MINOS+ Results and Future Plans

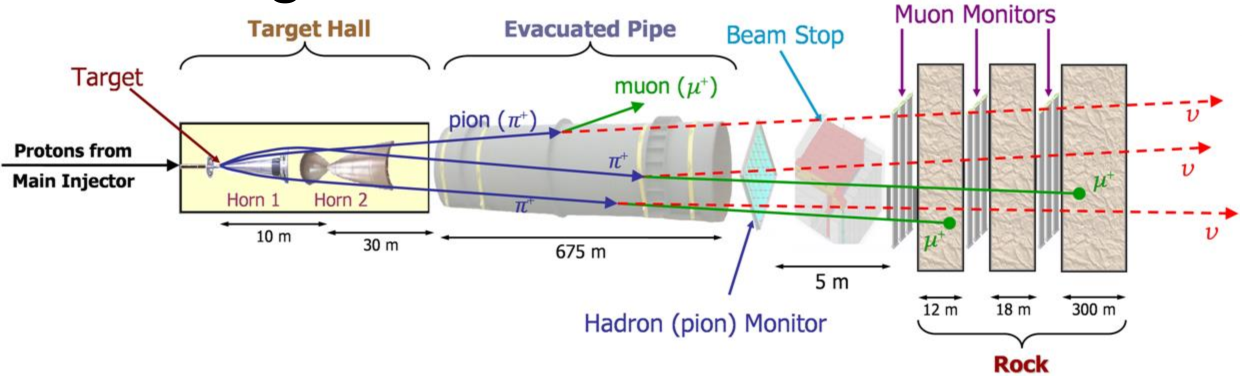
A.P. Schreckenberger – The University of Texas at Austin
(On behalf of the MINOS and MINOS+ Collaborations)

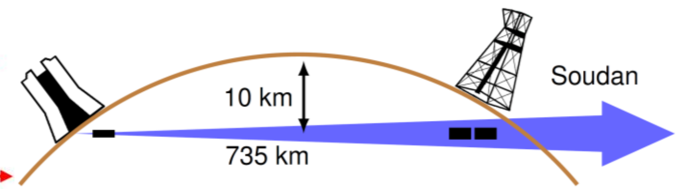
Why we are excited…

- MINOS/MINOS+ makes use of the NuMI beam
  - Most powerful neutrino beam in operation with upgrades in the works
- New results from both MINOS and MINOS+
  - Standard three-flavor oscillations
  - Exotic phenomena
  - **Sterile neutrino searches**

A Brief Reminder of MINOS

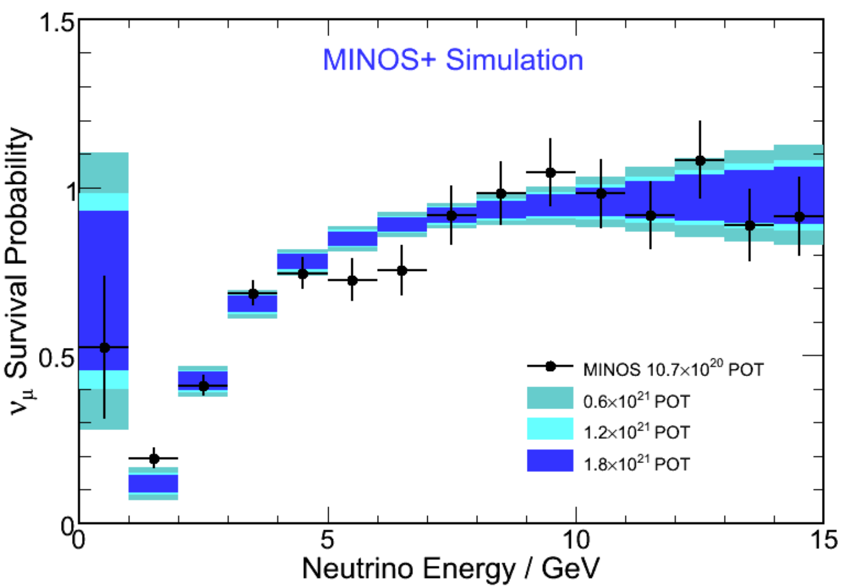
- Long baseline neutrino oscillation search

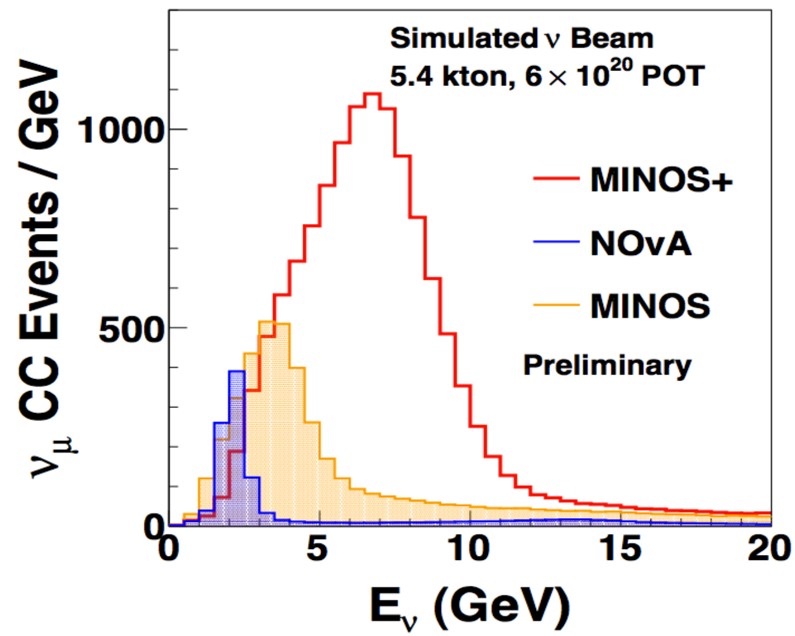




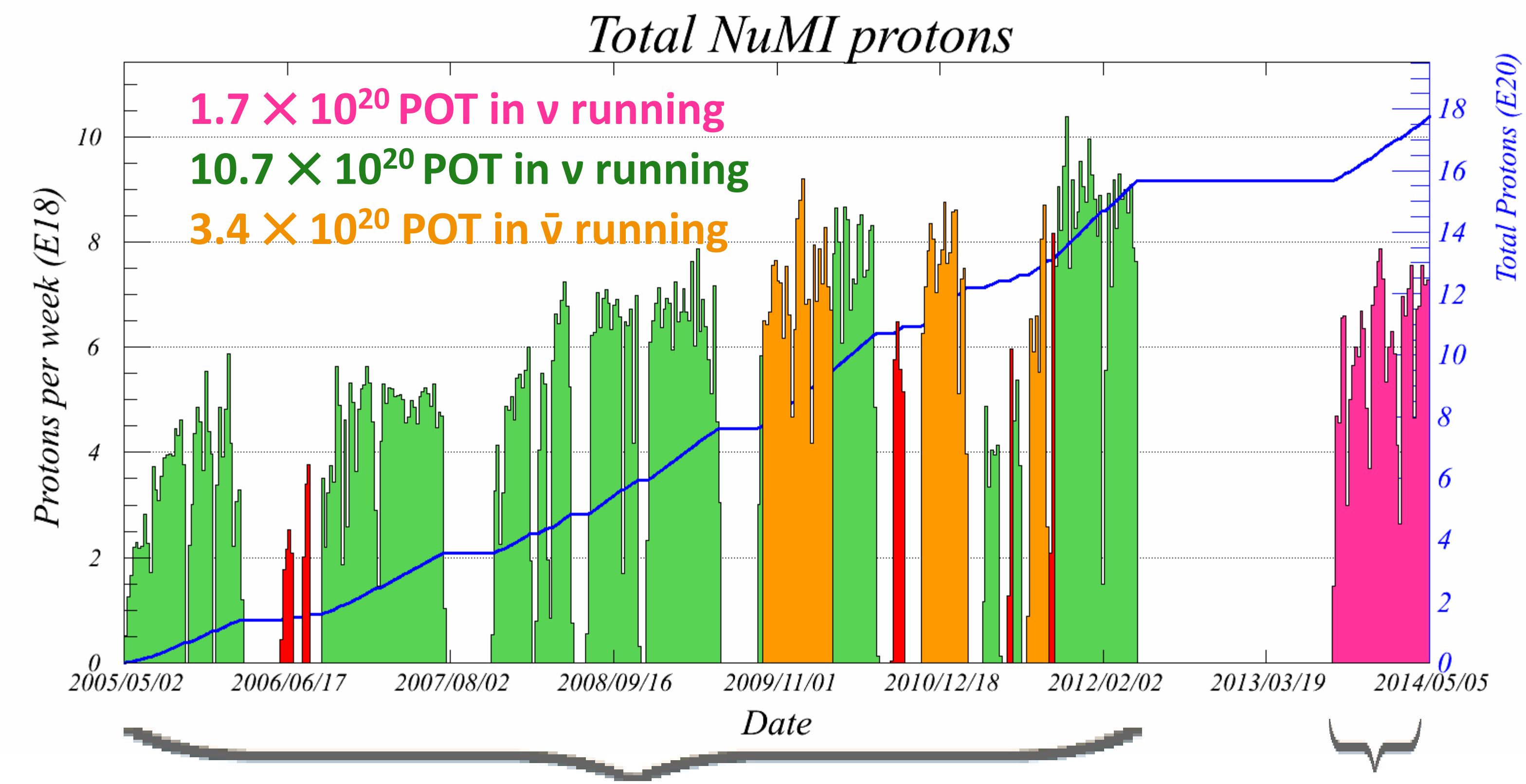
What about MINOS+

- Same magnetized MINOS detectors used in MINOS+
- Medium-energy NuMI beam
  - Higher energy spectra and decreased cycle time when compared to MINOS
  - New target design implemented to handle increased beam power
  - Expect roughly 4000 ν_μ CC events per 6×10^{20} protons-on-target (POT) year
- Only wide-band beam long baseline experiment operating in this decade
  - New physics to be investigated in this new energy window!





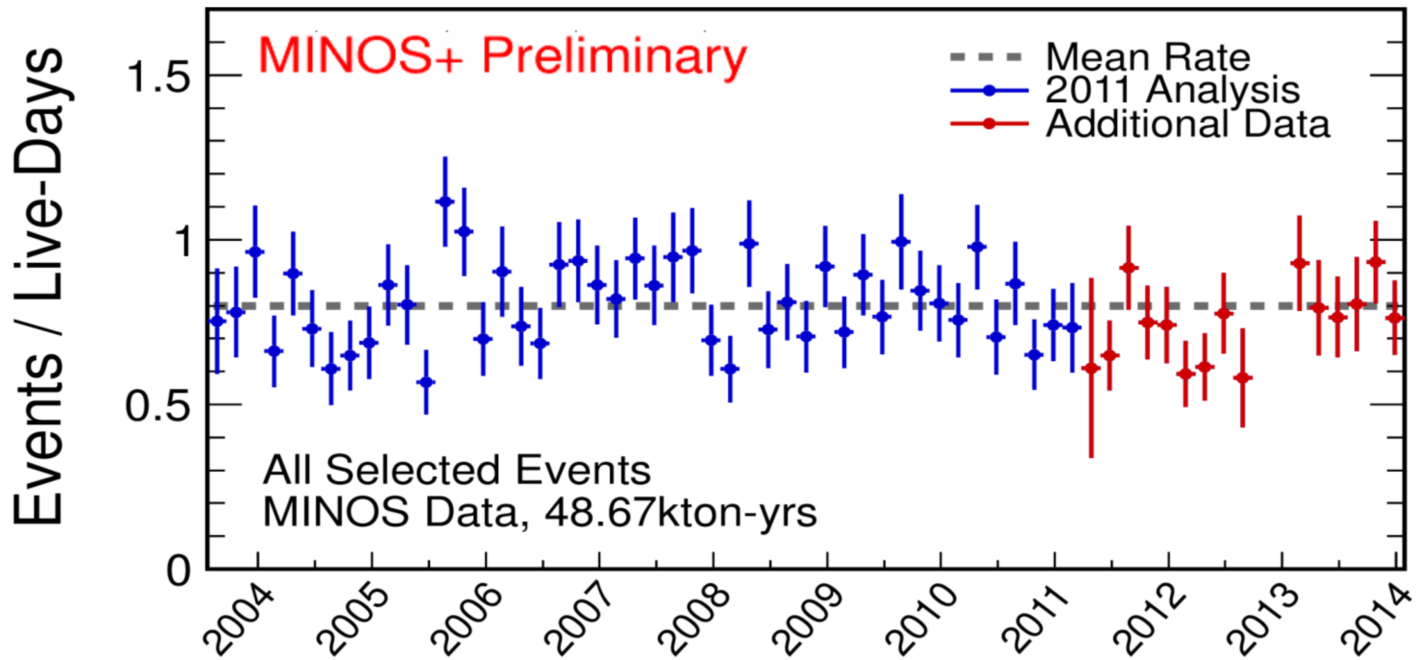
MINOS & MINOS+ Data



MINOS (2005-2012)

MINOS+

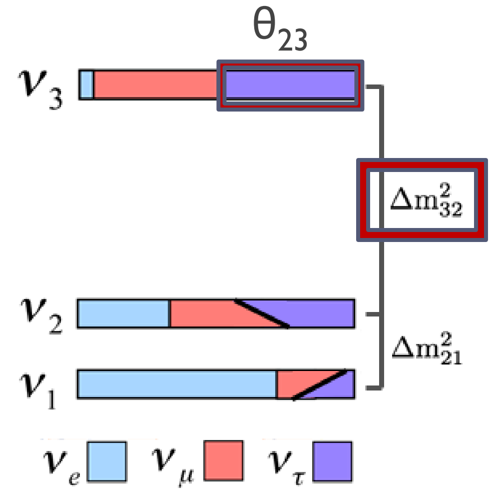
MINOS & MINOS+ Data



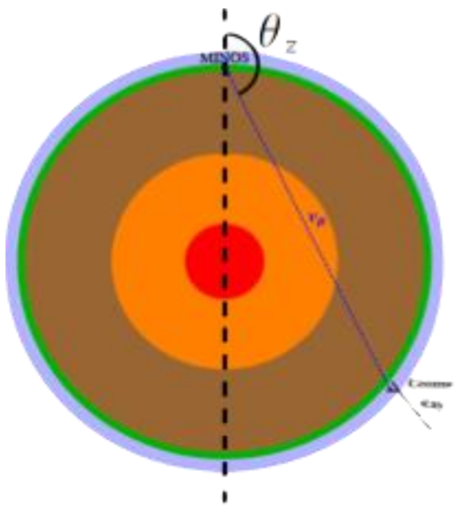
Updating oscillation parameter measurement with increased atmospheric neutrino statistics

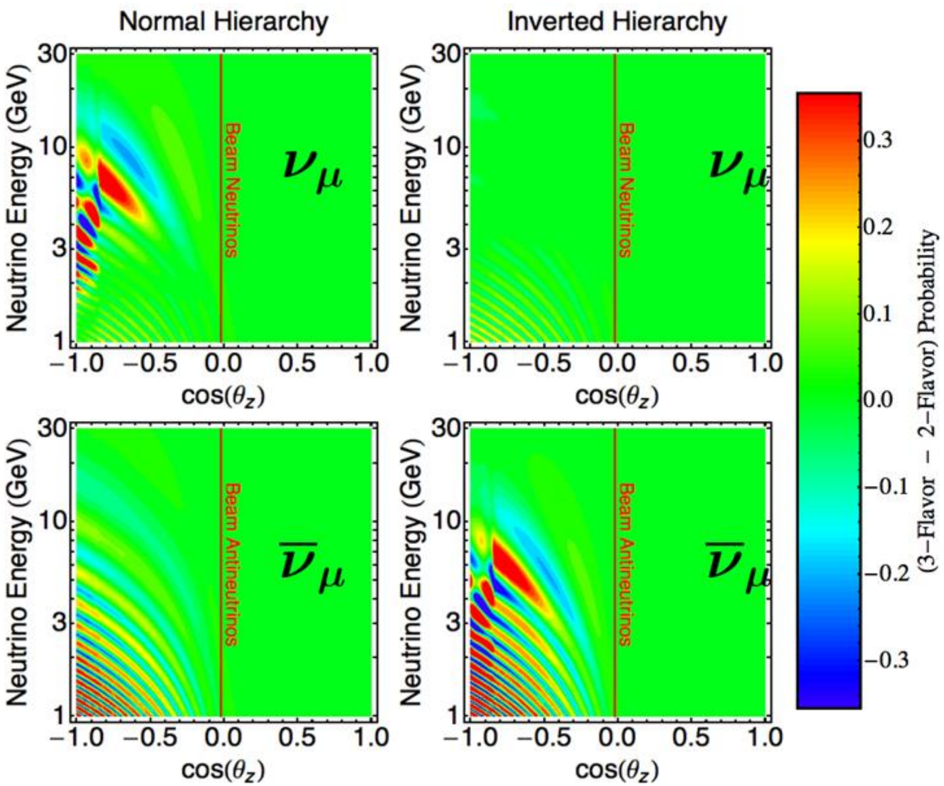
Additional 10.8 kton-year (+28%) over previous beam+atmospherics combined analysis [*PRL* ***112***, *191801 (2014)*]

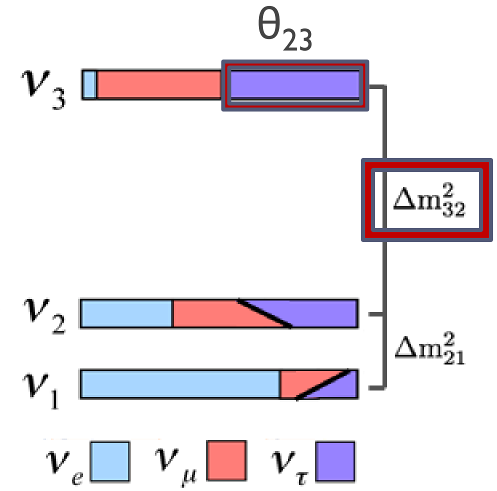
Three-Flavor Oscillations



- Combine various analyses from MINOS/MINOS+
  - Full MINOS ν_μ-CC and $\bar{\nu}_\mu$-CC disappearance sample
  - Full ν_e-CC, $\bar{\nu}_e$-CC appearance sample, described in *PRL 110 171801 (2013)*
  - Full MINOS and new MINOS+ atmospheric samples
- Sensitivity to θ_{13}, θ_{23} octant, mass hierarchy, and δ_{CP} from ν_e sample
- Enhanced by atmospheric data
  - Matter effects give rise to larger differences in multi-GeV, upward-going events

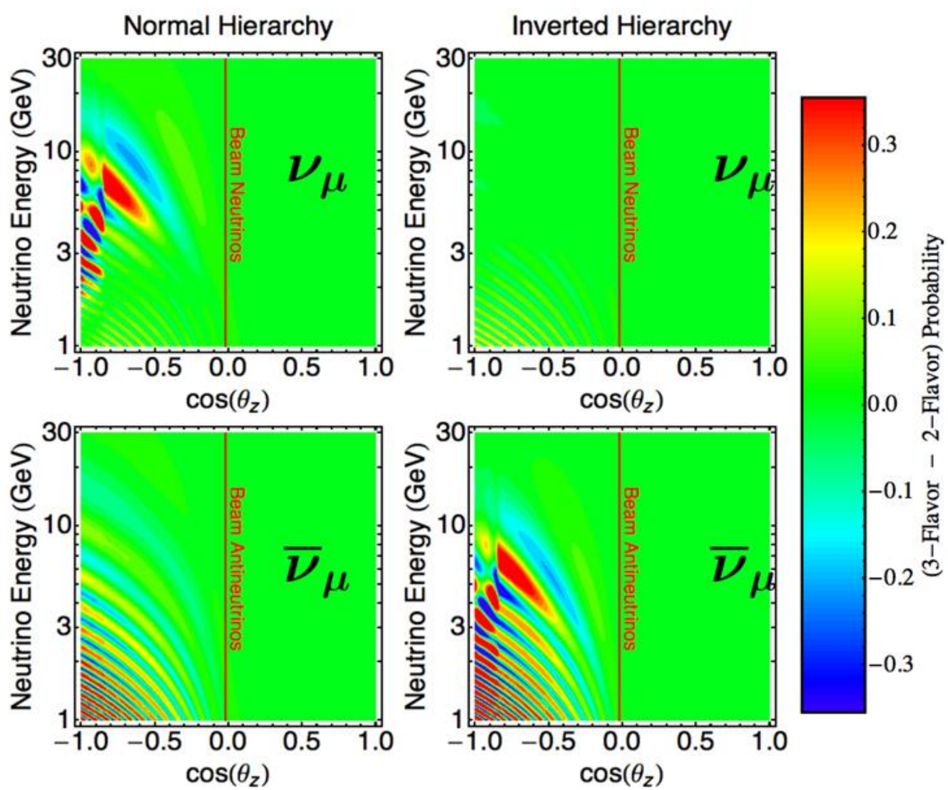






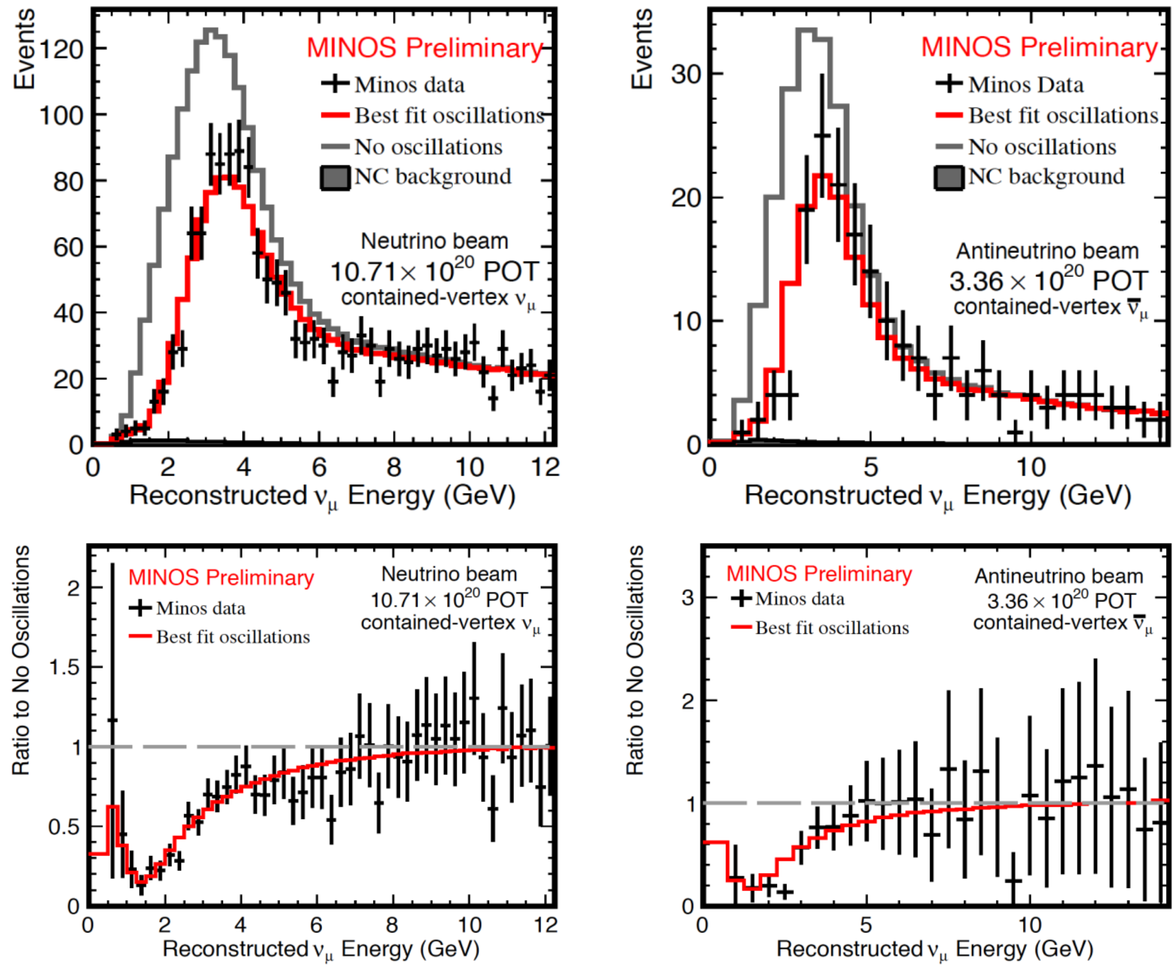
Three-Flavor Oscillations

- Combine various analyses from MINOS/MINOS+
  - Full MINOS ν_μ-CC and $\bar{\nu}_\mu$-CC disappearance sample
  - Full ν_e-CC, $\bar{\nu}_e$-CC appearance sample, described in *PRL 110 171801 (2013)*
  - Full MINOS and new MINOS+ atmospheric samples
- Sensitivity to θ_{13}, θ_{23} octant, mass hierarchy, and δ_{CP} from ν_e sample
- Enhanced by atmospheric data
  - Matter effects give rise to larger differences in multi-GeV, upward-going events
  - Effects are dependent on mass hierarchy and charge conjugation
- MINOS first to probe effect with event-by-event charge separation



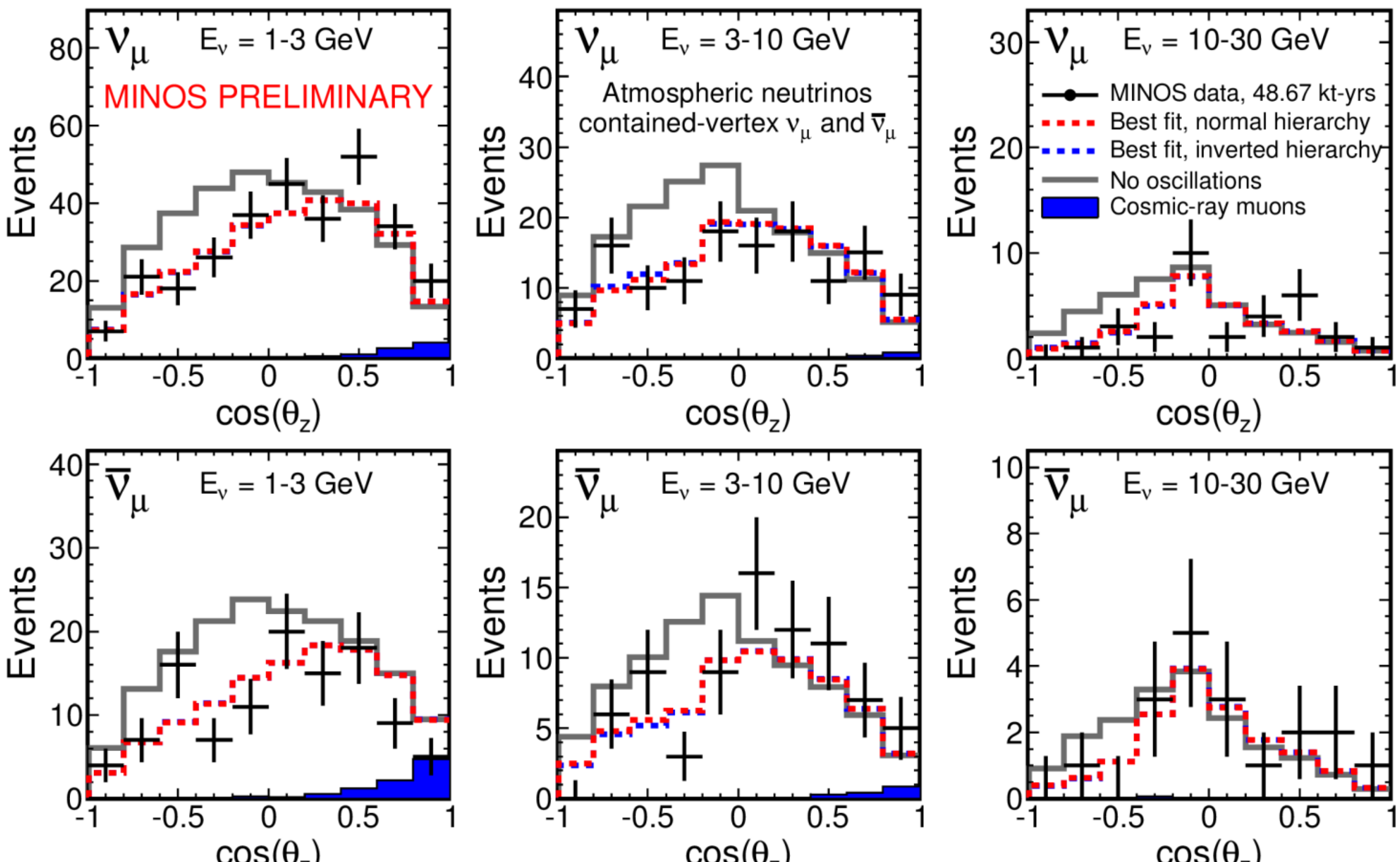
Analysis Fundamentals – Beam Data

- Use energy spectra to perform precision measurement of neutrino oscillations
- Make a fit to the three-flavor oscillation framework
- Use both the beam and atmospheric data to generate constraints on certain oscillation parameters



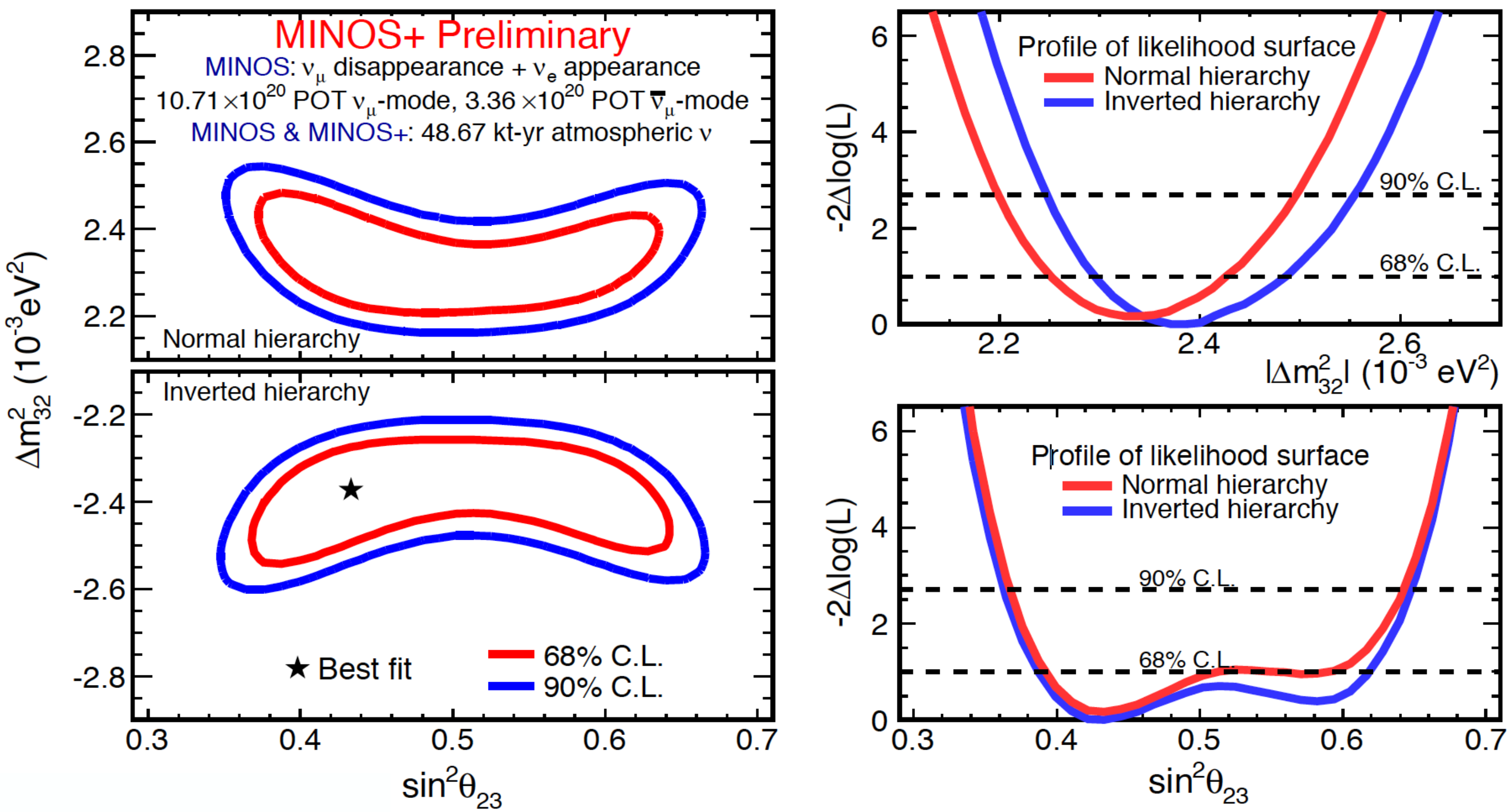
Analysis Fundamentals – Atmospheric Data

- Contained ν_μ events as a function of angle for three energy ranges
- Fits to three-flavor oscillation framework include non-fiducial events

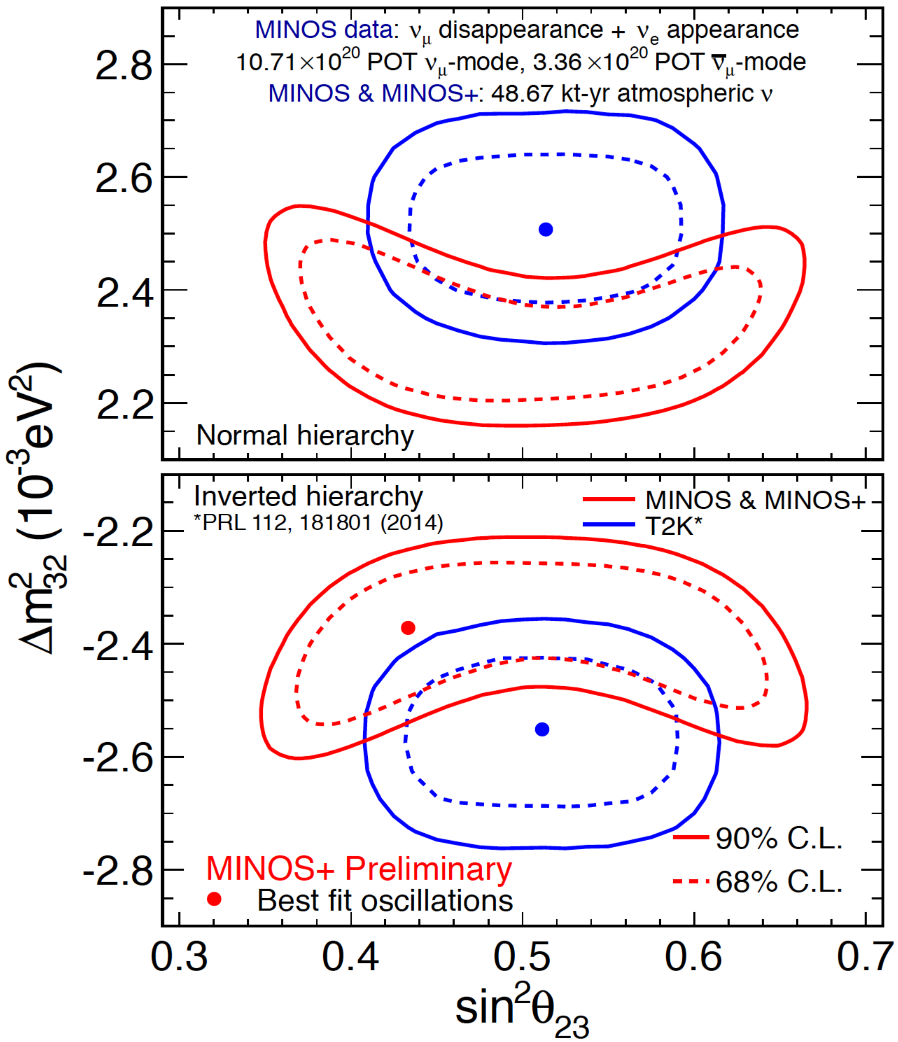


Combined Fit Allowed Regions

- Solar parameters fixed to $\Delta m^2_{21} = 7.54 \times 10^{-5}\text{eV}^2$ and $\sin^2\theta_{12} = 0.307$
- θ_{13} fit as nuisance parameter, constrained by reactor results: $\sin^2\theta_{13} = 0.0242 \pm 0.0025$
- θ_{23}, Δm^2_{32}, and δ_{CP} unconstrained
- 19 systematics included as nuisance parameters in fit



Three Flavor Takeaway



- Three-Flavor Best Fit

Inverted Hierarchy

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

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

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

Normal Hierarchy

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

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

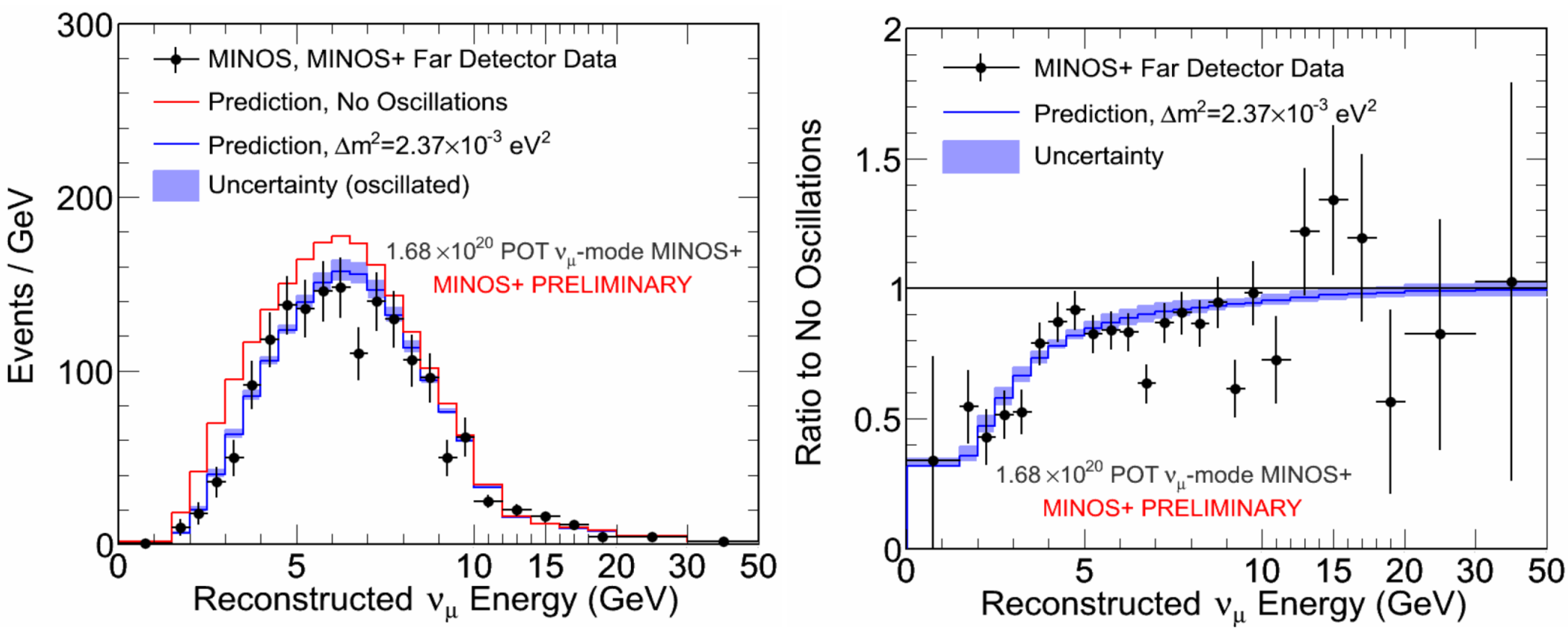
$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

- Most precise measurement of $|\Delta m^2_{32}|$
- Results highlight precision era of field

A Look Towards Tomorrow

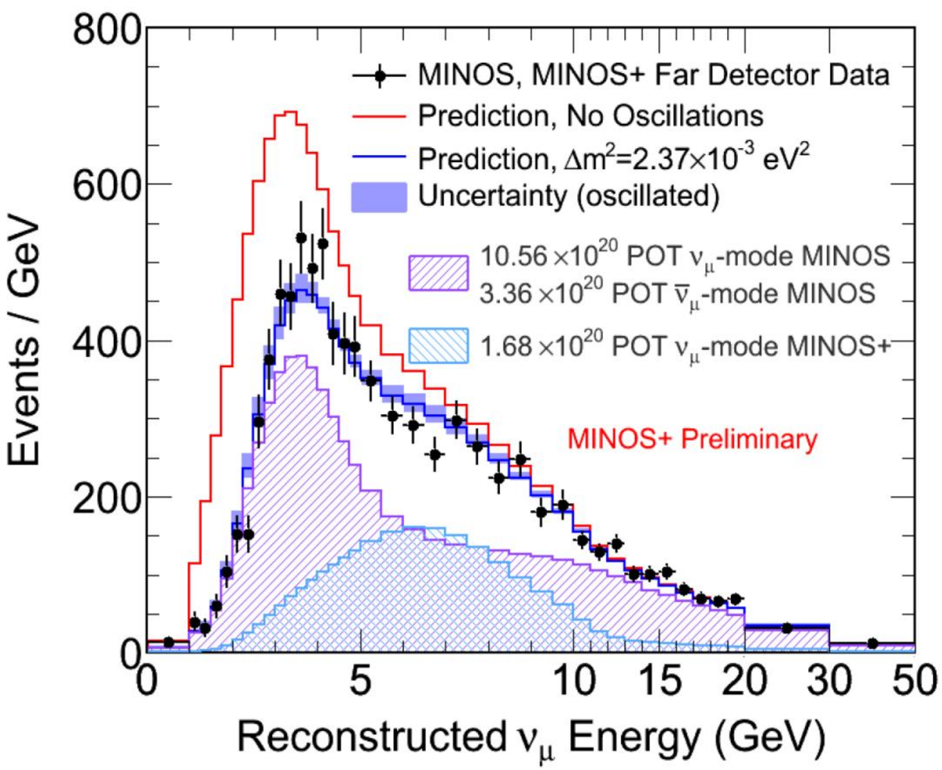
- MINOS+ Far Detector Beam Data
  - Data consistent with oscillation measurements from MINOS

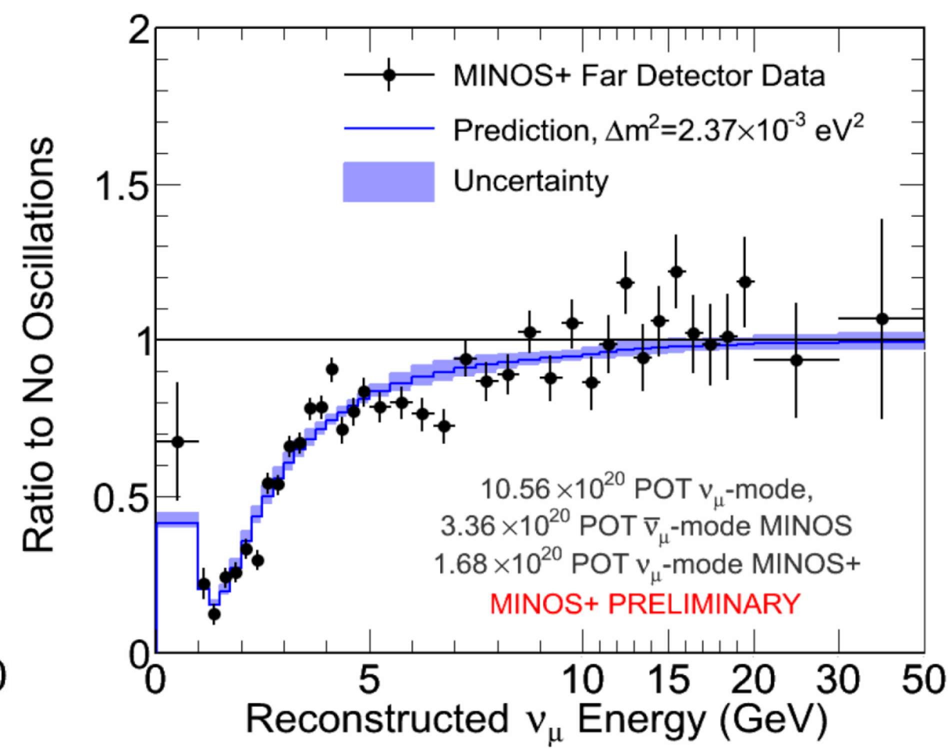
	μ^-	μ^+
Unoscillated Prediction	1254.8	52.03
Oscillated Prediction	1085.2	47.09
Data	1037	48



Adding MINOS and MINOS+ Samples

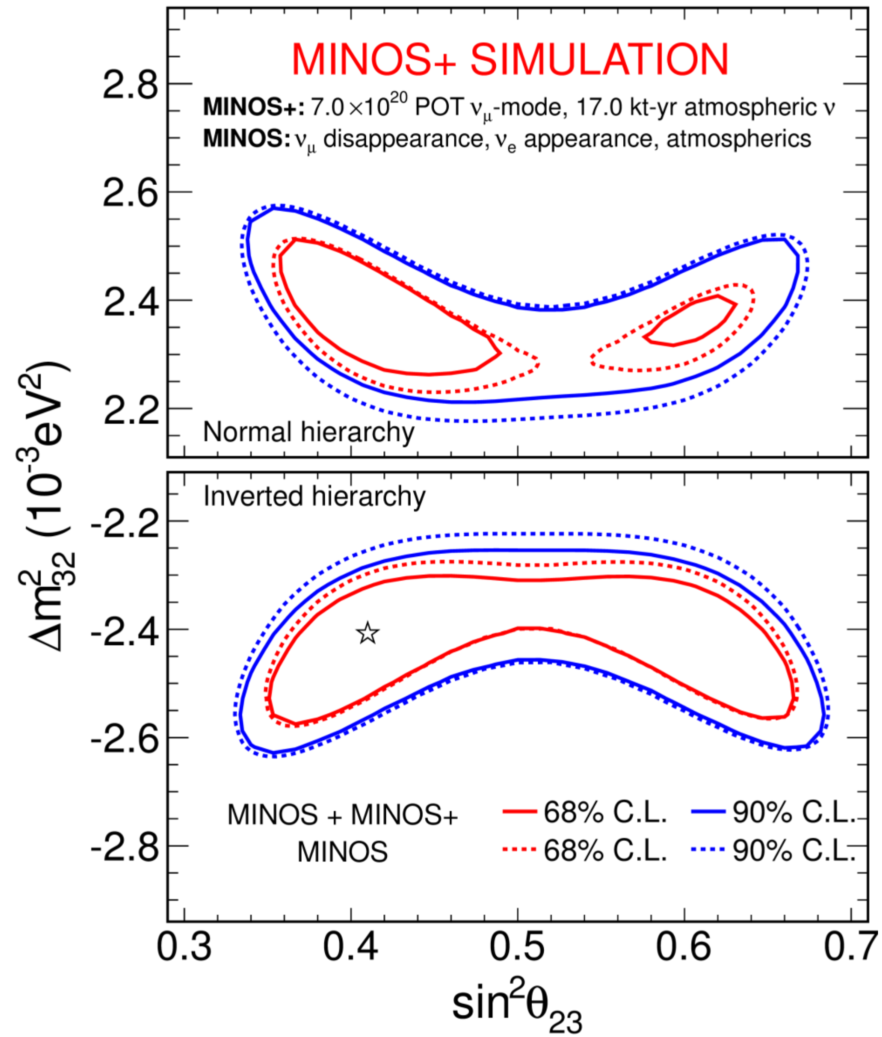
- Best resolution yet of survival probability curve
  - Expect combined MINOS/MINOS+ fit in the Fall
  - 3.5×10^{20} POT expected by September 2014 shutdown





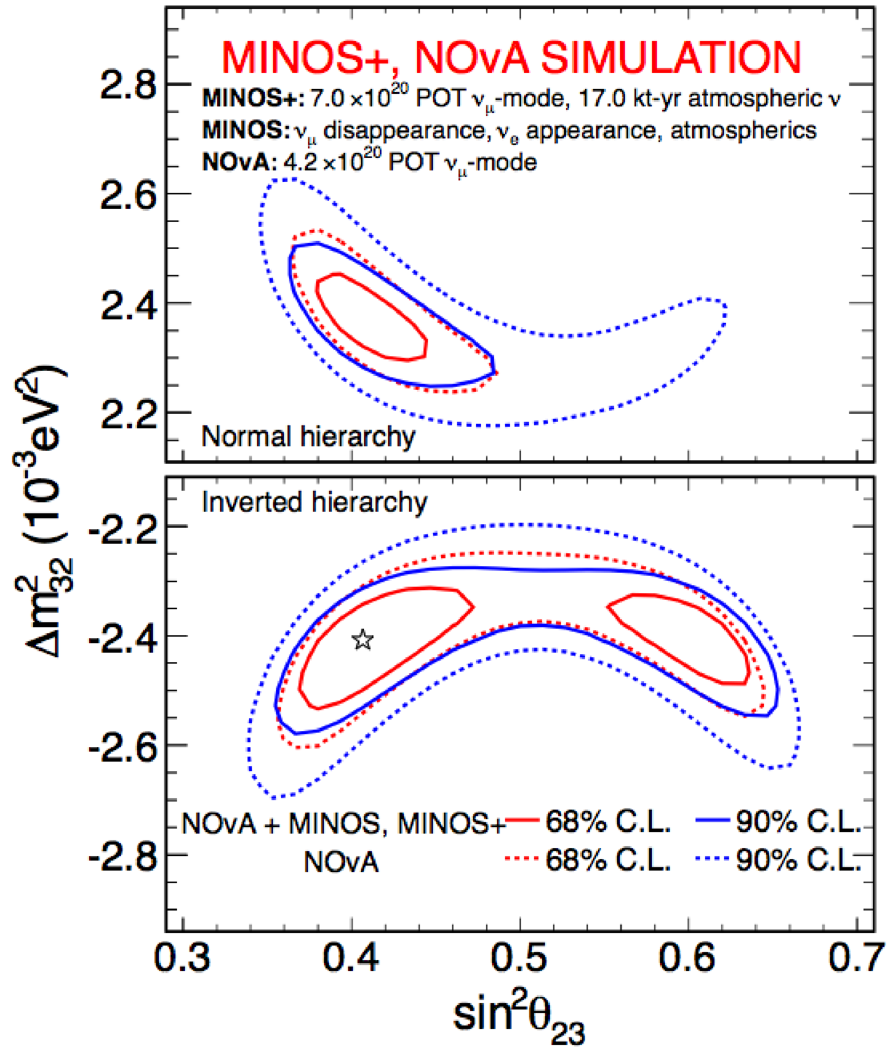
A Look Towards Tomorrow's Sensitivity

- 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)*



A Look Towards Tomorrow's Sensitivity

- 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)*
- NOvA sensitivity for 4.2×10^{20} POT
- During NOvA ramp-up, combination with MINOS+ maximizes improvement on oscillation parameter measurement



How standard are you? – An Intro to NSI

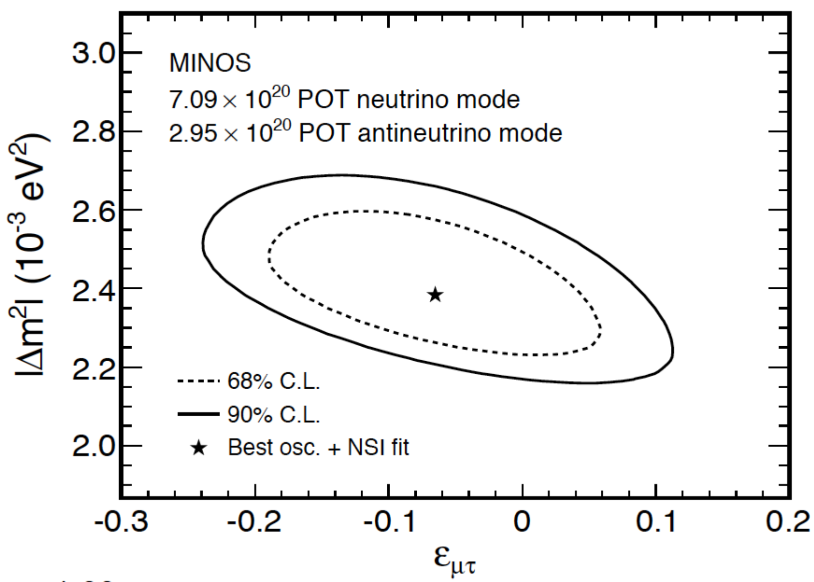
- Non-Standard Interaction (NSI) picture accommodates deviations from standard oscillation picture
  - Analogous to MSW matter effect

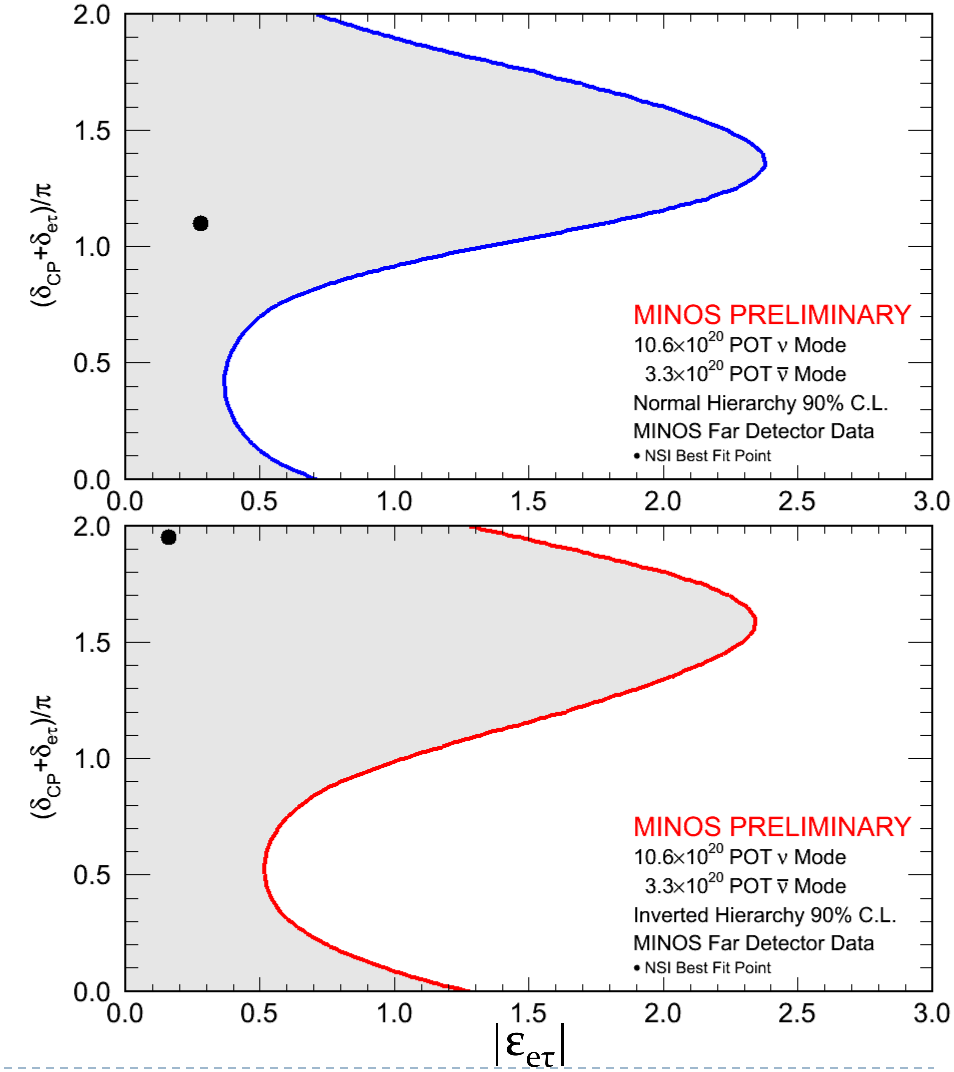
$$H = U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^{\dagger}_{PMNS} + \sqrt{2} G_F n_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^{\star}_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}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

- Fits to MINOS data performed for limits on $\varepsilon_{\mu\tau}$ and $\varepsilon_{e\tau}$
  - $\varepsilon_{\mu\tau}$ sensitivity comes from ν_{μ} CC disappearance analysis
  - $\varepsilon_{e\tau}$ sensitivity comes from ν_{e} CC appearance analysis

NSI Results

- $\varepsilon_{\mu\tau}$ study from *PRD* ***88****, 072011 (2013)*
- $\varepsilon_{e\tau}$ study is the first MINOS only analysis regarding this parameter
  - Presented at Neutrino 2014 in Boston
- Follows formulation from:
  Friedland, Lunardini, Maltoni
  PRD ***70****, 111301(2004)*
  Coelho, Kafka, Mann, Schneps, Altinok
  PRD ***86****, 113015 (2012)*

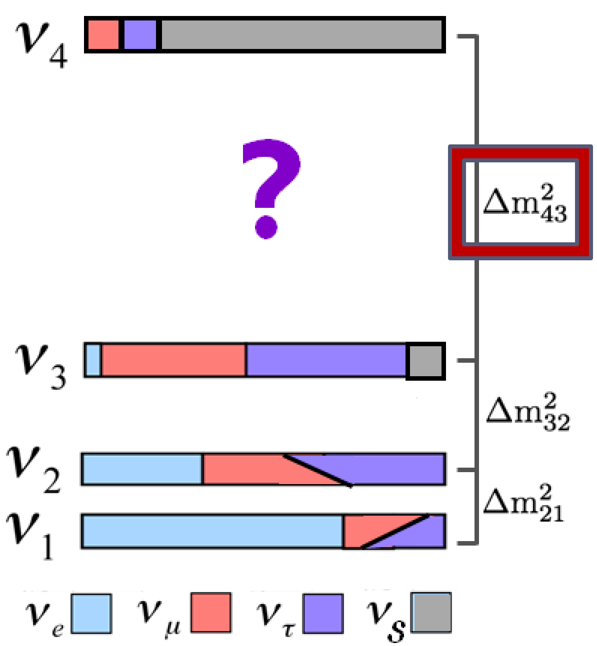


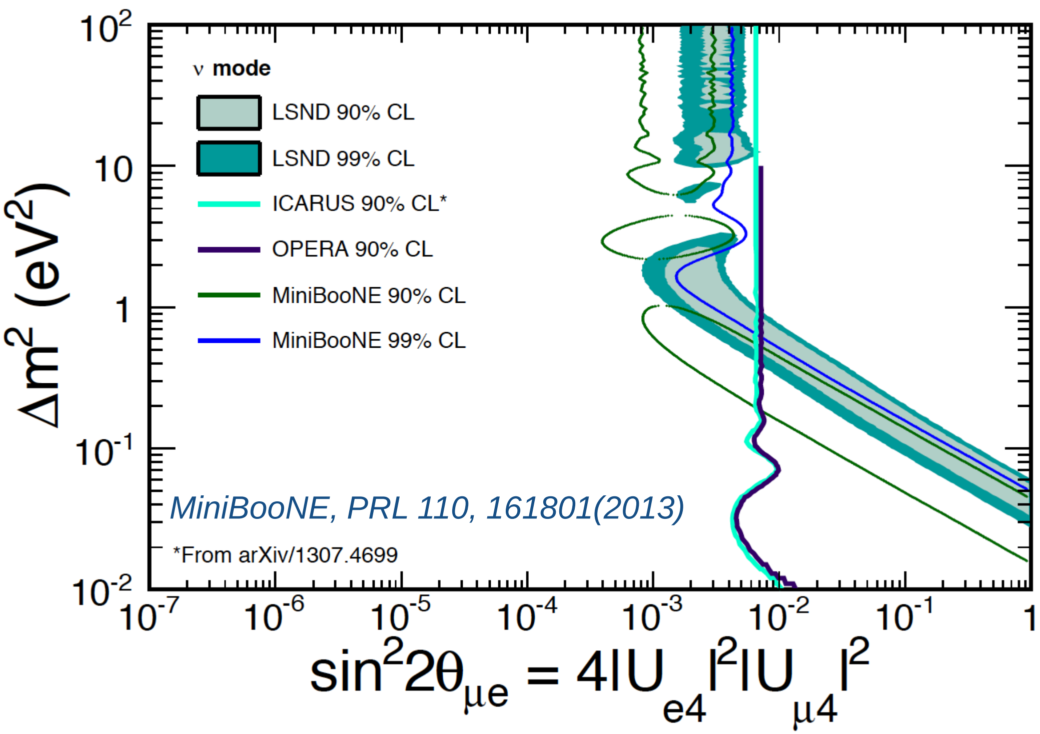



MINOS
Hunting for Sterile Neutrinos

Sterile Neutrinos – More than Three?

- Sterile neutrino: theorized additional states that do not interact through the weak force
  - Would add additional parameters to the oscillation model
- Anomalies in reactor, short-baseline, radiochemical experiments
  - Oscillations into light sterile neutrino possible explanation
- Evidence of sterile mixing is inconclusive due to tension between various experiment results





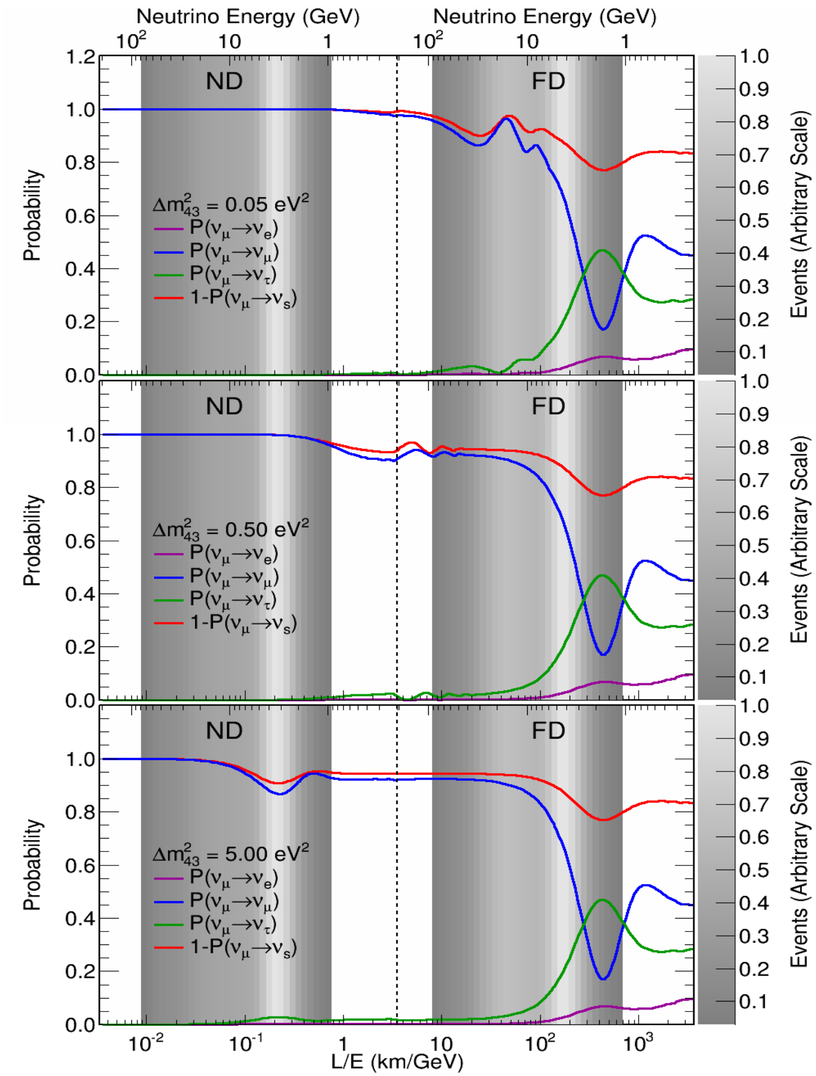
A Glimpse at Four-Flavor Oscillations

- $\nu_\mu \rightarrow \nu_s$ mixing yields energy-dependent depletions in ν_μ CC and NC spectra relative to 3-flavor mixing

- Small Δm^2_{43}:
  - Spectra distortions above oscillation maximum at Far Detector
  - No Near Detector effects

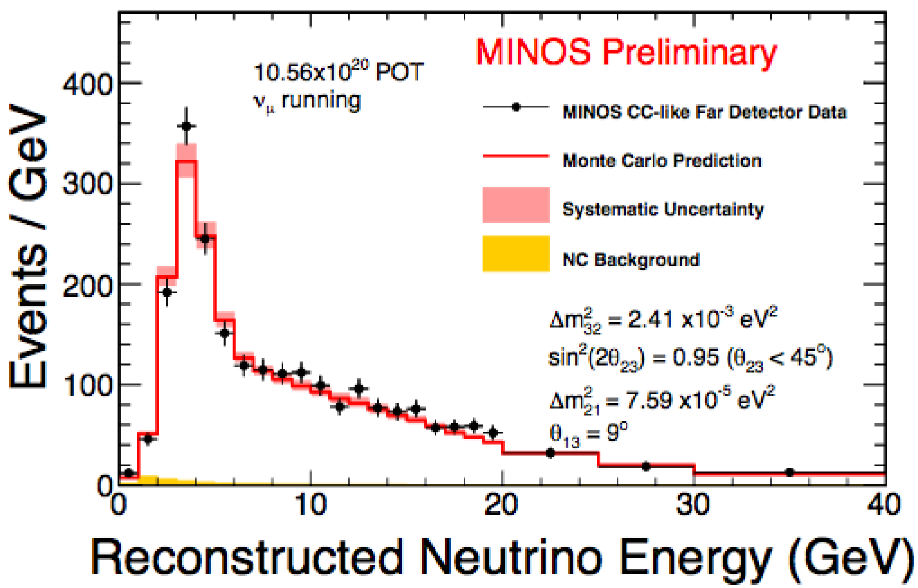
- Medium Δm^2_{43}:
  - Rapid oscillations average out at Far Detector
  - No Near Detector effects
  - Counting experiment

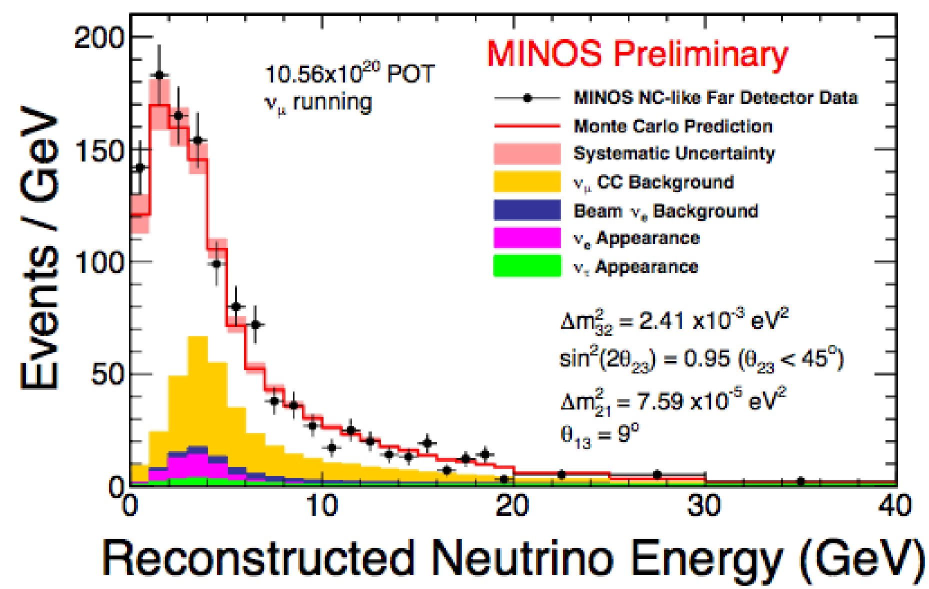
- Large Δm^2_{43}:
  - Rapid oscillations average out at Far Detector
  - Near Detector distortions affect Far Detector prediction



Far Detector CC and NC Spectra

- Comparison with 3-flavor prediction for full MINOS low-energy beam neutrino mode sample
  - Both CC and NC events important for sterile neutrino analysis
  - Focus on NC event rate to perform counting experiment search





Counting for Steriles

- Sterile neutrinos could appear in event rate deficit
  - 1221 NC-like events in 10.56×10^{20} POT MINOS sample
  - Construct rate metric that accounts for CC backgrounds

Results from MINOS data:

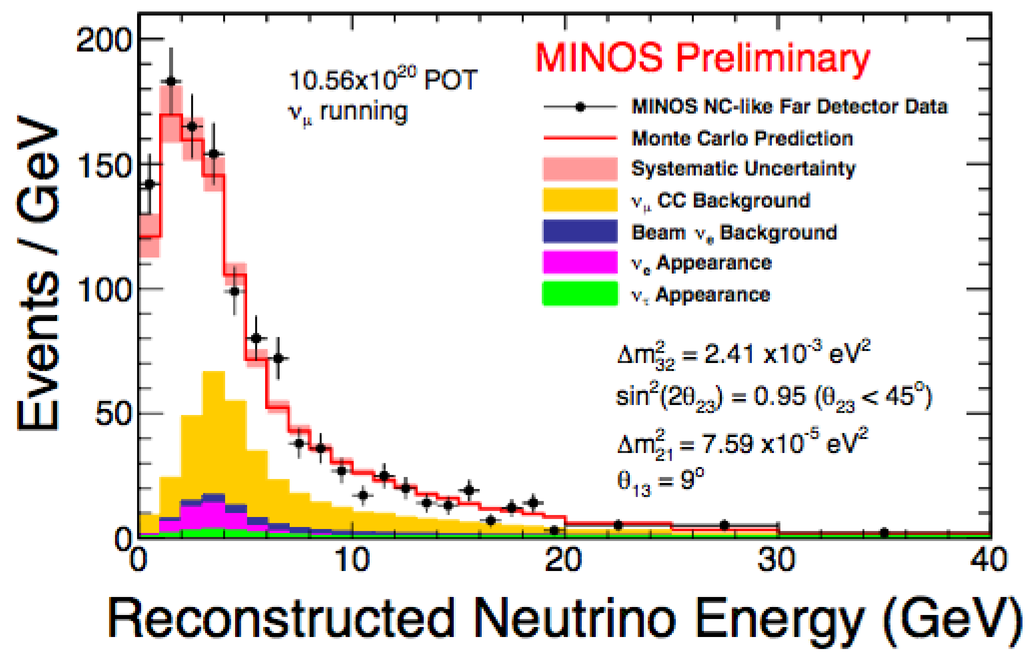
R = 1.049 ± 0.076 (0-200 GeV)

R = 1.093 ± 0.097 (0-3 GeV)

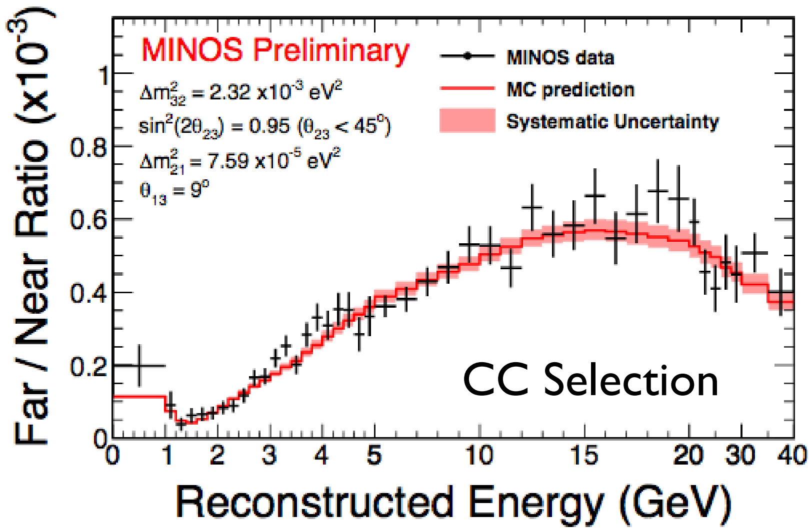
$$R = \frac{N_{Data} - \sum Backgrounds_{Pred\ cc}}{Signal_{Pred\ NC}}$$

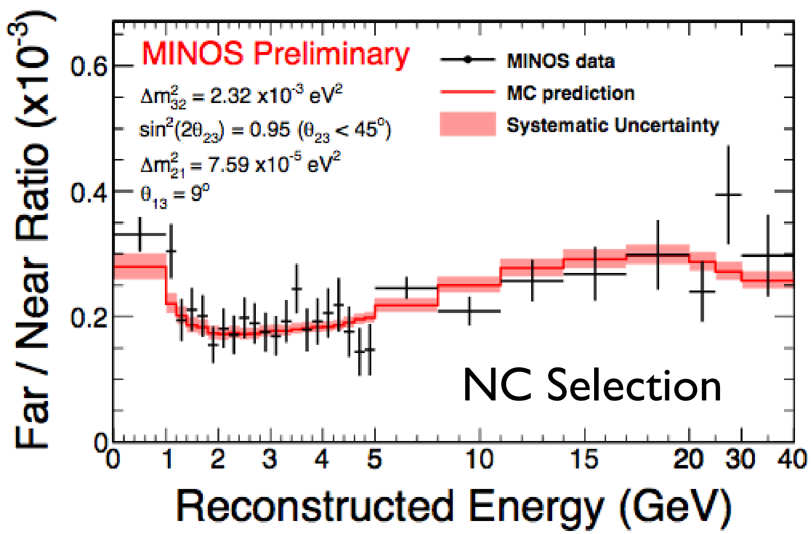
  - R < 1.0 hints sterile neutrino driven deficit

- **Results show no evidence for sterile neutrinos at $\Delta m^2_{43} = 0.5$ eV^2**



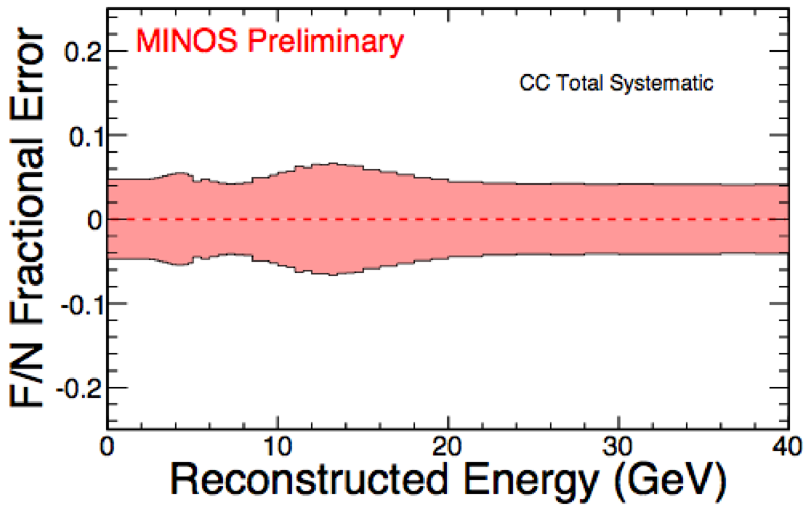
Expanded Analysis Approach

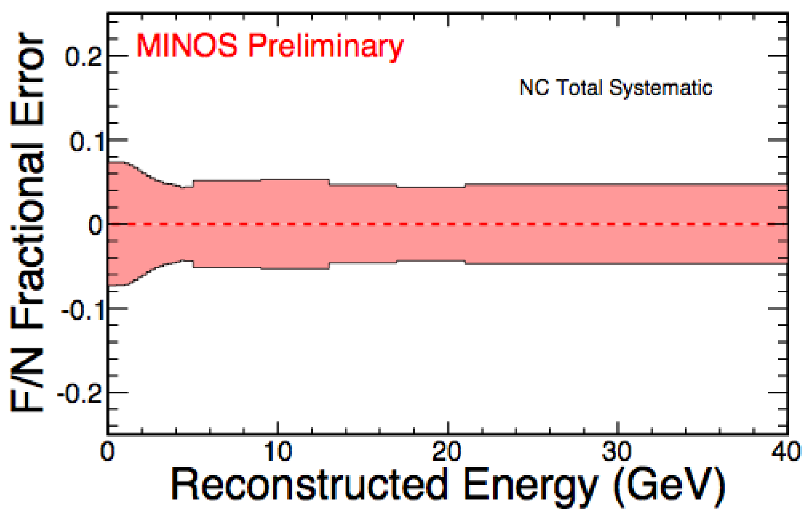




- Assume a four-flavor 3+1 oscillation model
  - Apply oscillations to both Near and Far Detector
  - Make use of distance to meson decay point from simulation
  - Fit for Δm^2_{43}, Δm^2_{32}, θ_{23}, θ_{24}, and θ_{34}
- Near Detector oscillation handling
  - Constrain ND event rate
  - Fit data directly to oscillated F/N ratio
- Systematics enter fit as covariance matrix
  - Re-evaluated beam flux uncertainties
- Feldman-Cousins correction applied to log-likelihood surfaces

Systematics





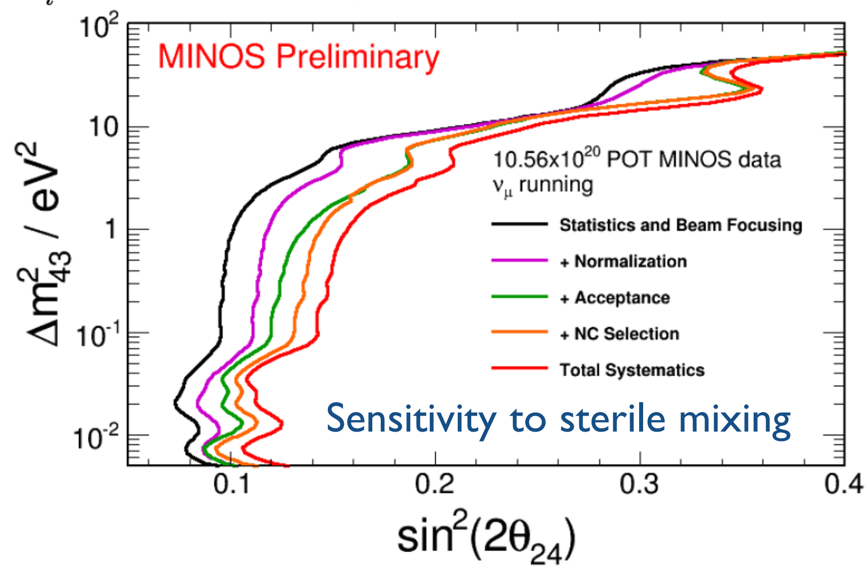
- 26 systematics included in fit
  - Hadron production, beam optics, detector acceptance, energy scale, cross-section

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

o_i : Observed events in bin i

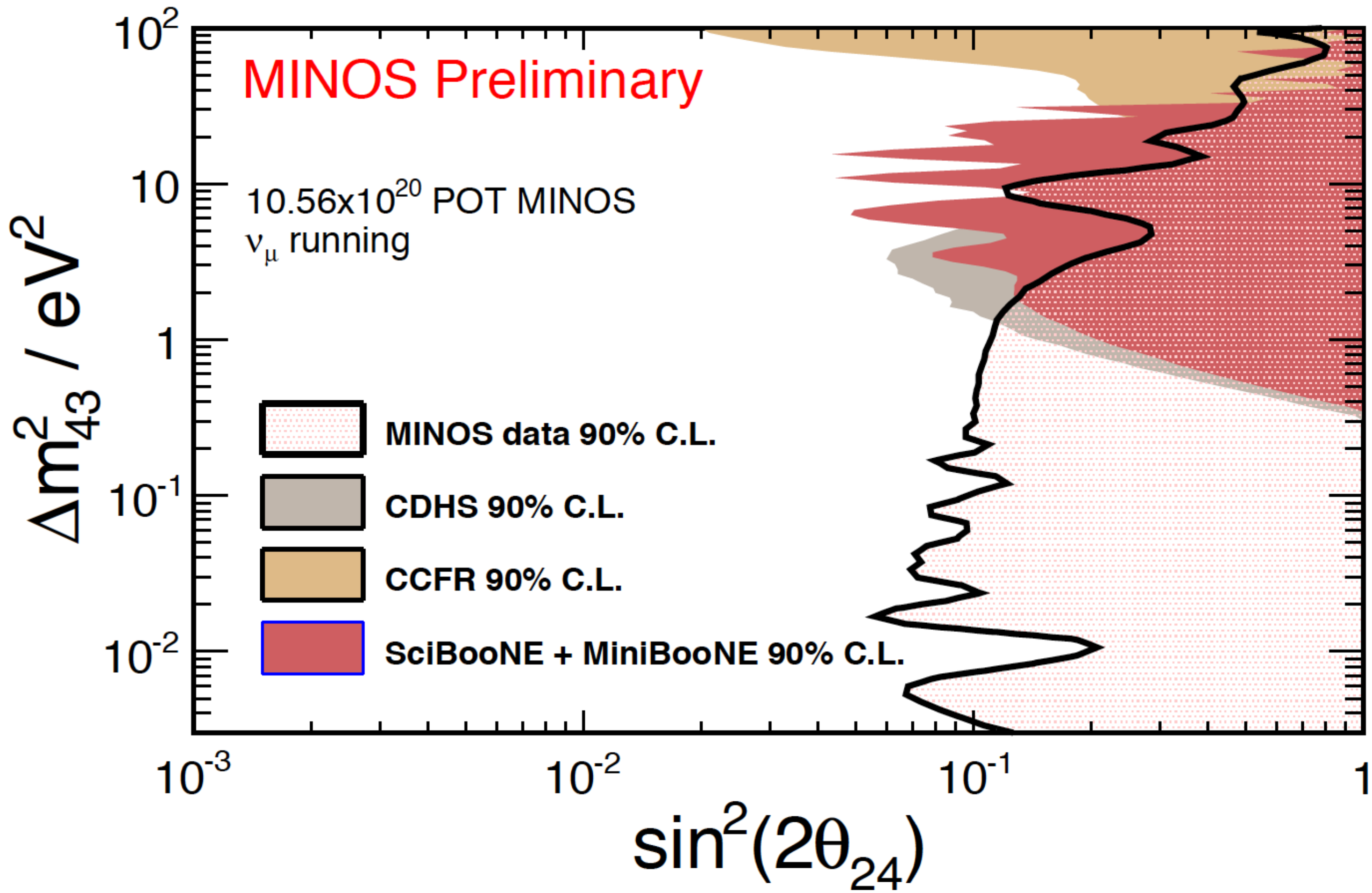
e_i : Predicted events in bin i

V : Covariance matrix

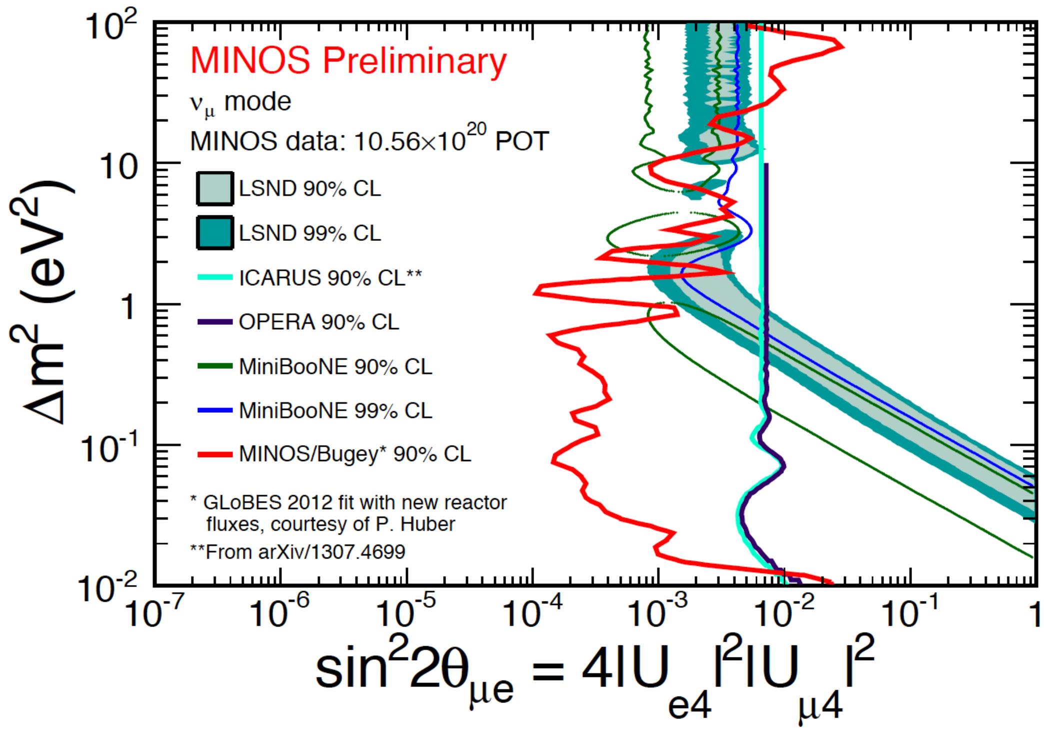


MINOS Disappearance Limit

- Feldman-Cousins corrected contour

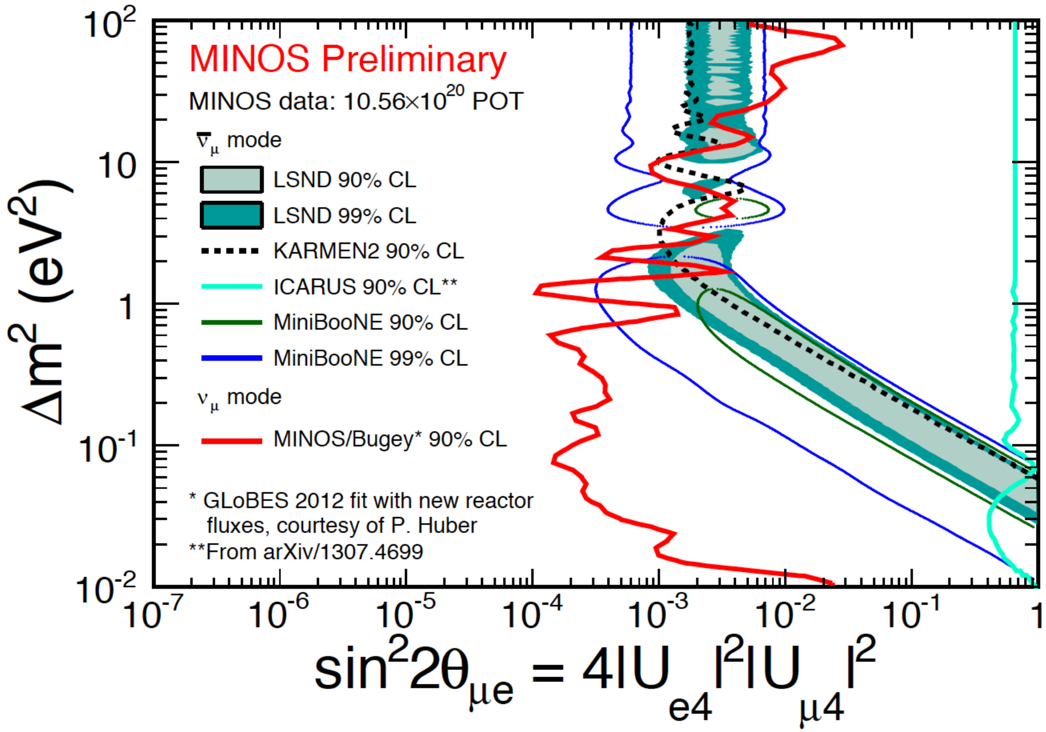


Comparison to Appearance Results



- Combine MINOS disappearance 90% C.L. in θ_{24} and Bugey reactor experiment 90% C.L. disappearance limit in θ_{14} (Neutrino Mode – MINOS and MiniBooNE)
- For a 3+1 model: $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$
- Bugey limit computed from GLoBES 2012 fit using new reactor fluxes, provided by Patrick Huber
- MINOS results increases tension between null and signal results for $\Delta m^2_{43} < 1$ eV^2

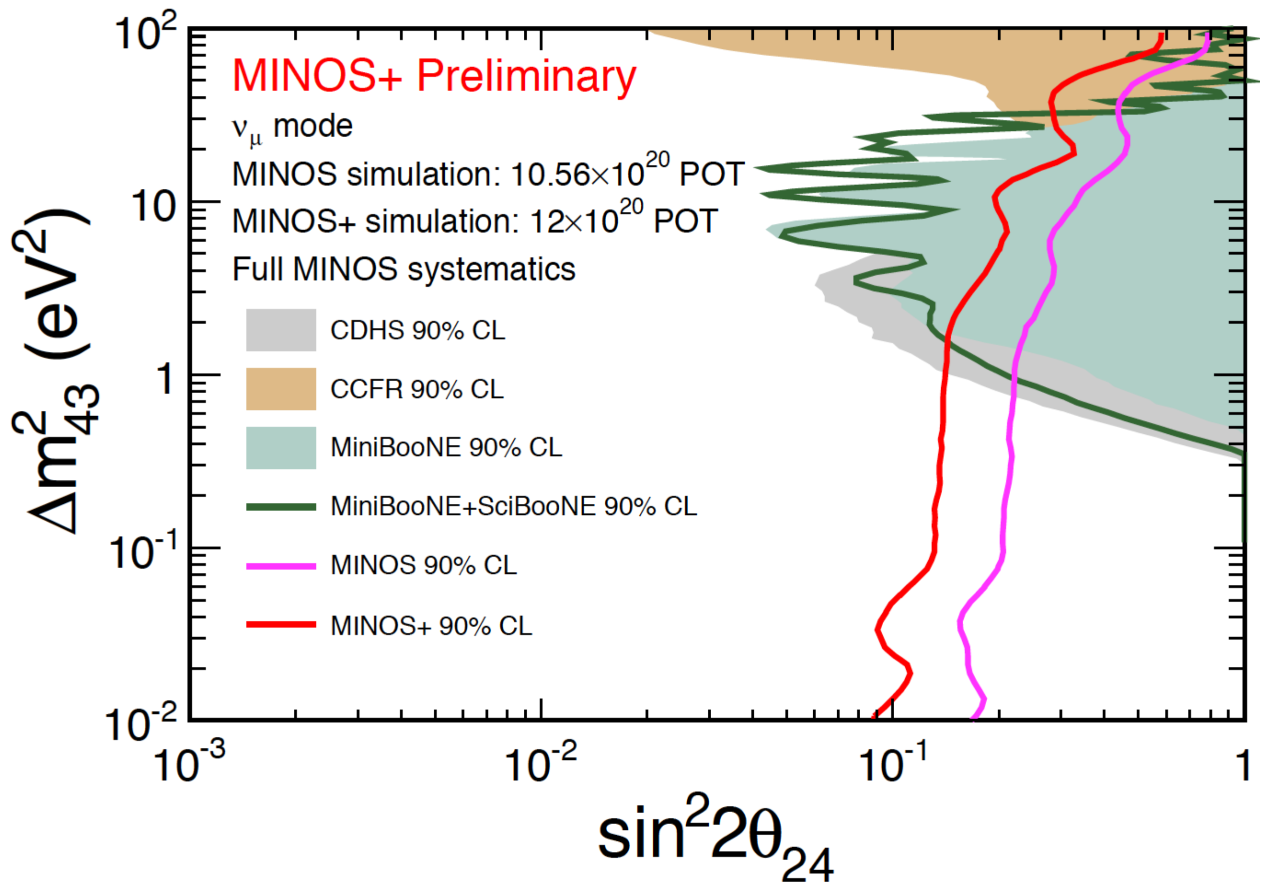
Comparison to Appearance Results



- Compare MINOS neutrino data to world antineutrino data
- Assuming 3+1 model and CPT conservation (makes SBL neutrino and antineutrino oscillations equivalent)
- MINOS results increases tension between null and signal results for $\Delta m^2_{43} < 1$ eV^2
- Work on 3.4×10^{20} POT antineutrino data sterile neutrino search underway

Sterile Neutrino in MINOS+

- Expected sensitivity from MINOS+ data by 2016, compared to other short-baseline experiments and MINOS



Summary

- MINOS completed a search for sterile neutrinos in a long-baseline experiment
  - No evidence of sterile neutrino oscillations found
  - Limits span four orders of magnitude of Δm^2_{43}

- MINOS placed new constraints on the non-standard interaction parameter $\varepsilon_{e\tau}$

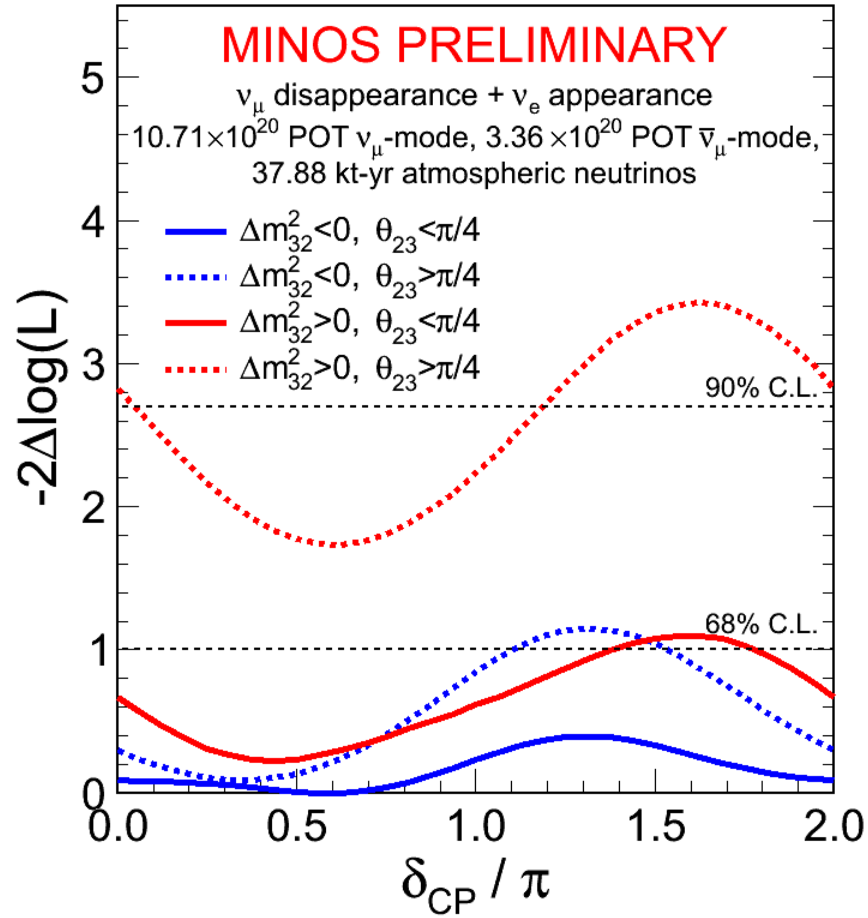
- MINOS three-flavor analysis improved with increased statistics from MINOS+ atmospheric data

- MINOS+ is taking data in the medium-energy NuMI beam
  - Precision test of oscillation parameters in different energy range
  - Results of oscillation analysis from beam data in Fall
  - Keep watch for any surprises

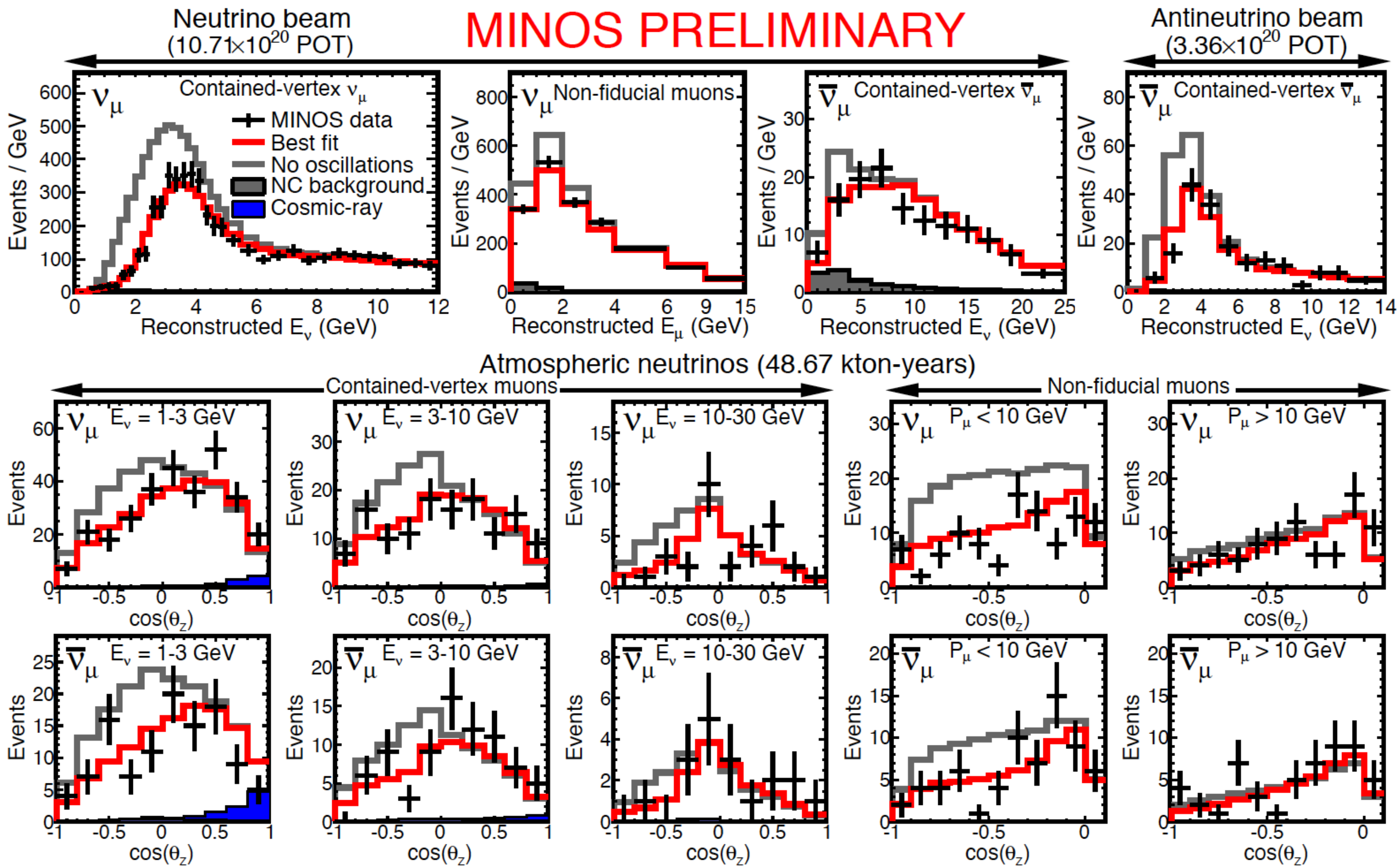
Additional Materials

Adding Appearance

- Sensitivity to θ_{13} in MINOS from ν_e appearance search
- Limits on δ_{CP} obtained by fitting data with respect to reactor experiments
  - First limits on this parameter shown by MINOS in PRL 110, 171801 (2013)
  - Addition of disappearance and atmospheric data further disfavor normal mass hierarchy and upper octant
- Published by PRL:
  PRL 112, 191801 (2014)



All MINOS FD Data – 3-flavor



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				$-2\Delta\log(L)$
	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				$-2\Delta\log(L)$
	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				$-2\Delta\log(L)$
	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: $-2\Delta\log\mathcal{L}=0.66$