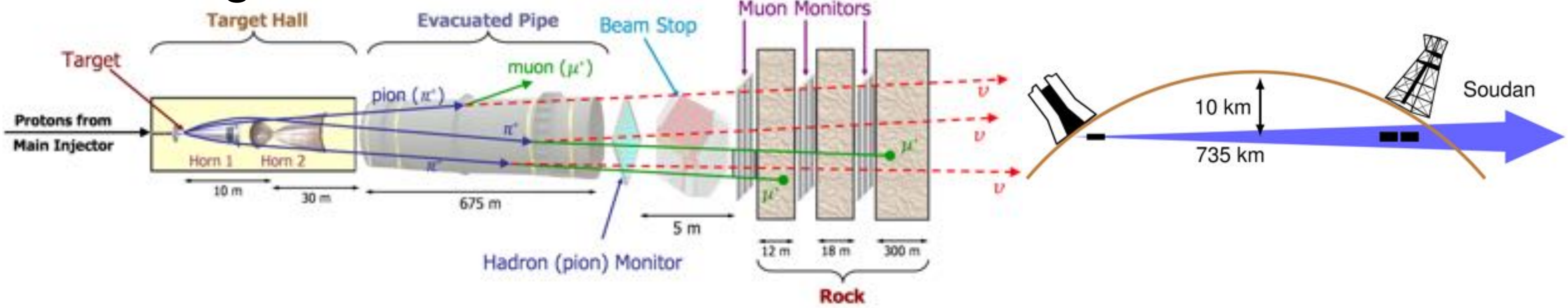
Still Scintillating: MINOS+

A.P. Schreckenberger - UT Austin
(on behalf of the MINOS+ collaboration)

A Brief Reminder of MINOS

- Long baseline neutrino oscillation search

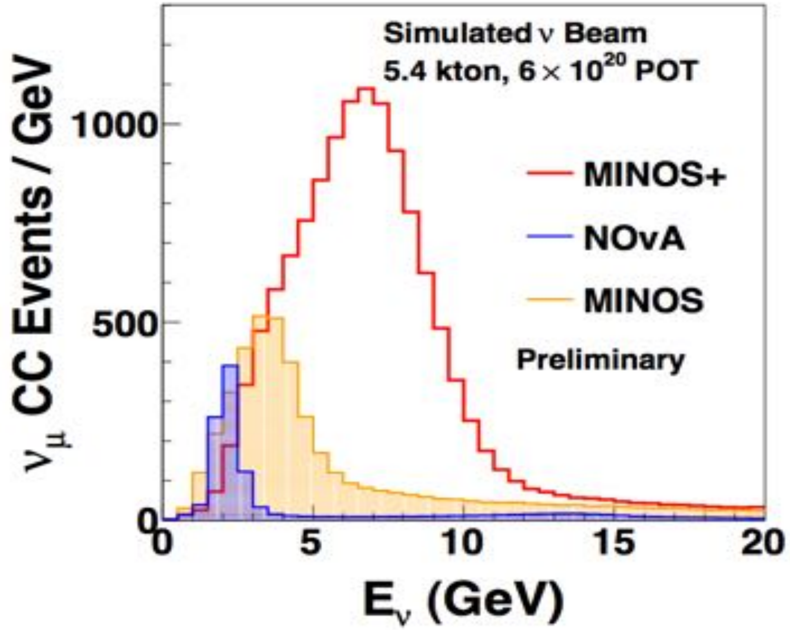


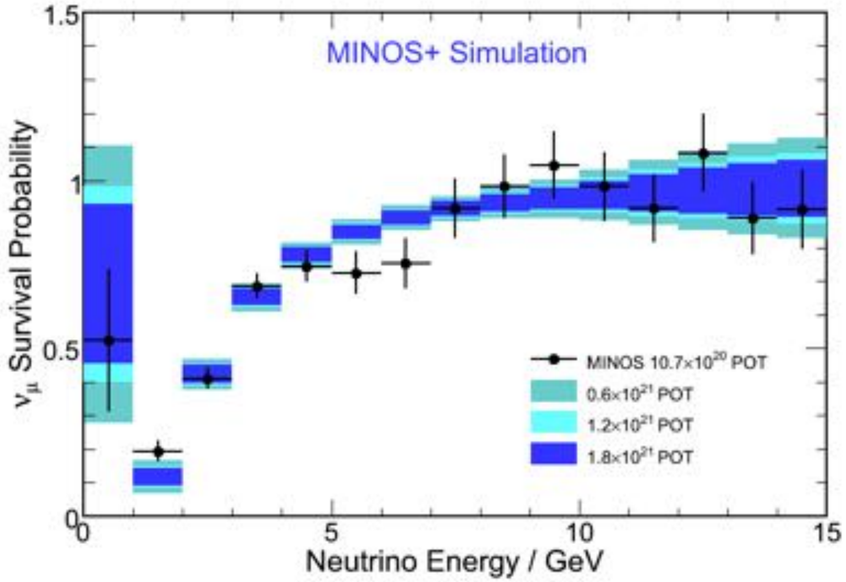
A Brief Reminder of MINOS

- Results from both MINOS and MINOS+ collaborations
  - Standard three-flavor oscillations
  - Exotic phenomena – NSI
  - **Sterile neutrino searches**
  - ***Extensive logo replacement search!***

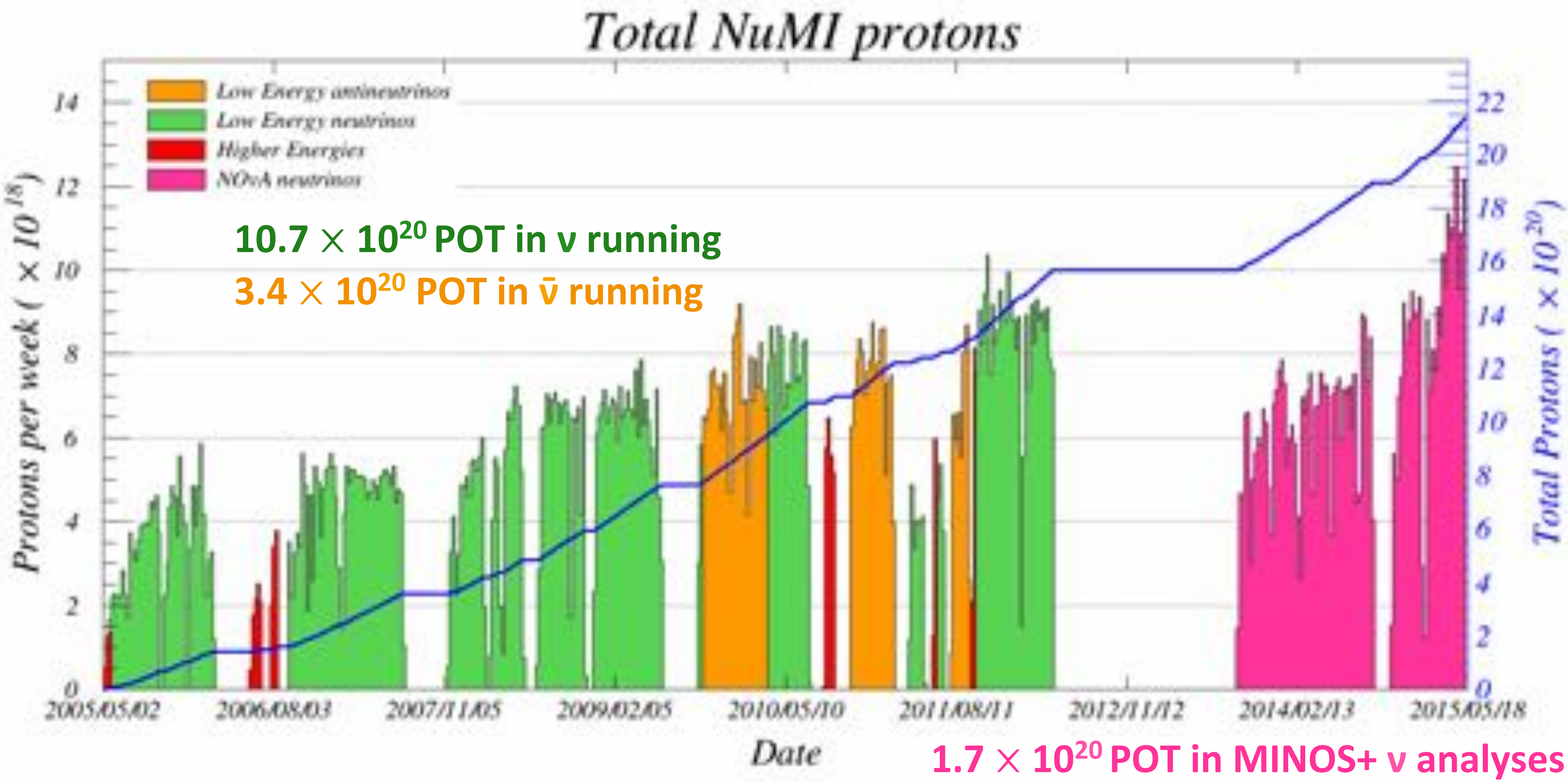
What about MINOS+

- Same magnetized MINOS detectors used in MINOS+ but now with…
- Medium-energy NuMI beam – higher energy spectrum and decreased cycle time when compared to MINOS
  - Currently running 3.3e13 protons-per-pulse every 1.33s
  - 425 kW beam power; peaked at around 480 kW
  - 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



10.7×10^{20} POT in ν running

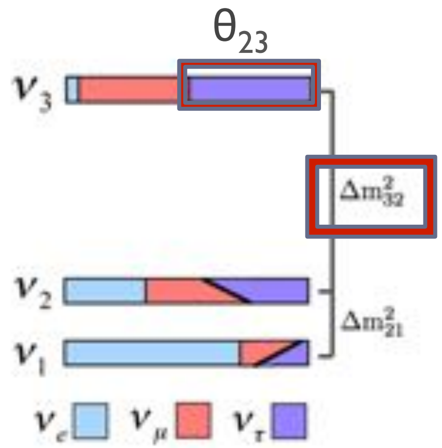
3.4×10^{20} POT in $\bar{\nu}$ running

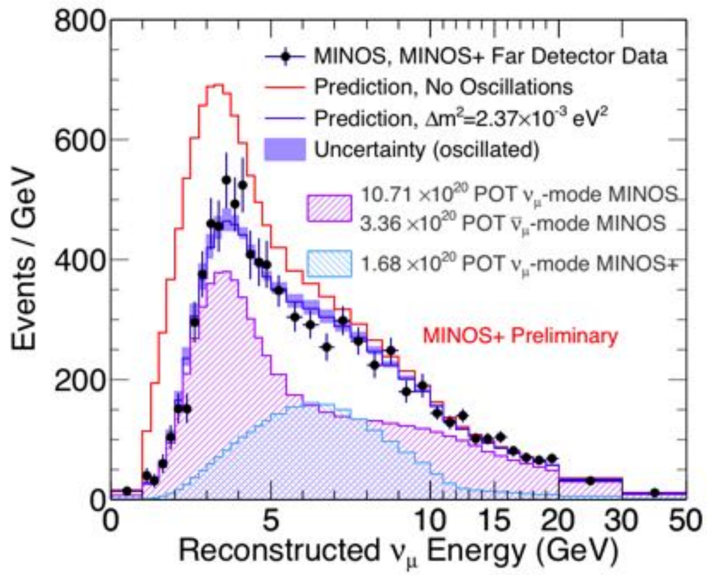
1.7×10^{20} POT in MINOS+ ν analyses

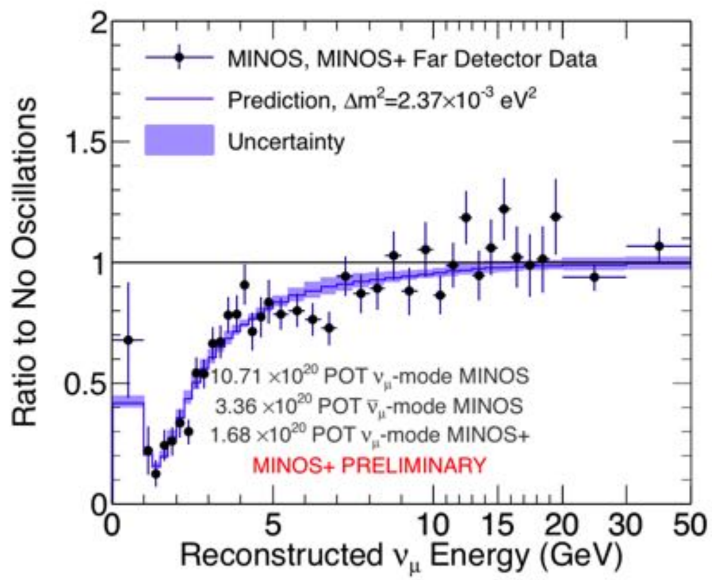
5.8×10^{20} POT in total MINOS+ data

Three-Flavor Oscillations

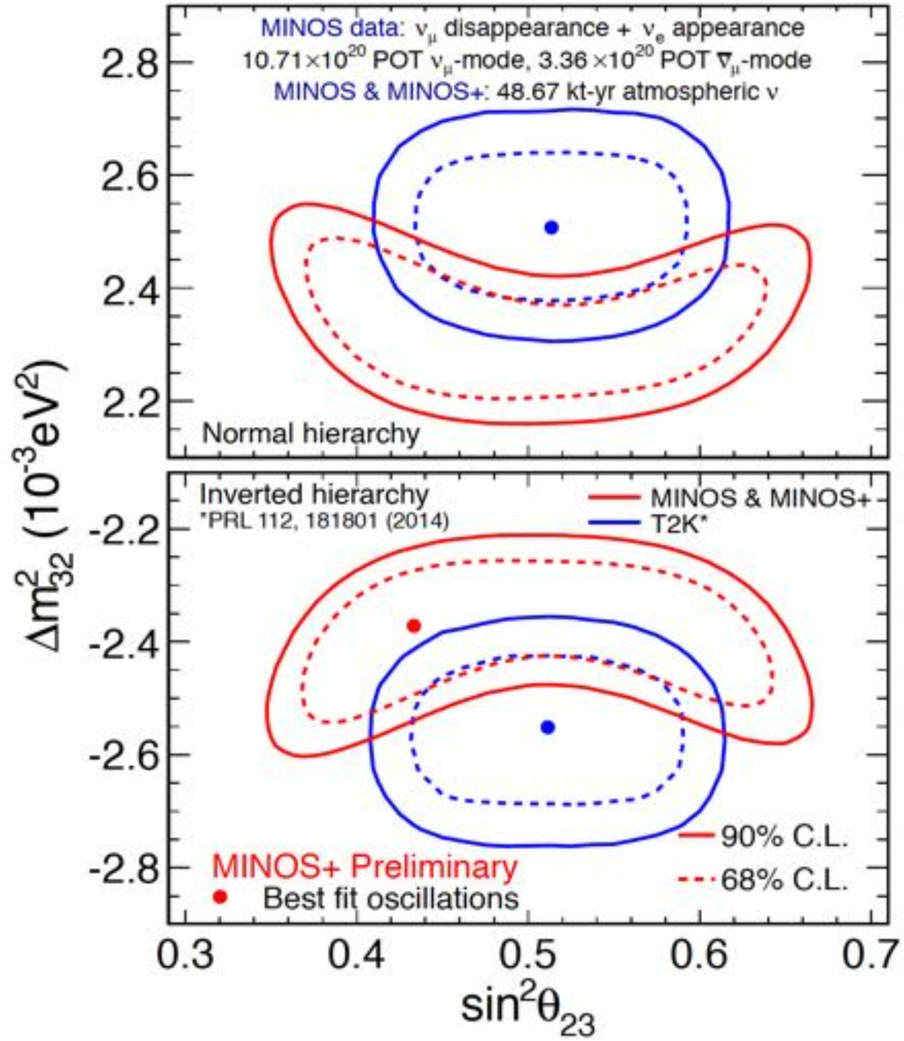
- Staple measurements of the experiment
- Updated Δm^2_{32} results using both MINOS and MINOS+ data
  - Full MINOS ν_μ-CC and $\bar{\nu}_\mu$-CC disappearance sample
  - Full ν_e-CC, $\bar{\nu}_e$-CC appearance sample, described in *PRL 110 171801 (2013)*
  - Full MINOS and MINOS+ atmospheric samples







Three-Flavor Oscillations



- Three-Flavor 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 $|\Delta m^2_{32}|$
- Results highlight precision era of field

Non-Standard Interactions

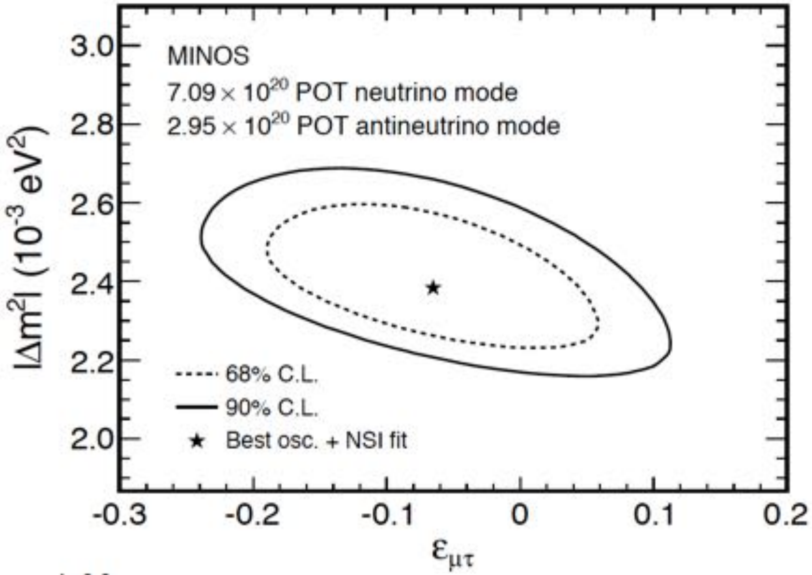
- Non-Standard Interaction (NSI) framework accommodates deviations from standard oscillation picture
  - Analogous to MSW matter effect

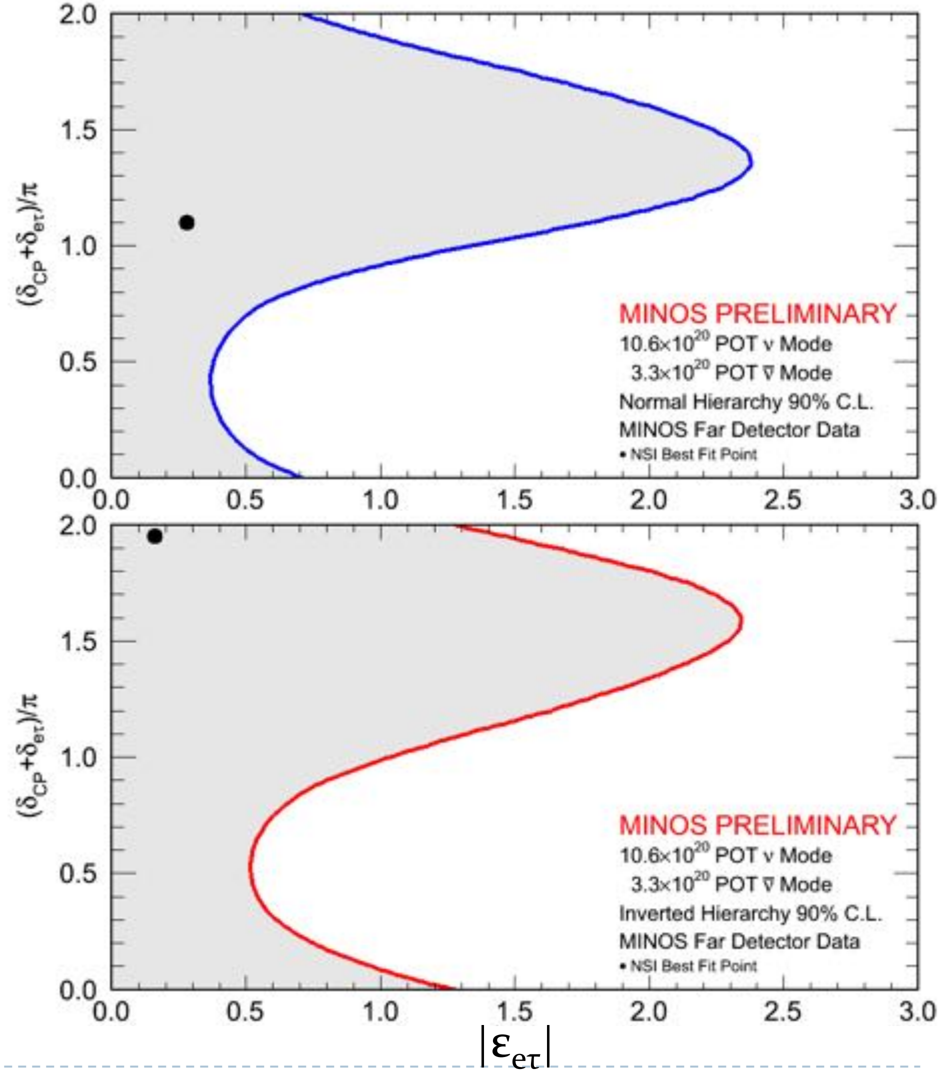
$$H = U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^{\dagger}_{PMNS} + \sqrt{2} G_F n_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^{\star}_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}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

- Fit MINOS data to get 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
  - Effort to maximize gains of the robust MINOS dataset

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)*
  - Work currently ongoing to implement final uncertainties into the fit

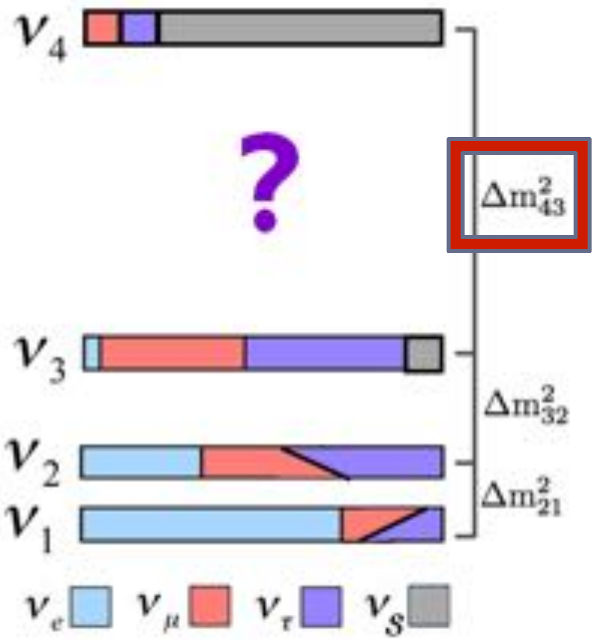


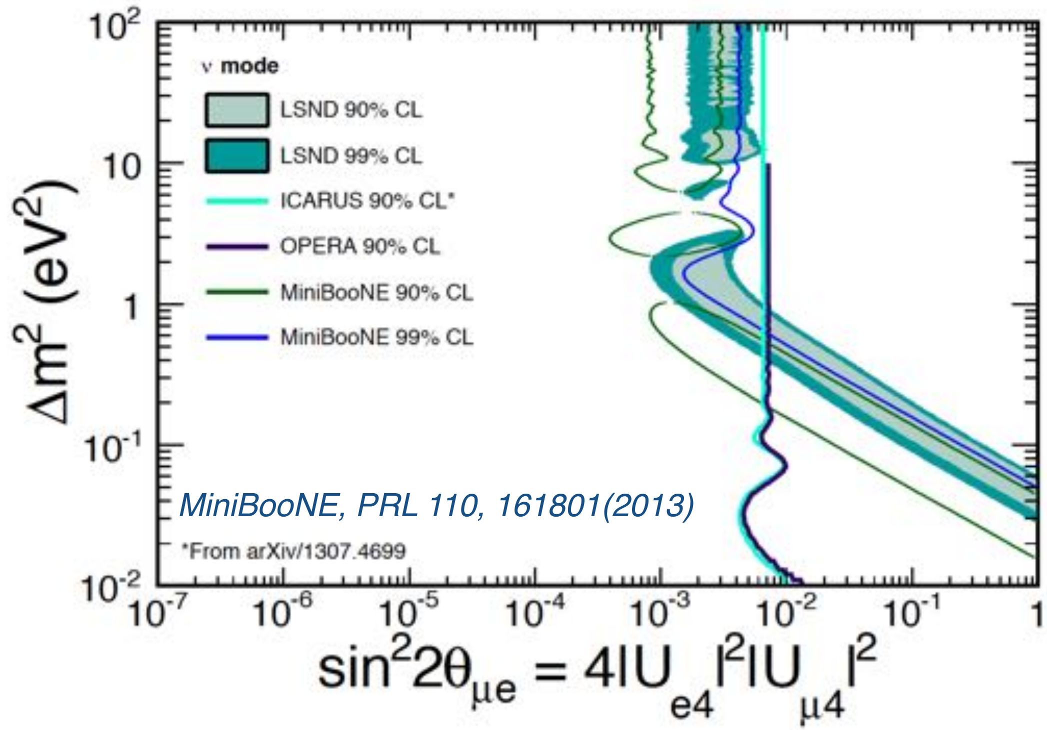



MINOS
Hunting for Sterile Neutrinos

Sterile Neutrinos – To 3, or 3+1, or 3+N?

- Sterile neutrinos: the flavor of the day driven by anomalies in reactor, short-baseline, radiochemical experiments
  - Oscillations with light sterile neutrino - possible explanation
- Evidence of sterile mixing is inconclusive due to tension between various experiment results
  - Complicates analyses due to added parameters in the oscillation model





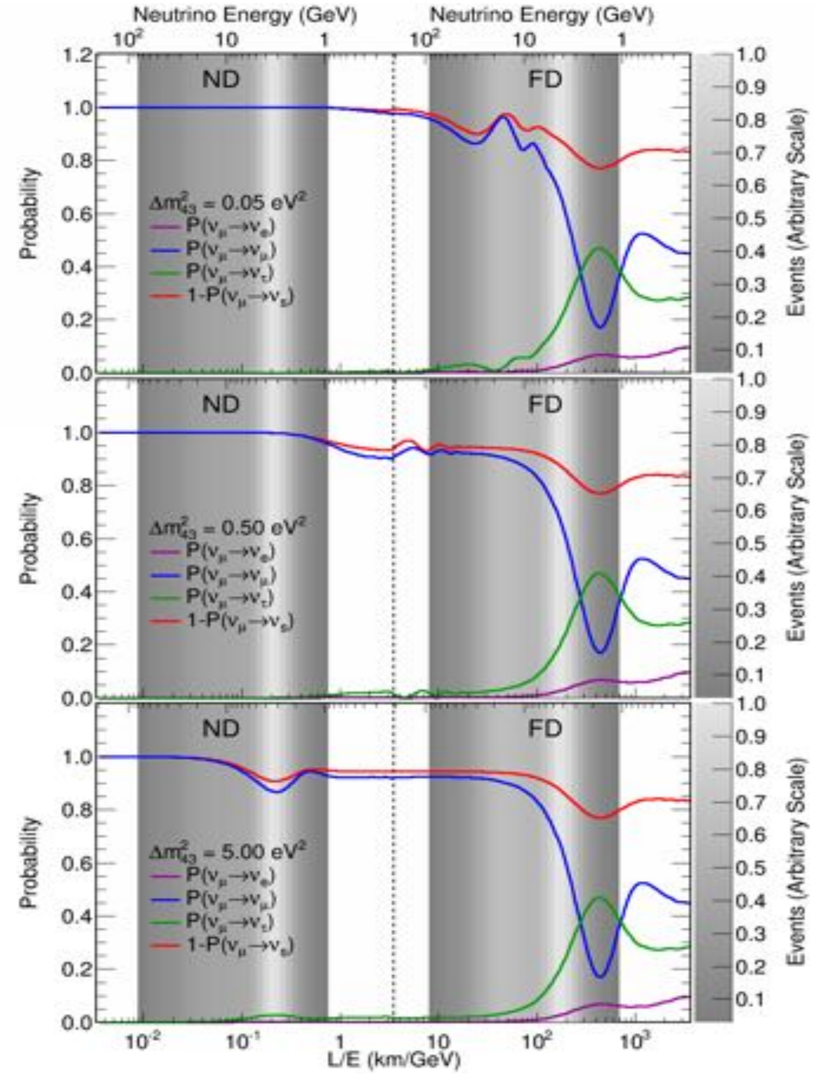
A Glimpse at Four-Flavor Oscillations

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

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

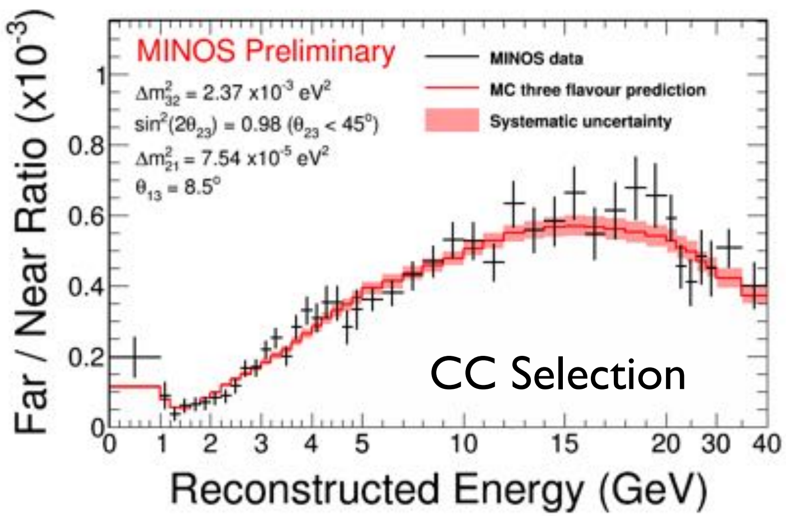
- Medium Δm_{43}^2 :
  - Rapid oscillations average out at Far Detector
  - No Near Detector effects
  - Counting experiment

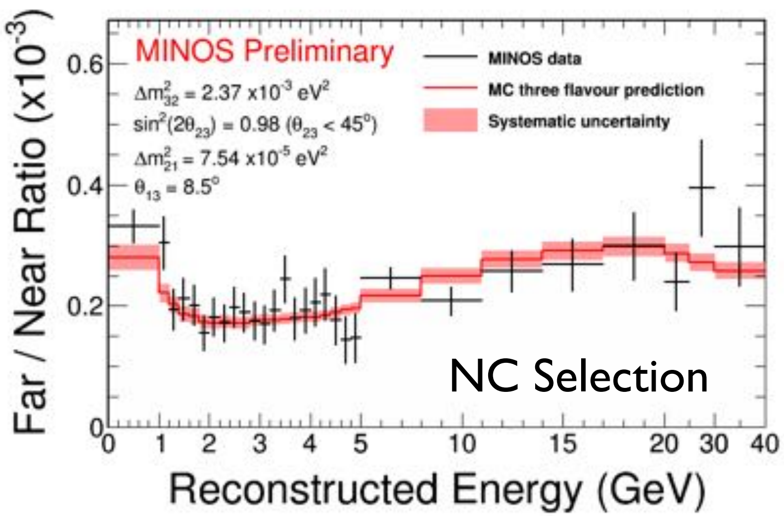
- Large Δm_{43}^2 :
  - Rapid oscillations average out at Far Detector
  - Near Detector distortions affect Far Detector prediction



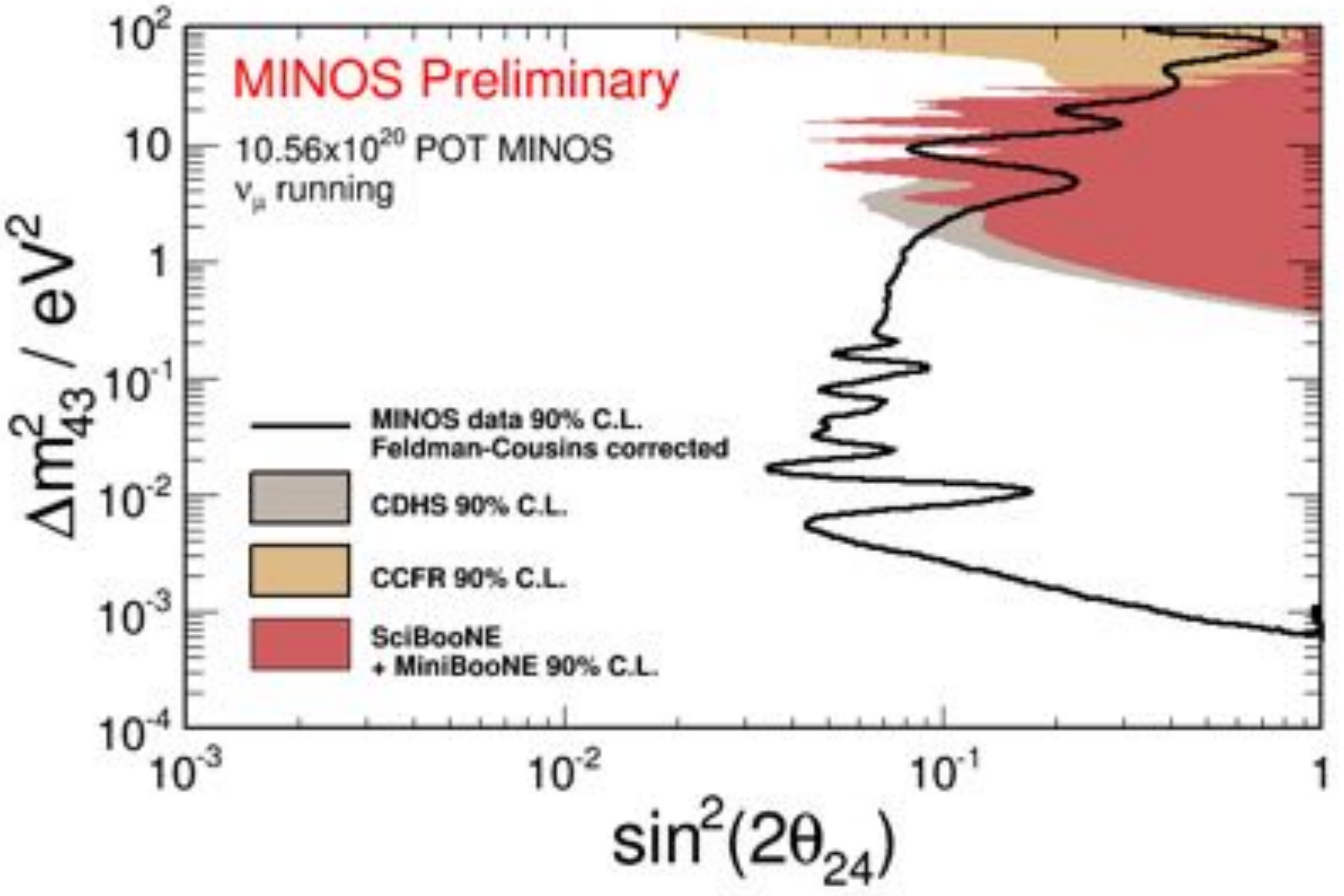
Results from MINOS Data

- Three-flavor analysis performed by fitting data to predicted Far Detector spectrum
  - Relied on the Near Detector being unoscillated control
  - Different approach needed as sterile model impacts Near Detector spectrum at mass splittings > 1 eV^2
    - Constrain ND event rate
    - Fit data directly to oscillated F/N ratio to place limits on θ_{24}

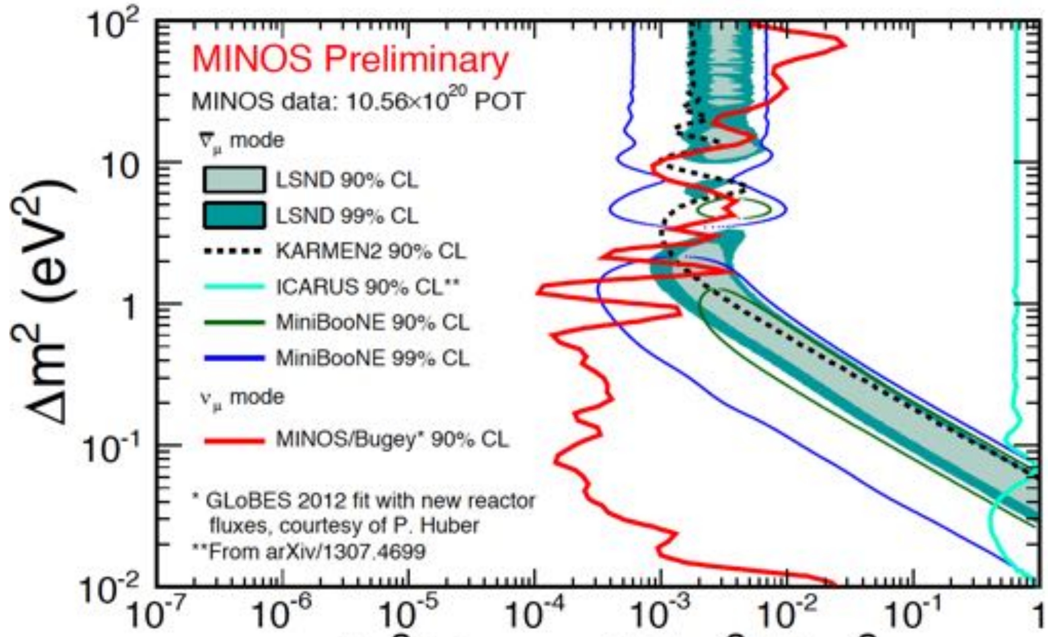




Sterile Limit via Disappearance Channel



Comparison to SBL Results



For a 3+1 model:

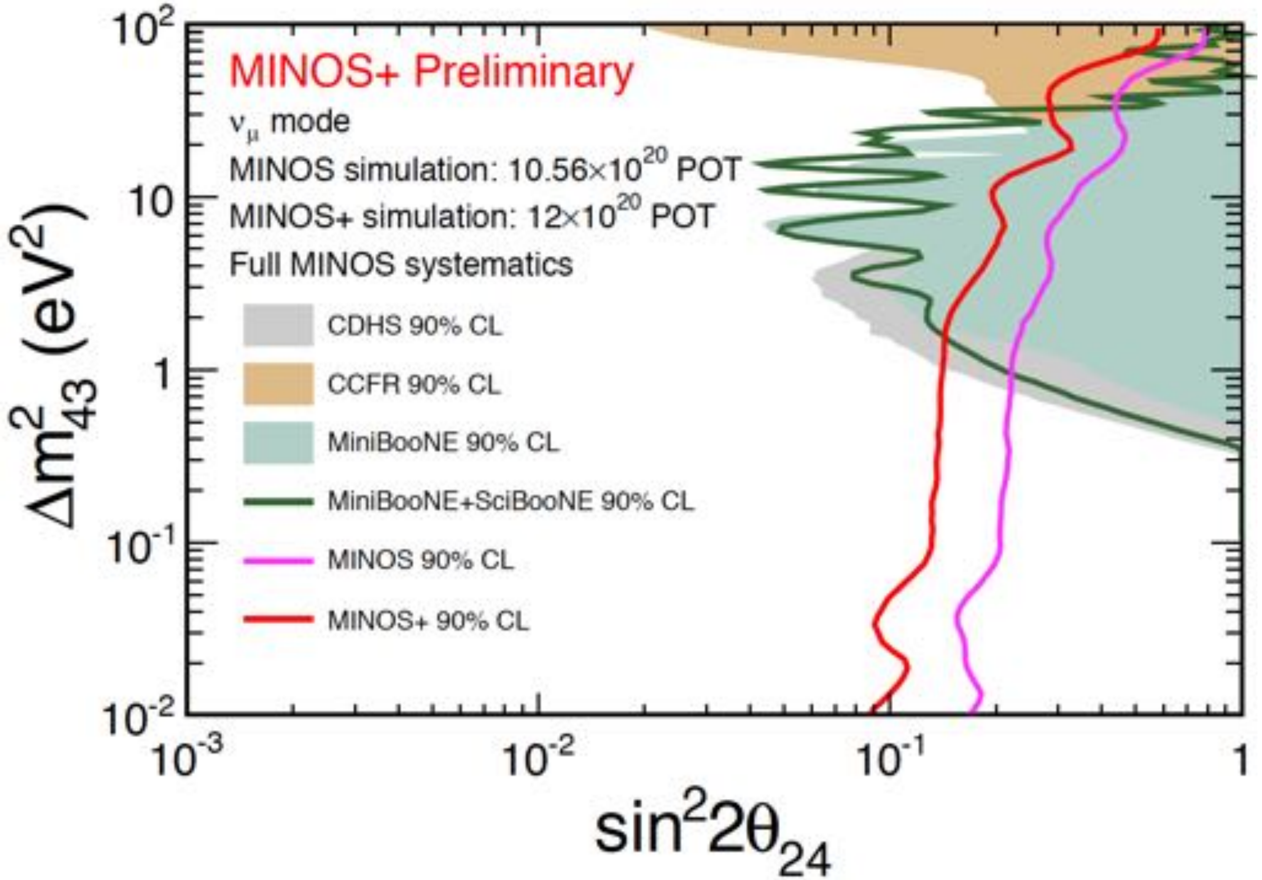
$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

- 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)
  - Bugey limit computed from GLoBES 2012 fit using new reactor fluxes, provided by Patrick Huber
- Assuming CPT conservation (makes SBL neutrino and antineutrino oscillations equivalent) – Antineutrino-mode sterile search underway!
- **MINOS results increase tension between null and signal results for** $\Delta m_{43}^2 < 1$ **eV²**

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 using muon neutrino disappearance
  - No evidence of sterile neutrino oscillations found
  - Limits span five orders of magnitude of Δm_{43}^2

- MINOS placed constraints on the non-standard interaction parameters $\varepsilon_{e\tau}$ and $\varepsilon_{\mu\tau}$
  - Work is being finalized for publication of $\varepsilon_{e\tau}$ result

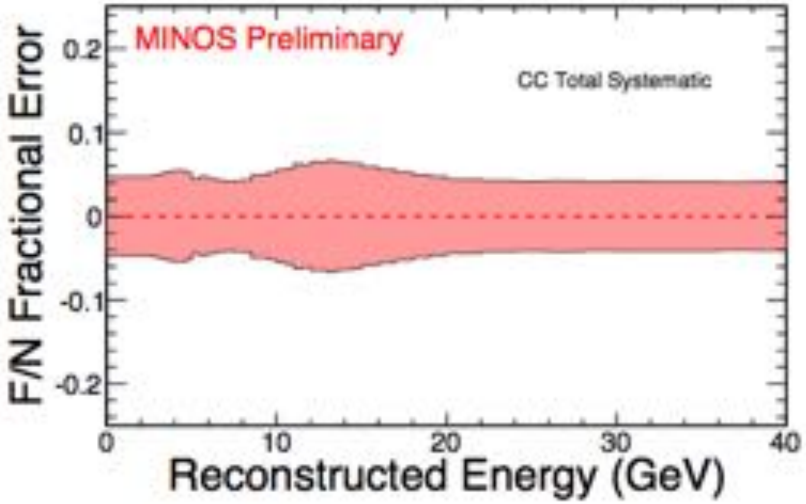
- MINOS three-flavor analysis improved with increased statistics from MINOS+ atmospheric data

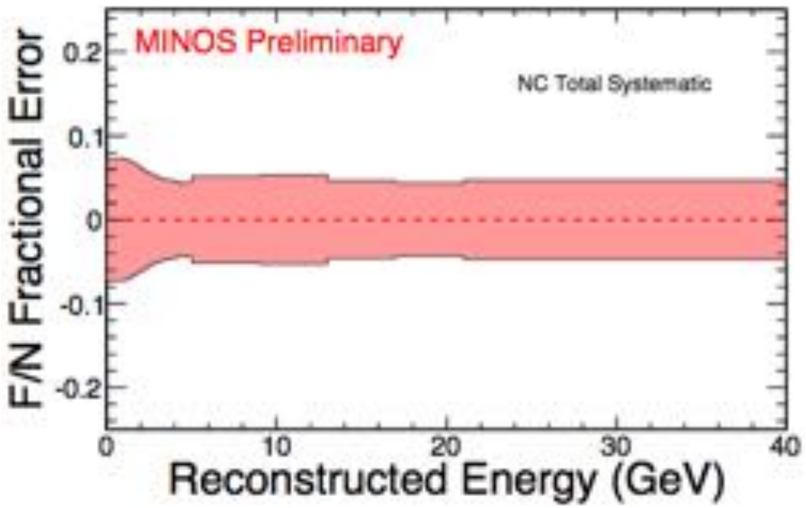
- MINOS+ is taking data in the medium-energy NuMI beam
  - Sterile searches continuing in disappearance channel with MINOS+ data
    - Developing electron neutrino appearance channel sterile search as well!
  - Excited to continue to provide quality results to the physics community

Backup

Where the wild things are…

Sterile Search Systematics





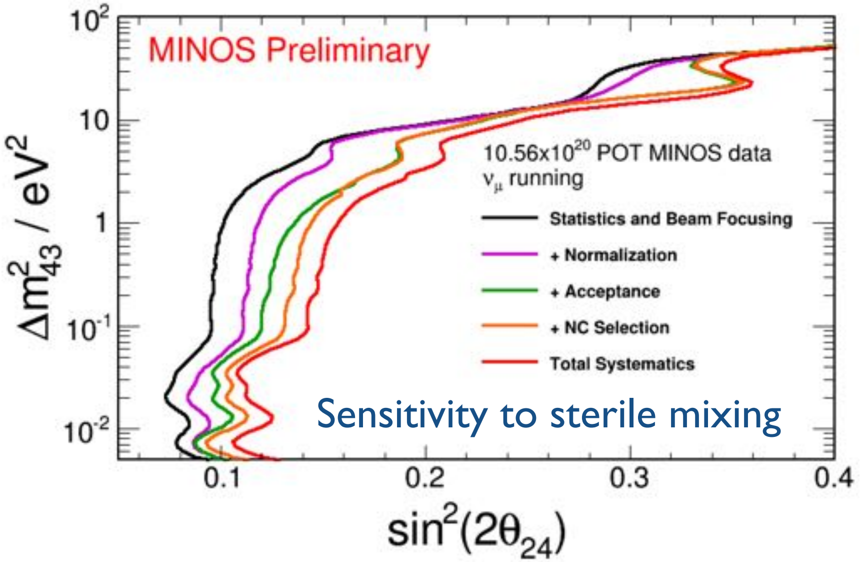
- 26 systematics included in fit
  - Hadron production, beam optics, detector acceptance, energy scale, cross-section

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

o_i : Observed events in bin i

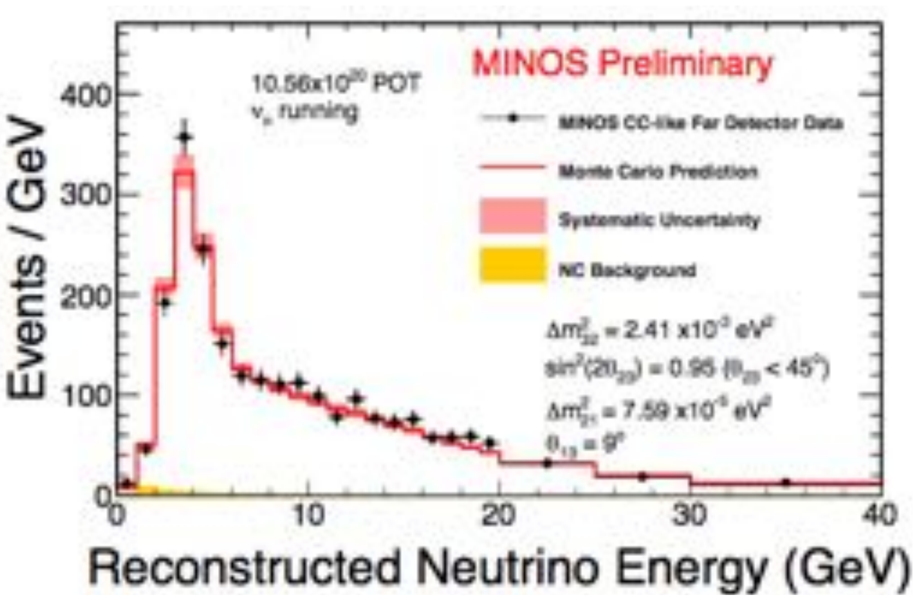
e_i : Predicted events in bin i

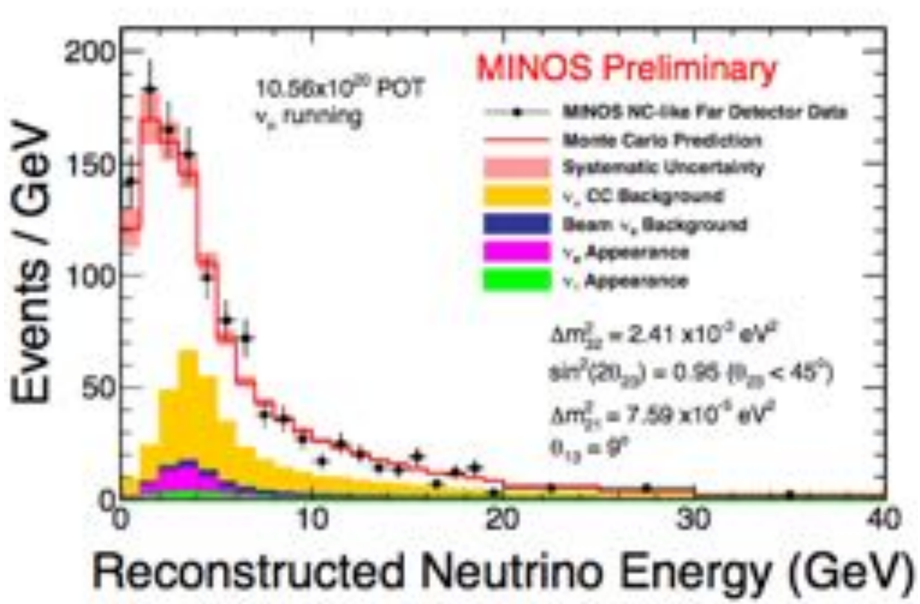
V : Covariance matrix



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
  - First, 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

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

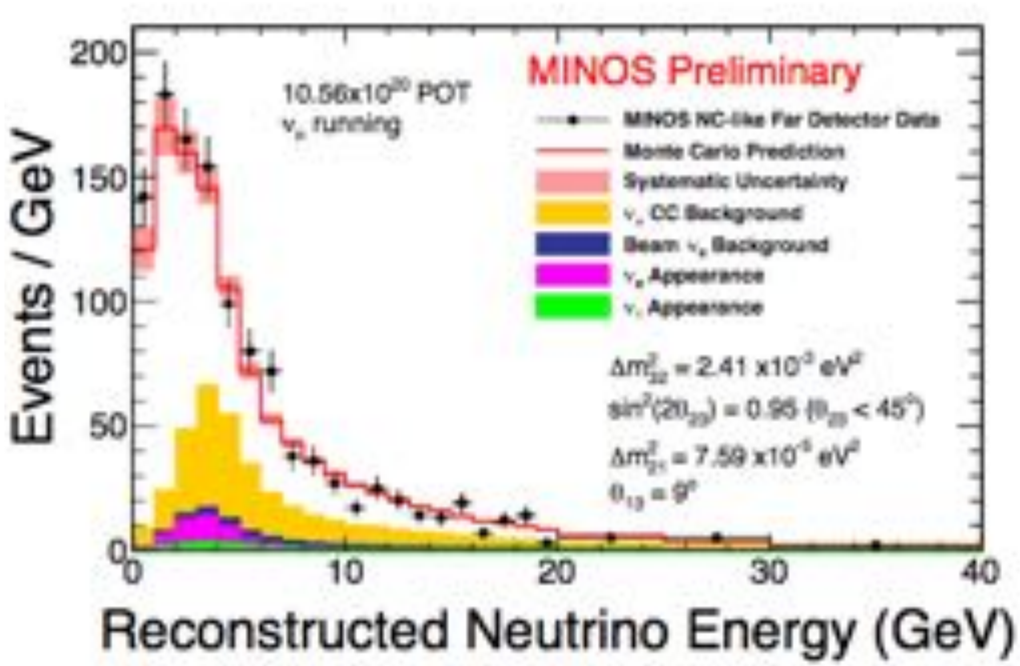
  - R < 1.0 hints sterile neutrino driven deficit

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

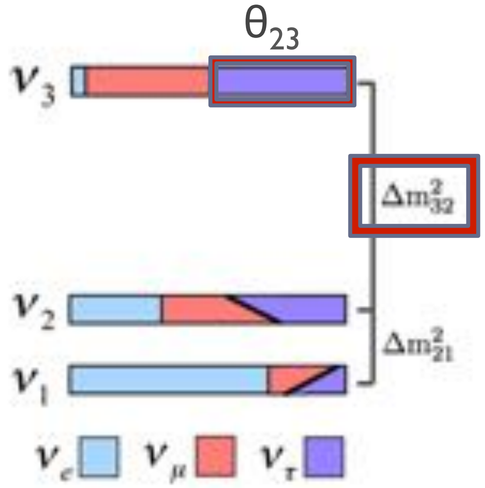
Results from MINOS data:

R = 1.075 ± 0.107 (0-40 GeV)

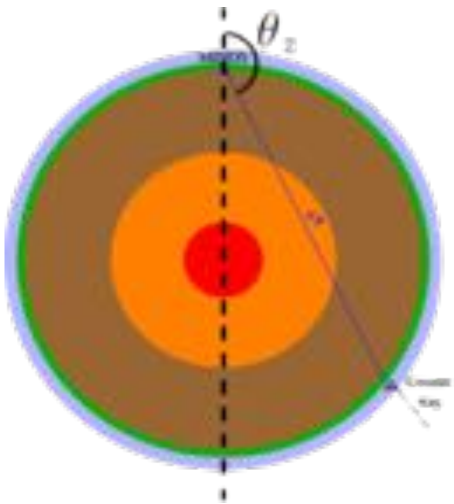
R = 1.109 ± 0.096 (0-3 GeV)

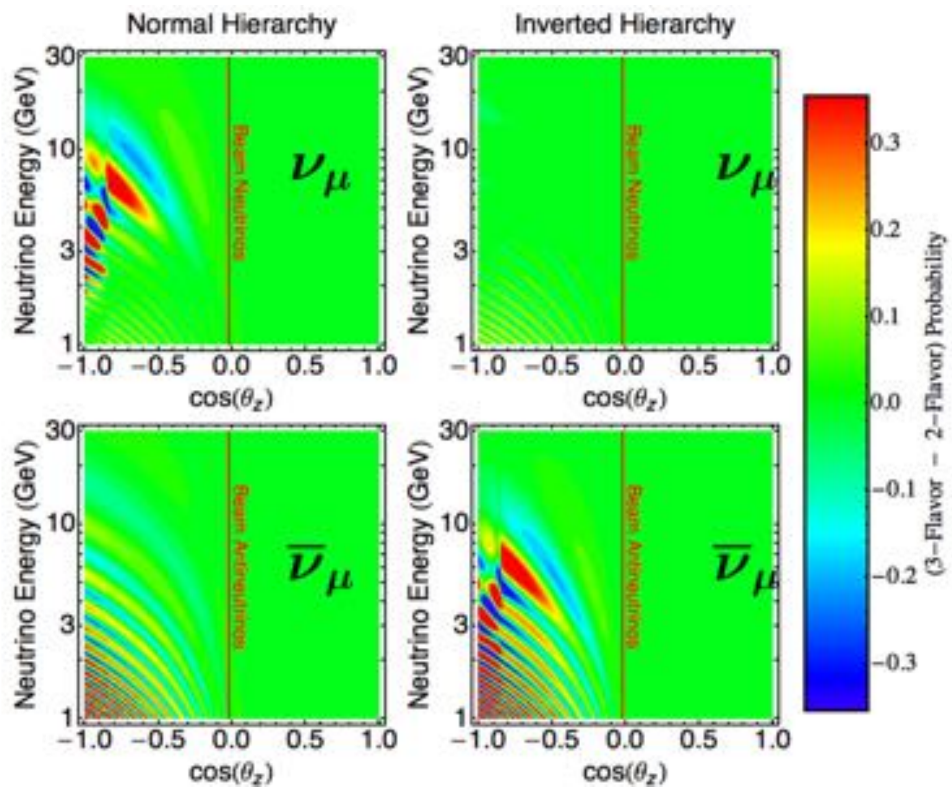


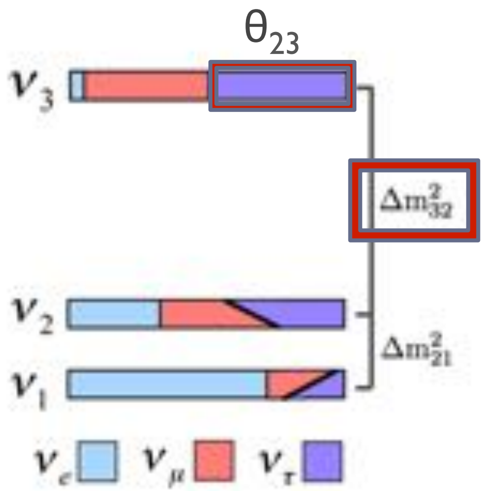
Three-Flavor Oscillations



- 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

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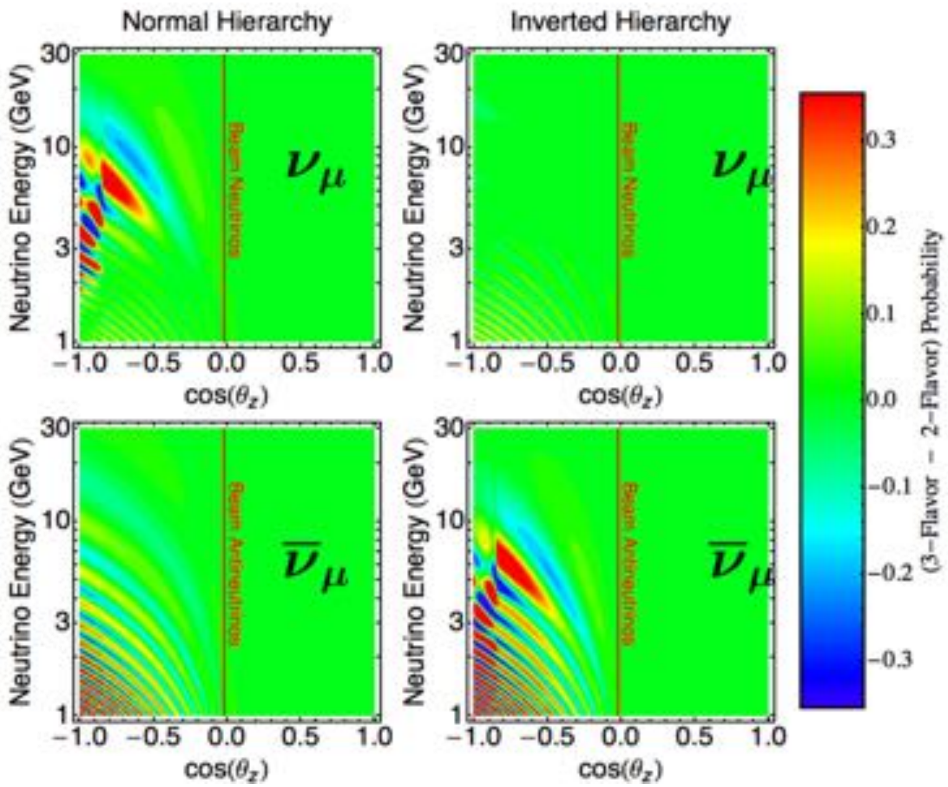
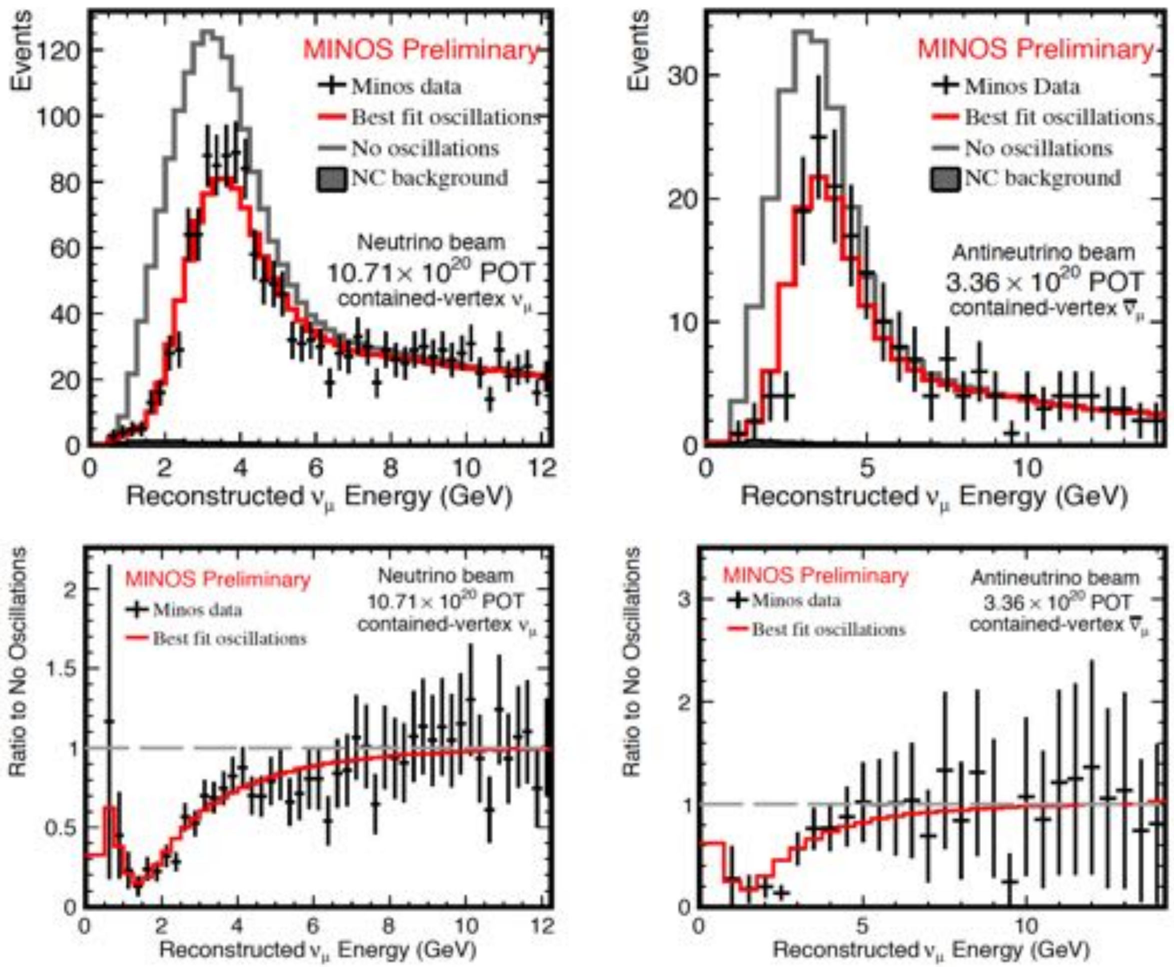
- Sensitivity to θ_{13}, θ_{23} octant, mass hierarchy, and δ_{CP} from ν_e sample
- Enhanced by atmospheric data
  - Matter effects give rise to larger differences in multi-GeV, upward-going events
  - Effects are dependent on mass hierarchy and charge conjugation
- MINOS first to probe effect with event-by-event charge separation



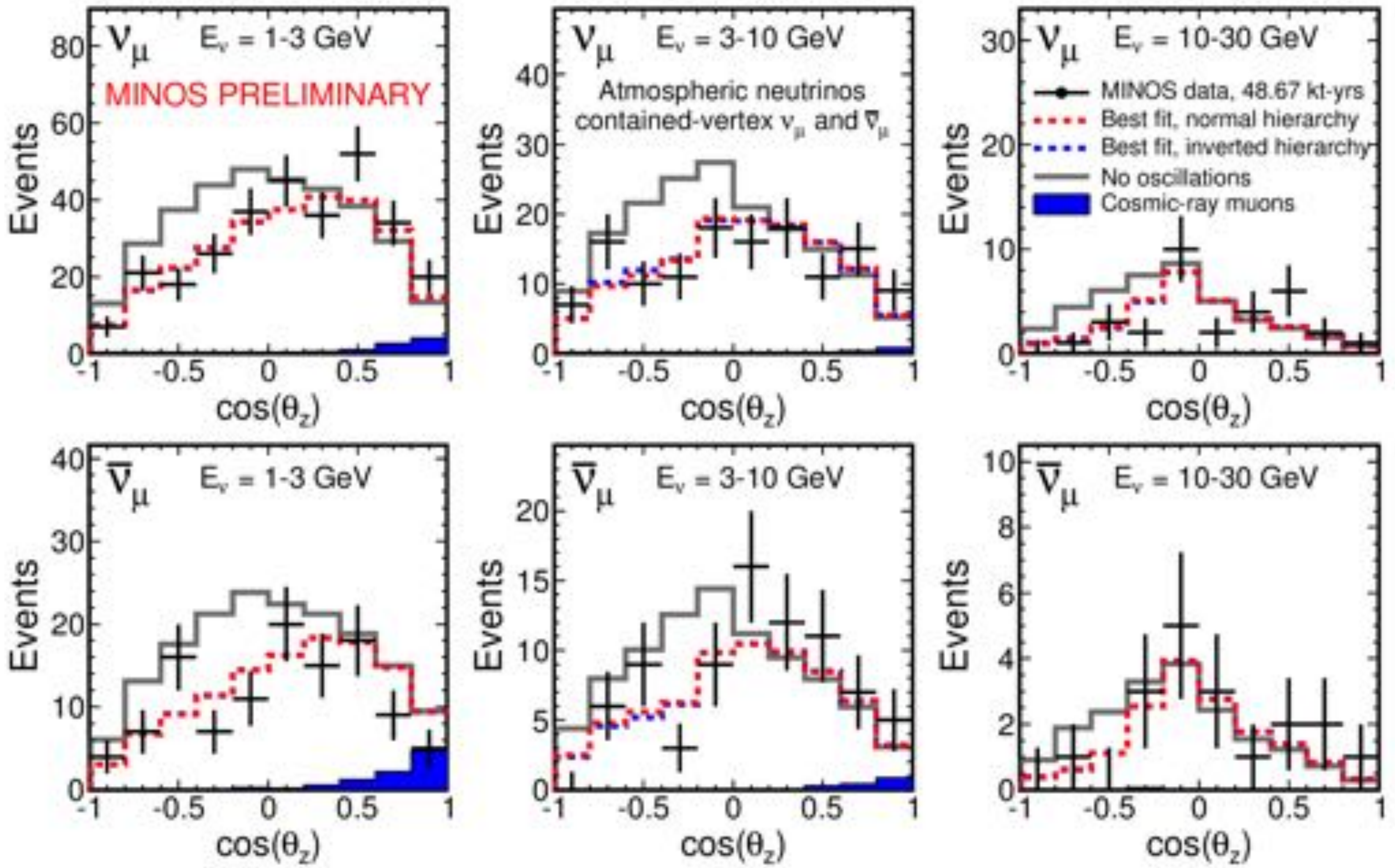
Analysis Fundamentals – Beam Data

- 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

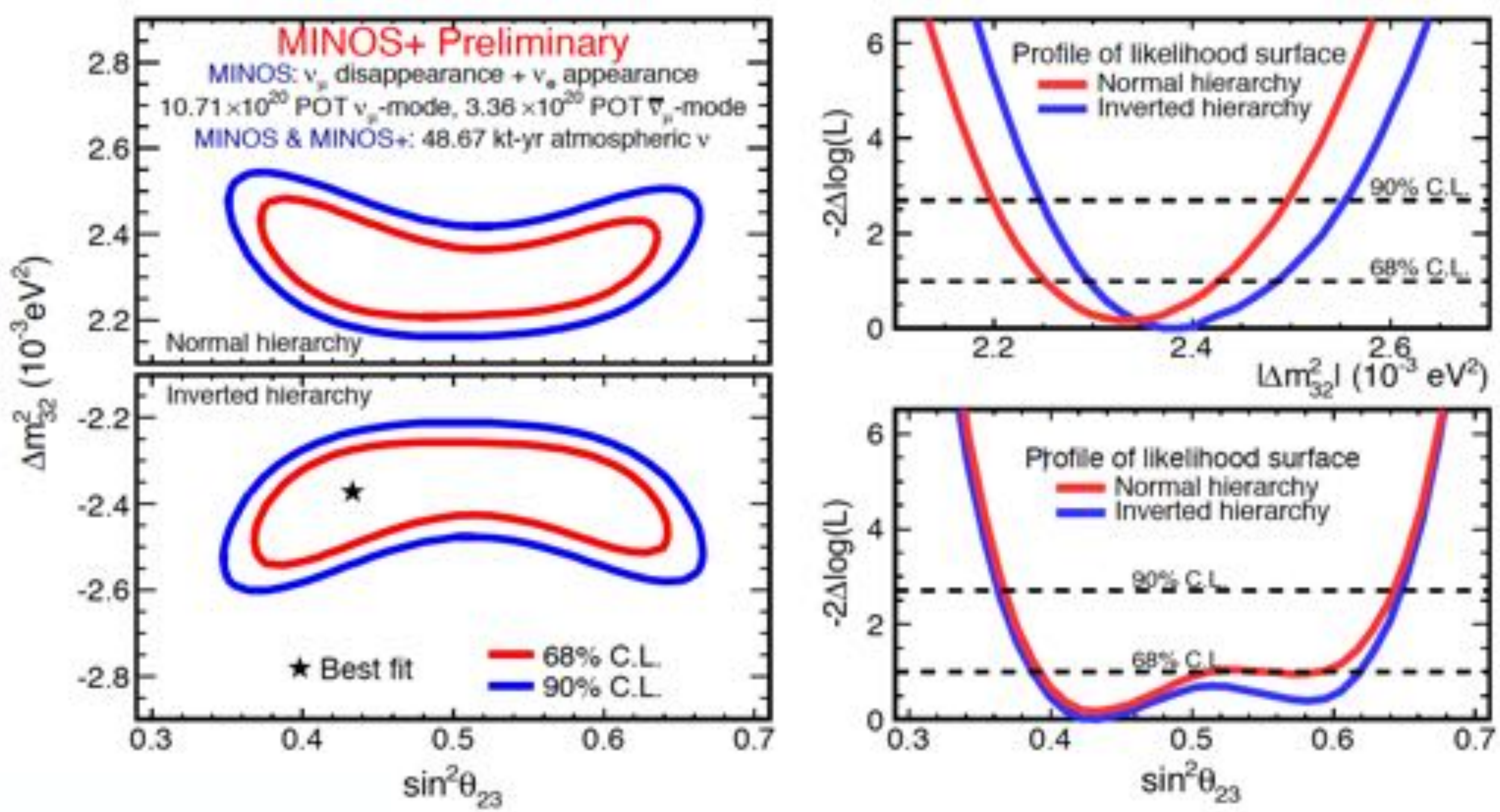
- Contained ν_μ events as a function of angle for three energy ranges
- Fits to three-flavor oscillation framework include non-fiducial events



A.P. Schreckenberger - University of Texas at Austin - WIN2015

Combined Fit Allowed Regions

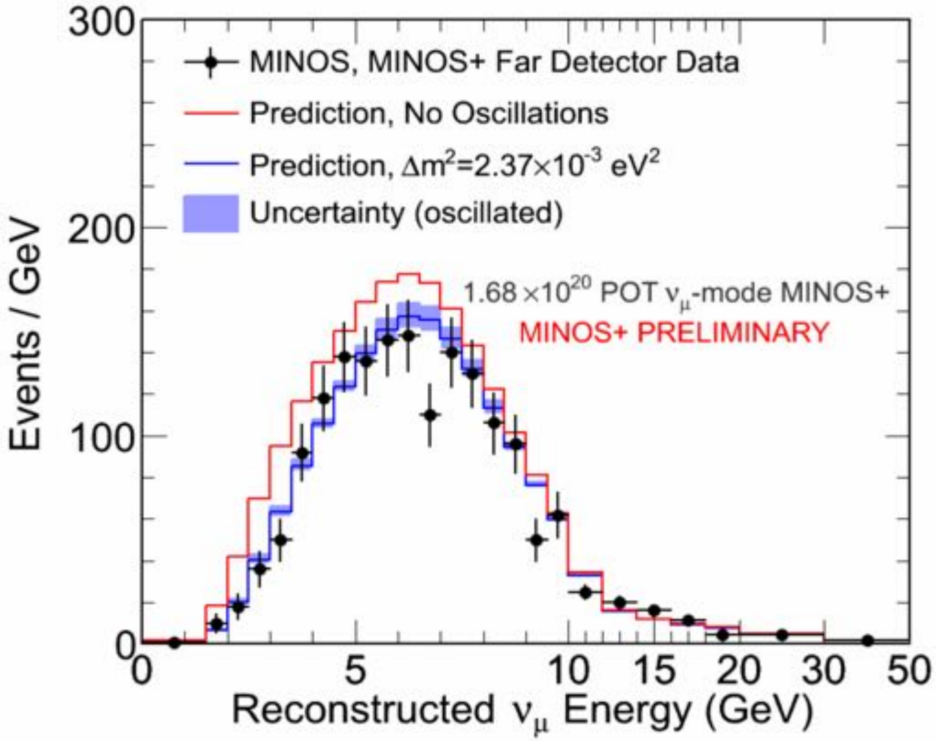
- Solar parameters fixed to $\Delta m_{21}^2 = 7.54 \times 10^{-5}$ eV^2 and $\sin^2\theta_{12} = 0.307$
- θ_{13} fit as nuisance parameter, constrained by reactor results: $\sin^2\theta_{13} = 0.0242 \pm 0.0025$
- θ_{23}, Δm_{32}^2, and δ_{CP} unconstrained
- 19 systematics included as nuisance parameters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

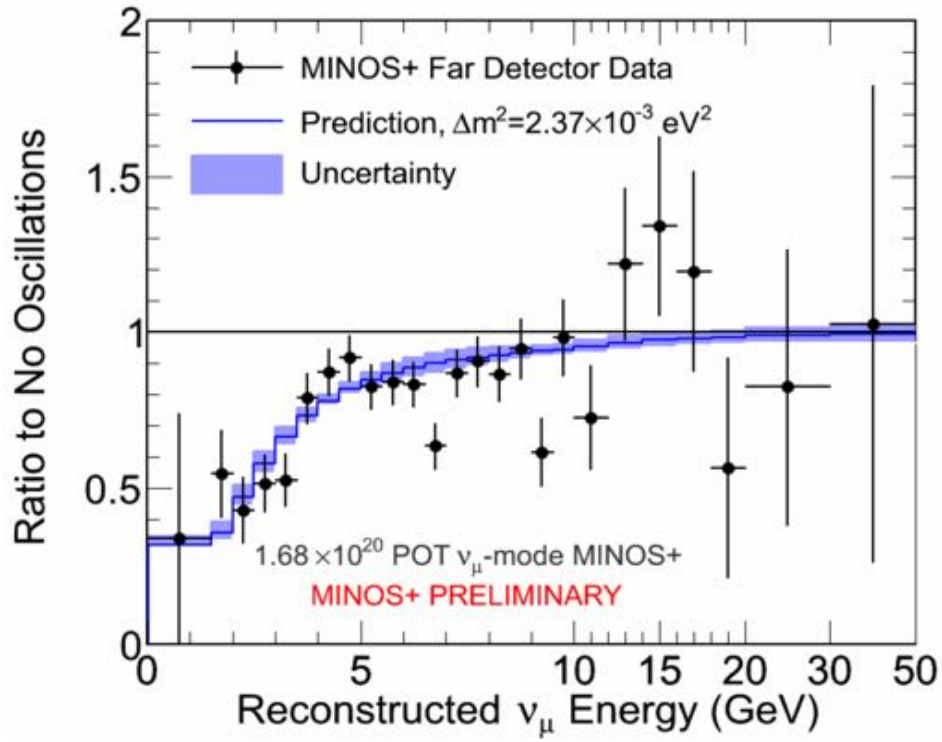


A Look Towards Tomorrow

- 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



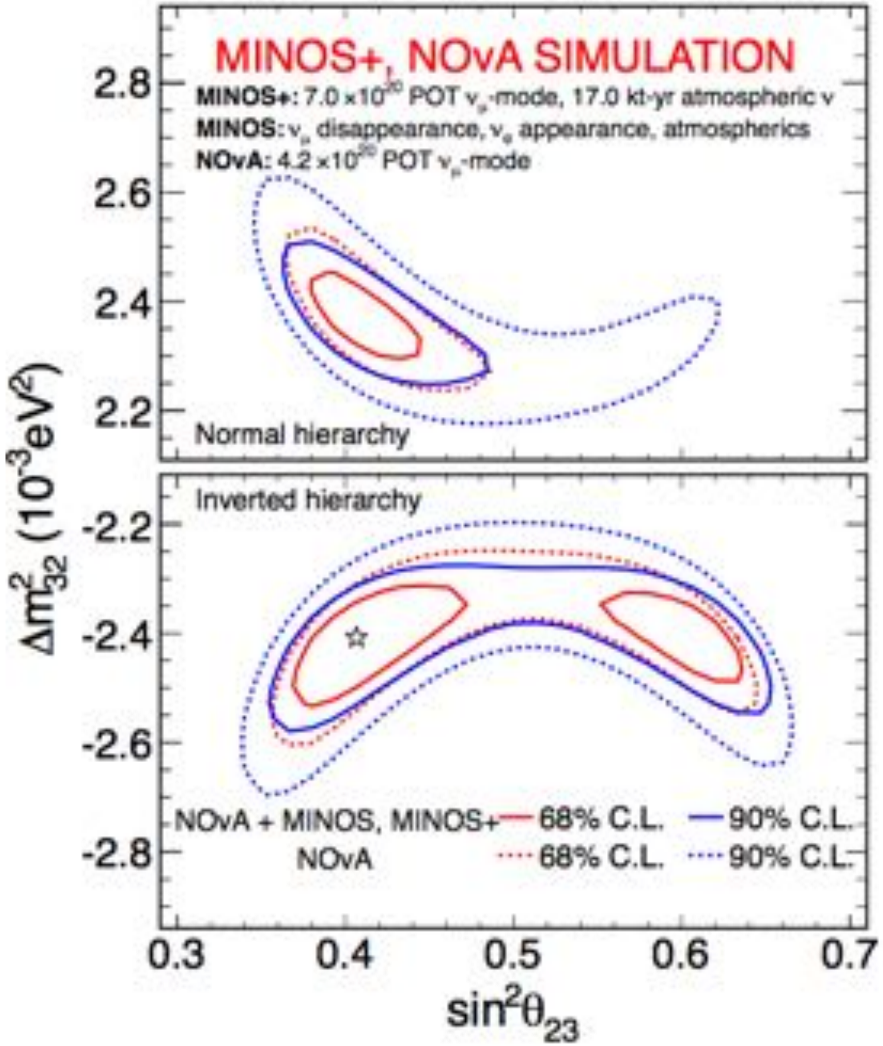


MINOS/MINOS+/NO νA Combination

- 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



The First δ_{CP} Constraints

- 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
  - Combined result published by PRL: **PRL 112, 191801 (2014)**