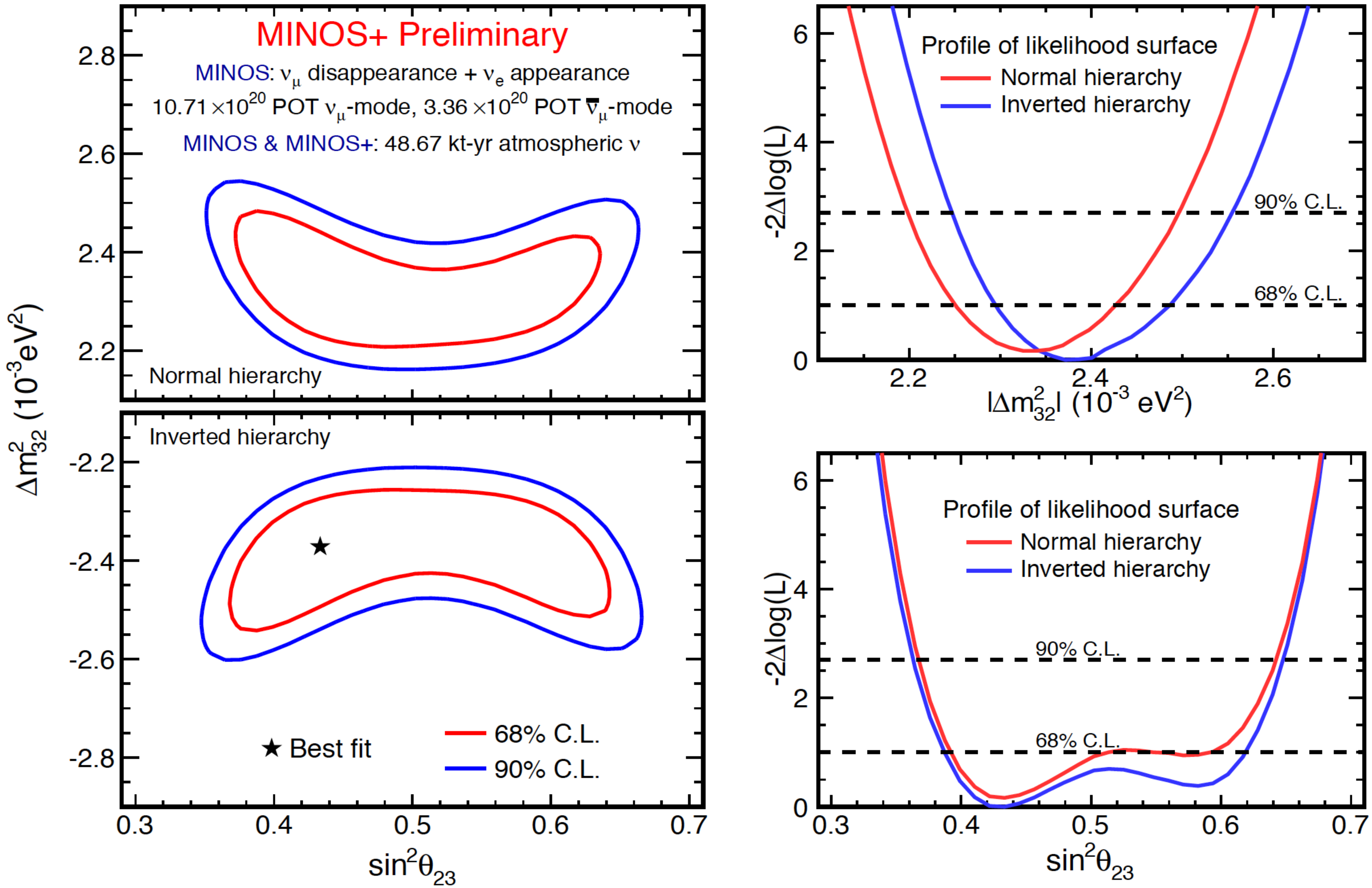
FD Atmospherics Data

- Showing three-flavor oscillations fit to FD atmospherics data



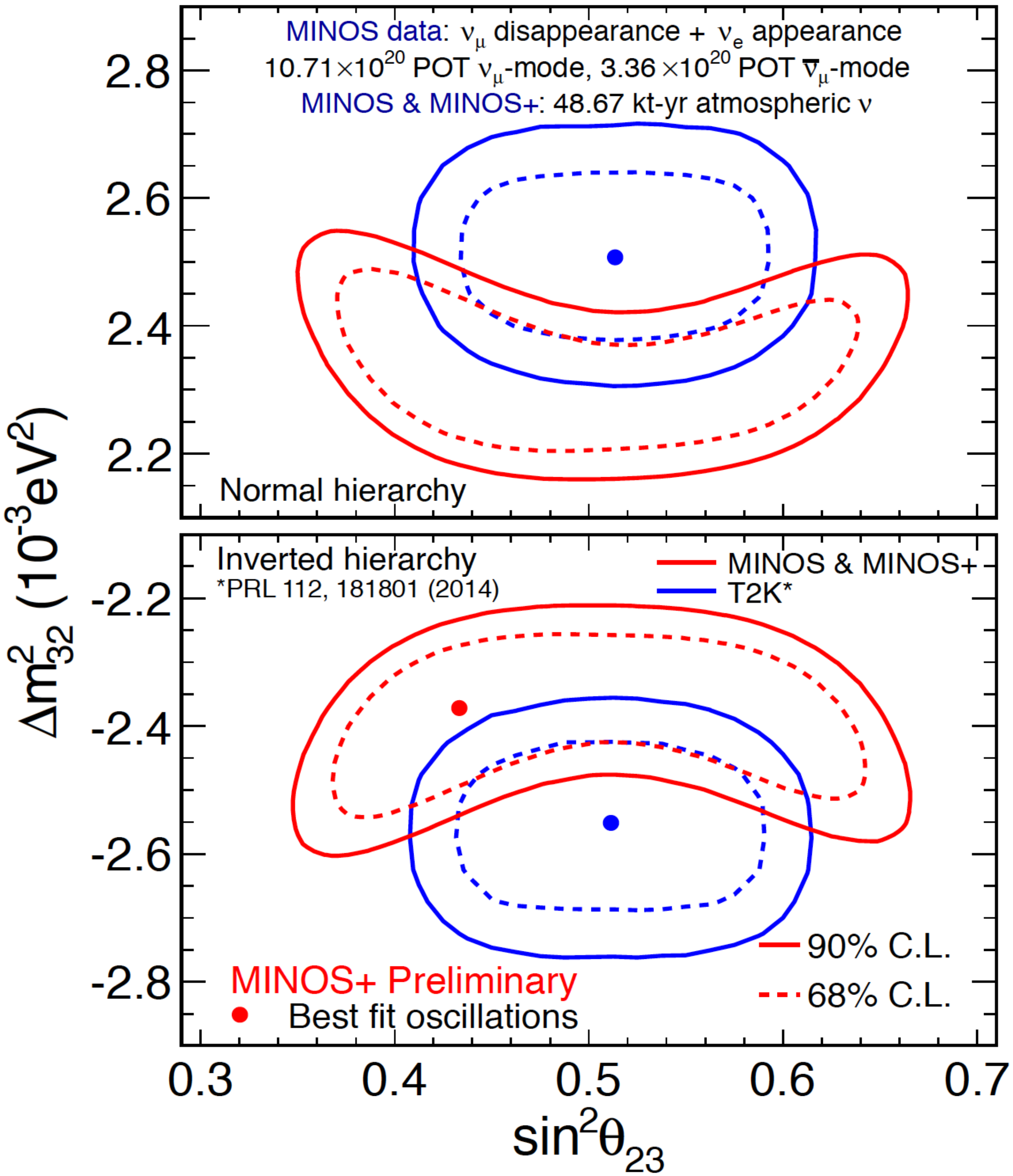
- Plots show several ranges of E_ν for contained-vertex ν_μ events
- Non-fiducial events also included in the fit

Combined Fit Allowed Regions



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

Combined Fit Results



Three-Flavor Oscillations 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

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

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

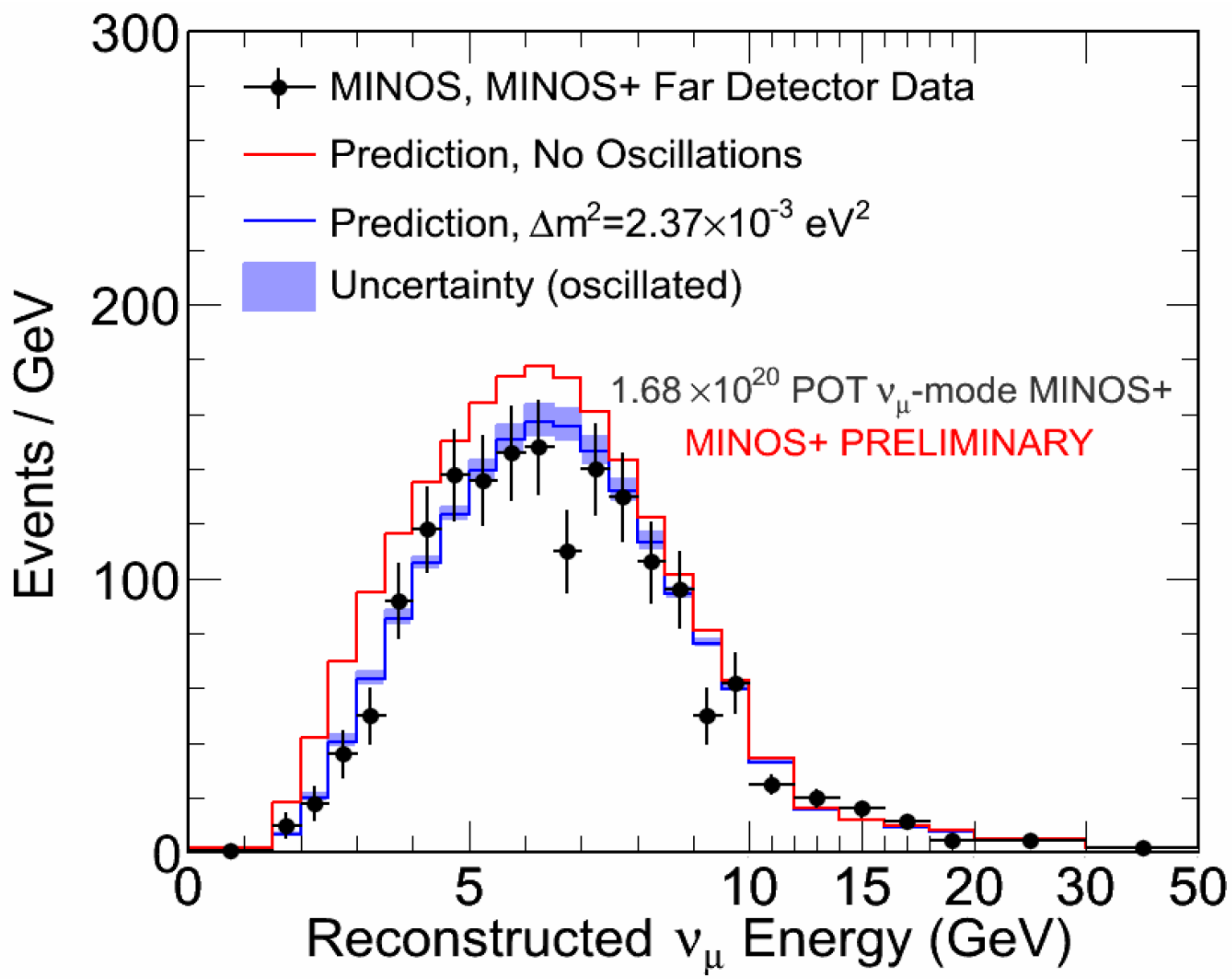
$$0.37 < \sin^2\theta_{23} < 0.64 \text{ (90\% C.L.)}$$

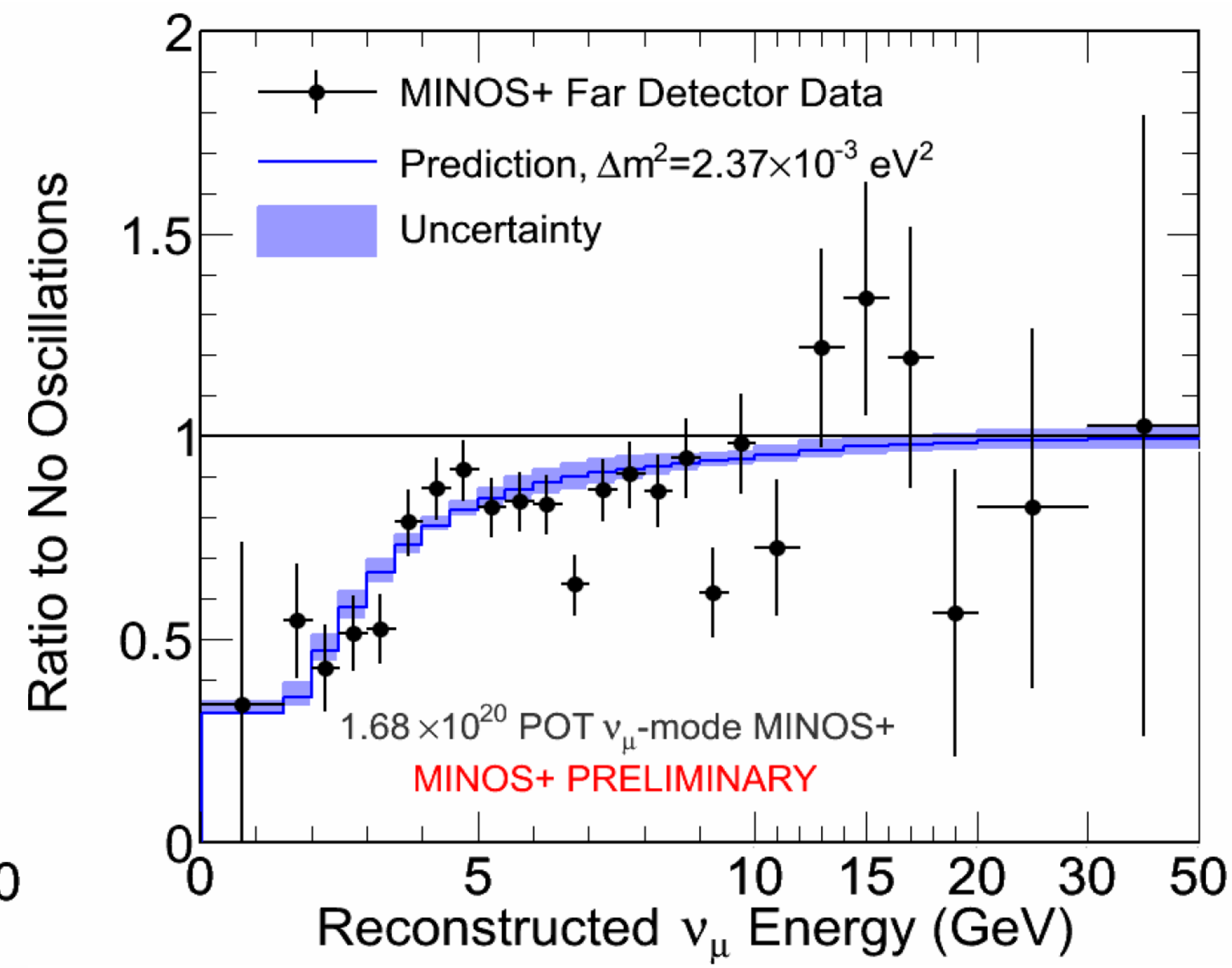
- **Most precise measurement of $|\Delta m^2_{32}|$**
- Consistent with maximal mixing

ID#131 MINOS+ POSTER

Far Detector Beam Data

MINOS+ FD Beam Data

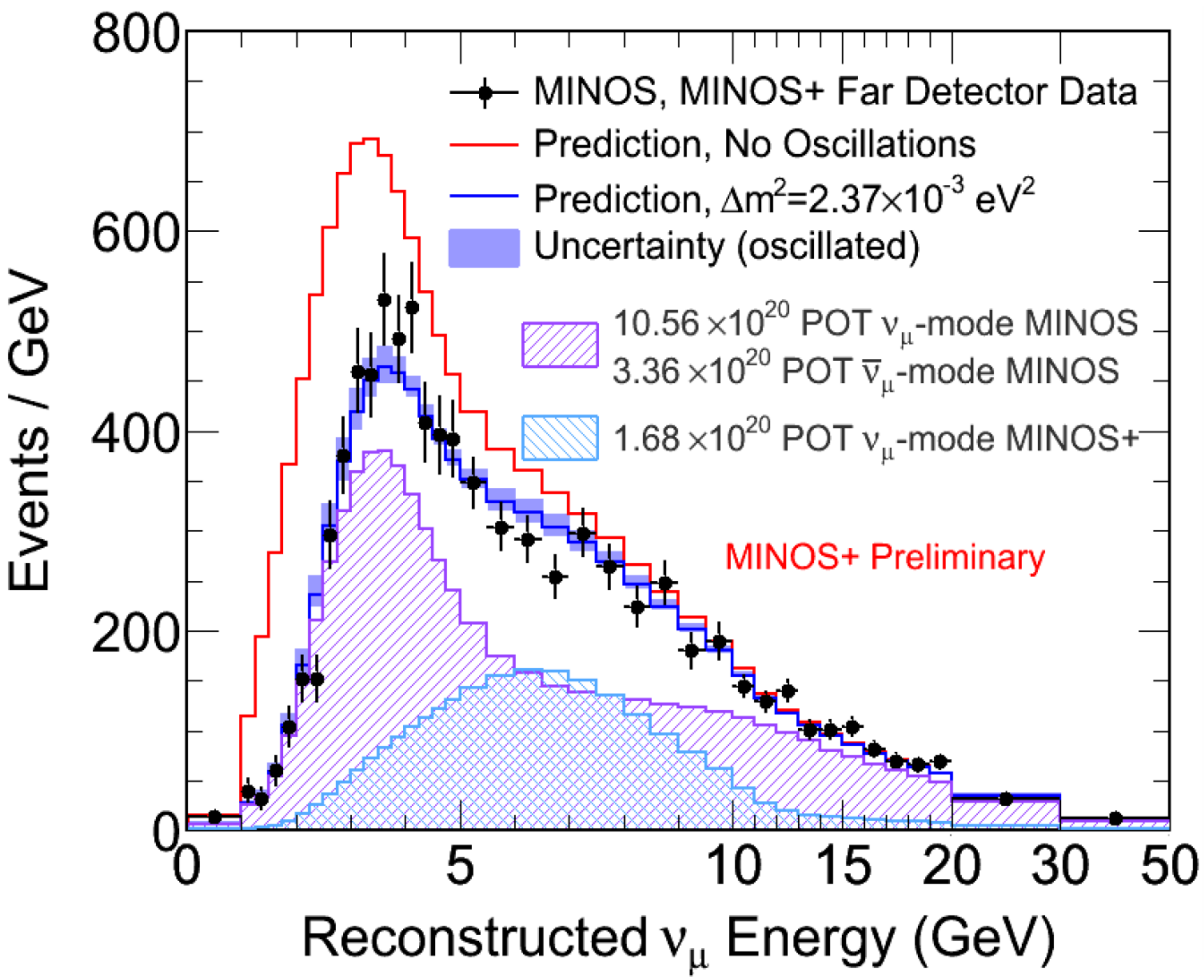


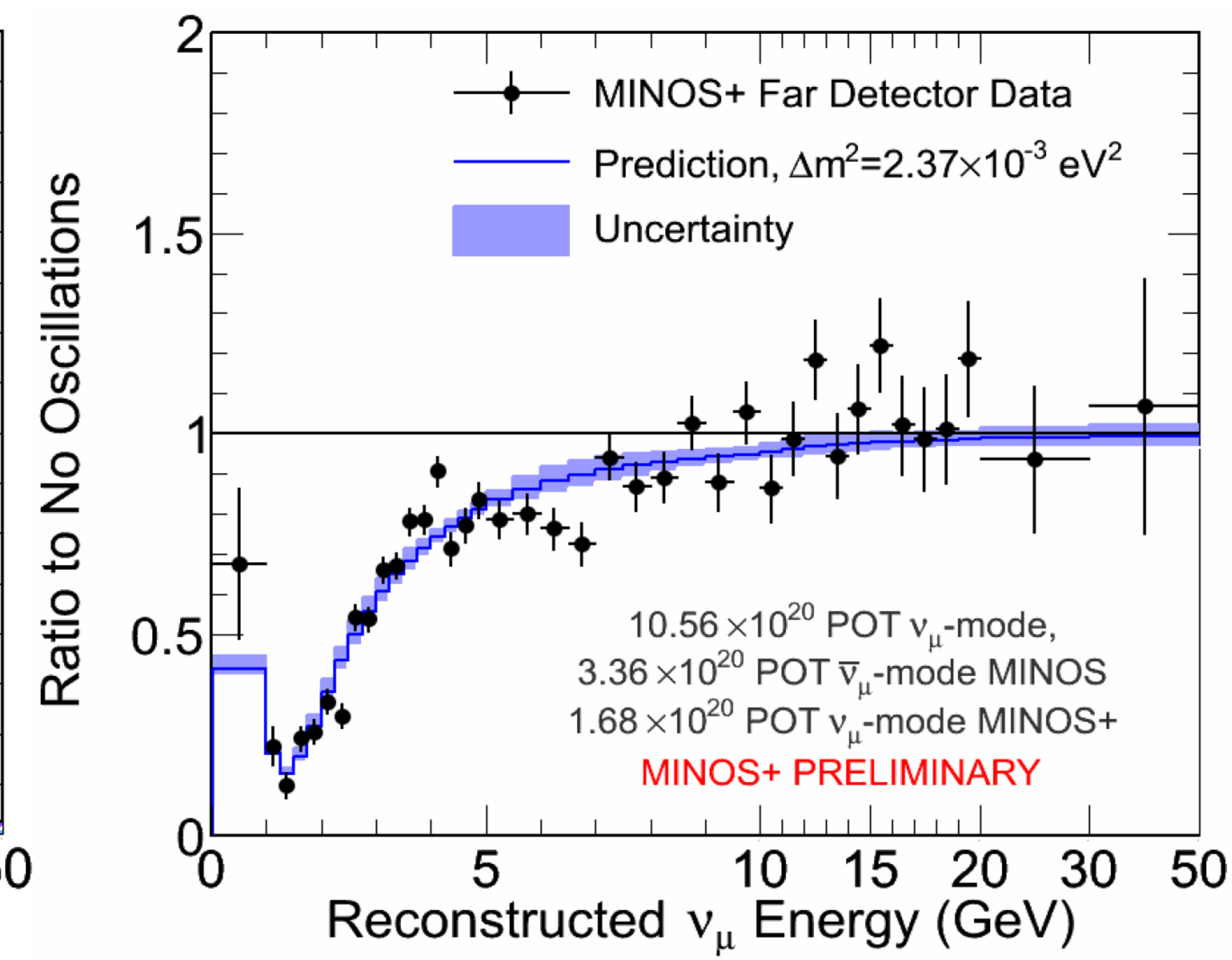


	μ^-	μ^+
Unoscillated Prediction	1254.8	52.0
Oscillated Prediction	1087.7	47.2
Data	1037	48

- MINOS+ data consistent with neutrino oscillations measured by MINOS

MINOS & MINOS+ FD Beam Data

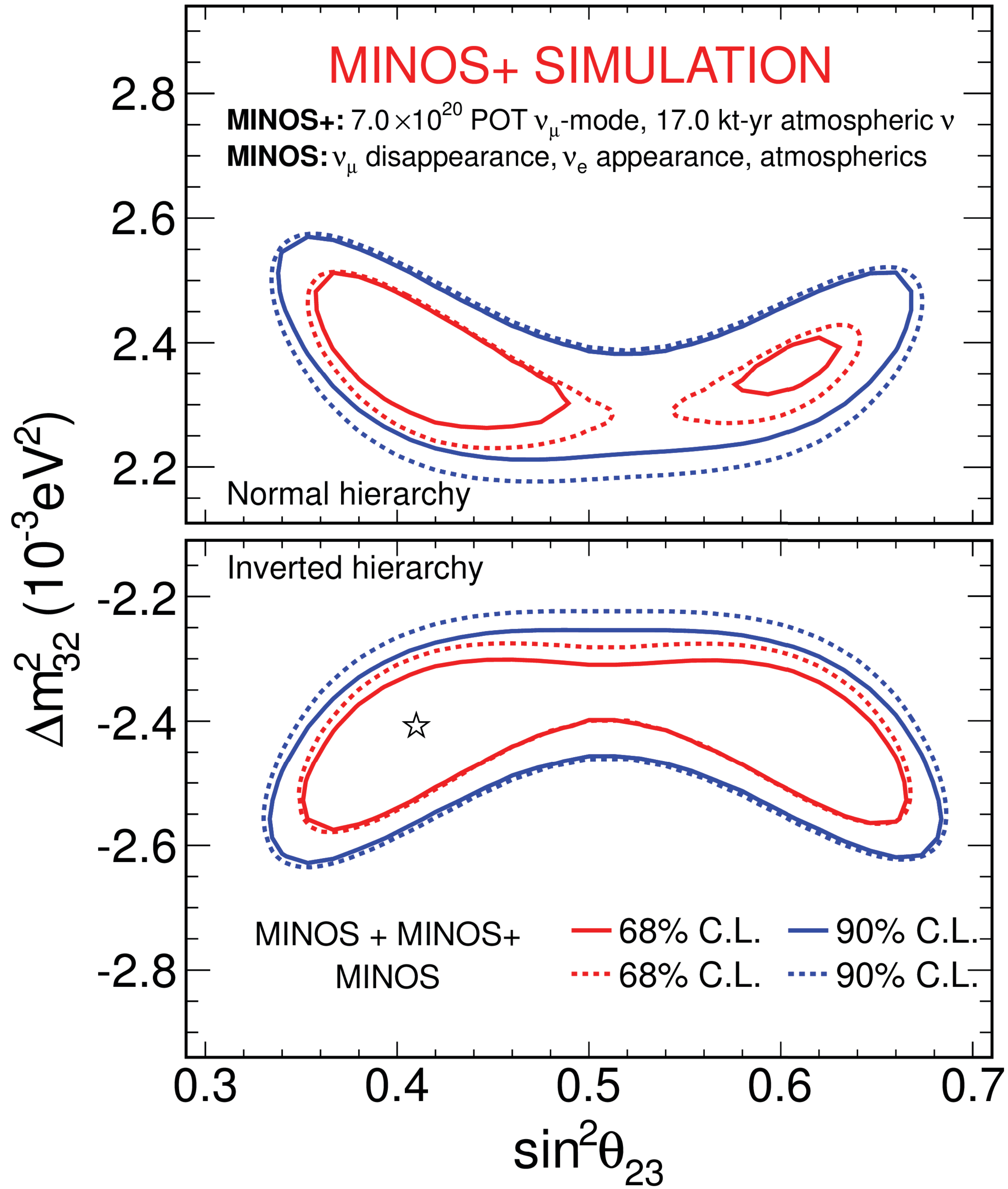




- Best resolution yet of survival probability curve!
- MINOS+ will collect 3.5×10^{20} POT by September 2014
- Expect first MINOS & MINOS+ combined beam fit in the future

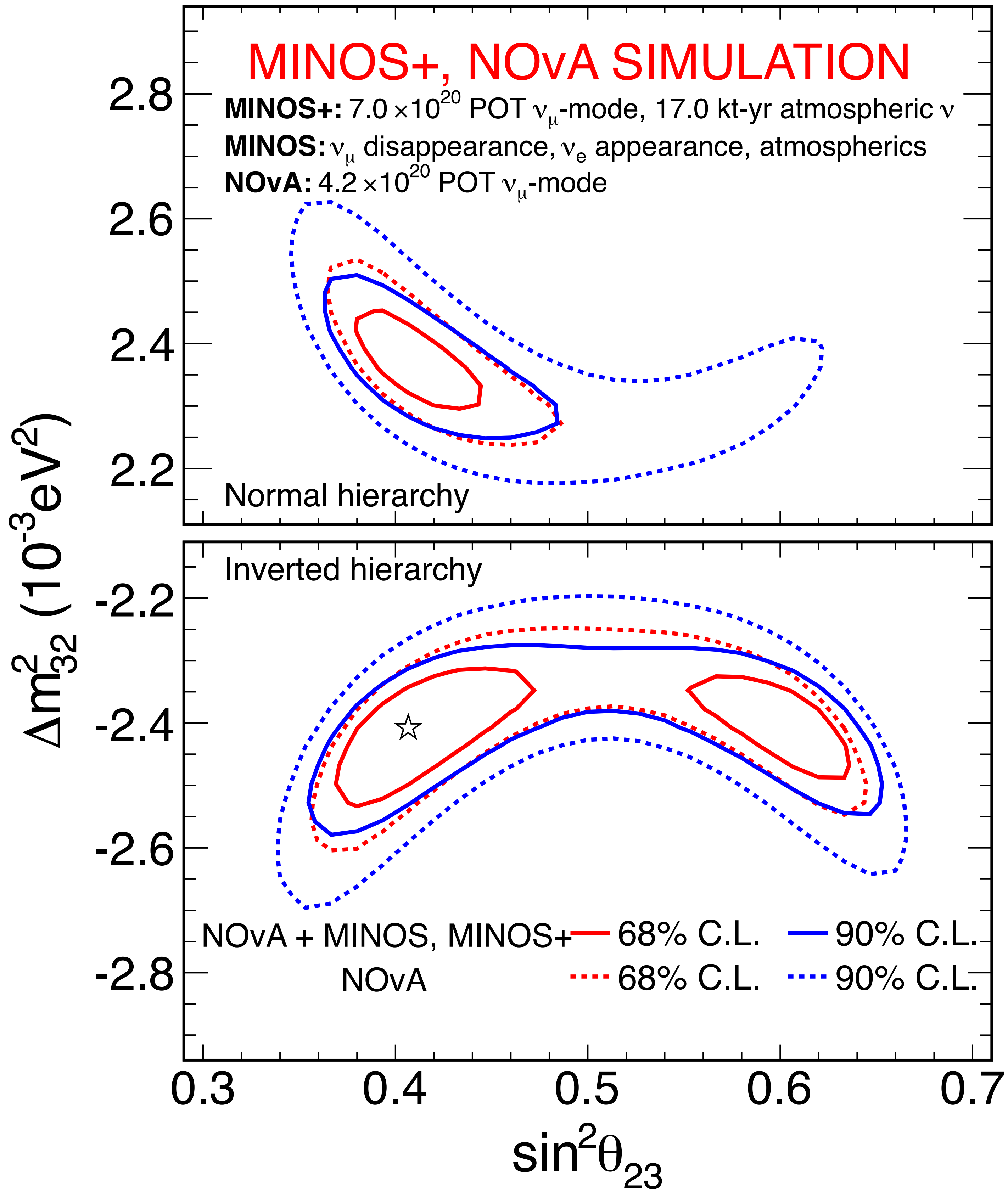
Oscillation Parameter Reach

- Showing projected MINOS & MINOS+ combined sensitivity by 2015 compared to MINOS results
- Sensitivities assume MINOS three-flavor best fit results from *PRL **112**, 191801 (2014)*



Combination with NOvA

- Comparison between NOvA-only and NOvA & MINOS+ combination contours for the projected exposure at the 2015 shutdown
- Sensitivities assume MINOS three-flavor best fit from *Phys. Rev. Lett.* ***112****, 191801 (2014)*
- During NOvA ramp-up, the NOvA & MINOS+ combination maximizes improvement on oscillation parameter measurement



New MINOS Results

Non-Standard Neutrino Interactions

- Non-Standard Interactions provide a framework to accommodate deviations from standard oscillations

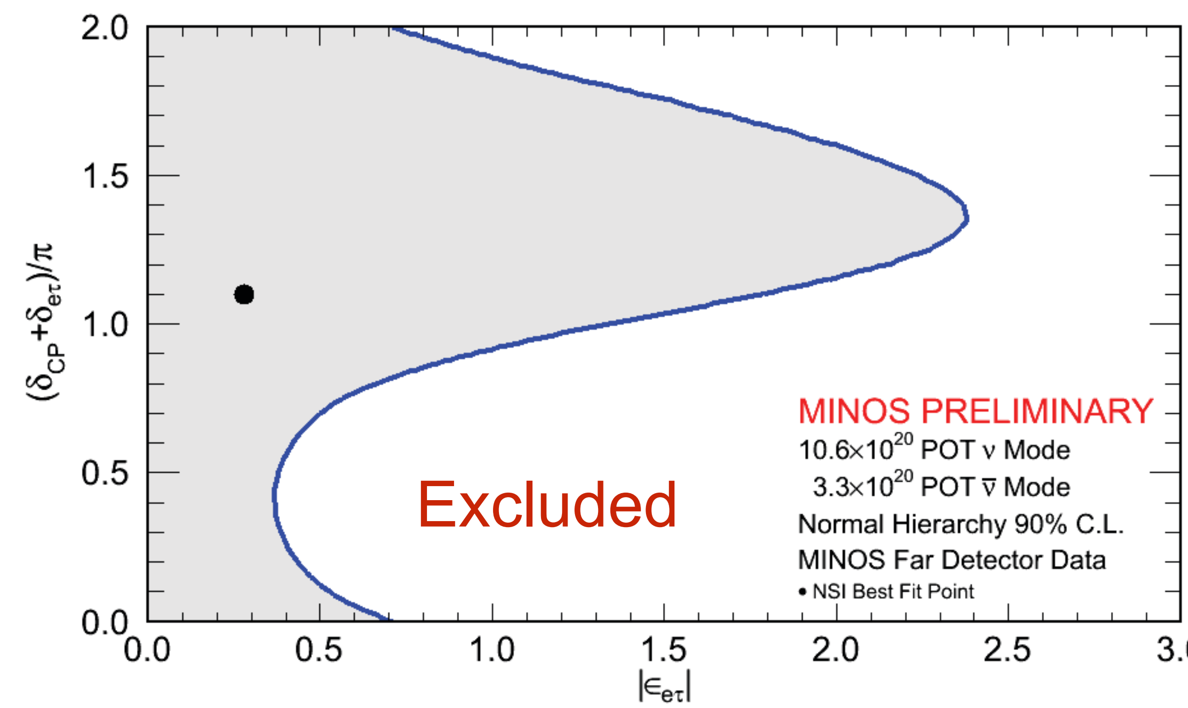
$$H = U_{PMNS}\begin{bmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E}\end{bmatrix}U^\dagger_{PMNS} + \sqrt{2}G_F n_e\begin{bmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^\star_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau}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

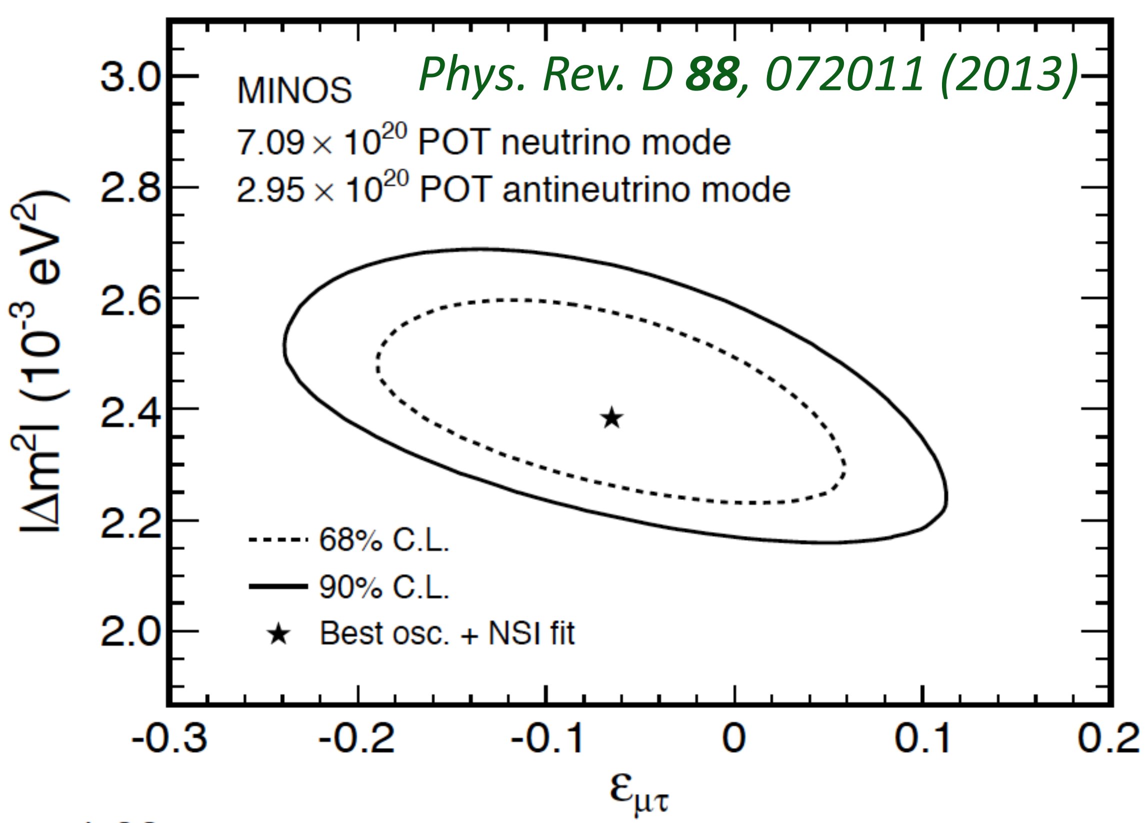
- MINOS is sensitive to NSI parameters $\varepsilon_{\mu\tau}$ and $\varepsilon_{e\tau}$ through ν_μ, $\bar{\nu}_\mu$ disappearance, and ν_e, $\bar{\nu}_e$ appearance

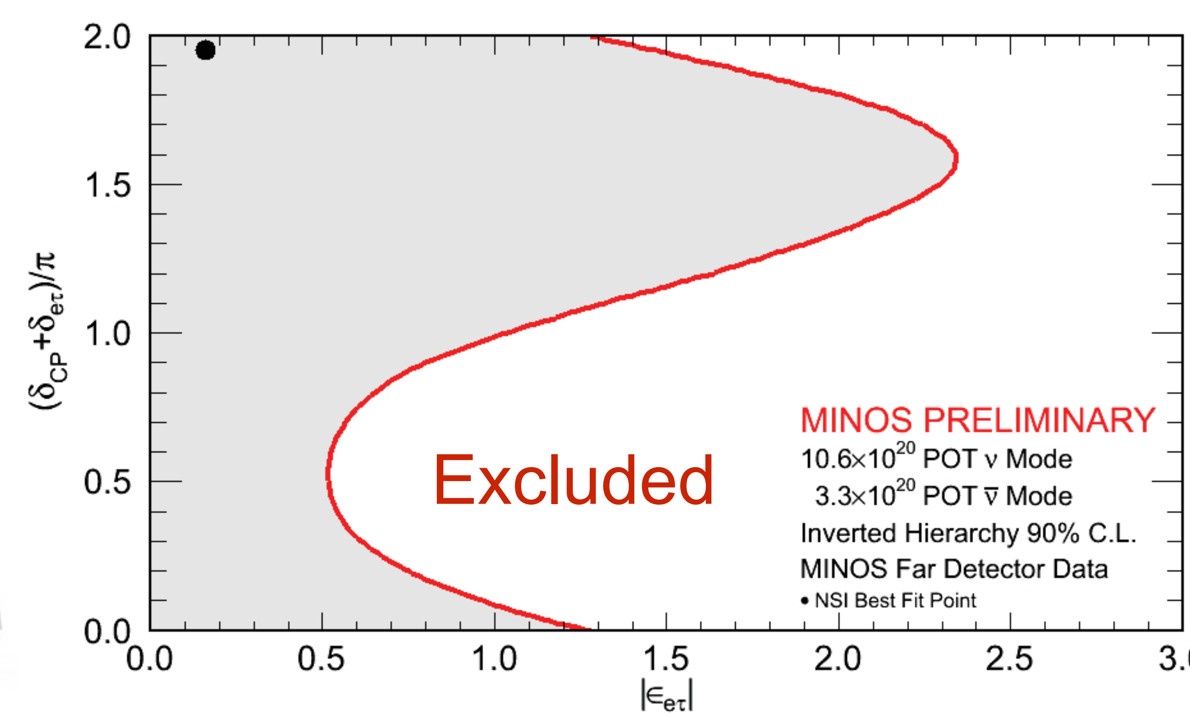
- New $\varepsilon_{e\tau}$ analysis follows NSI formulation from:

*Friedland, Lunardini, Maltoni, PRD **70**, 111301 (2004)*

*Coelho, Kafka, Mann, Schneps, Altinok, PRD **86**, 113015 (2012)*



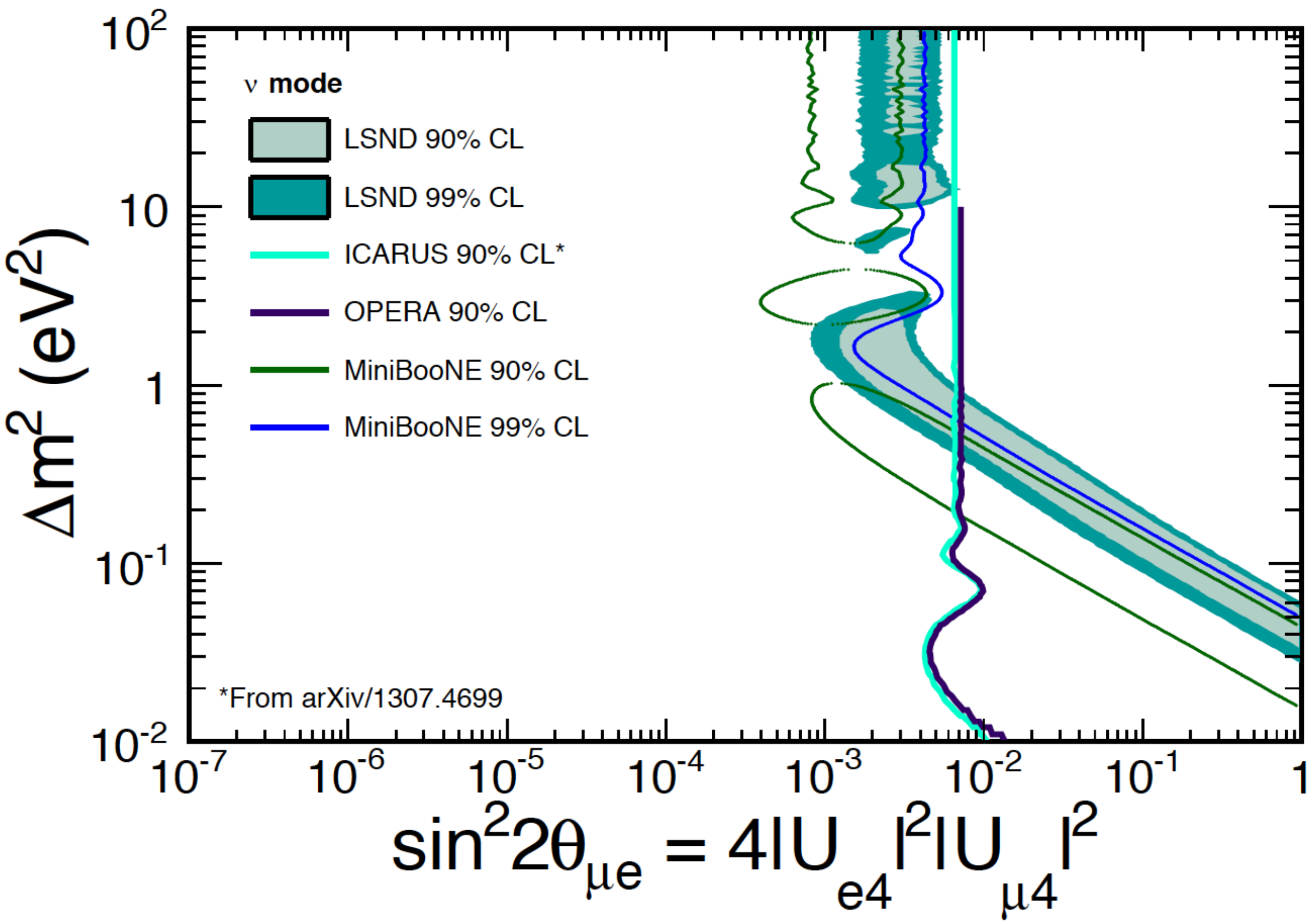




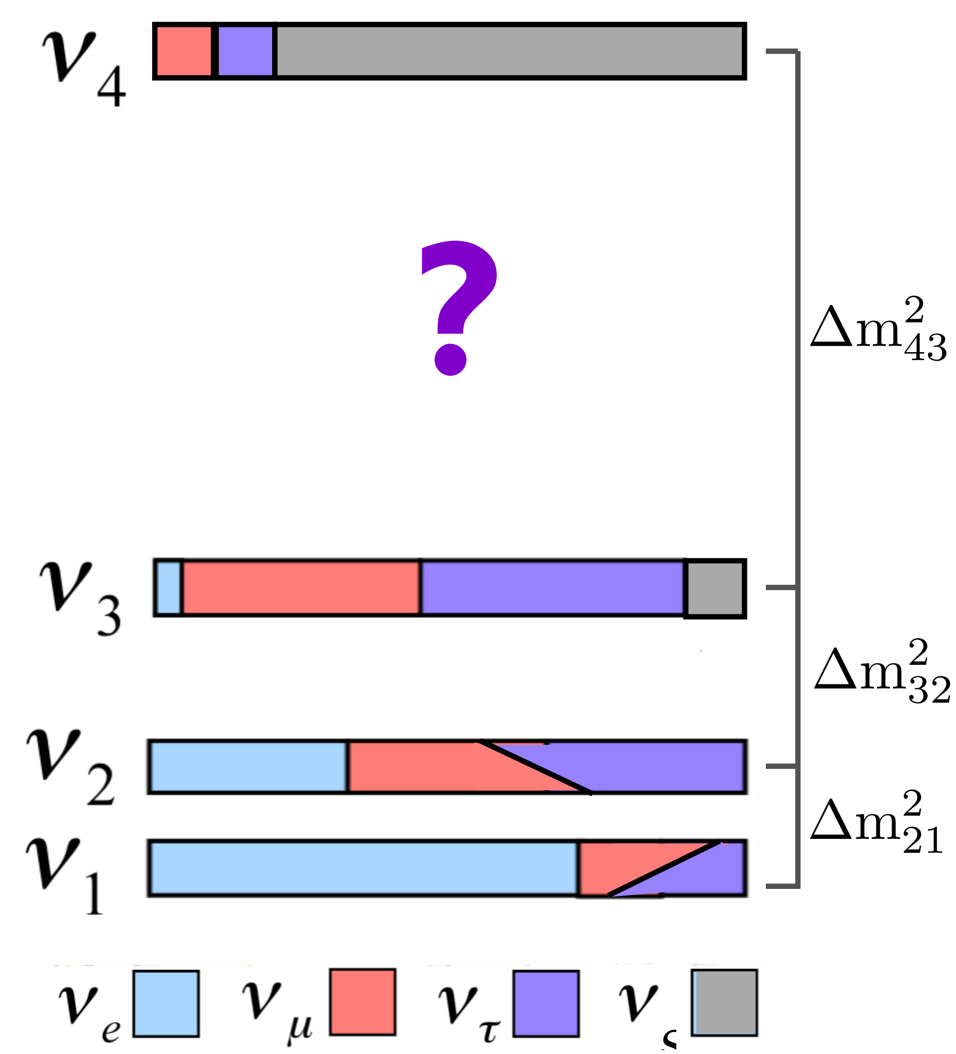
New Search for Sterile Neutrinos

More than Three Neutrinos?

- Oscillations into light sterile neutrinos may explain anomalies seen in SBL, reactor, and radiochemical experiments
- Evidence for sterile neutrino mixing remains inconclusive due to severe tension between appearance and disappearance measurements

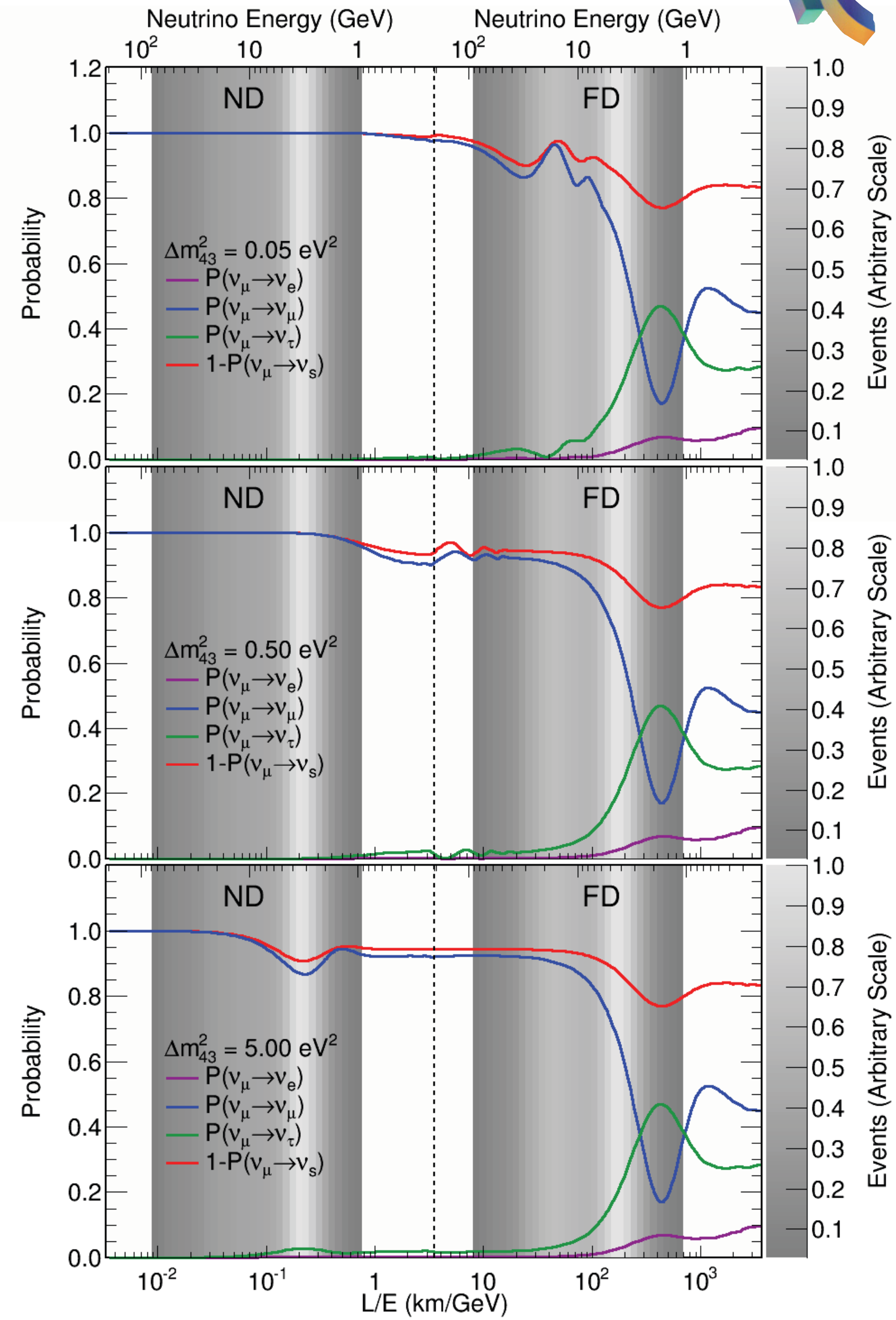


MiniBooNE, PRL 110, 161801(2013)



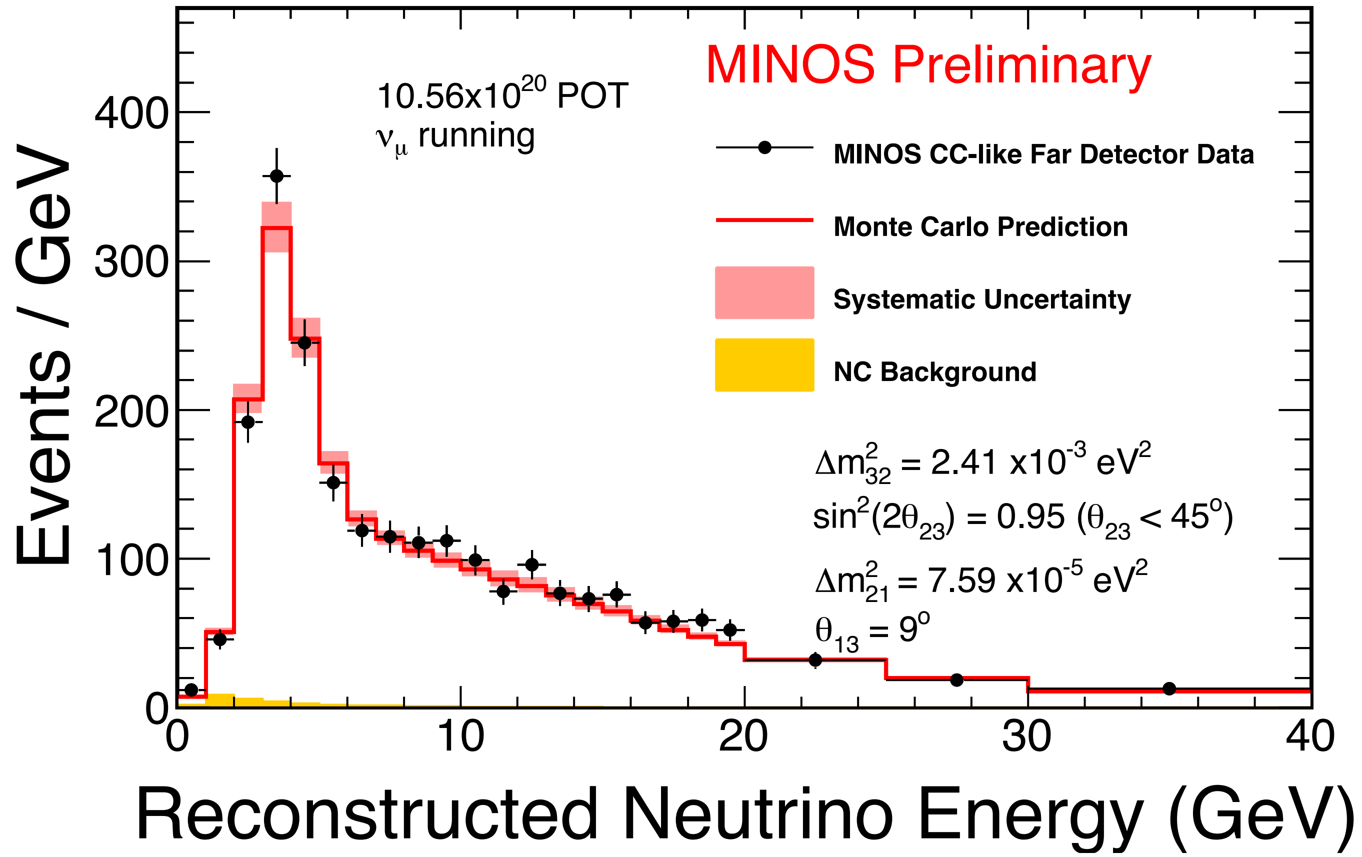
4-Flavor Oscillations

- $\nu_\mu \rightarrow \nu_s$ mixing causes energy-dependent depletion of NC and ν_μ-CC energy spectra w.r.t 3-flavor mixing
- Small Δm^2_{43} (> Δm^2_{32}):
  - FD spectral distortions at energies above 3-flavor oscillation maximum
  - No ND effects
- Medium Δm^2_{43}:
  - Rapid oscillations at FD average out
  - No ND effects
  - Counting experiment
- Large Δm^2_{43}:
  - Rapid oscillations at FD average out
  - ND spectral distortions affect extrapolation to FD



FD CC and NC Energy Spectra

- Comparison with 3-flavor prediction for full MINOS low-energy beam neutrino mode sample: 10.56×10^{20} POT
- Selected ν_μ-CC and CC candidates in both detectors
  - 2721 ν_μ-CC-like events in FD
  - 1221 NC-like events in FD



- NC Selection

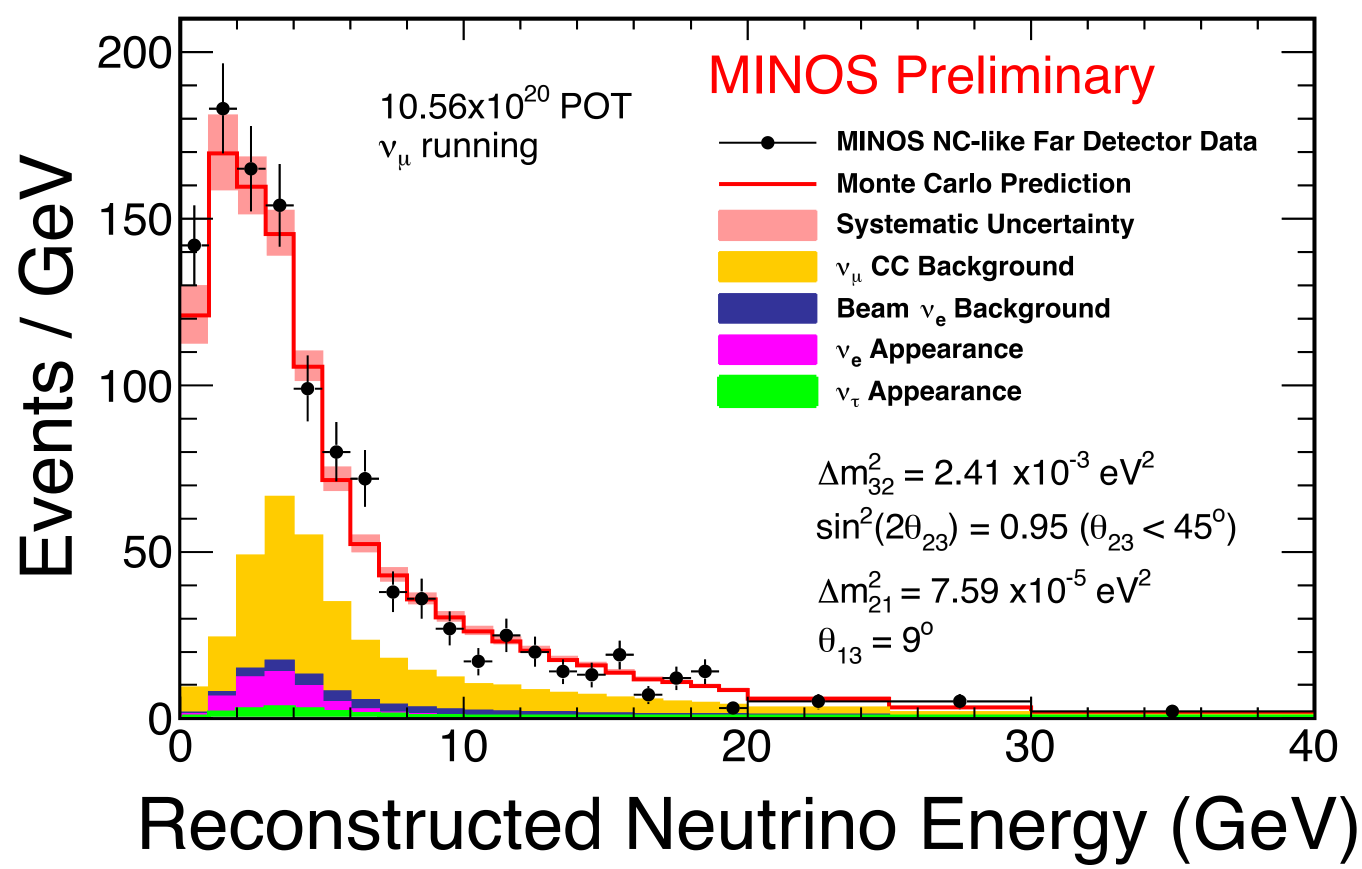
$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

Predicted CC background from all flavors

Predicted NC interaction signal

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

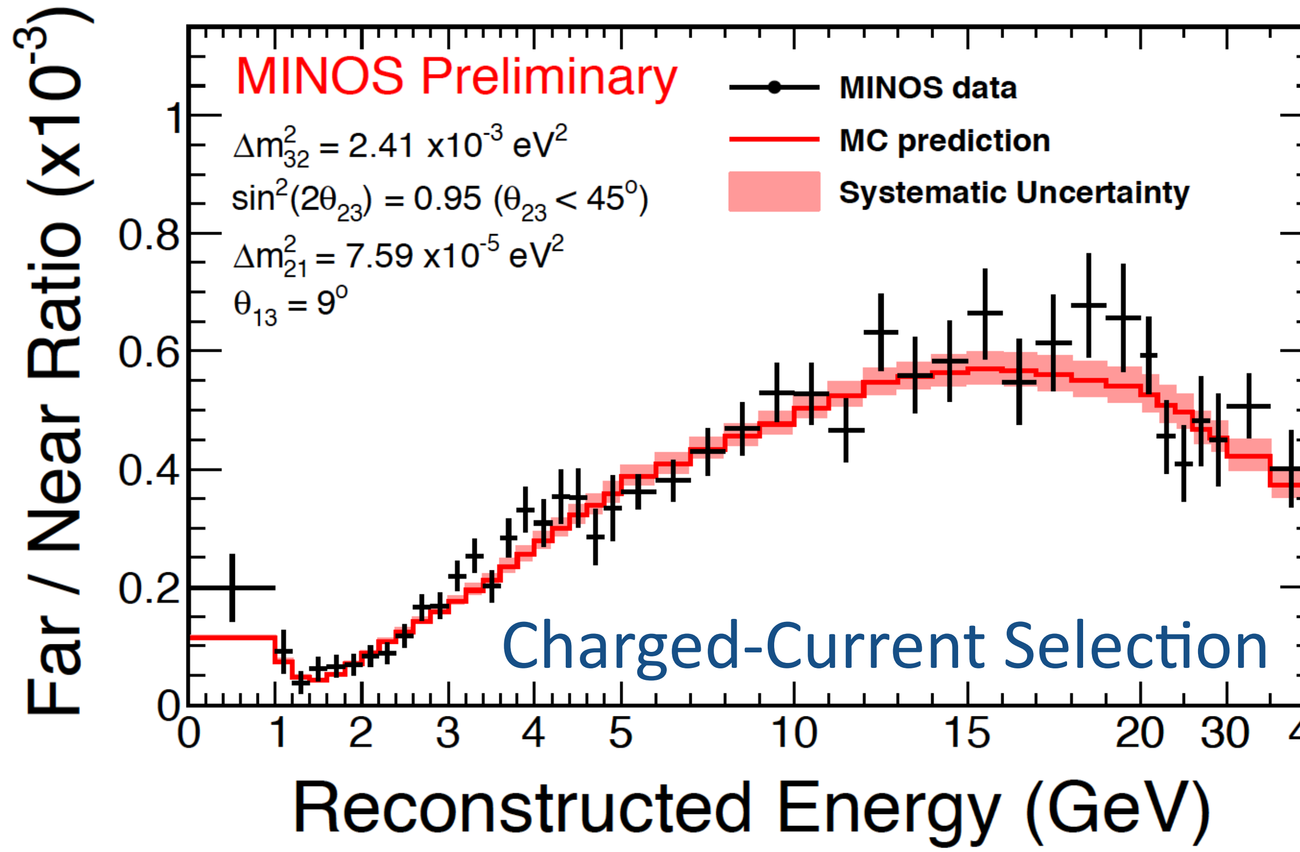
0-3 GeV: $R = 1.093 \pm 0.097$

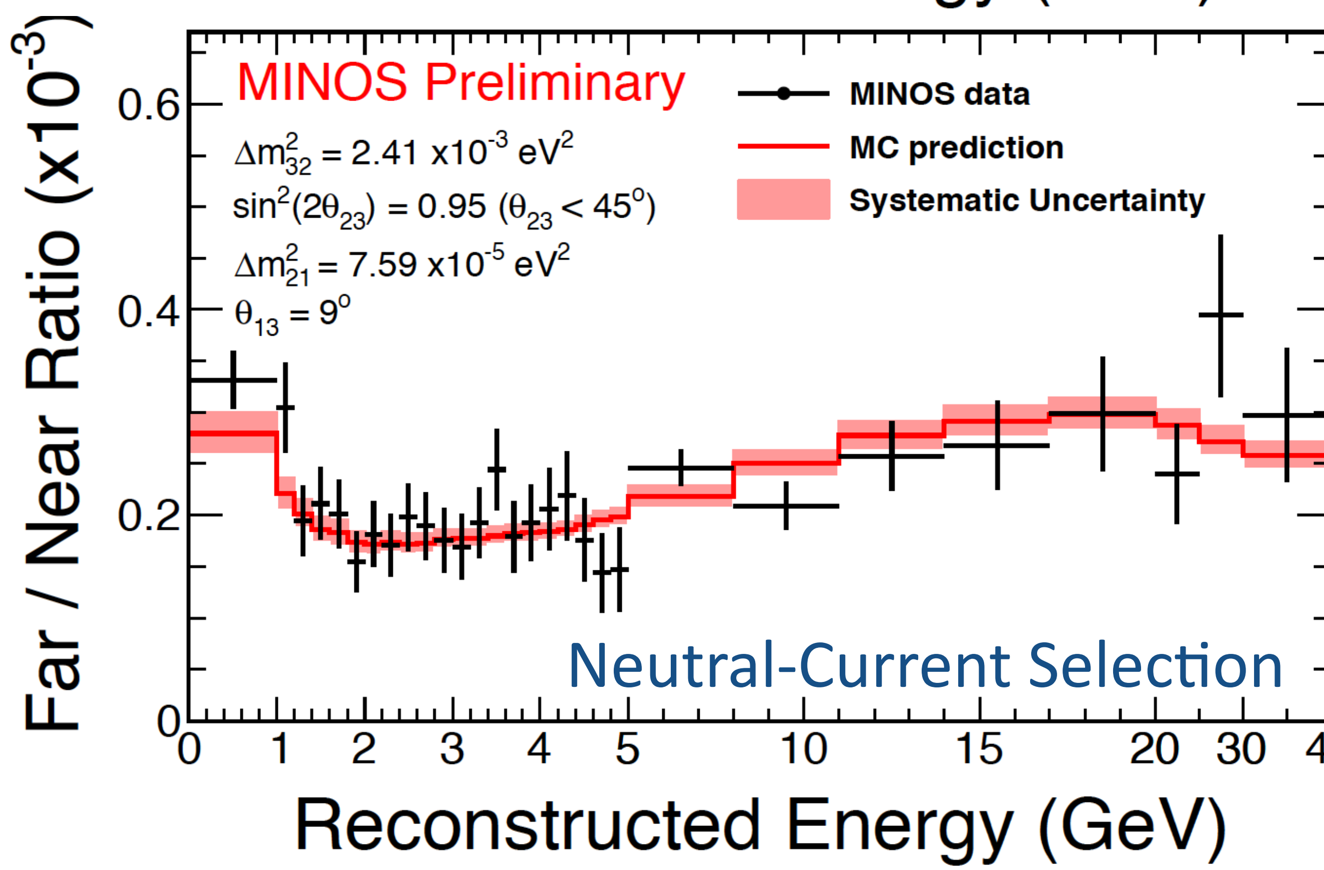


- No evidence for oscillations into sterile neutrinos at $\Delta m^2_{43} \simeq 0.5$ eV^2

4-Flavor Analysis Strategy

- Assume 3+1 sterile neutrino mixing scenario
  - Apply oscillations to both ND and FD
  - Use distance to meson decay point
  - Fit for $|\Delta m^2_{32}|$, θ_{23}, $|\Delta m^2_{43}|$, θ_{24}, θ_{34}
- To account for ND distortions, fit oscillated F/N ratio directly to F/N data ratio
  - Include constraint on ND rate
- Re-assessed systematic uncertainties affecting high-energy tail of spectrum
  - Re-evaluated beam flux uncertainties
- Log-likelihood surfaces are Feldman-Cousins corrected





Systematics

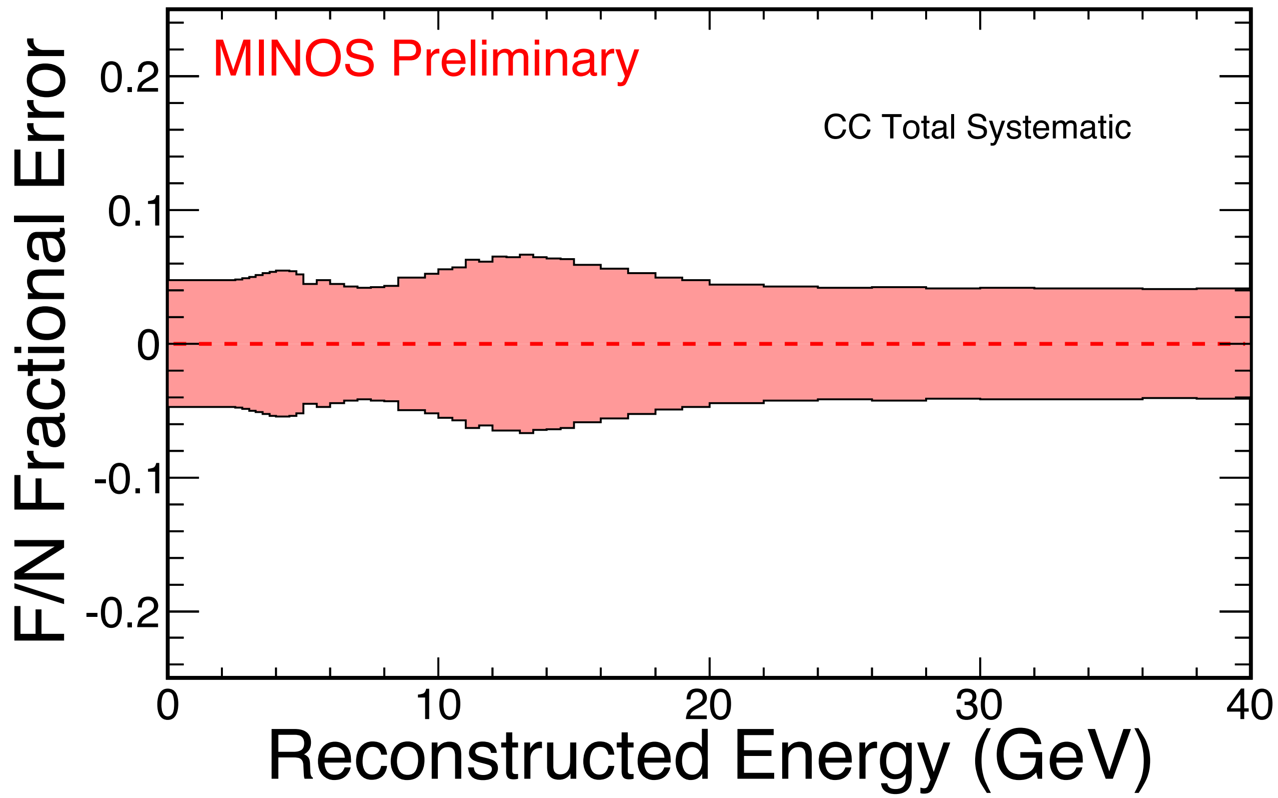
- Including 26 systematic uncertainties in fit via covariance matrices, accounting for:
  - Normalization
  - Detector acceptance
  - NC selection
  - Hadron production, beam optics, cross sections, energy scale, and backgrounds

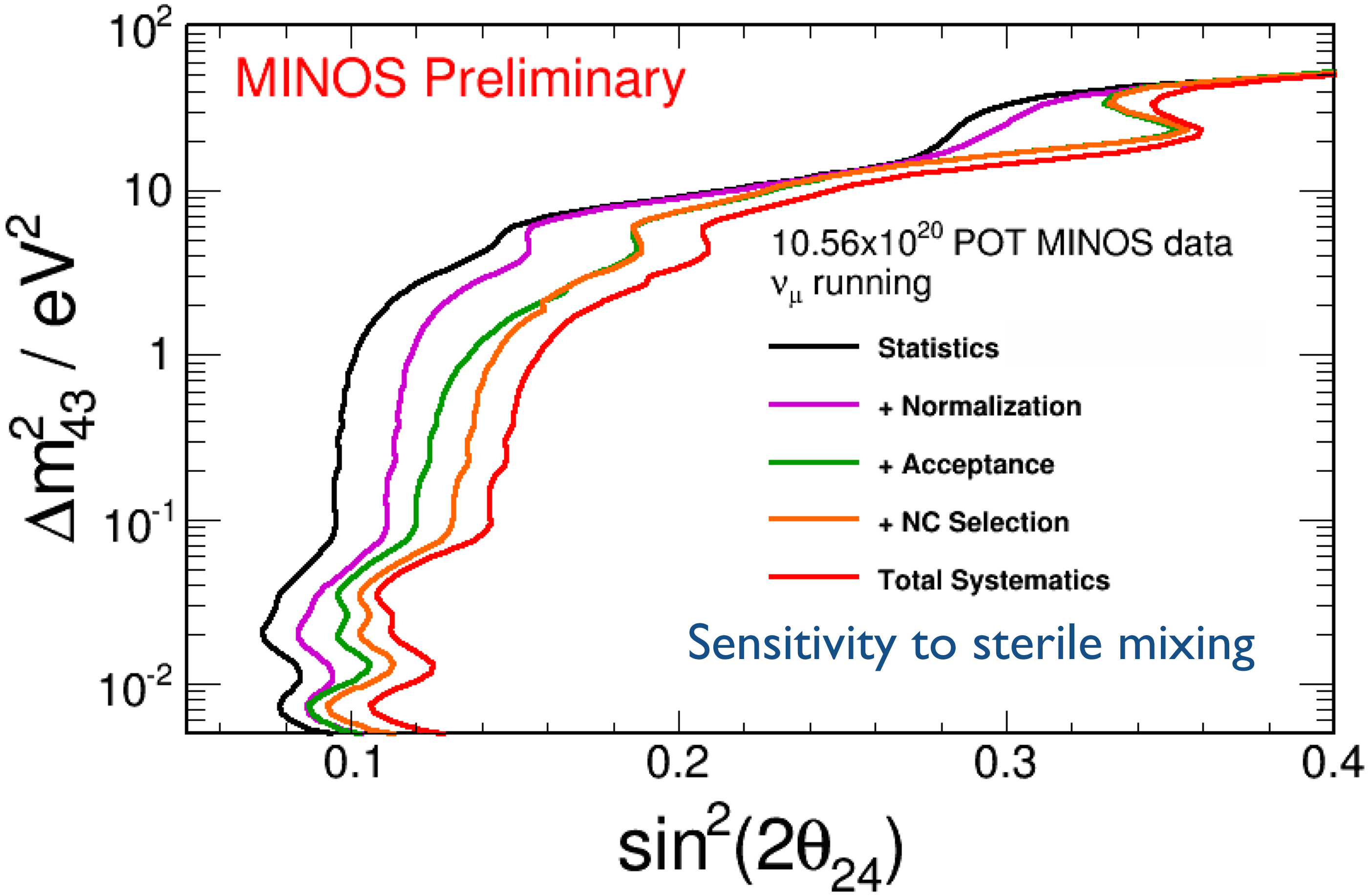
$$\chi^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} (o_i - e_i)^T [V^{-1}]_{ij} (o_j - e_j)$$

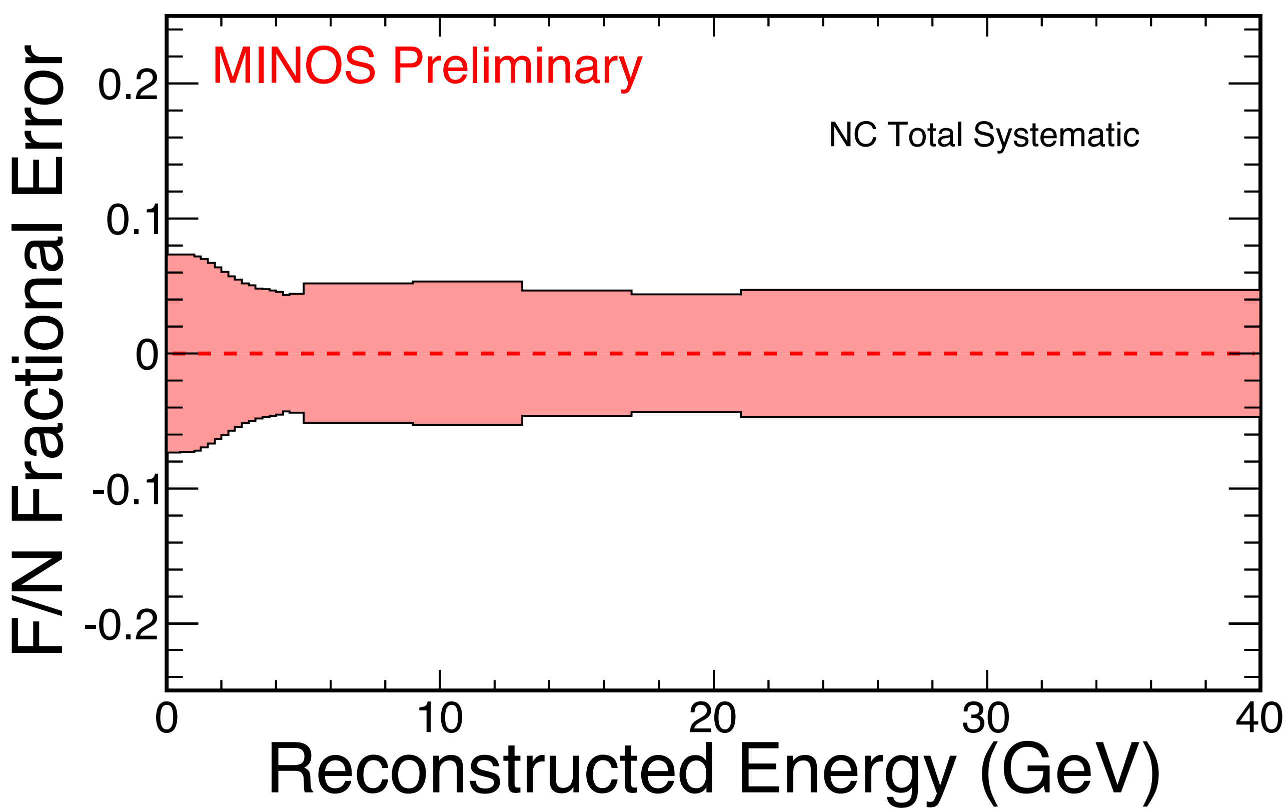
o_i : Observed events in bin i

e_i : Predicted events in bin i

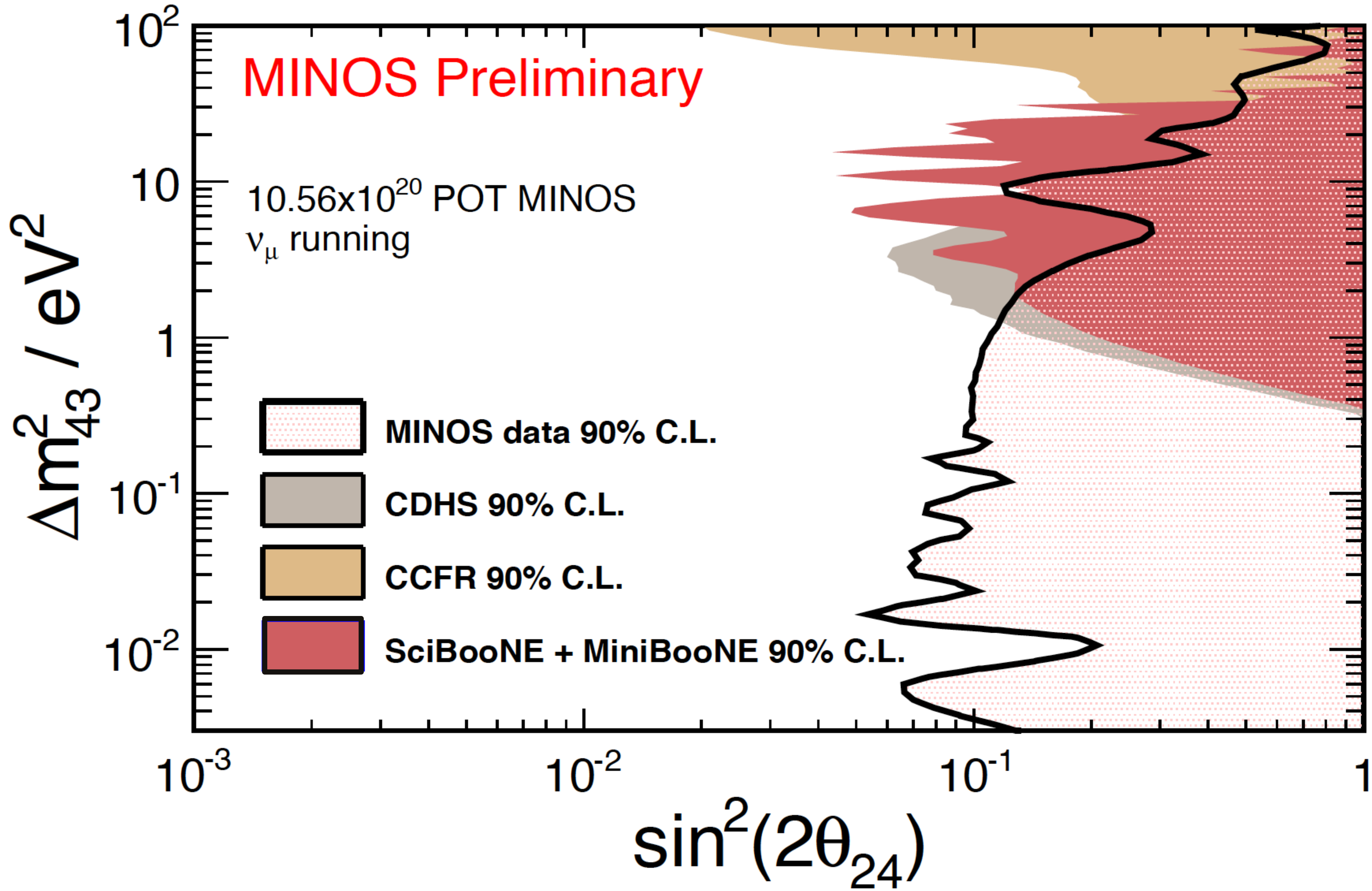
V : Covariance matrix







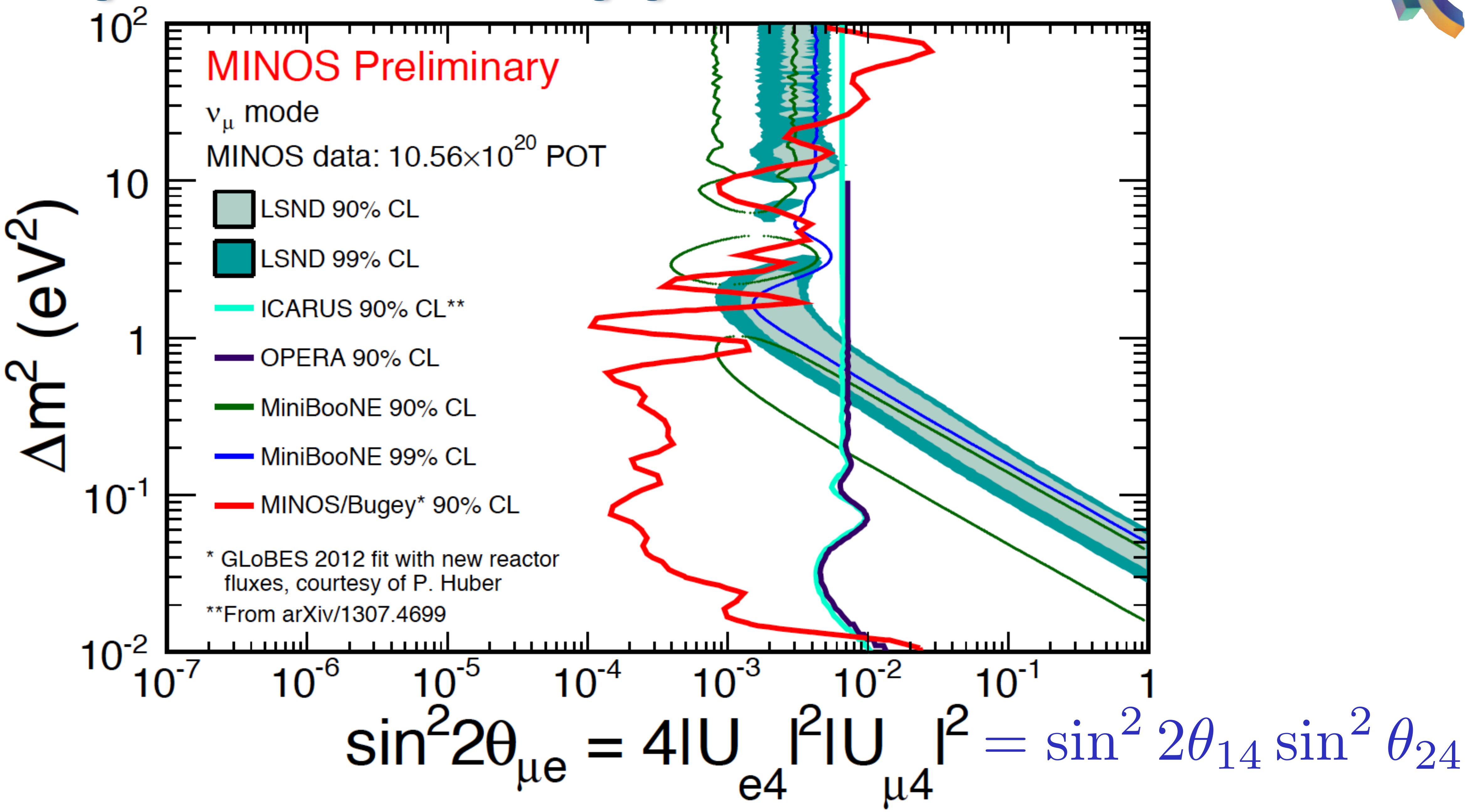
MINOS Disappearance Limit



- Limit is Feldman-Cousins corrected

MINOS 90% C.L. exclusion limit ranges over 4 orders of magnitude in Δm^2_{43}!
Strongest constraint on ν_μ disappearance into ν_s for $\Delta m^2_{43} < 1\ eV^2$

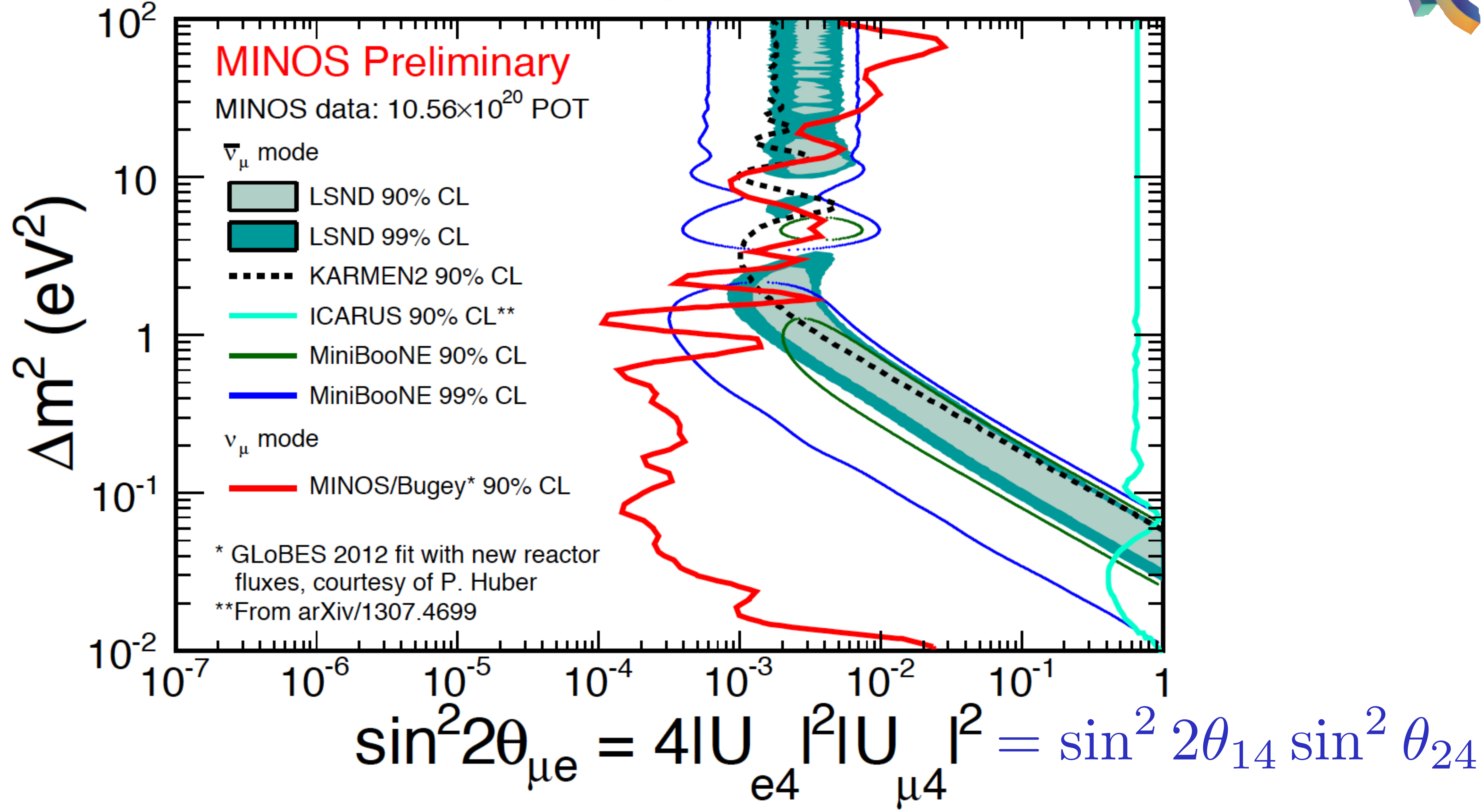
Comparison to Appearance Results



- **With MiniBooNE Neutrino Mode**
- Assuming 3+1 model, combine MINOS disappearance 90% C.L. limit in θ_{24} to Bugey reactor experiment 90% C.L. disappearance limit in θ_{14}
- Bugey limit computed from GLoBES 2012 fit using new reactor fluxes, provided by Patrick Huber

MINOS data increases tension between null and signal results for $\Delta m^2_{43} < 1$ eV^2

Comparison to Appearance Results



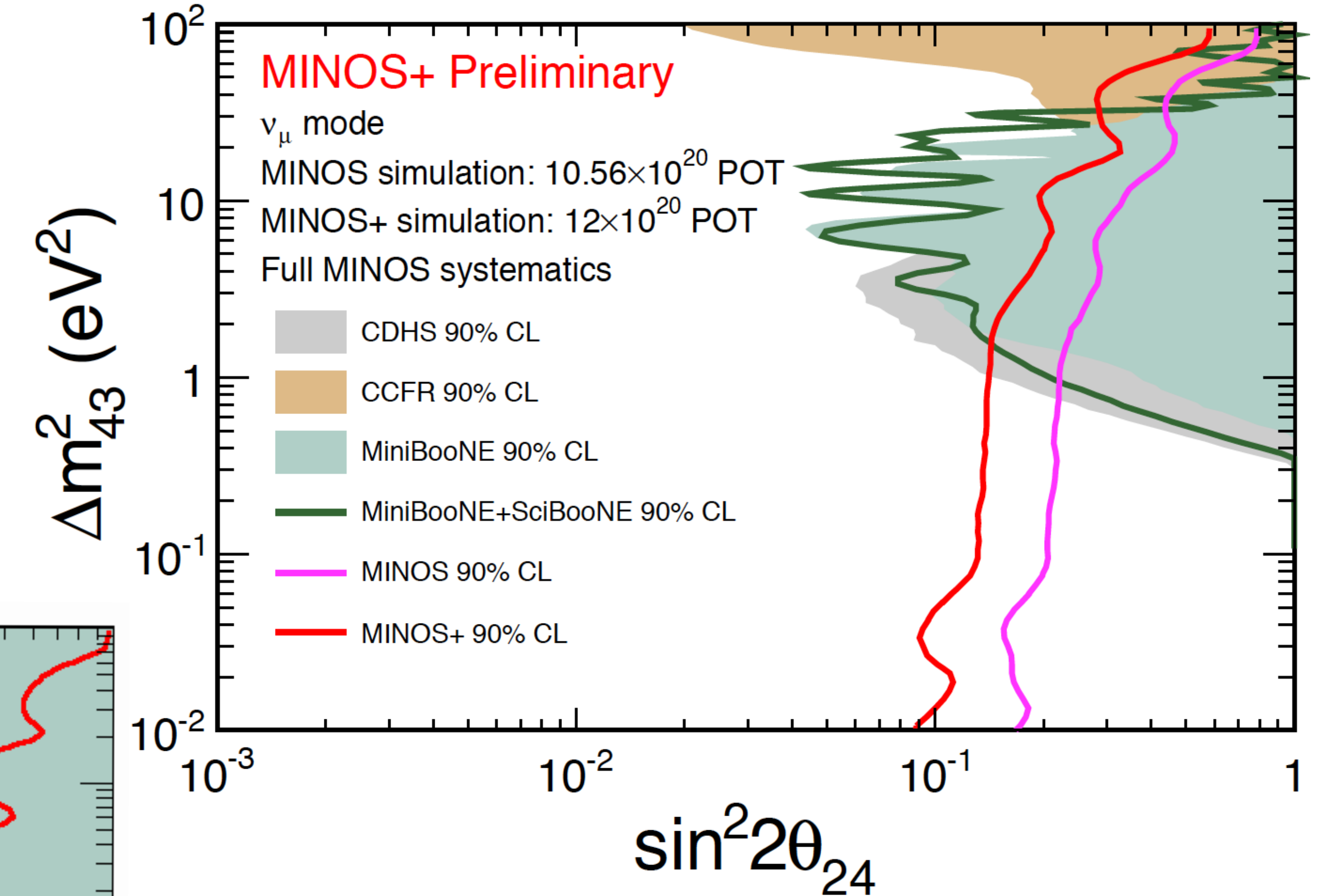
- **With MiniBooNE Antineutrino Mode**
- Assuming a 3+1 model and CPT conservation so SBL neutrino and antineutrino oscillations are identical

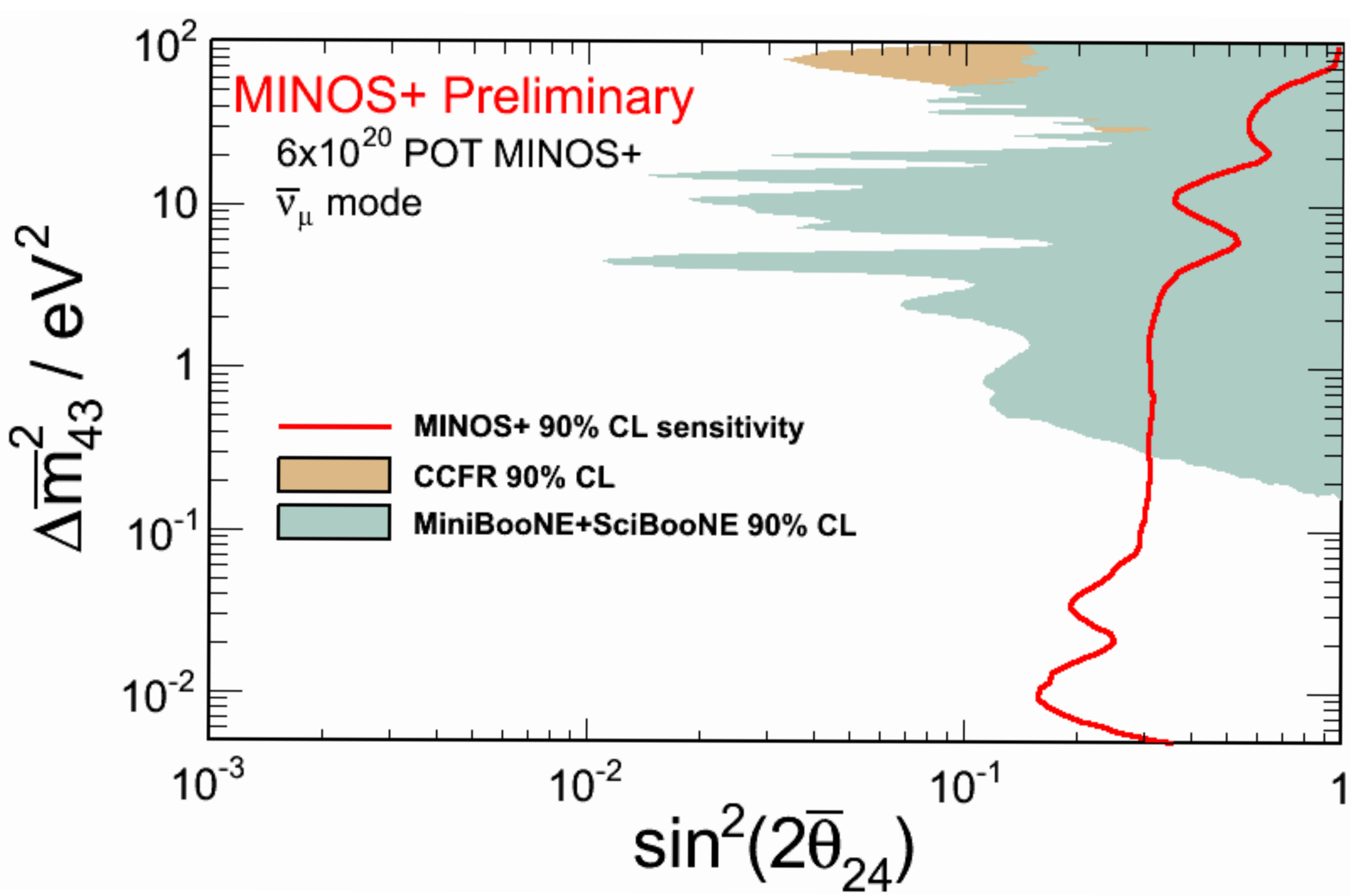
- Working on sterile neutrino search in 3.4×10^{20} POT of MINOS antineutrino running

MINOS data increases tension between null and signal results for $\Delta m^2_{43} < 1$ eV^2

Future Prospects with MINOS+

- MINOS+ vs MINOS disappearance limits by 2016, compared to SBL disappearance experiments





- Projected MINOS+ sensitivity to sterile neutrino mixing for 1 year of antineutrino running

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

Summary

NEW

- MINOS completed a search for sterile neutrinos in a long-baseline experiment
  - No evidence found for sterile neutrino mixing
  - Set strong constraints on sterile neutrino oscillations over wide range of Δm^2_{43}

NEW

- First MINOS constraints on NSI parameter $\varepsilon_{e\tau}$

UPDATE

- Improved MINOS standard oscillation measurement with new sample of MINOS+ atmospheric neutrinos

COMING SOON!

- MINOS+ taking good data with new NuMI beam
  - Precision test of oscillations in unexplored energy range
  - Results of oscillation analysis of beam data in near future
  - **Surprises around the corner?**

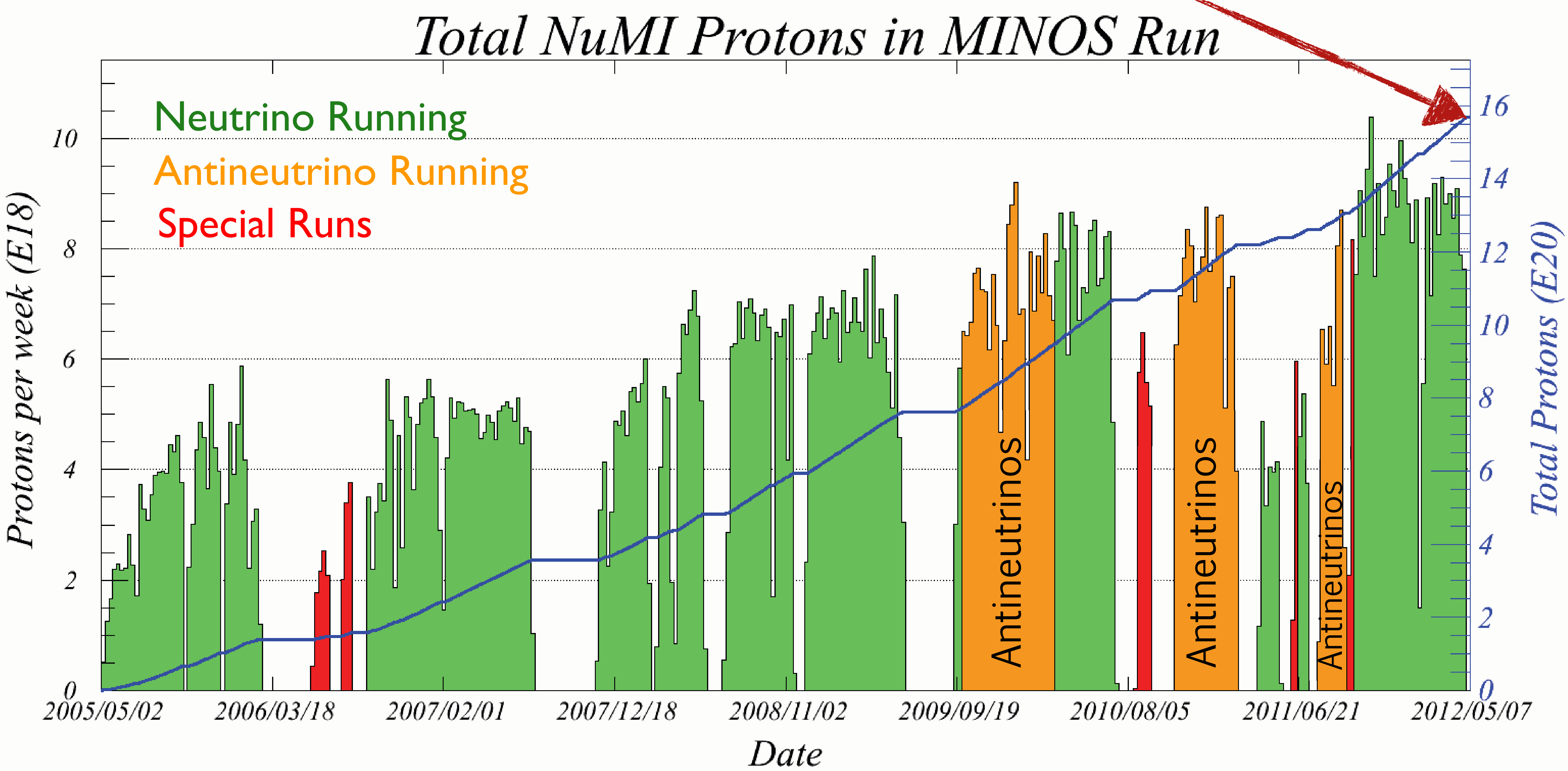
Visit the 10 posters by MINOS+ students and postdocs!

The MINOS+ Collaboration

Supplements

Accumulated Beam Data

15.6×10^{20} protons-on-target delivered between 2005 and 2012!



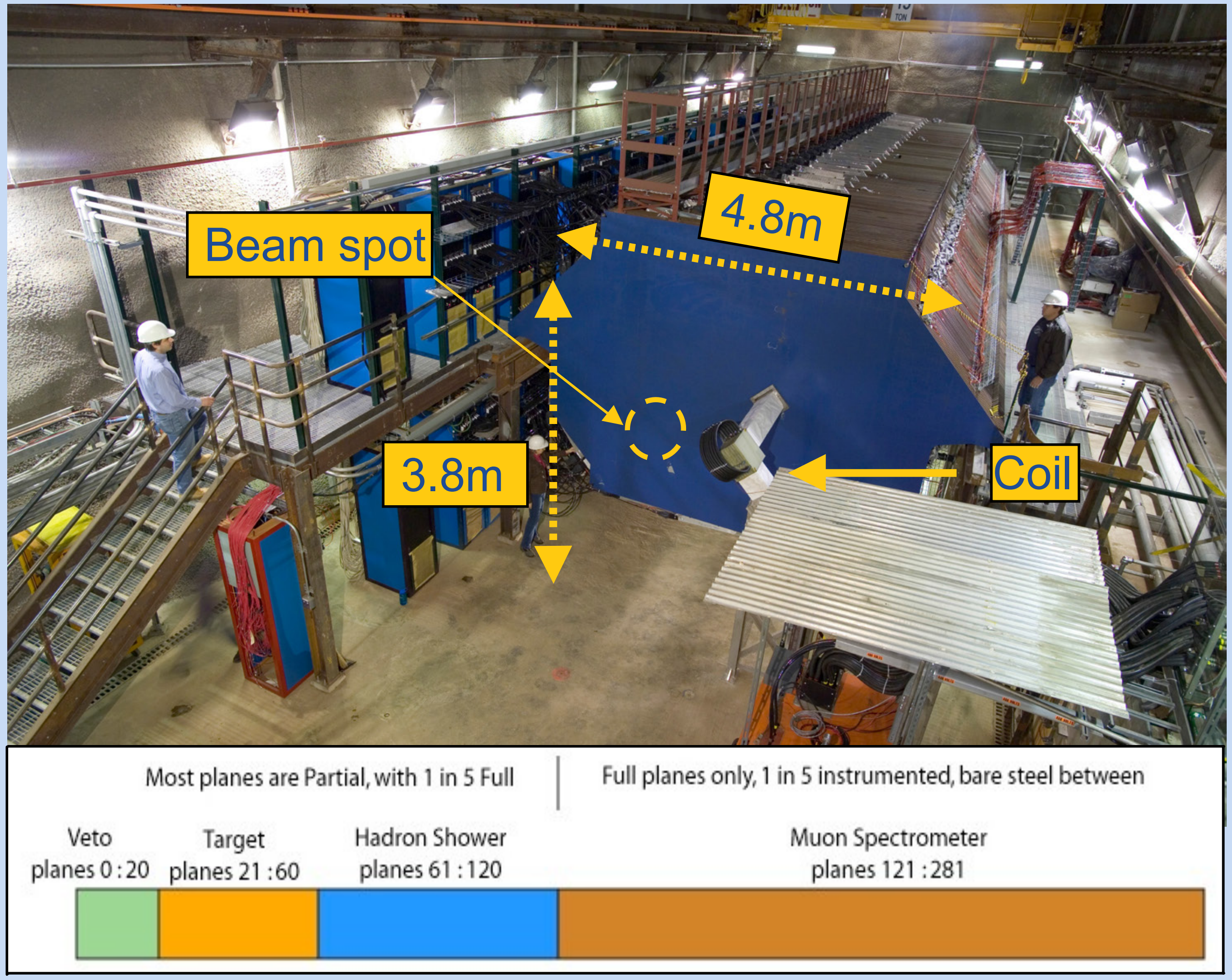
- Result from NuMI beam run during MINOS era
  - **10.7 x 10^{20} POT in neutrino running**
  - **3.4 x 10^{20} POT in antineutrino running**

The MINOS Detectors

- Magnetized tracking sampling calorimeters composed of steel-scintillator planes

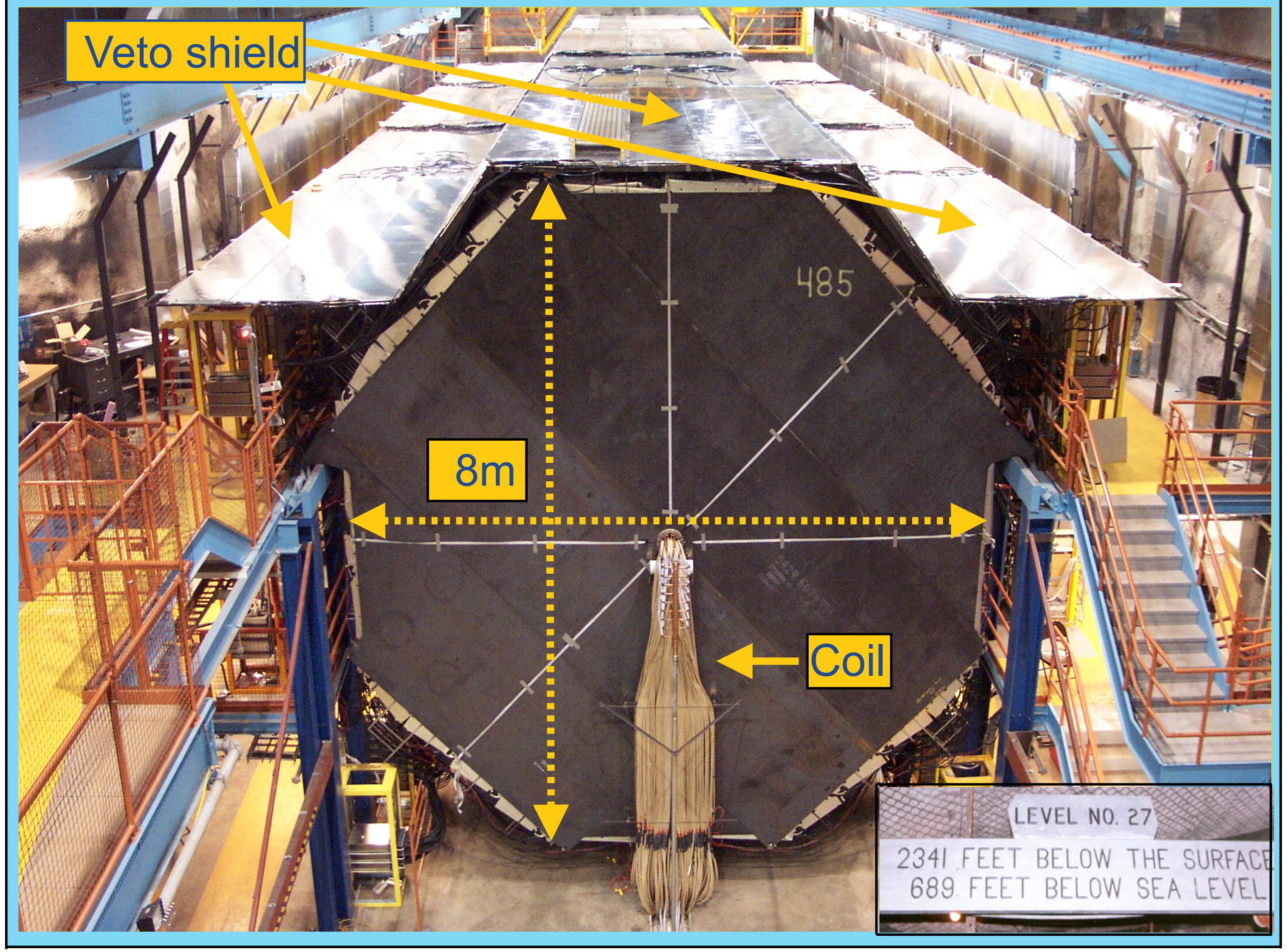
Near Detector

- 980 ton total mass
- Located 1 km downstream of the target at Fermilab
- 100 m depth



Far Detector

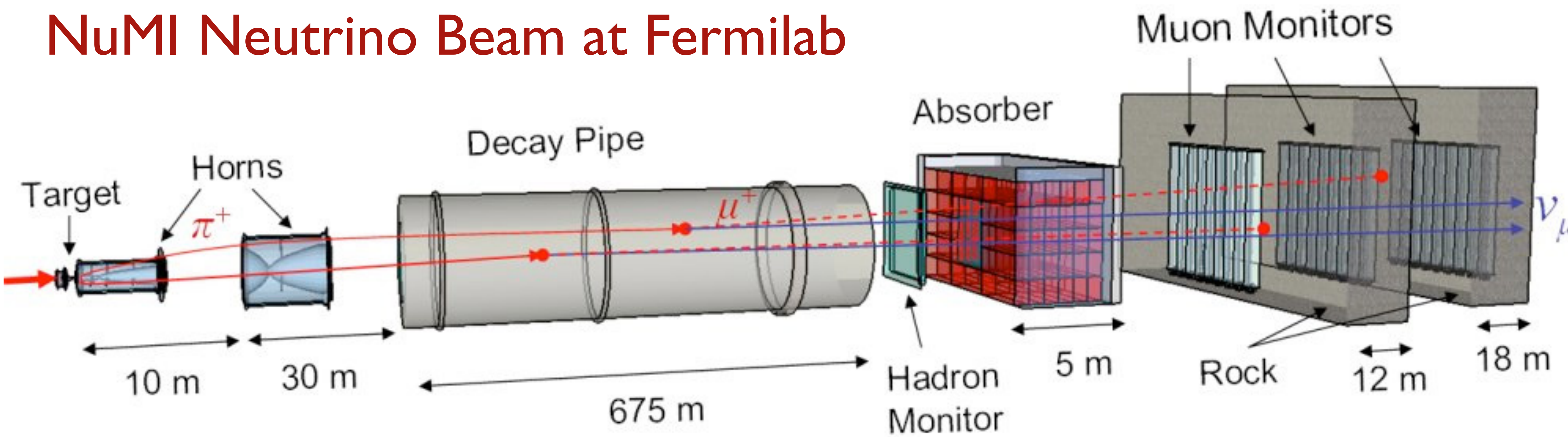
- 5.4 kton, 2 supermodules
- Located 735 km away in Soudan mine, MN
- 714 m depth
- Veto shield enables atmospheric neutrino studies

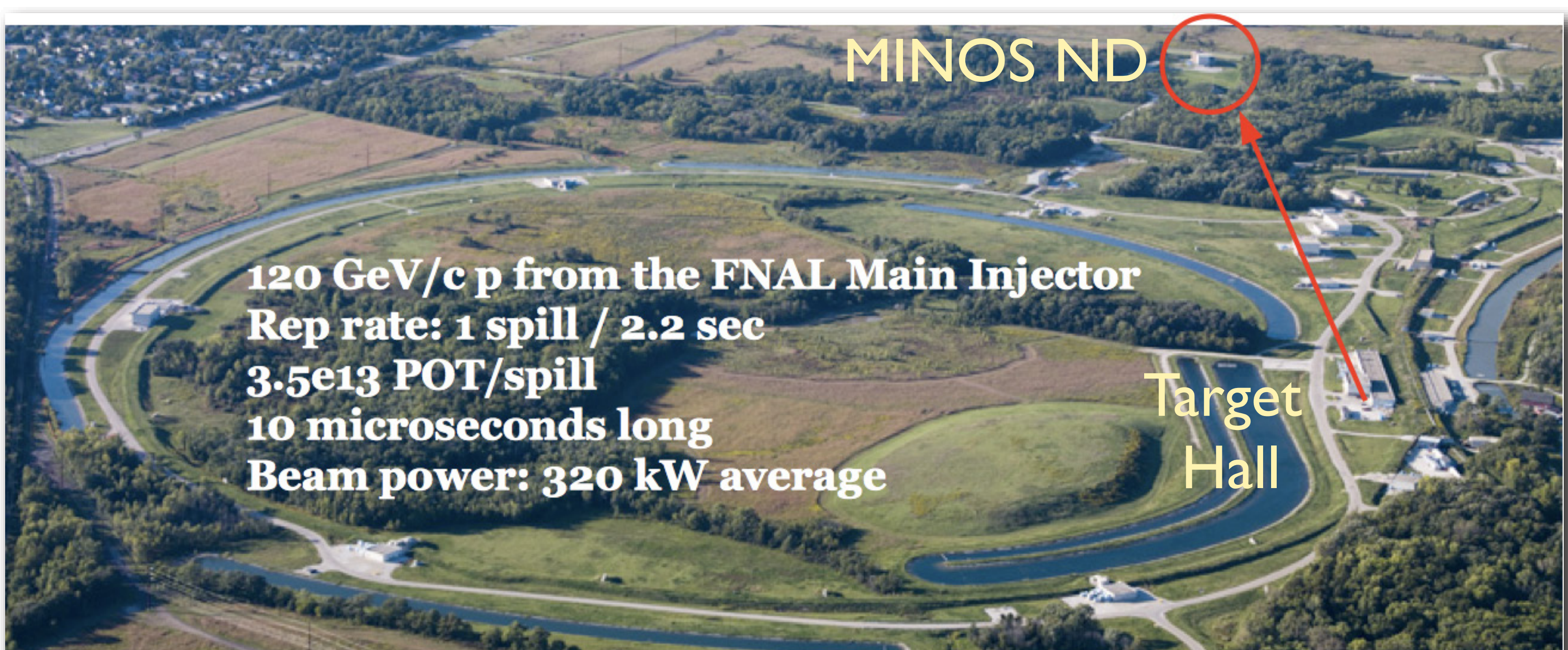


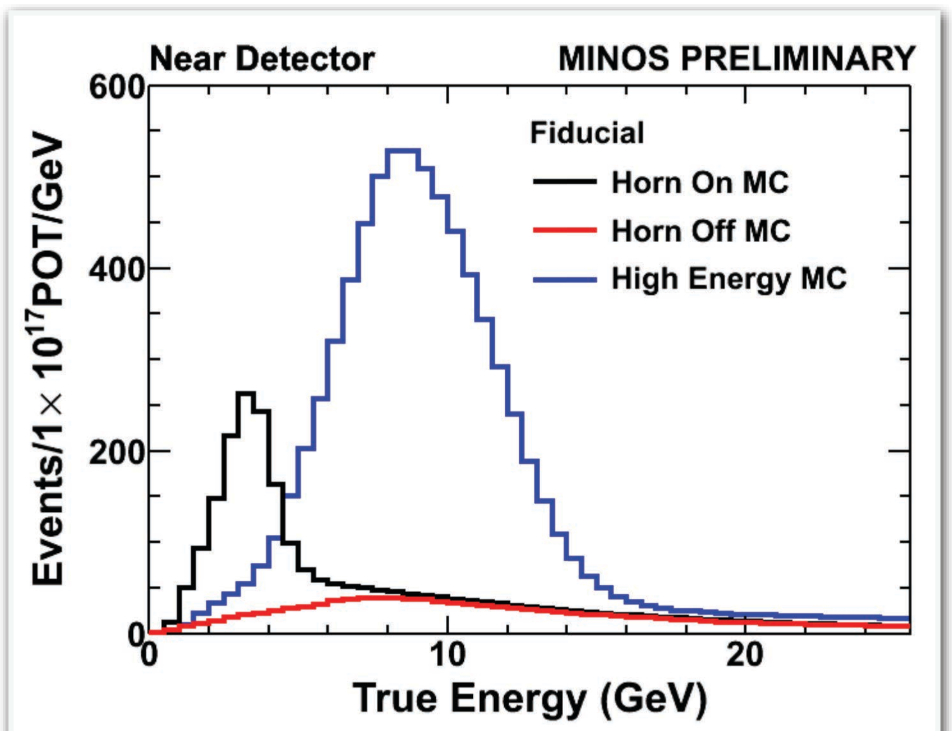
- Functionally equivalent: same materials, same segmentation, same mean B field~1.3T
  - Cancellation of neutrino beam flux and cross-section uncertainties

The NuMI Neutrino Beam

NuMI Neutrino Beam at Fermilab







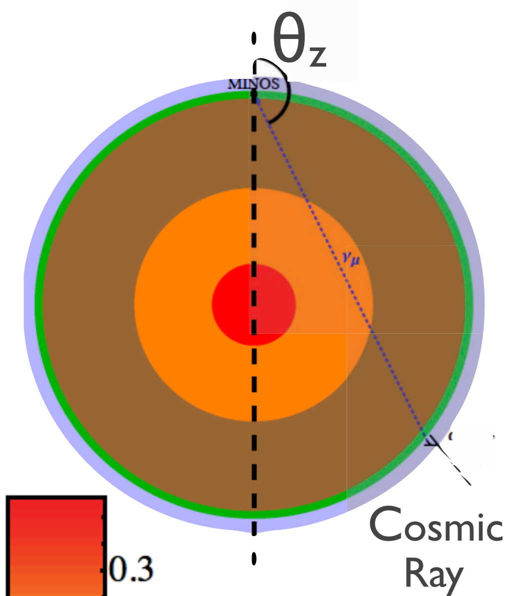
Three-Flavor Neutrino Oscillations

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{\mu\mu}) \sin^2\left(1.27\Delta_{\mu\mu}\frac{L}{E}\right) + \mathcal{O}\left(\Delta_\odot\right)^2$$

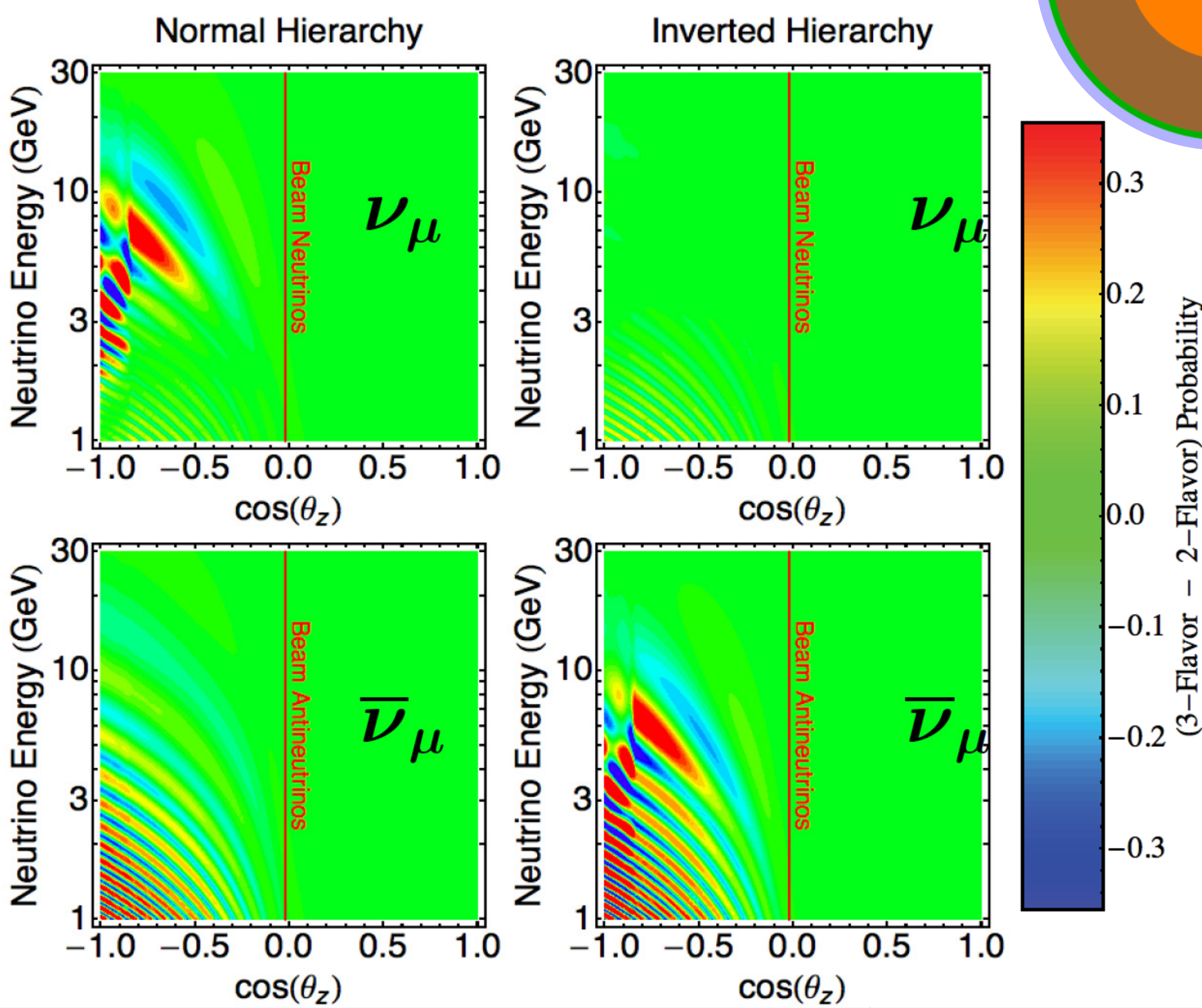
$$\sin^2(\theta_{\mu\mu}) = \sin^2(\theta_{23})\cos^2(\theta_{13}) \qquad \Delta_{\mu\mu} = \Delta m^2_{32} + \frac{|U_{\mu 1}|^2}{1-|U_{\mu 3}|^2}\Delta m^2_{21}$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2(2\theta_{\mu e})\sin^2\Delta_{\mu e} + \tilde{J}\sin\delta\sin\Delta\odot\sin^2\Delta_{\mu e} + \mathcal{O}\left(\Delta_\odot\right)^2$$

Dependence on θ_{13}, θ_{23} octant, mass hierarchy, and δ_{CP}

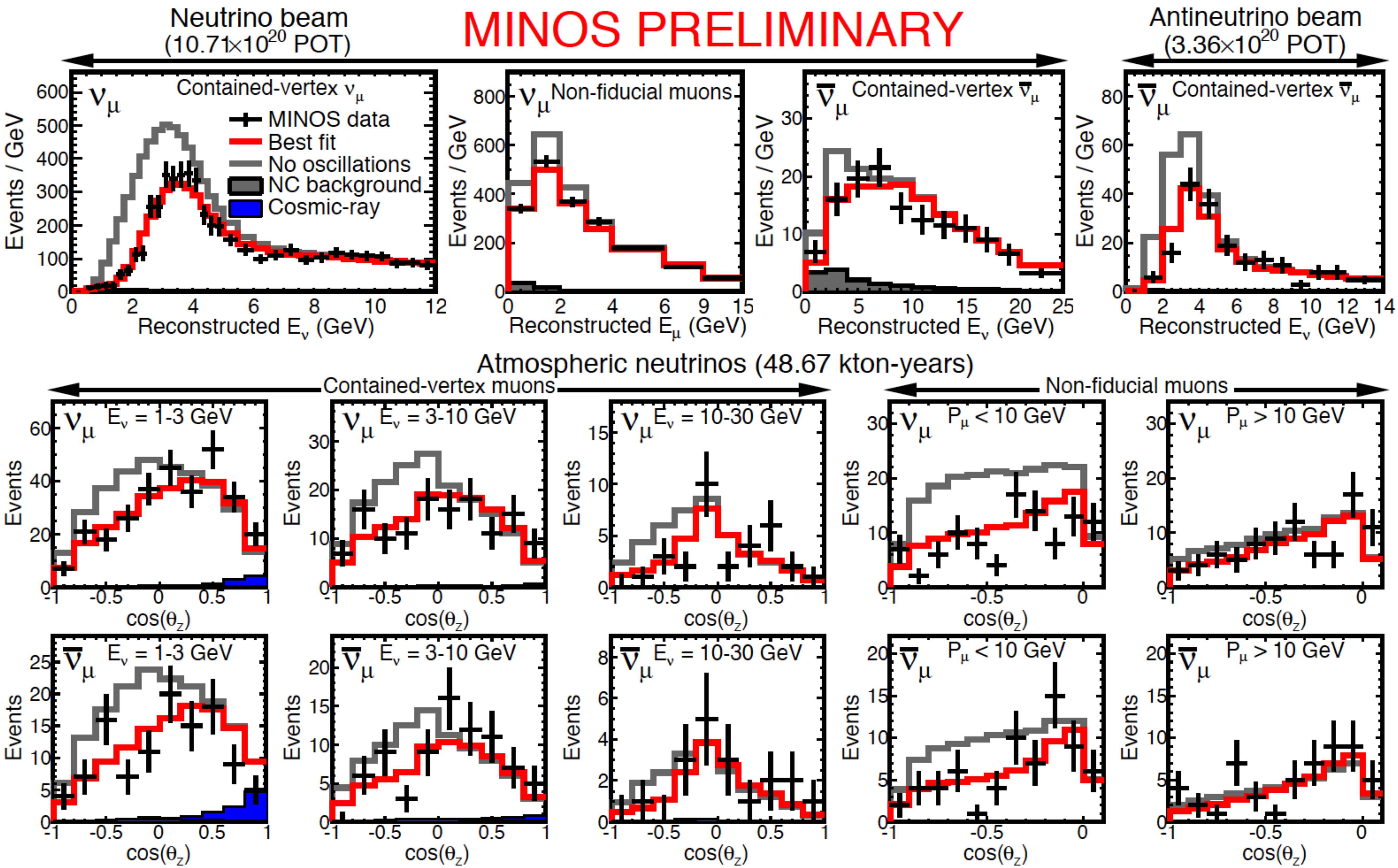


- Matter effects give rise to larger differences in multi-GeV, upward atmospheric events
- Effect is seen in neutrinos or antineutrinos, depending on hierarchy
- MINOS first to probe effect with event-by-event charge separation



All FD MINOS Data

- Showing three-flavor oscillations fit to FD disappearance+appearance beam data



Beam and Atmospheric Event Yields

Data Set	Simulation No osc.	Simulation With osc.	Events Observed
ν_μ from ν_μ beam	3201	2496	2579
$\bar{\nu}_\mu$ from ν_μ beam	363	319	312
Non-fiducial ν from ν_μ beam	3197	2807	2911
Atm. contained-vertex $\nu_\mu + \bar{\nu}_\mu$	1414	1024	1134
Atm. non-fiducial $\mu^+ + \mu^-$	732	575	590
Atm. showers	932	877	899

	Data	Expectation ($\Delta m^2_{32} = 2.10 \times 10^{-3}, \sin^2\theta_{23} = 0.5$)					
		cosmic	atmos $\nu_e/\bar{\nu}_e$ & $\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_\tau/\bar{\nu}_\tau$ CC	NC	ν-induced μ	Total
CV_μ	1134	44 ± 4	1023 ± 150	3 ± 1	32 ± 8	7 ± 2	1109 ± 158
NIM	590	0 ± 0	20 ± 3	0 ± 0	0 ± 0	571 ± 143	591 ± 143
CV_e	899	110 ± 11	636 ± 79	5 ± 1	159 ± 40	1 ± 0	911 ± 120
Total	2623	2611 ± 244					

	Data	Expectation (no oscillations)					
		cosmic	atmos $\nu_e/\bar{\nu}_e$ & $\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_\tau/\bar{\nu}_\tau$ CC	NC	ν-induced μ	Total
CV_μ	1134	44 ± 4	1327 ± 196	0 ± 0	32 ± 8	11 ± 3	1414 ± 204
NIM	590	0 ± 0	33 ± 5	0 ± 0	0 ± 0	699 ± 175	732 ± 175
CV_e	899	110 ± 11	661 ± 83	0 ± 0	159 ± 40	1 ± 0	932 ± 124
Total	2623	3078 ± 296					

Best Fit Results

Atmospheric Data Only

Hierarchy	Best fit oscillation parameters				-2Δlog(L)
	Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	
Normal	2.03	0.50	0.0242	0	-
Inverted	2.13	0.50	0.0242	1.57	0.559

Atmos+Disappearance Data

Hierarchy	Best fit oscillation parameters				-2Δlog(L)
	Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	
Normal	2.31	0.59	0.0243	0	0.020
Inverted	2.37	0.43	0.0243	1.57	-

Atmos+Disappearance+Appearance Data

Hierarchy	Best fit oscillation parameters				-2Δlog(L)
	Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	
Normal	2.34	0.43	0.0242	1.77	0.16
Inverted	2.37	0.43	0.0243	1.77	-

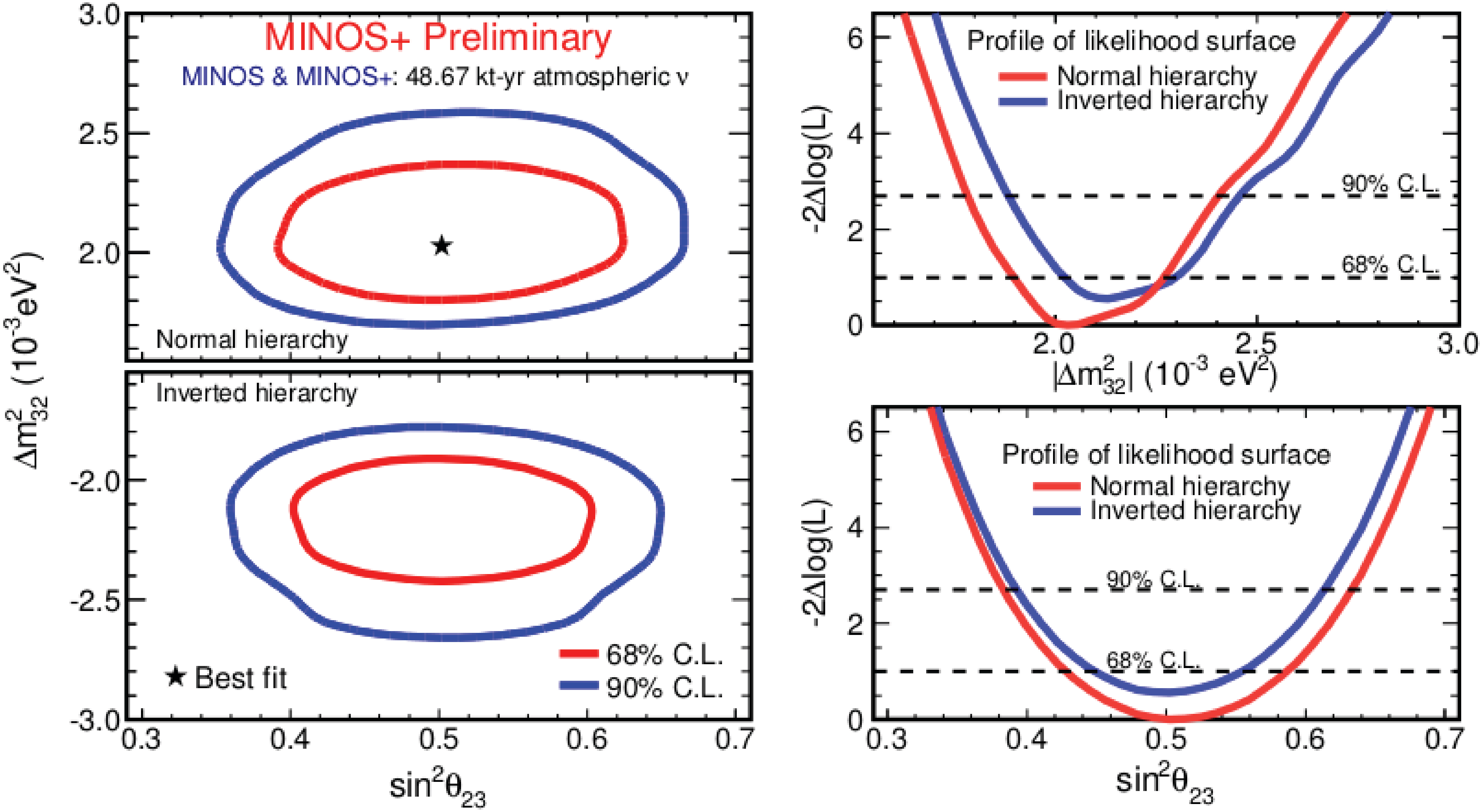
Hierarchy	Parameter	Best fit	Confidence limits
Normal	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.34	2.25 - 2.43 (68% C.L.)
	$\sin^2\theta_{23}$	0.43	0.39 - 0.59 (68% C.L.) 0.37 - 0.64 (90% C.L.)
Inverted	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.37	2.30 - 2.48 (68% C.L.)
	$\sin^2\theta_{23}$	0.43	0.38 - 0.62 (68% C.L.) 0.36 - 0.65 (90% C.L.)

Preference for inverted hierarchy: $-2\Delta\log\mathcal{L}=0.16$

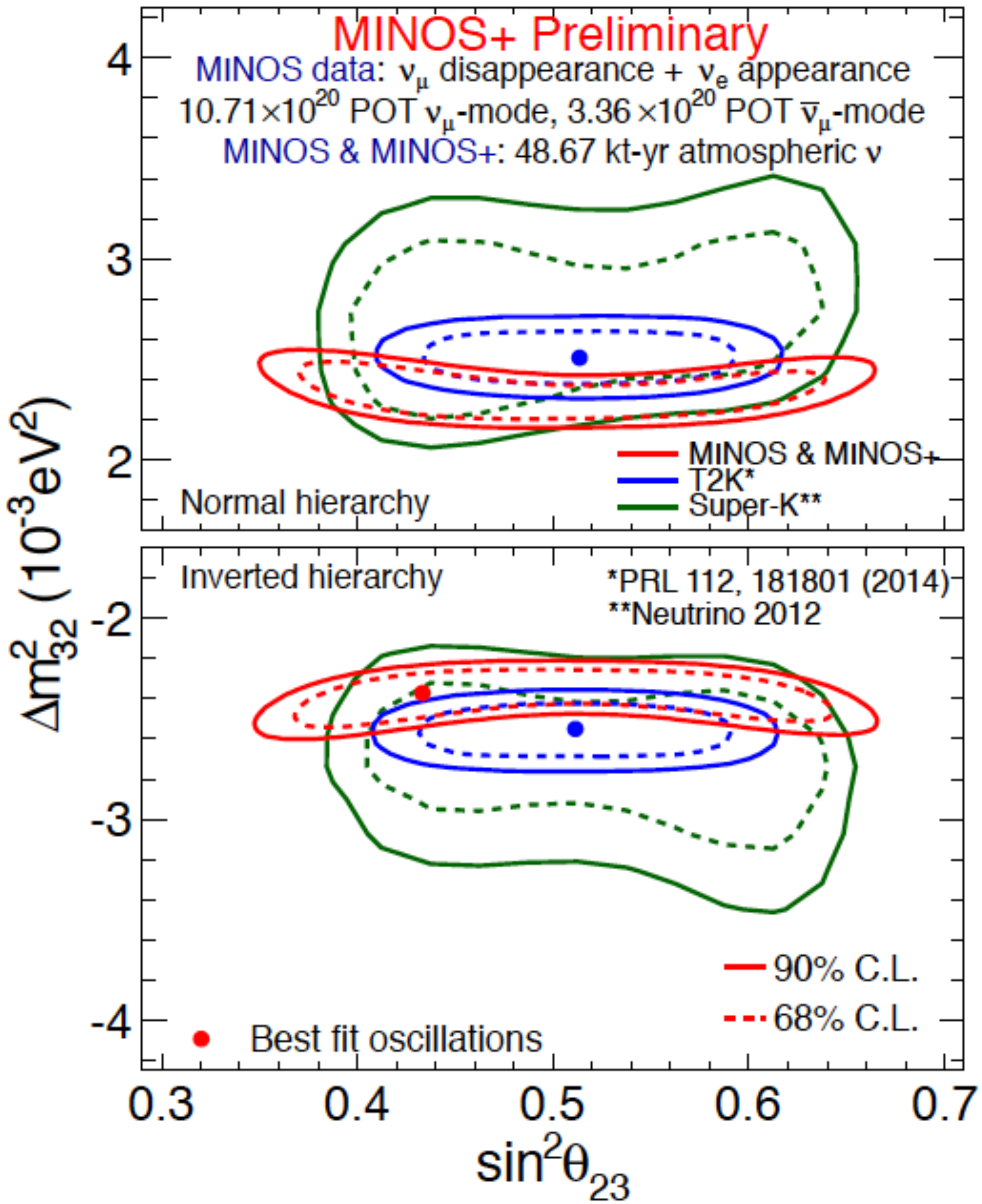
Preference for lower octant of θ_{23}: $-2\Delta\log\mathcal{L}=0.38$

Preference for non-maximal mixing: $-2\Delta\log\mathcal{L}=0.66$

Atmospherics Data



Combined Fit Results



Three-Flavor Oscillations Best Fit

Inverted Hierarchy

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

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

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

Normal Hierarchy

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

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

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

- **Most precise measurement of $|\Delta m^2_{32}|$**
- Consistent with maximal mixing

Electron Neutrino Appearance

Probability for ν_e appearance in a ν_μ beam is given by:

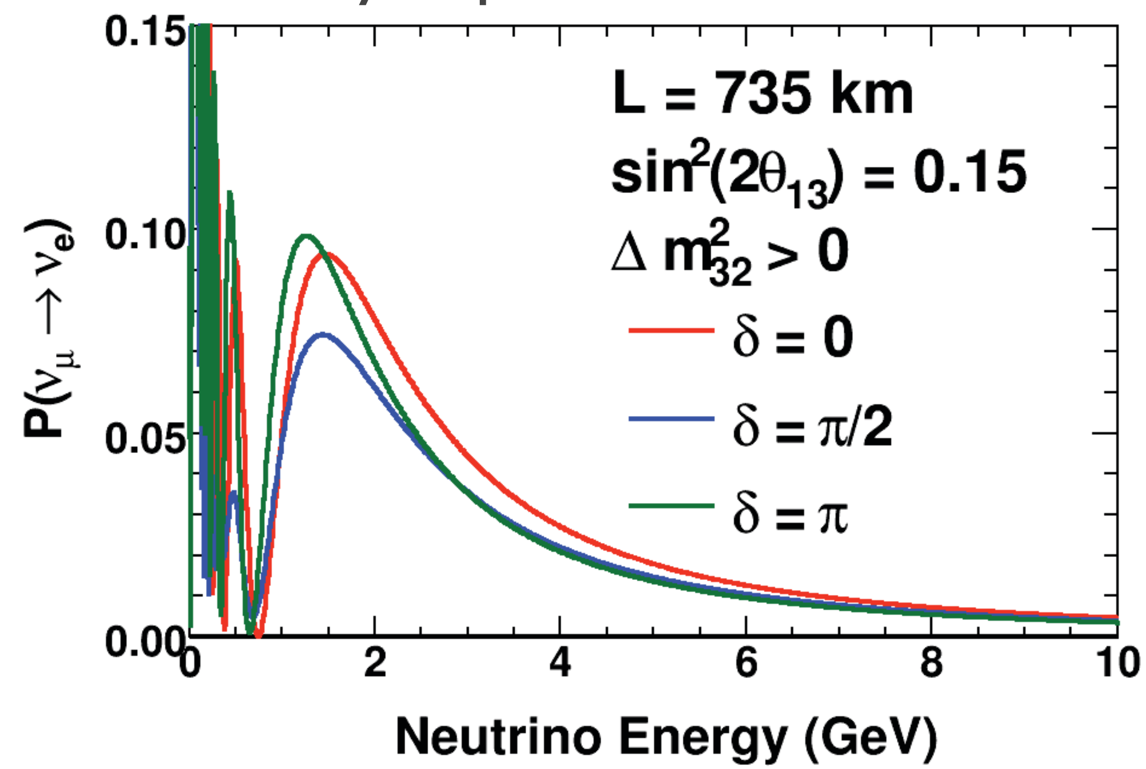
$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30}$$

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2}$$
$$+2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$\overset{(+)}{-}2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

- Interference term:
  - - for neutrinos
  - + for antineutrinos

$$if\ \delta_{CP} \neq 0,$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq P(\nu_\mu \to \nu_e)$$

Probability depends on θ_{13} and δ_{CP}



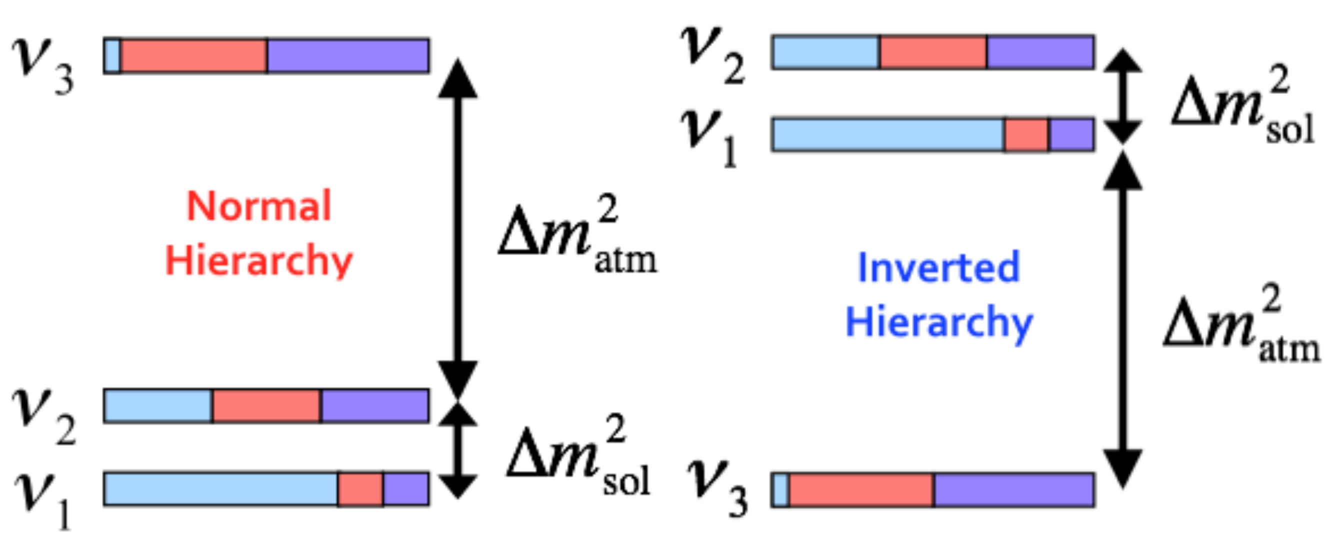
Electron Neutrino Appearance

Probability for ν_e appearance in a ν_μ beam is given by:

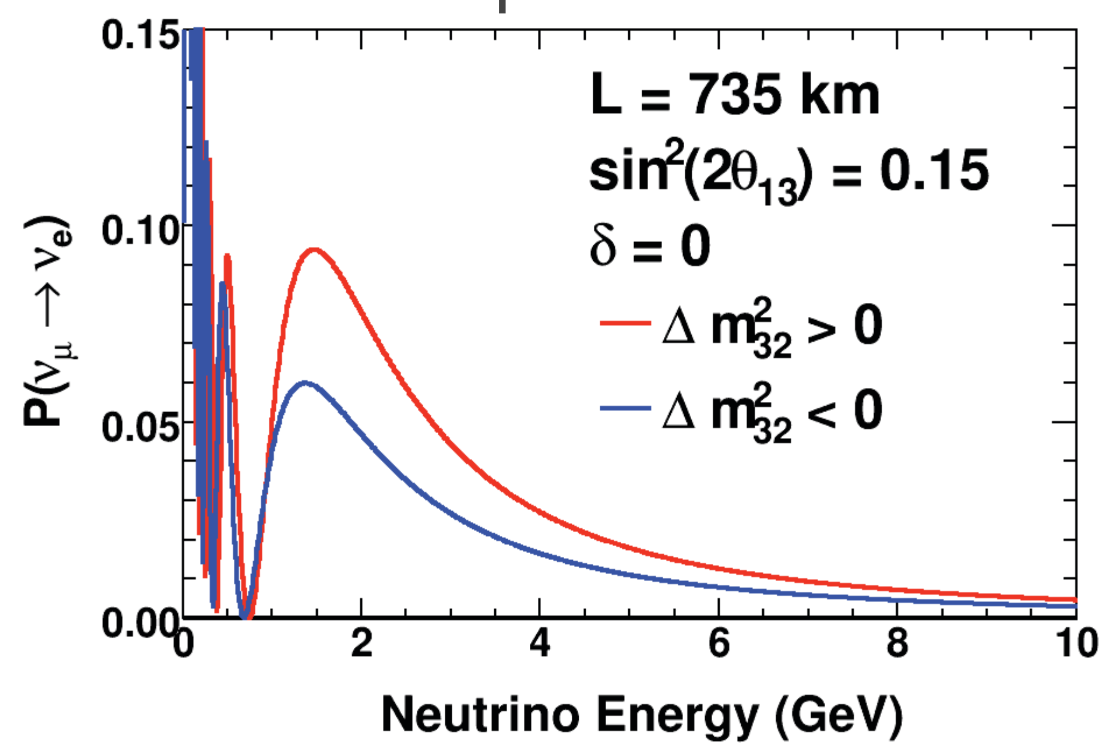
$$A \overset{(-)}{\equiv +} \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}} \qquad \Delta \equiv \frac{\Delta m_{31}^2 L}{4E} \qquad \alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sim \frac{1}{30}$$

$$\begin{aligned} P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2} \\ & + 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta \\ & \overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta \end{aligned}$$

In matter, ν_e+e CC scattering modifies oscillation probability by ~30% for MINOS



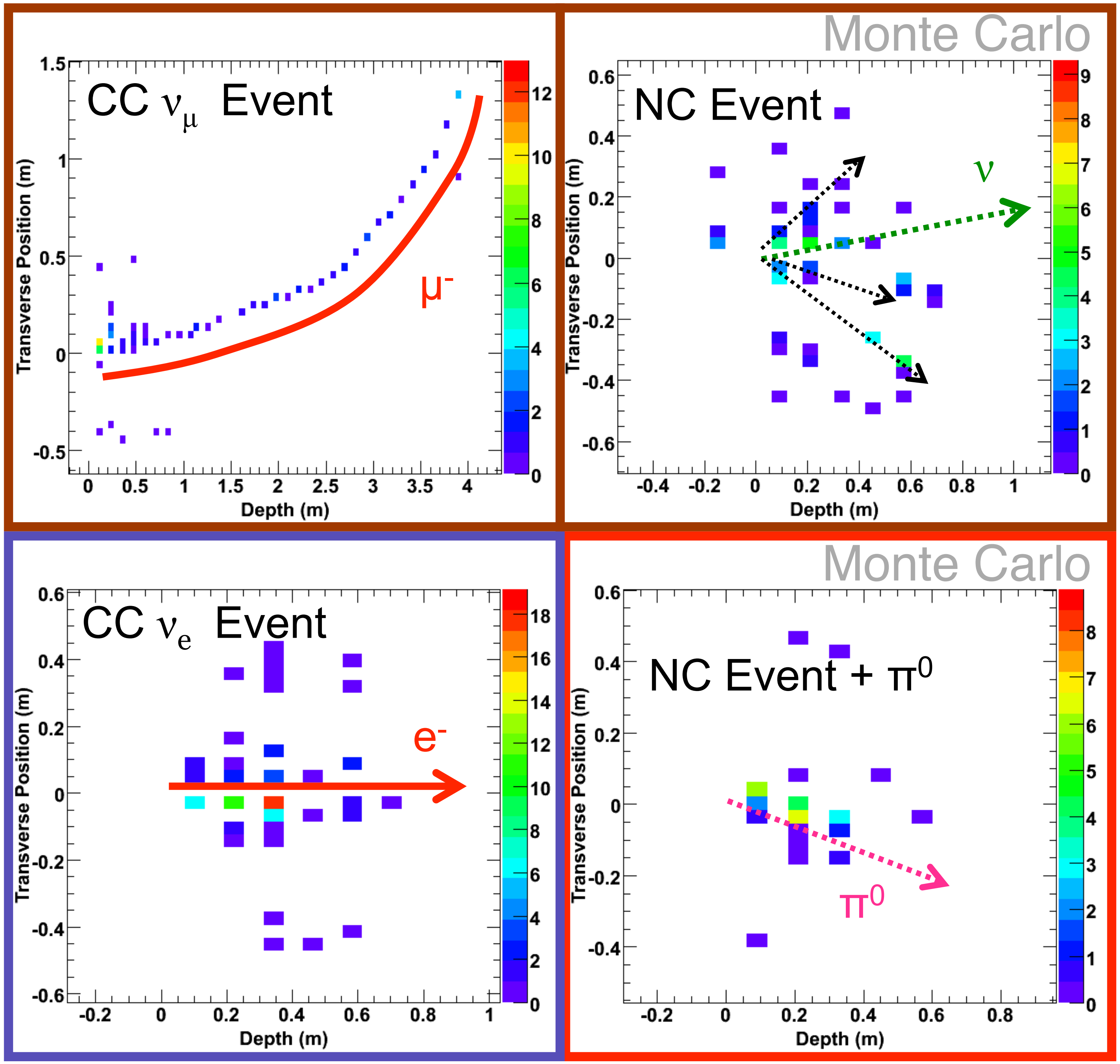
Matter effects => dependence on mass hierarchy



MINOS ν_e Signal and Backgrounds

Reducible Background

Signal



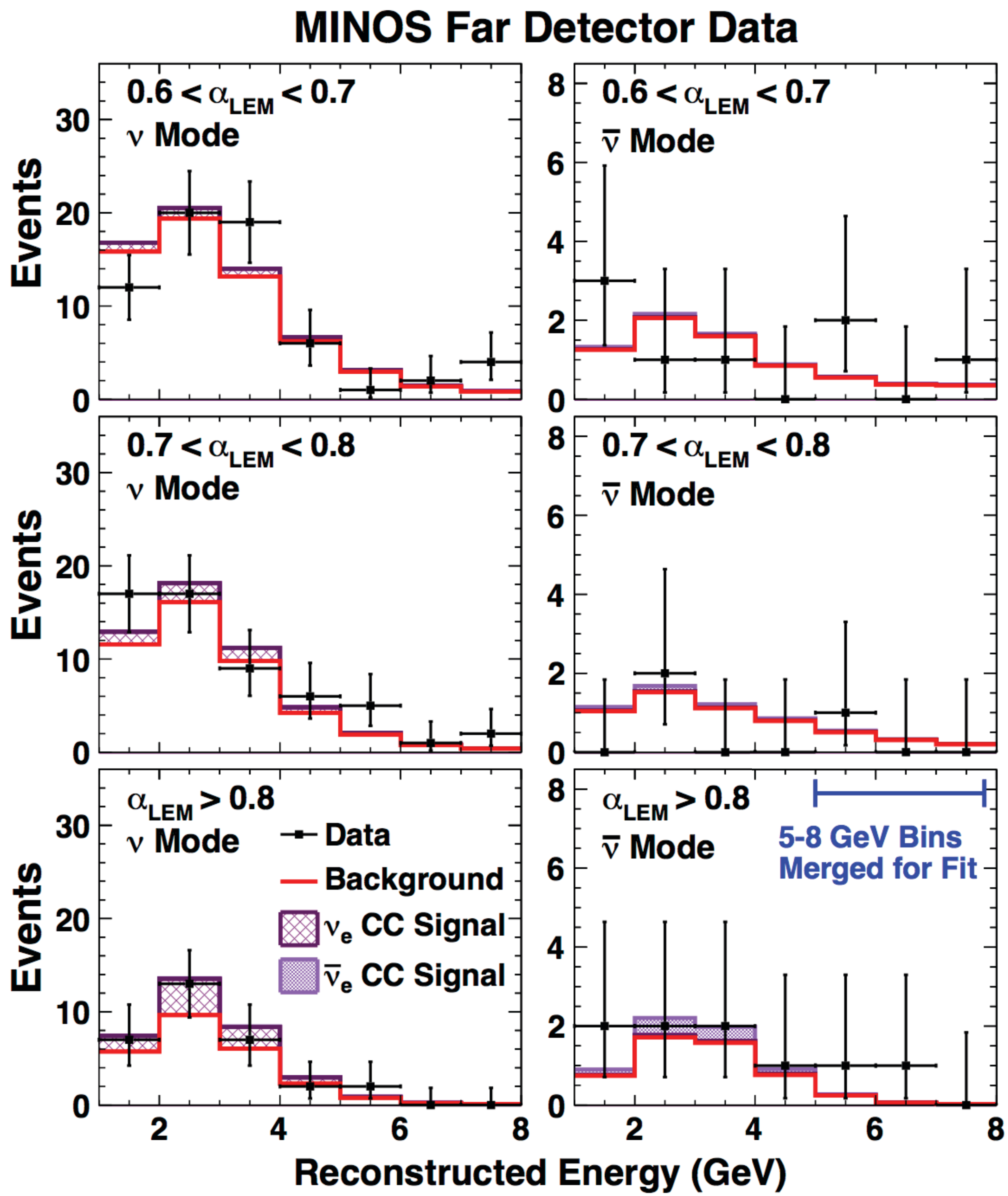
Irreducible Background

- Steel thickness ~ 1.4 radiation lengths, strip width 4.1 cm > Molière radius

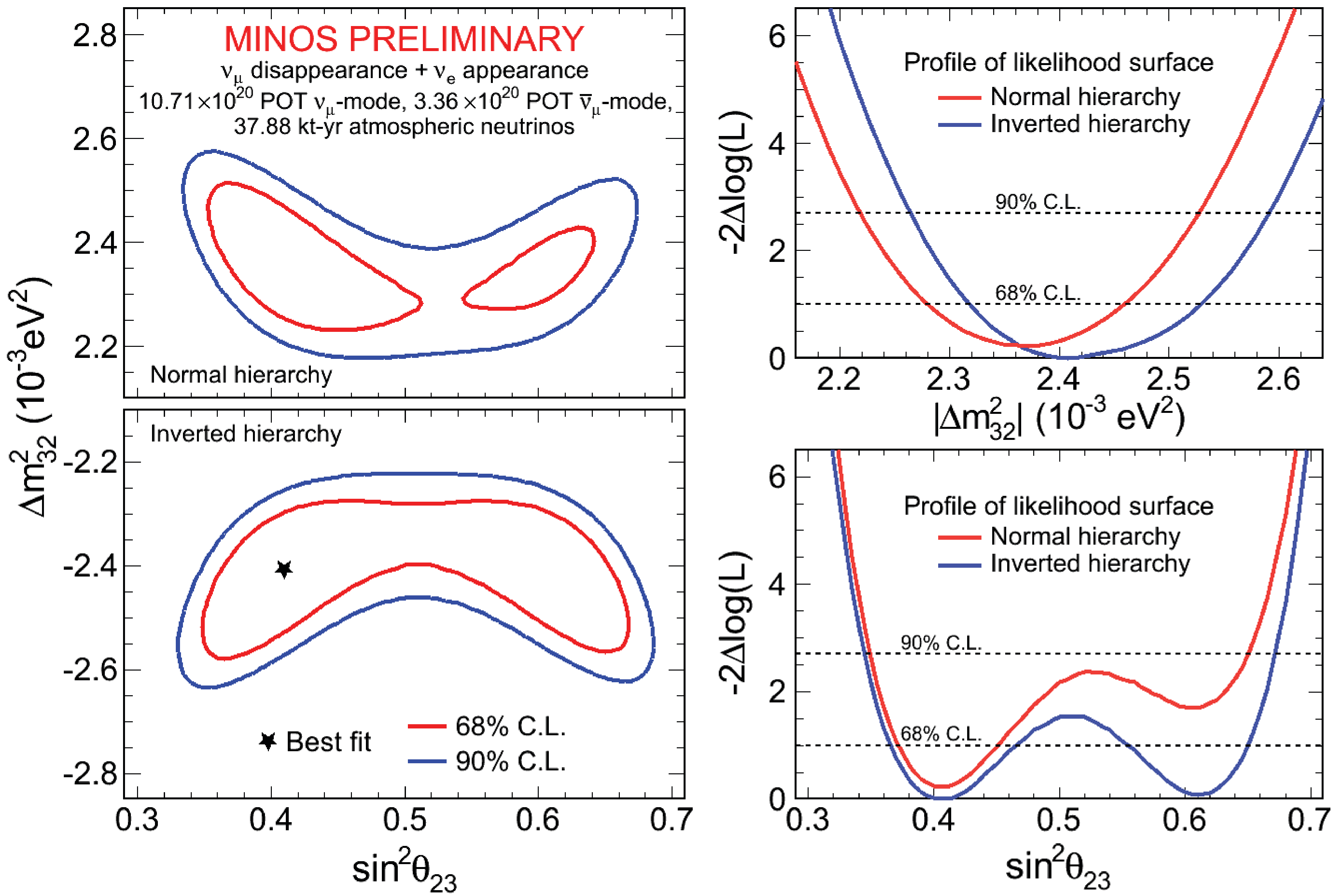
FD Electron Neutrino Appearance

- FD event yields for normal mass hierarchy, δ_{CP}=0, θ_{23}=π/4

	ν-beam	$\bar{\nu}$-beam
$\theta_{13} = 0$	69.1	10.5
$\theta_{13} = 0.1$	+26.0	+3.1
Obs.	88	12



Previous Combined Fit Results

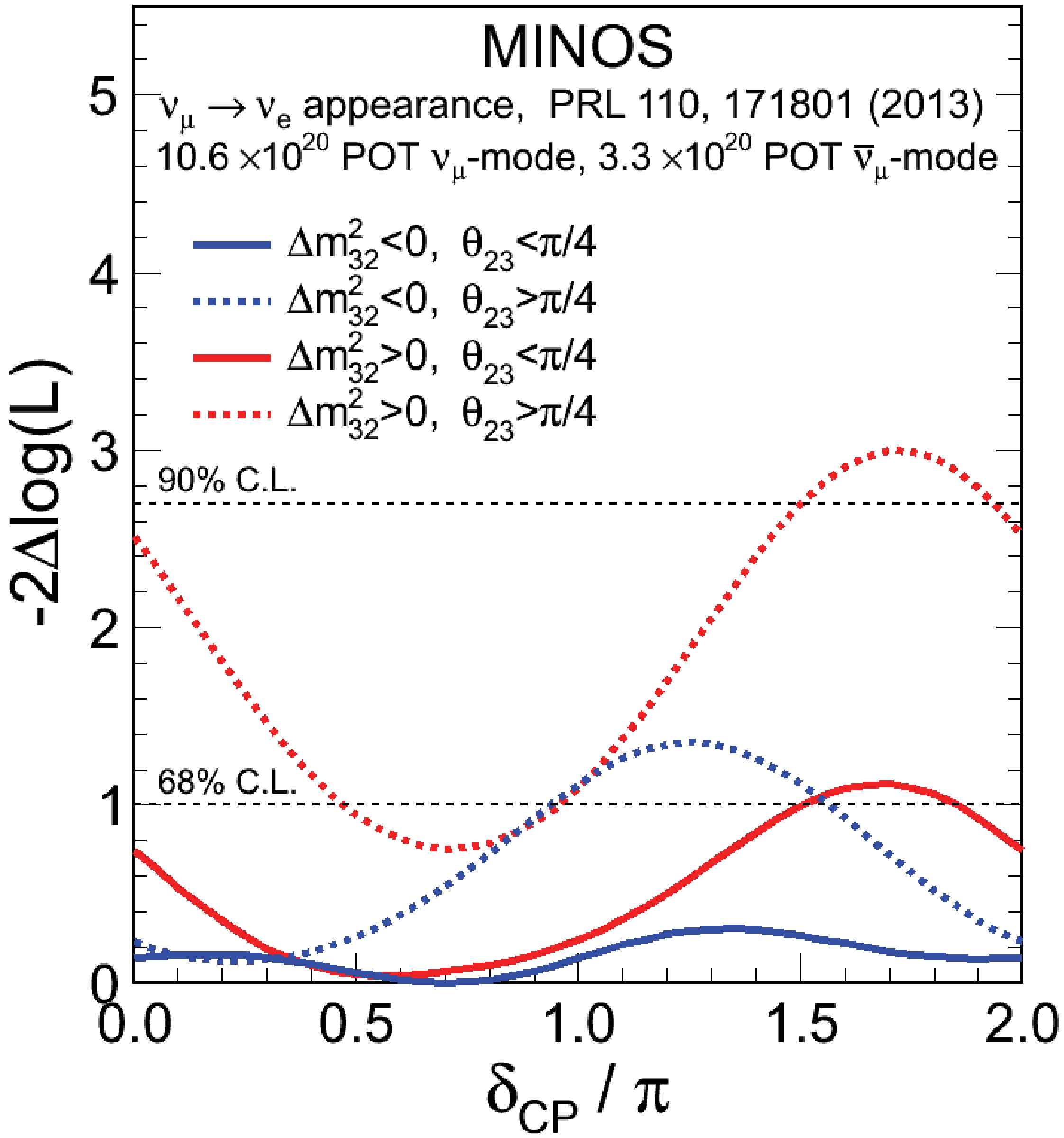


Phys. Rev. Lett. ***112****, 191801 (2014)*

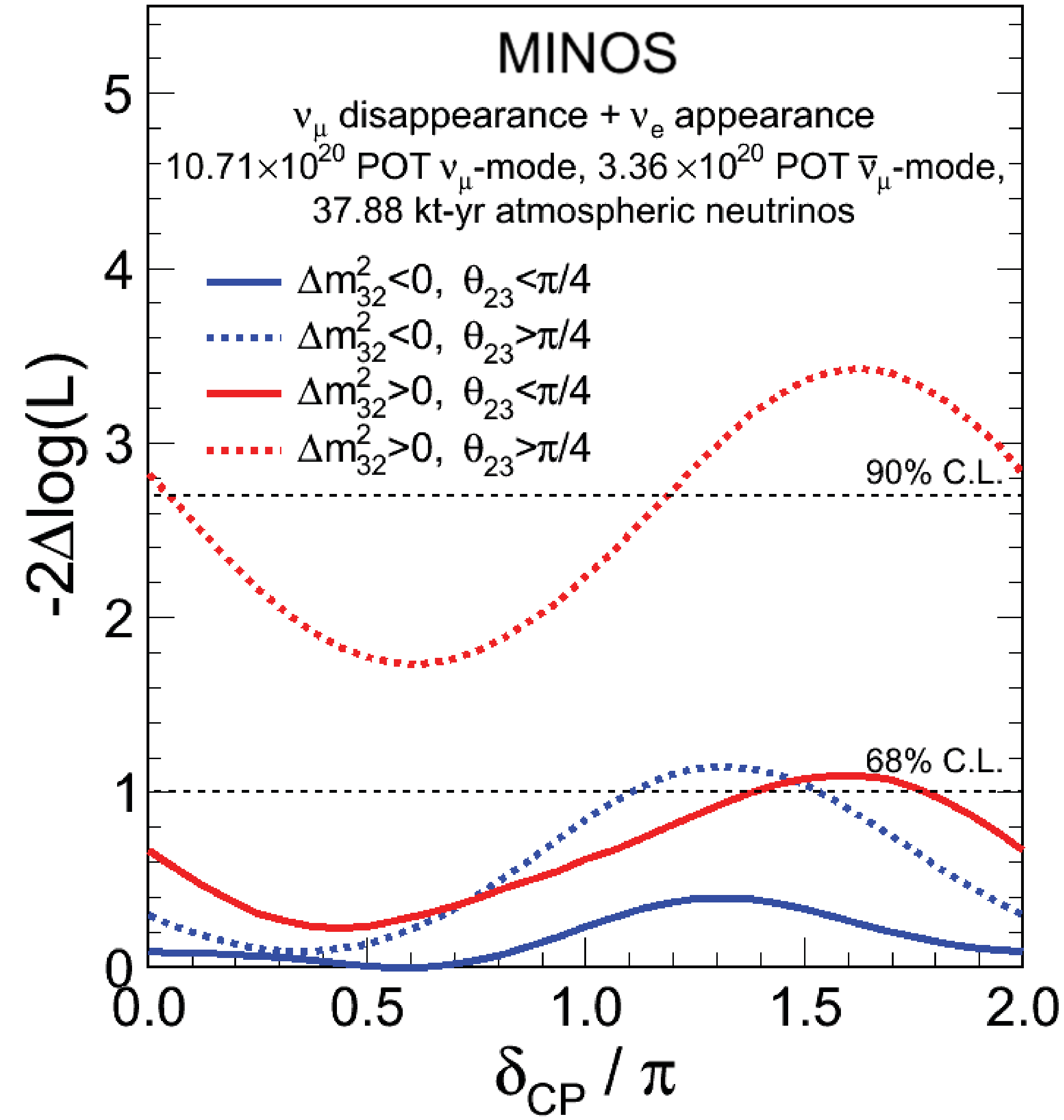
- Solar mixing parameters fixed
- θ_{13} fit as nuisance parameter, constrained by reactor results
- δ_{CP} , θ_{23}, Δm^2 unconstrained
- Major systematic uncertainties included as nuisance parameters

Dependence on δ_{CP}

Appearance Only



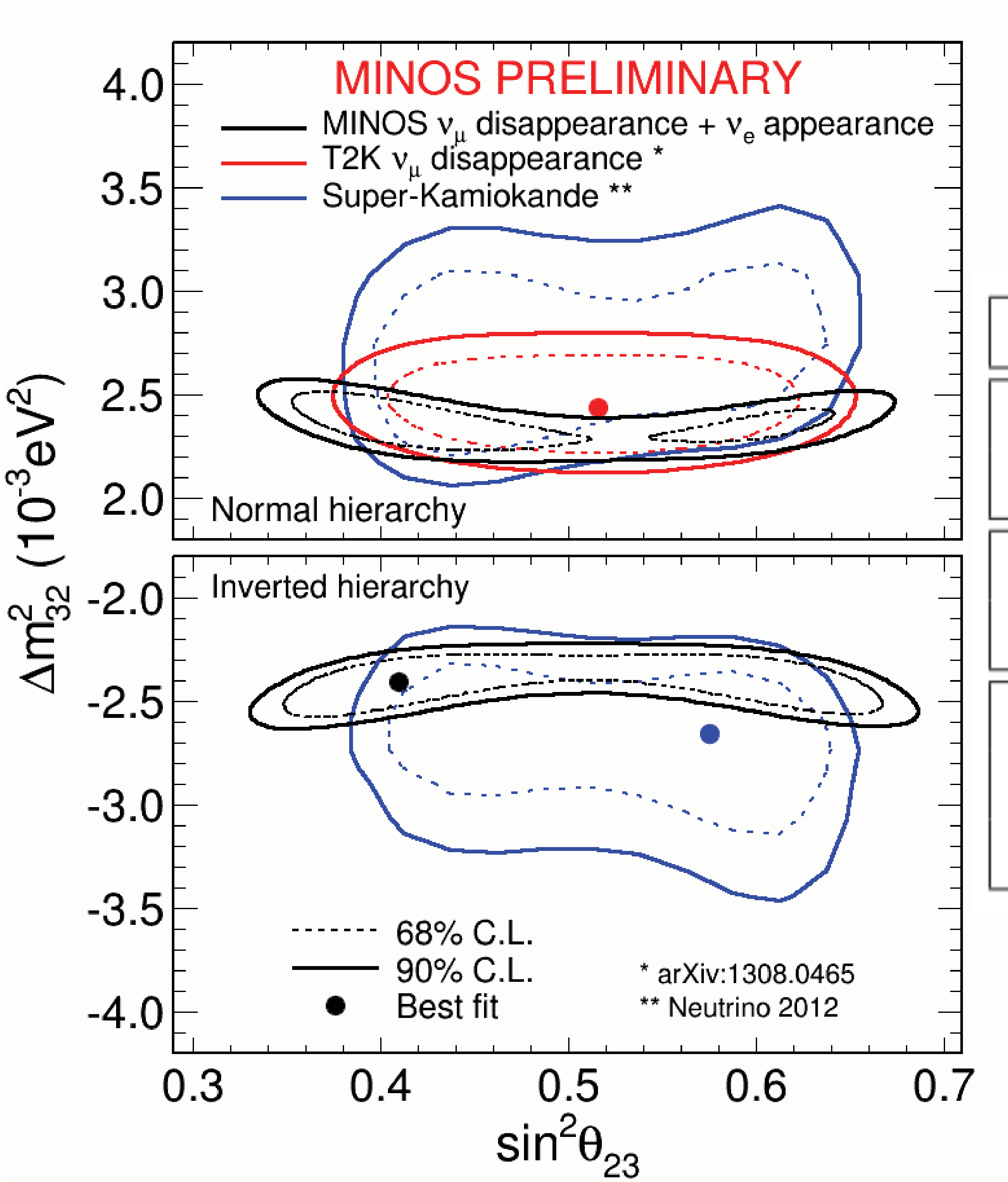
Disappearance + Appearance



Phys. Rev. Lett. ***112***, *191801 (2014)*

- Adding disappearance data (beam+atmospherics) further disfavors normal hierarchy and upper octant

Previous Combined Fit Results



	Parameter	Best fit	Confidence limits
Normal hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}$eV^2	2.37	$2.28 - 2.46$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.35 - 0.65$ (90% C.L.)
Inverted hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}$eV^2	2.41	$2.32 - 2.53$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.34 - 0.67$ (90% C.L.)

Preference for inverted hierarchy: $-2\Delta\log L = 0.23$

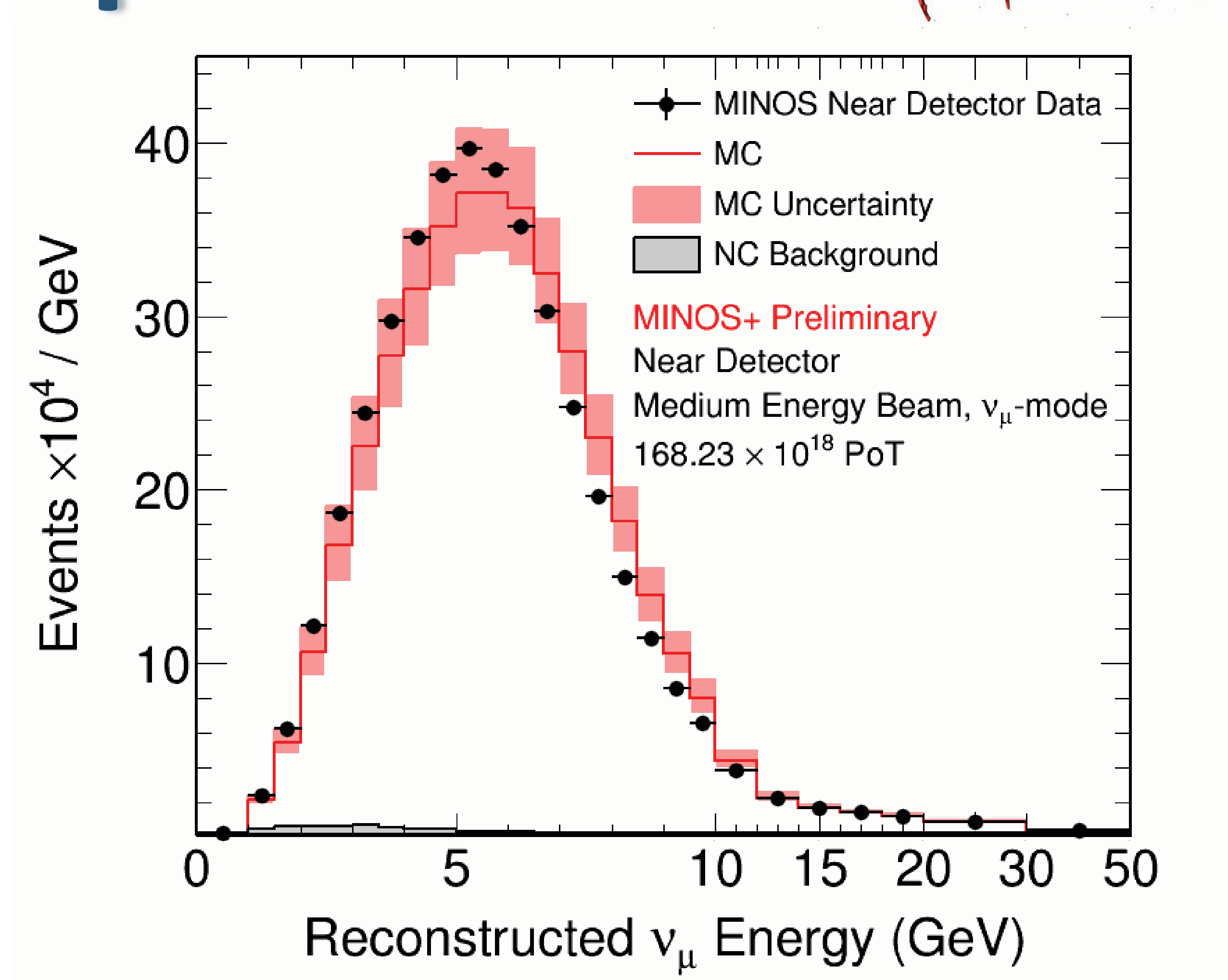
Preference for lower octant: $-2\Delta\log L = 0.09$

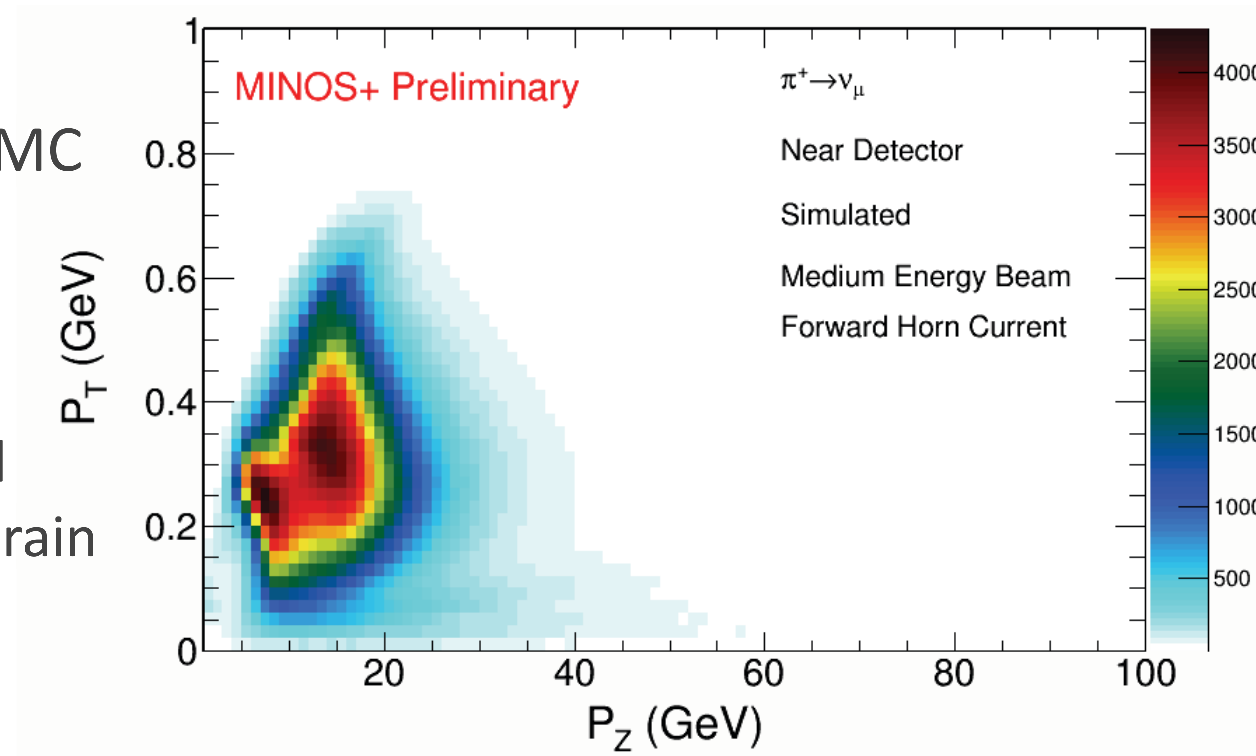
Preference for non-maximal mixing: $-2\Delta\log L = 1.54$ ($\Rightarrow$ 79% C.L.)

Phys. Rev. Lett. ***112****, 191801 (2014)*

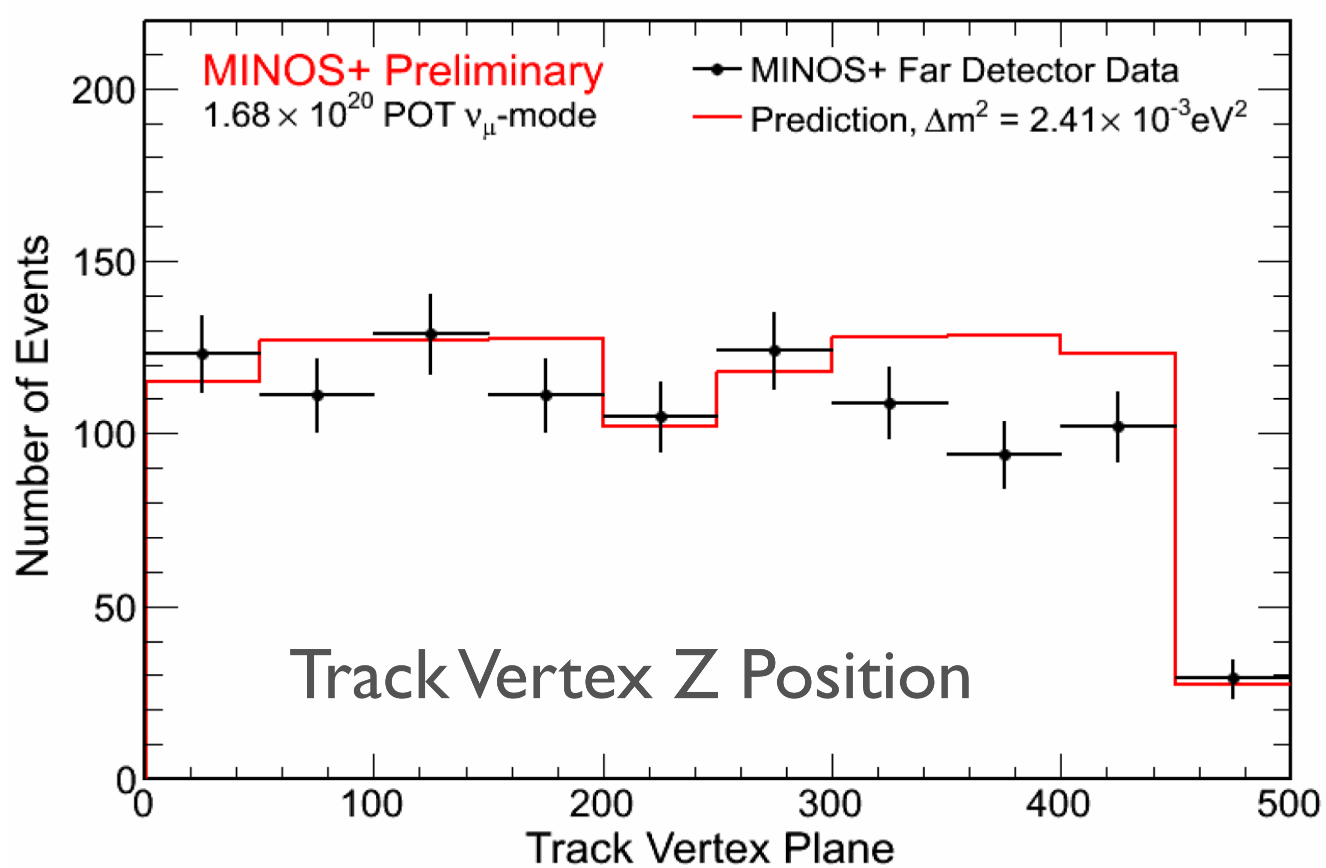
Data/MC Comparison

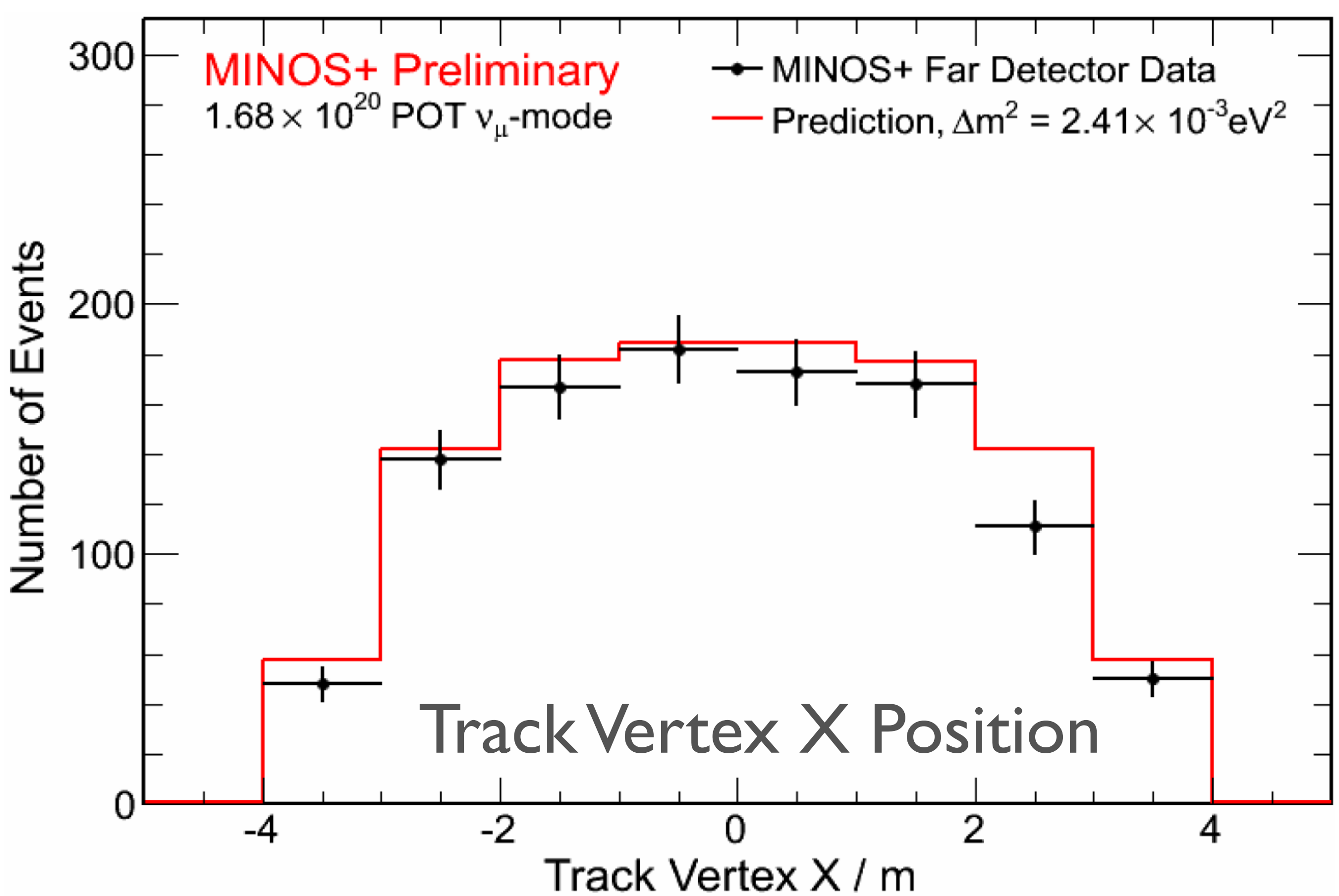
- Reconstruction algorithms have been optimized for higher-intensity in MINOS+, to mitigate pile-up effects in the ND
- New NOvA target has different hadron production from MINOS target
  - Incorporated new π^+, π^-, K^+, K^- production in p_T, p_Z fits
  - Both medium-energy and horn-off data used in the fits
  - Fits constrained by NA49 data
  - Fit results used to tune MINOS+ MC
- Working on improving MINOS+ data/MC agreement
  - Optimizing CC selection criteria
  - Revisiting beam optics simulation
  - Use external data from NOvA ND and NA61 NuMI, when available, to constrain beam fits

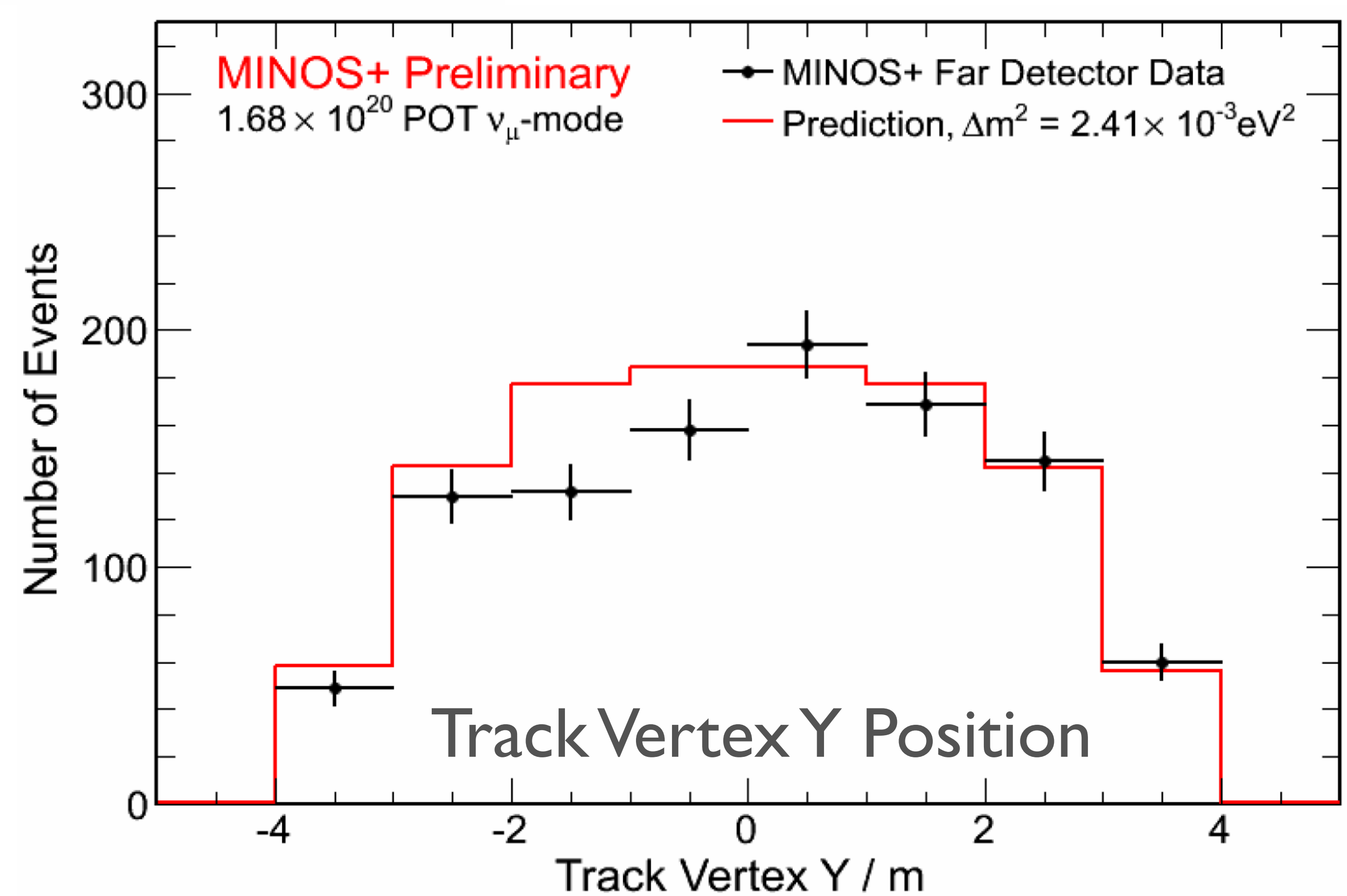




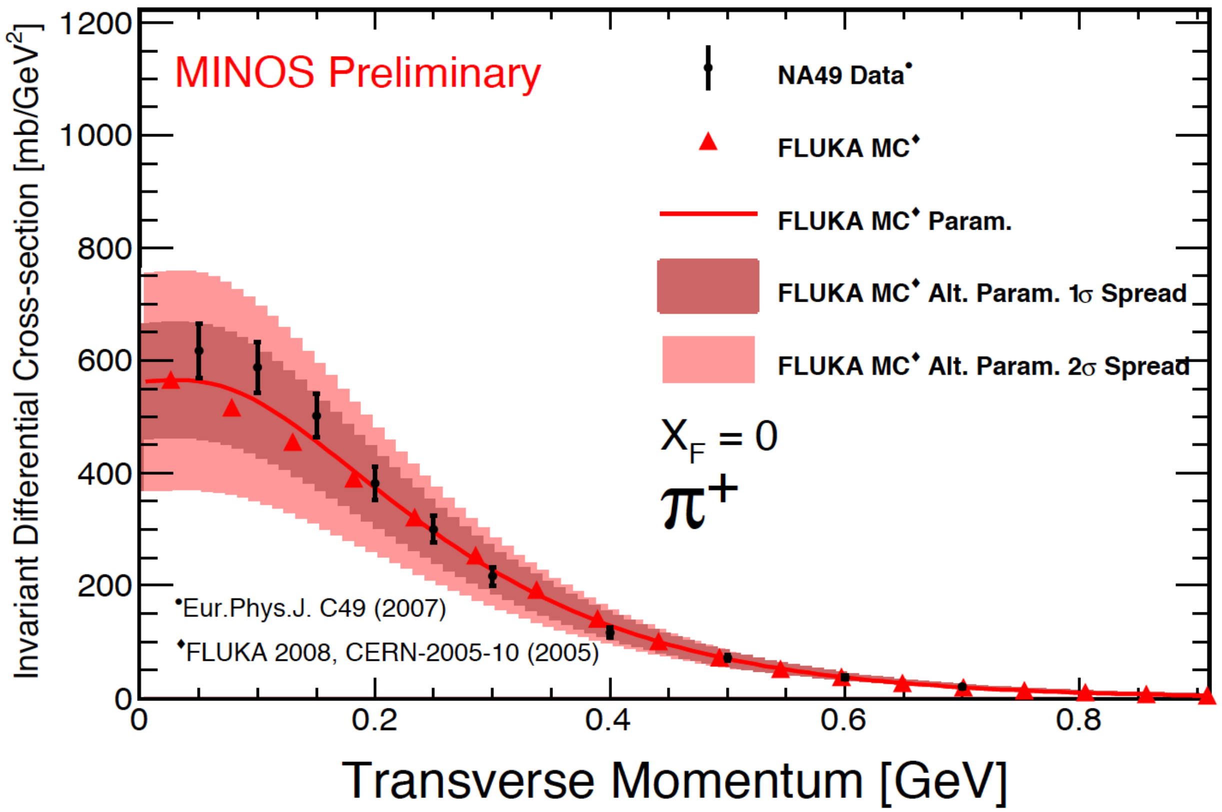
FD Data/MC Comparisons

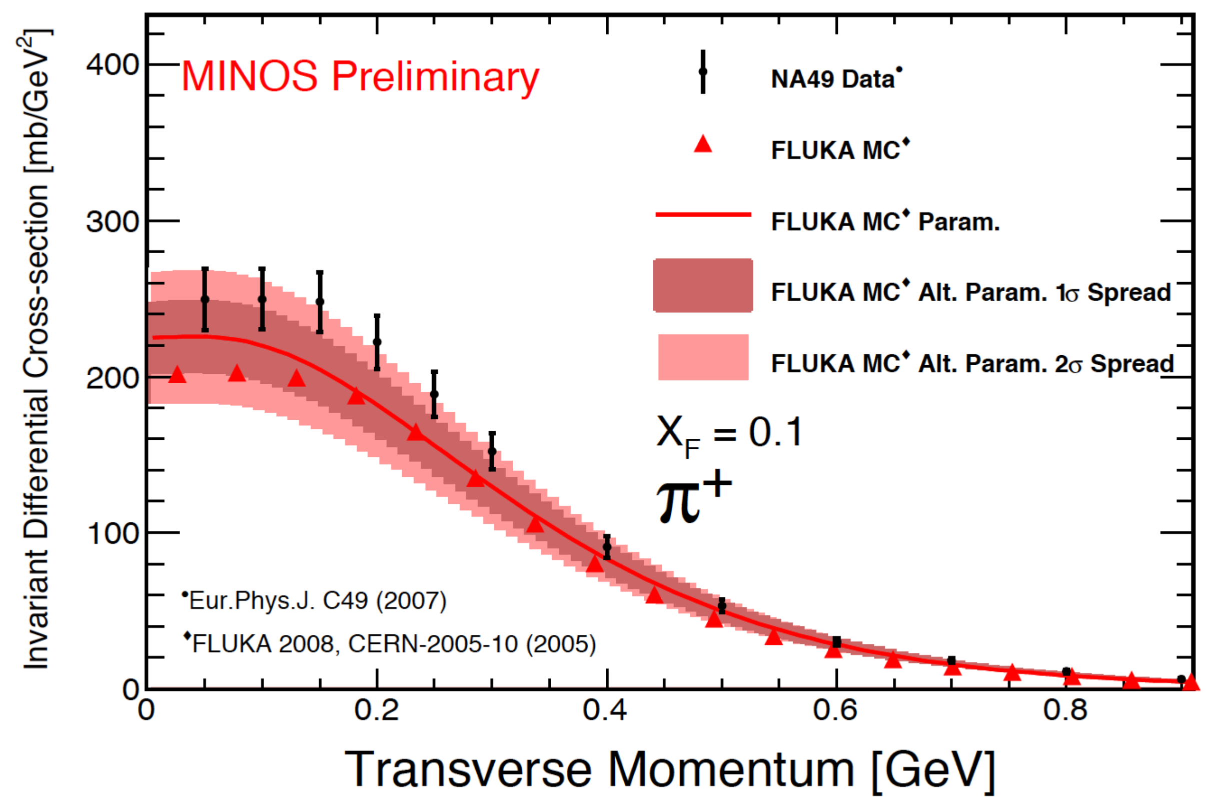


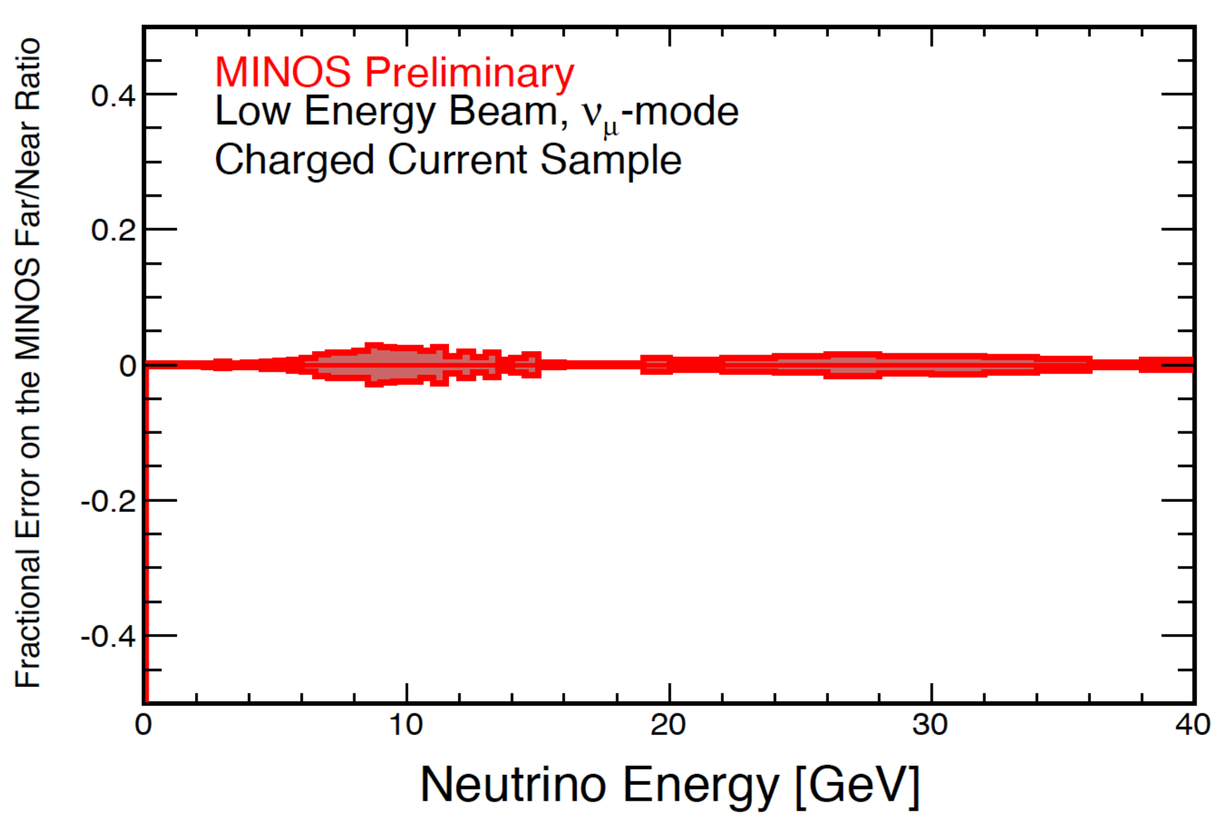


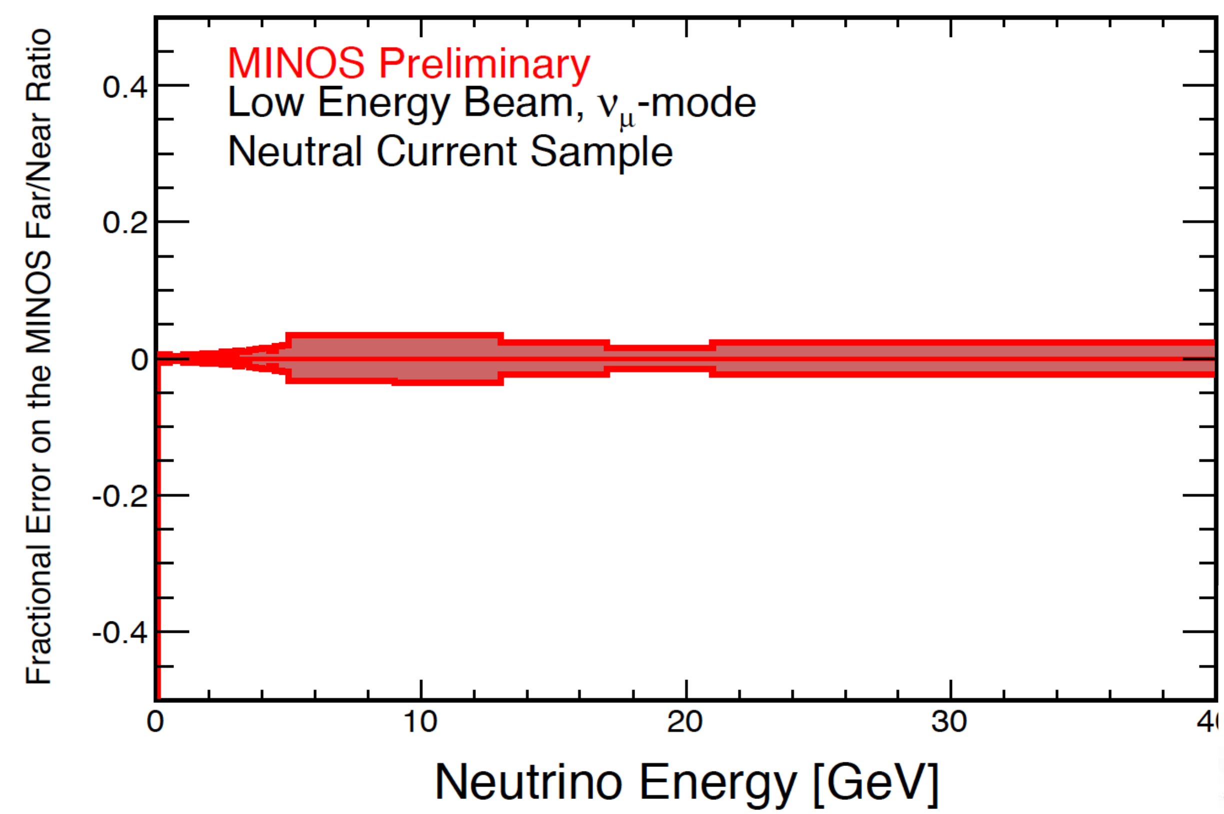


Hadron Production Uncertainties

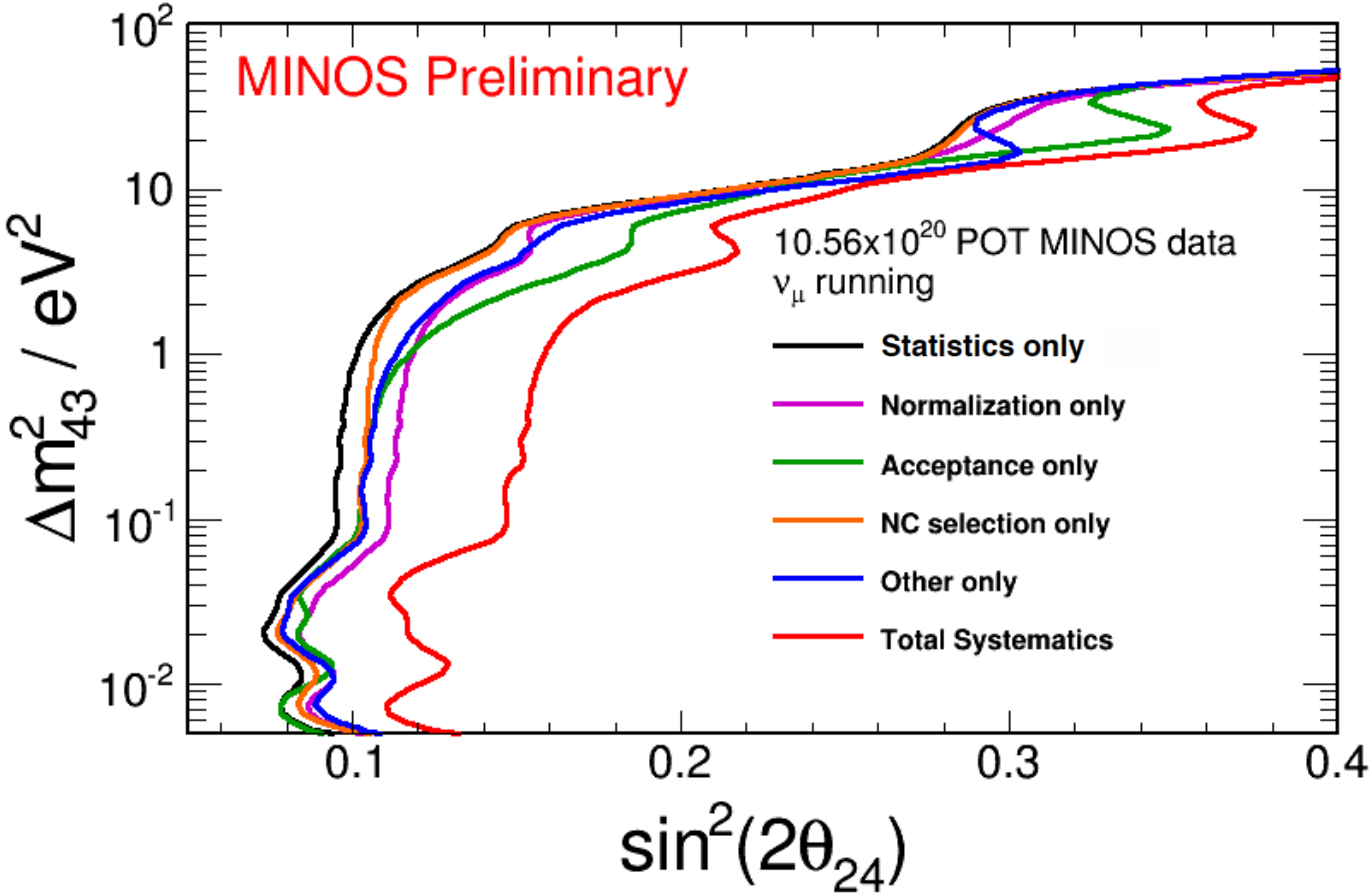




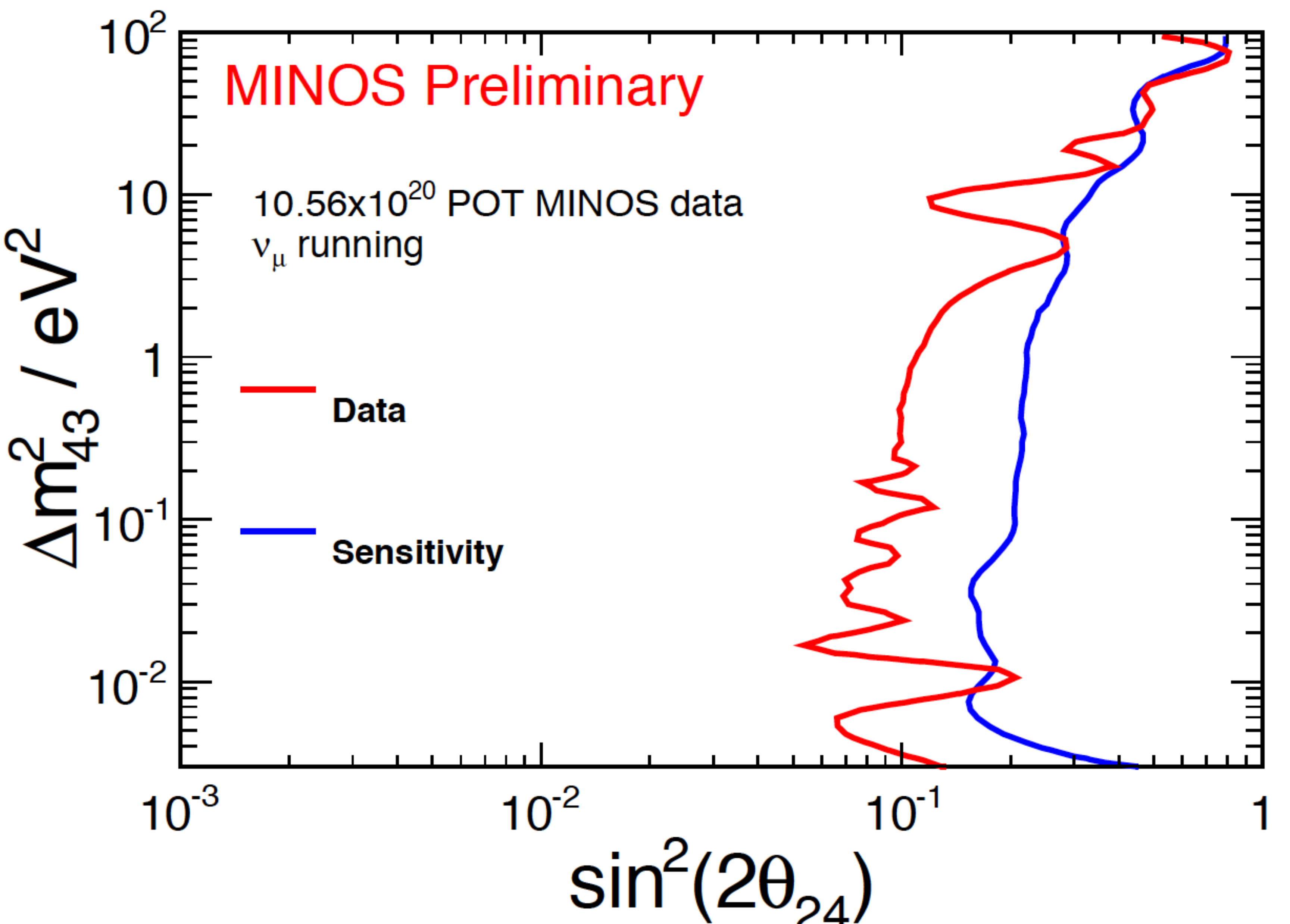




Effect of Systematics on Sensitivity



Sterile Limit Data and Sensitivity



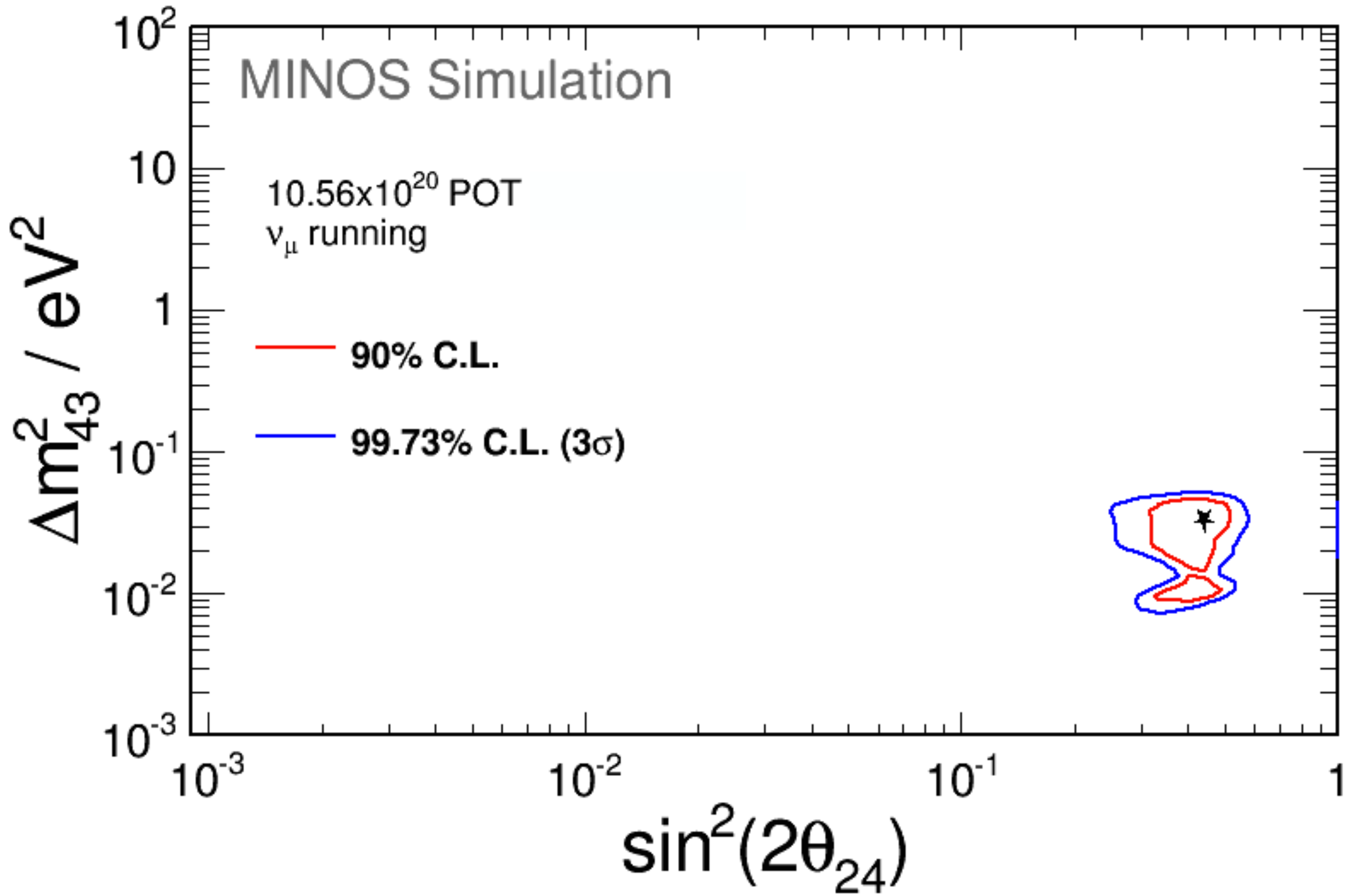
- For $\Delta m^2_{43} = 0.5$ eV²:

$\theta_{24} < 13°$ at 90% C.L. $\Rightarrow$ $|U_{\mu 4}|^2 \approx \sin^2\theta_{24} < 0.050 \quad (90\%\ \text{C.L.})$

$\theta_{34} < 44°$ at 90% C.L. $\Rightarrow$ $|U_{\tau 4}|^2 \approx \cos^2\theta_{24}\sin^2\theta_{34} < 0.024 \quad (90\%\ \text{C.L.})$

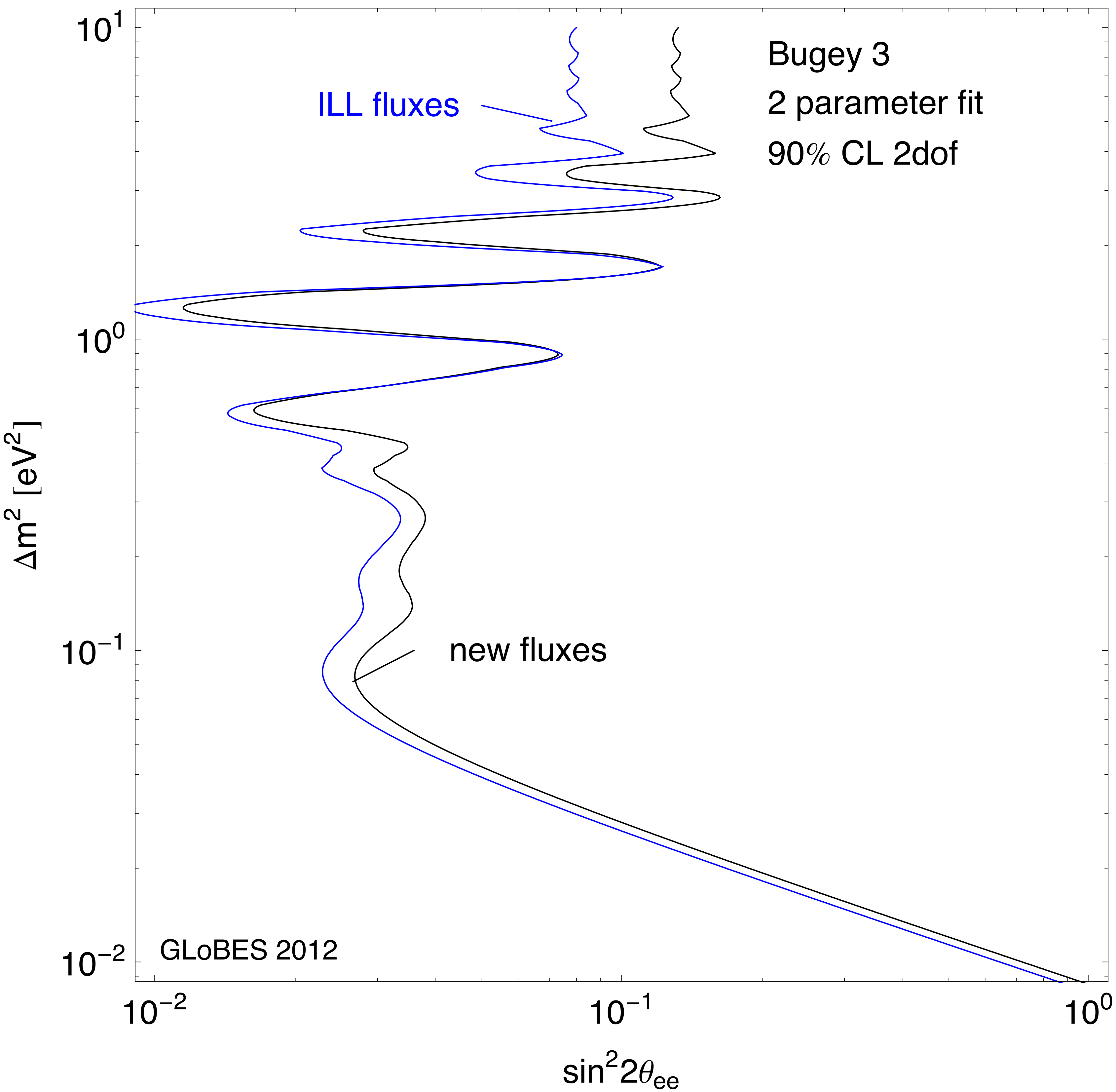
- Constraint on θ_{34}, which governs ν_τ, ν_s mixing, is inaccessible to SBL ν_μ beam experiments

Sensitivity to Sterile Signal



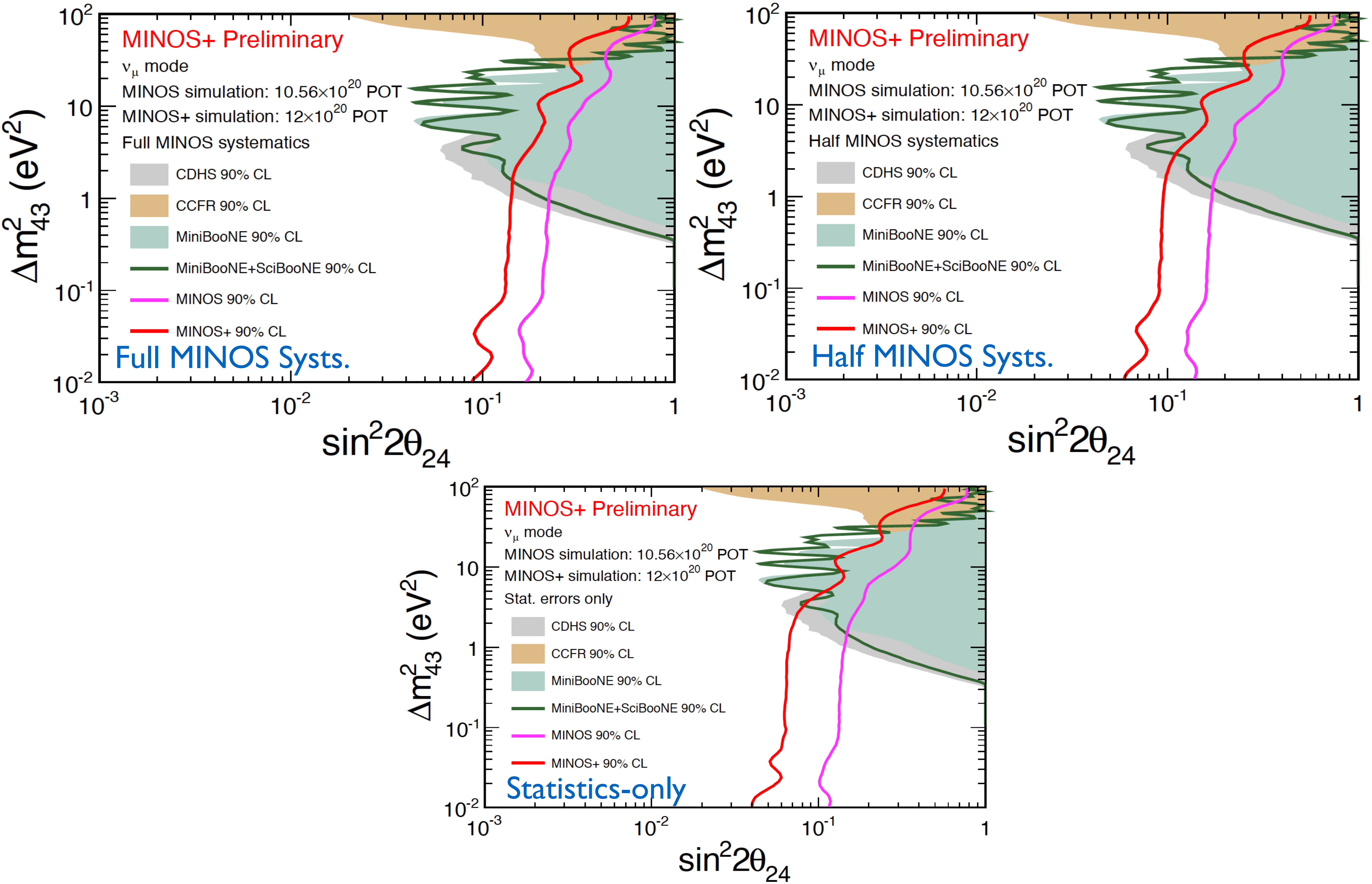
- Input sterile signal at MiniBooNE best fit for antineutrino sample
  - Δm^2_{43}=0.043 eV^2, $\sin^2\theta_{24}$=0.44

Bugey Limit



- Bugey limit computed from GLoBES 2012 fit using new reactor fluxes, provided by Patrick Huber

Projected MINOS+ Sensitvities



Large Extra-Dimensions

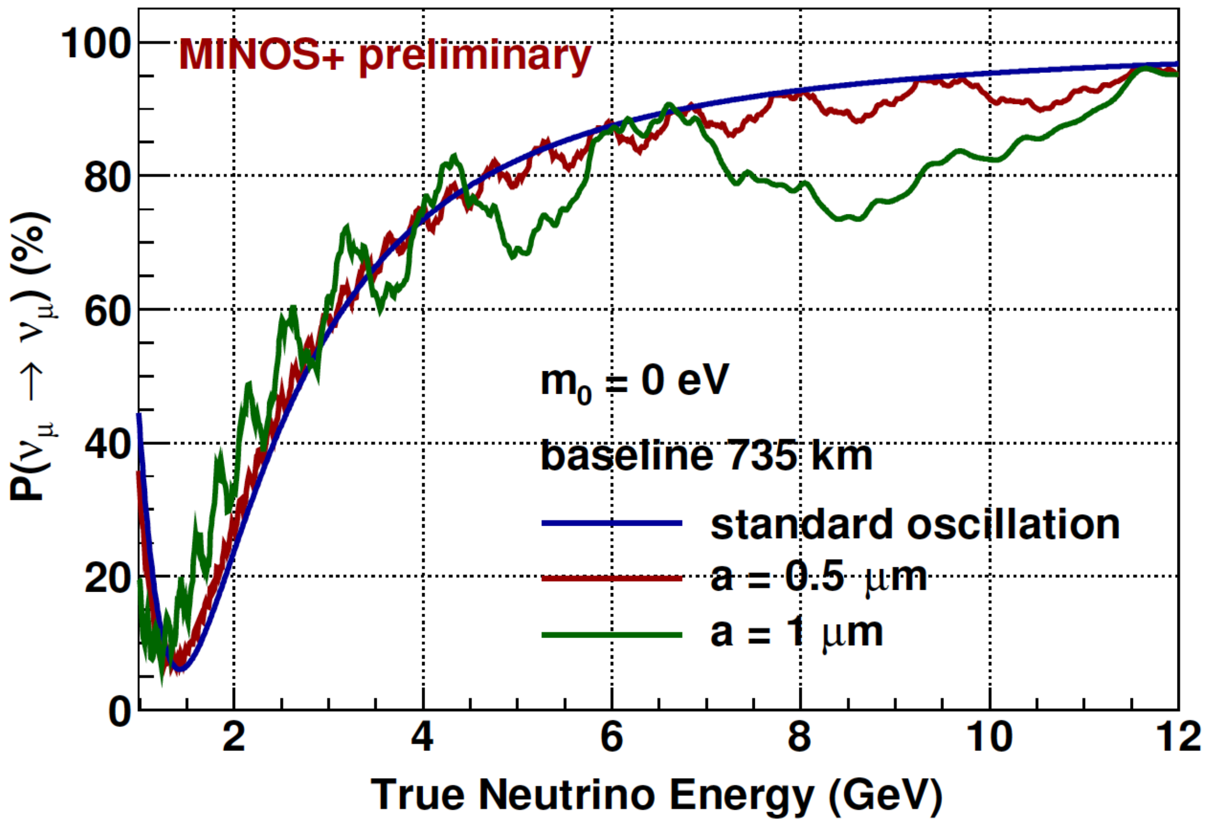
- Three active neutrinos live in 4-dimensional space-time, but can mix with sterile neutrinos that propagate in more than 4-dimensions

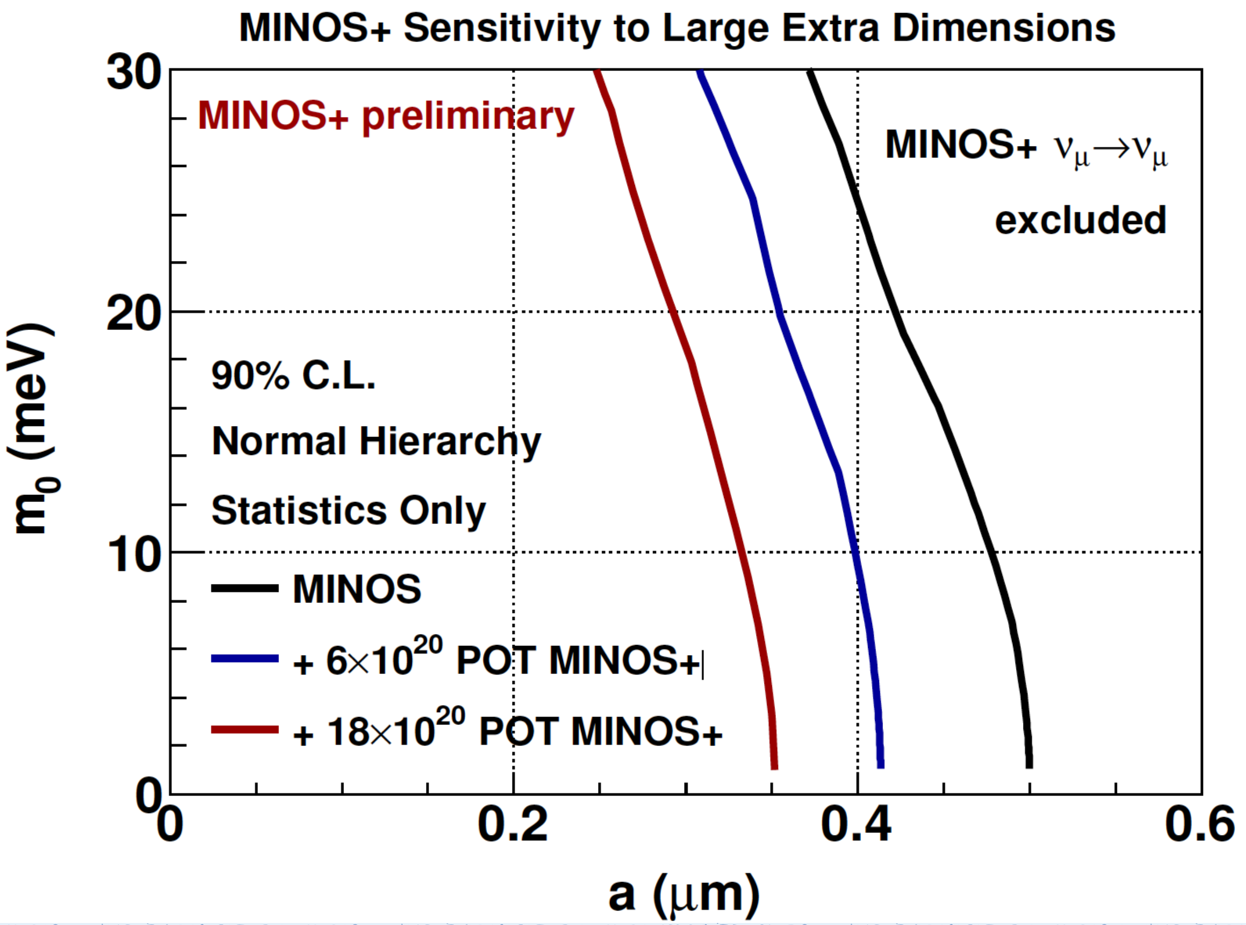
*Arkani-Hamed, Dimopoulos, Dvali, March-Russel Phys. Rev. D **65**, 024032 (2002)*

*Machado, Nunokawa, Funchal, Phys. Rev. D **84**, 013003 (2011)*

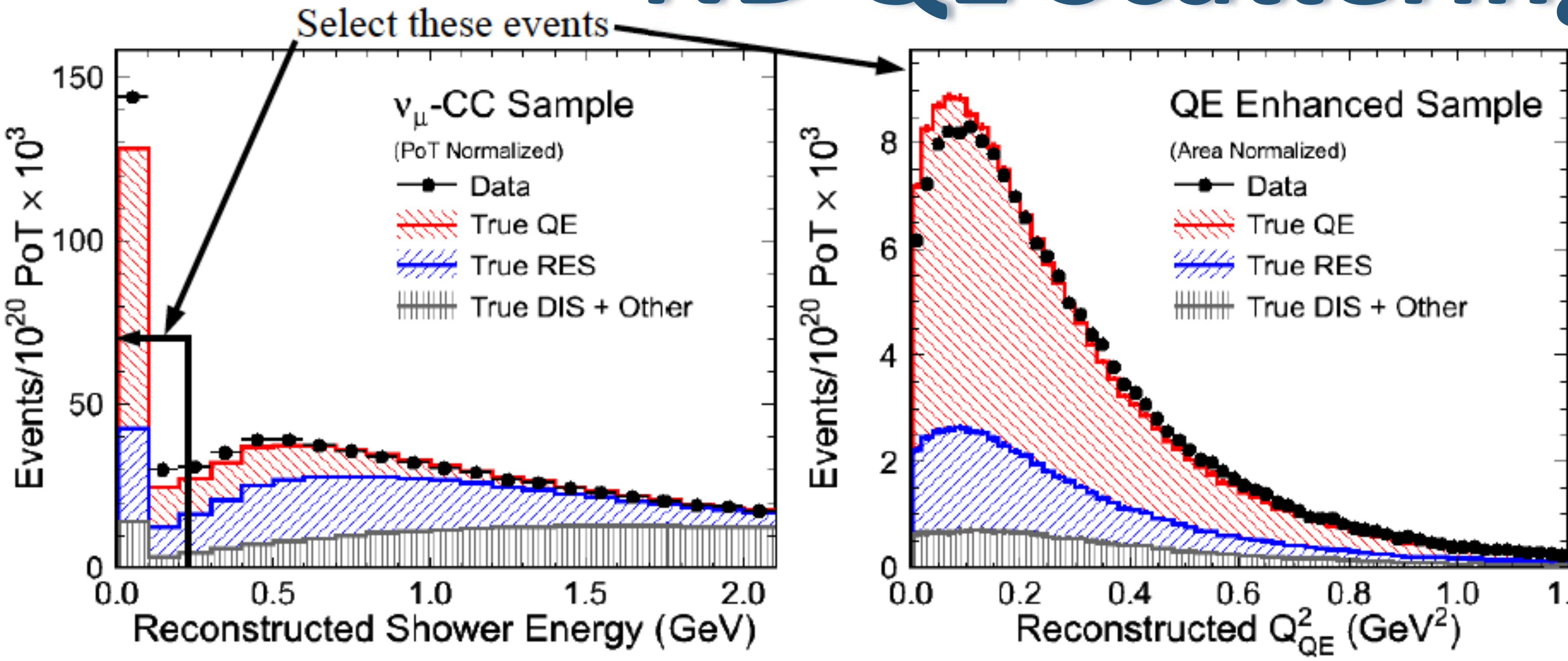
- Perturbations to standard oscillations depend on the lightest neutrino mass m_0, and the extra-dimension size a

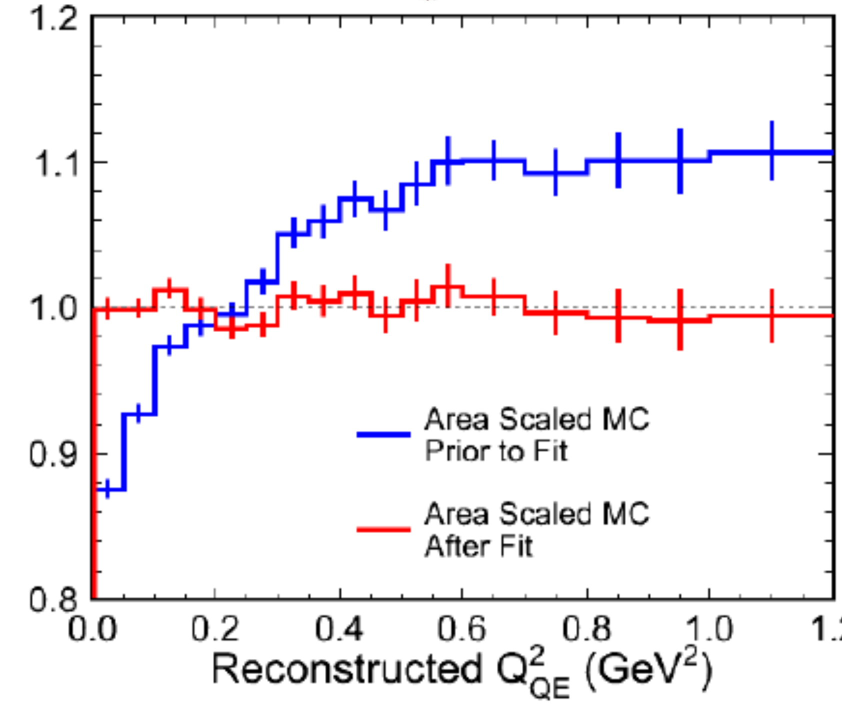
- MINOS and MINOS+ data can exclude extra-dimensions larger than 0.4 μm with 6×10^{20} POT of MINOS+ exposure





ND QE Scattering





Select events passing CC criteria.
Require a single muon track that stops in the Near Detector.
Require reconstructed E_{had} < 225 MeV.

Selects QE events with 49% efficiency and 66% purity.
221,300 events in CCQE Enhanced sample. Estimate 146,300 are QE events.

Largest contributions to systematic error:
Shower energy
Detector assymetries
Final state interactions
Resonance Suppression

Final Result:

$$M_A^{QE} = 1.23^{+0.13}_{-0.09}(fit)^{+0.12}_{-0.15}(syst)\ GeV$$

Systematic Source	+ve Uncertainty (GeV)	-ve Uncertainty (GeV)
E_{had} selection cut	0.062	0.062
RES nuclear effects	0.005	0.088
INTRANUKE parameters	0.066	0.066
Detector Asymmetries	0.059	0.059
Hadronic energy offset	0.047	0.046
DIS cross sections	0.024	0.022
μ^- angular resolution	0.016	0.015
ν flux tuning params.	0.008	0.008
Quadrature Sum	0.122	0.149