Latest Results from MINOS and MINOS+

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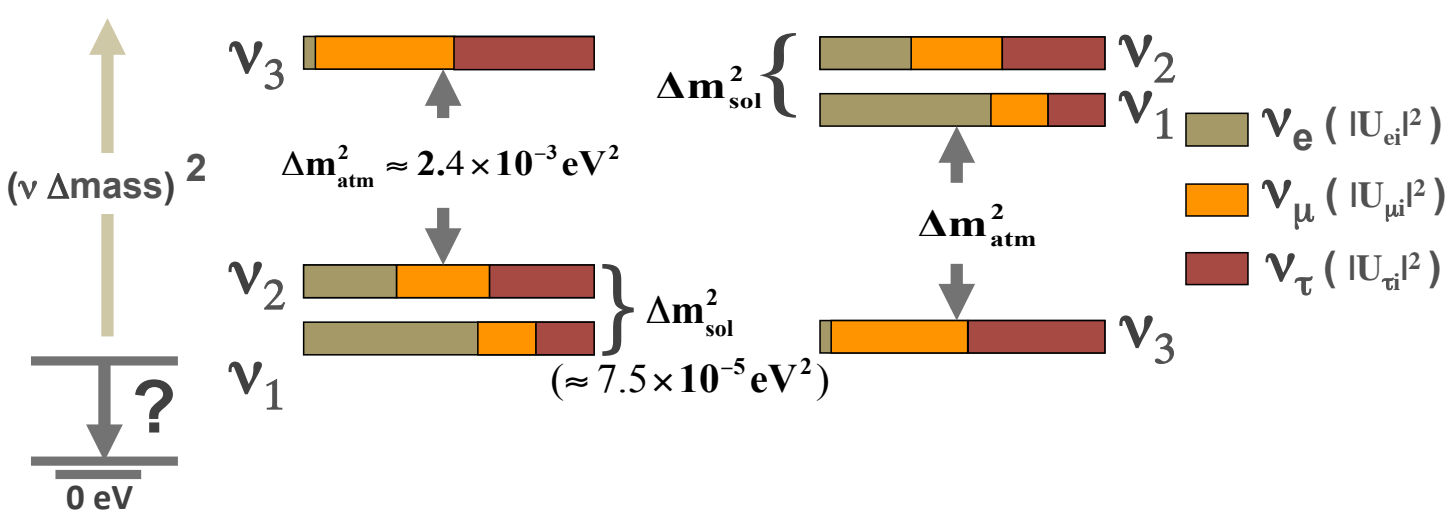
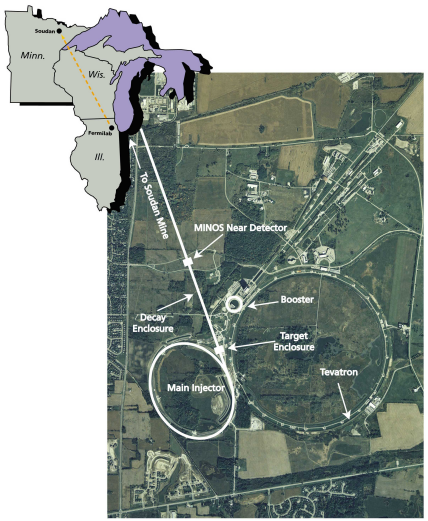
on behalf of the **MINOS+ Collaboration**

Outline

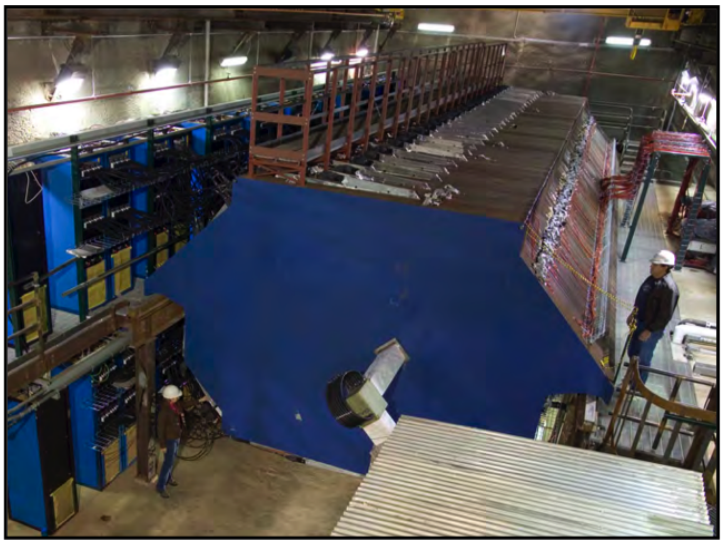
- Overview of the **M**ain **I**njector **N**eutrino **O**scillation **S**earch Detector
- Exciting physics program:
  - P($\nu_\mu \to \nu_\mu$) sensitive to **atmospheric parameters** (θ_{23}, Δm^2_{32}) and testing the 3 flavor paradigm
  - P($\bar{\nu}_\mu \to \bar{\nu}_\mu$) adds additional sensitivity to **mass hierarchy**, θ_{23} octant, and **matter effects**.
  - P($\nu_\mu \to \nu_e$) sensitive to θ_{13}, θ_{23} octant, mass hierarchy, δ_{CP}
  - The search for **sterile oscillations** ($\nu_\mu \to \nu_s$)
  - Other exciting physics searches (**LED**, **NSI**, etc)

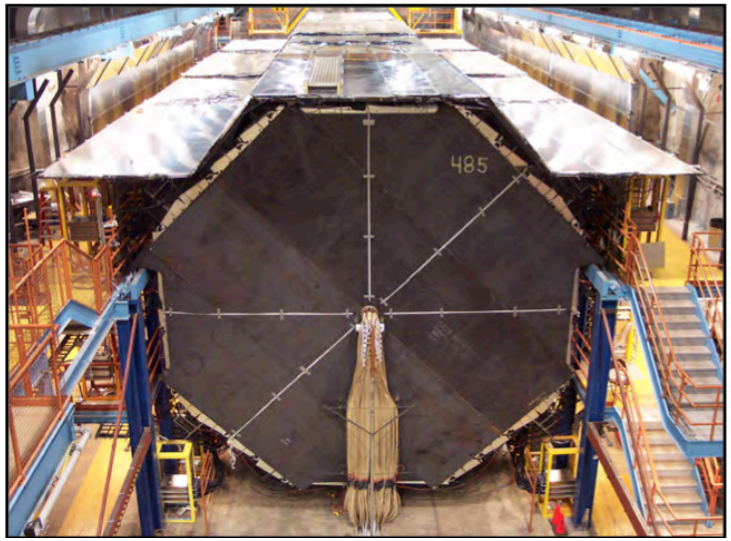


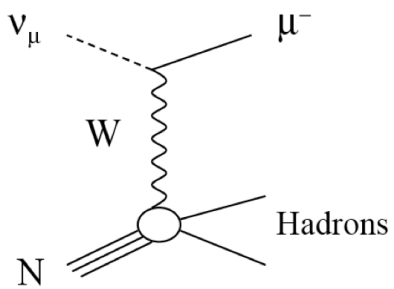


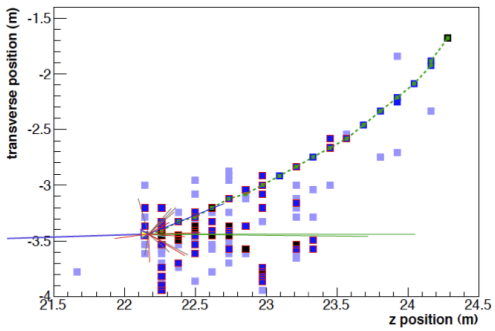
The MINOS Detector

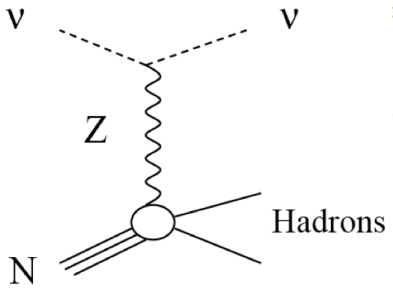
- L_{Near} = 1 km, m_{Near} = 0.98 kton
- L_{Far} = 735 km, m_{Far} = 5.4 kton
- Two functionally similar steel-scintillator sampling calorimeters
  - 2.5cm thick steel planes, plastic scintillator with WLS fibers to M16/M64 Hamamatsu PMTs

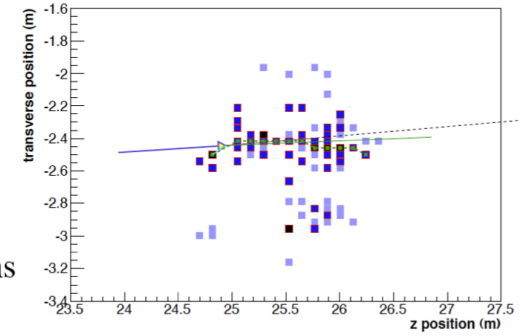






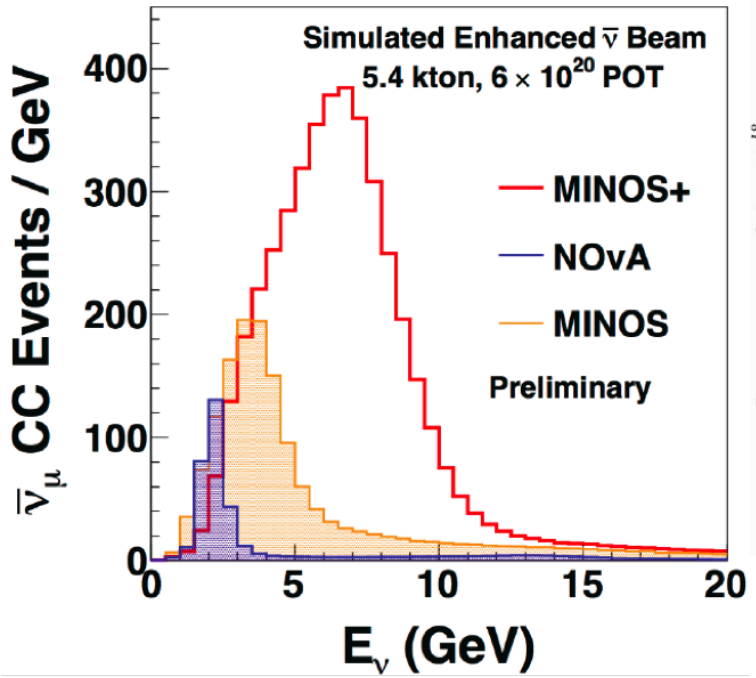


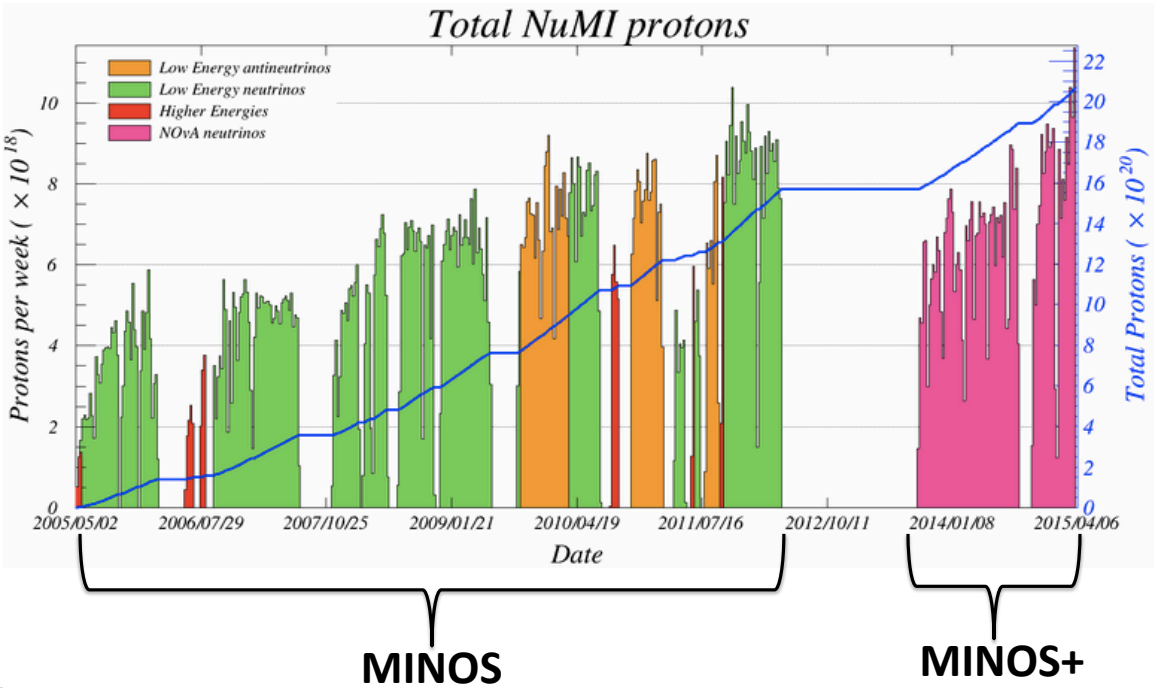




The NuMI Beam

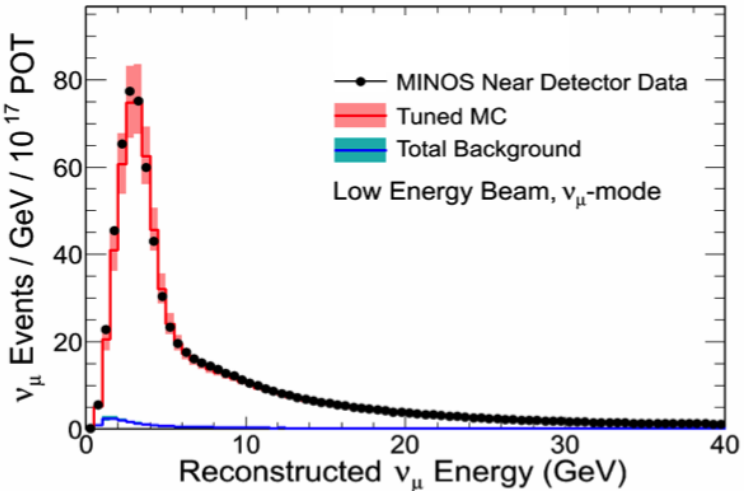
- Data collected from low energy beam February 2006 to April 2012
- Medium energy NOνA-era beam since September 2013
  - **500+ kW**, 120 GeV beam, with 3.2×10^{13} protons per pulse
  - MINOS+ has recorded 7.6×10^{20} PoT and counting (10×10^{20} PoT projected).
- Beneficiaries of the Fermilab proton improvement plan (PIP)

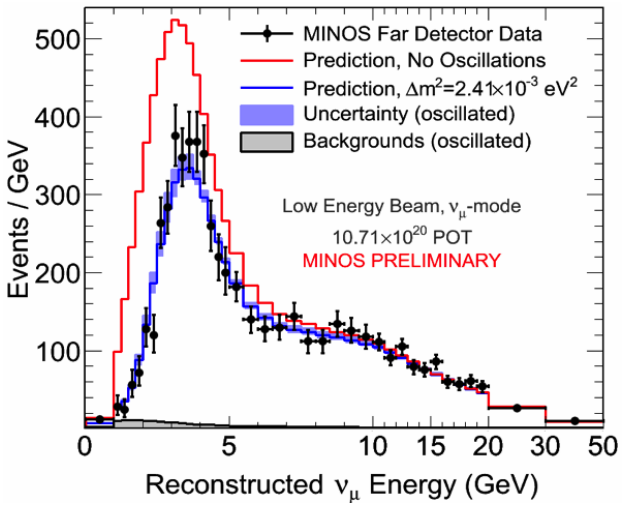


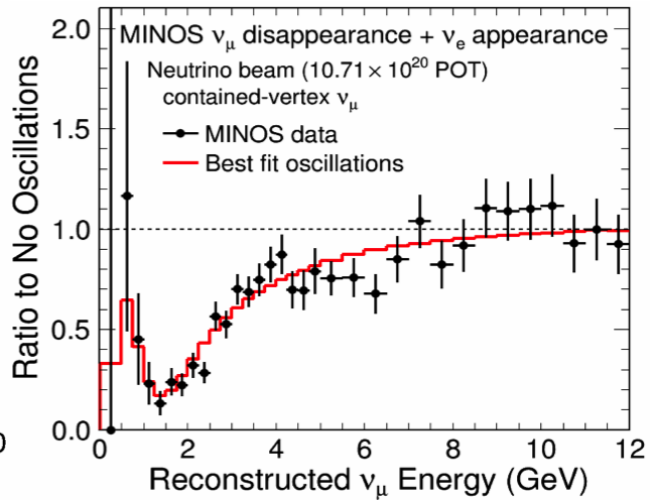


MINOS ν_μ Disappearance

- Near Detector data used to predict unoscillated Far Detector spectrum.
- Low energy NuMI beam optimized for primary oscillation peak.
- PRL 110, 251801, 2013

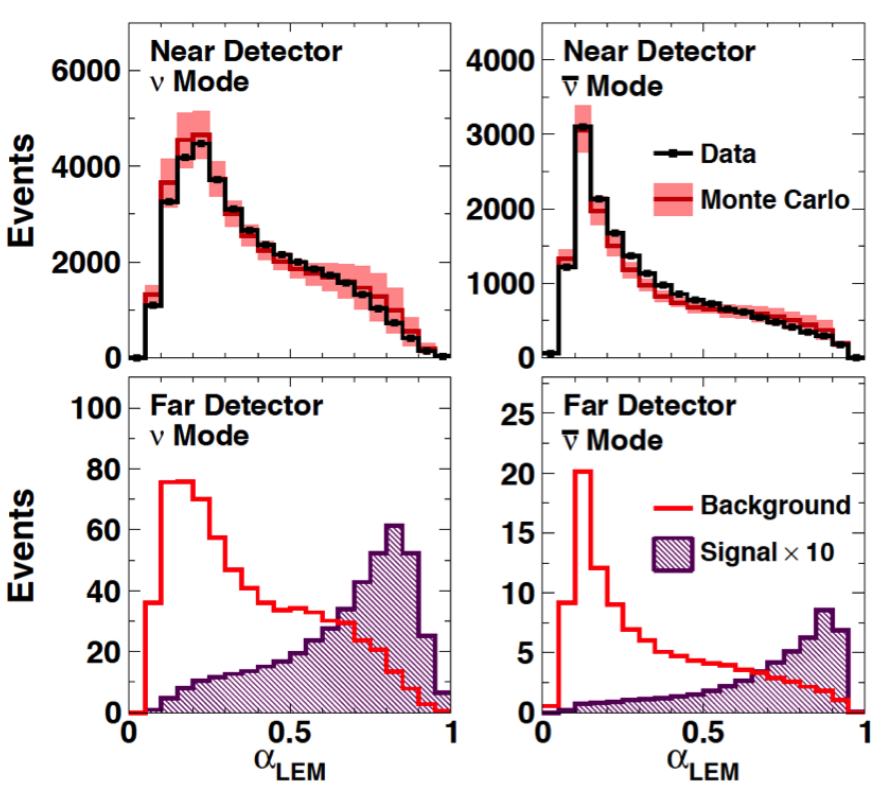


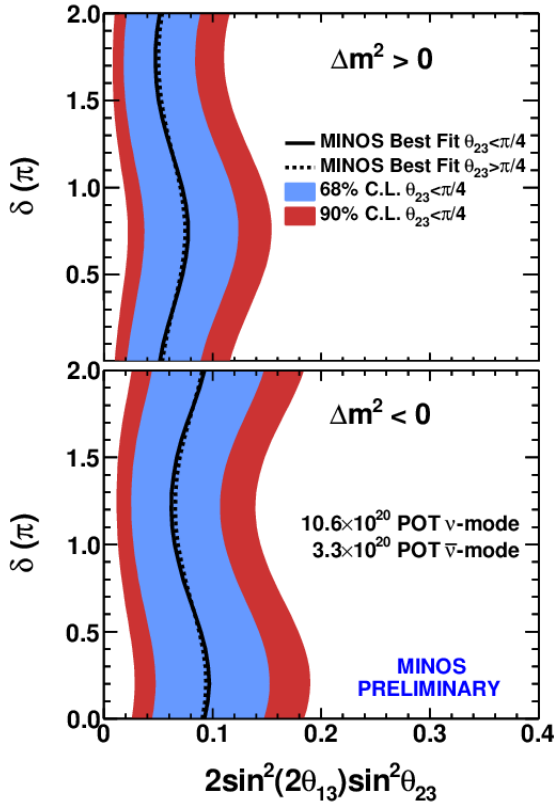




MINOS ν_e Appearance

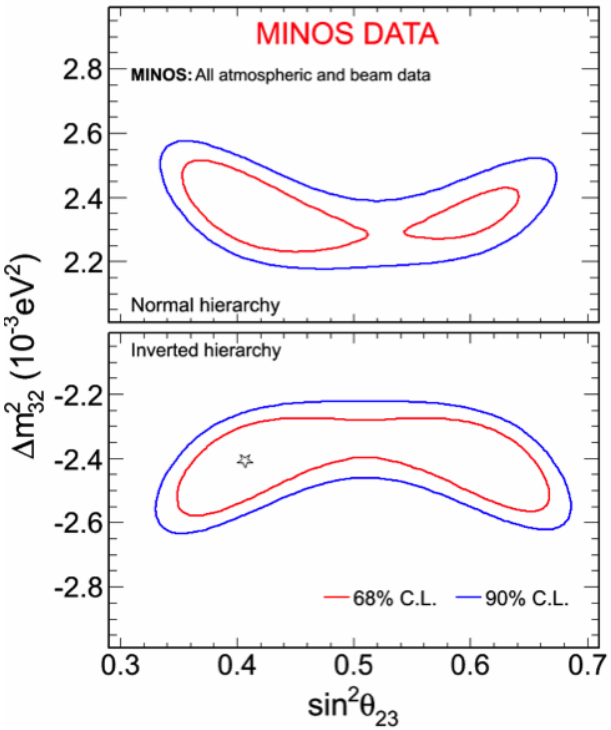
- MC-based Library Event Matching (LEM) technique used to distinguish ν_e events from NC events.
- Non-zero value of θ_{13}
- Sensitivity to δ_{CP} when incorporating reactor limits (Dooble Chooz, Daya Bay, RENO) and $\theta_{23}/\Delta m^2_{32}$ measurements.
- PRL 110, 171801, 2013

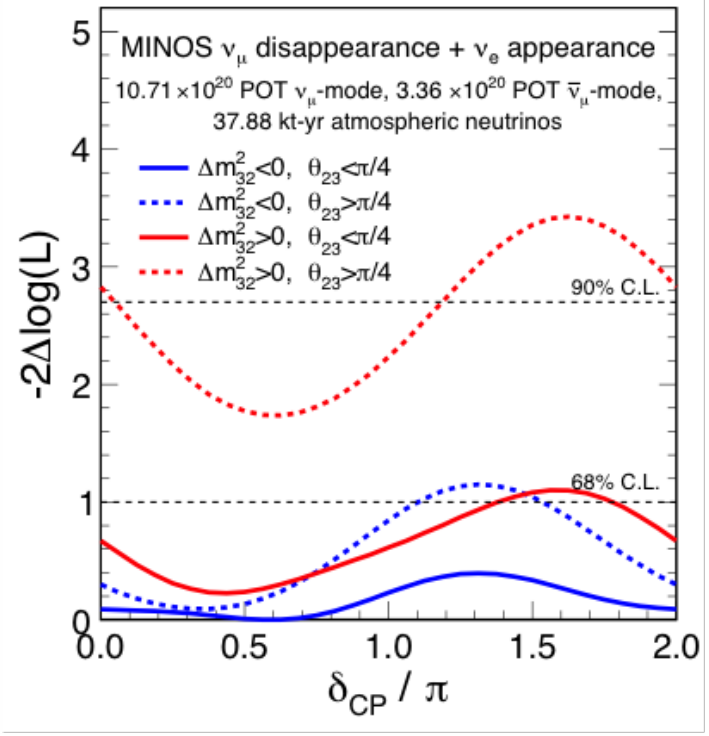




MINOS Combination: ν_e + ν_μ (Beam and Atmospheric)

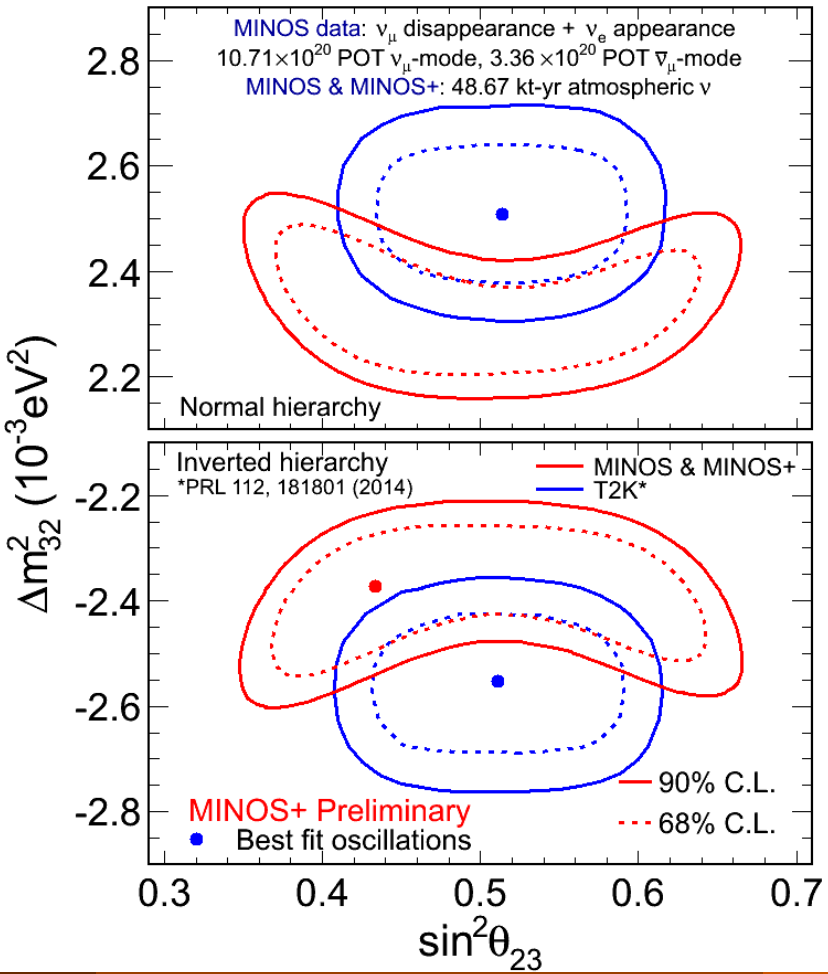
- Neutrino physics enters a precision era!
- Normal Hierarchy:
  - $|\Delta m^2_{32}| = [2.28 - 2.46] \times 10^{-3}$ eV^2 (68% CL)
  - $\sin^2_{23} = [0.35 - 0.65]$ (90%CL)
- Inverted Hierarchy:
  - $|\Delta m^2_{32}| = [2.32 - 2.53] \times 10^{-3}$ eV^2 (68% CL)
  - $\sin^2_{23} = [0.34 - 0.67]$ (90%CL)
- PRL 112, 191801 (2014)





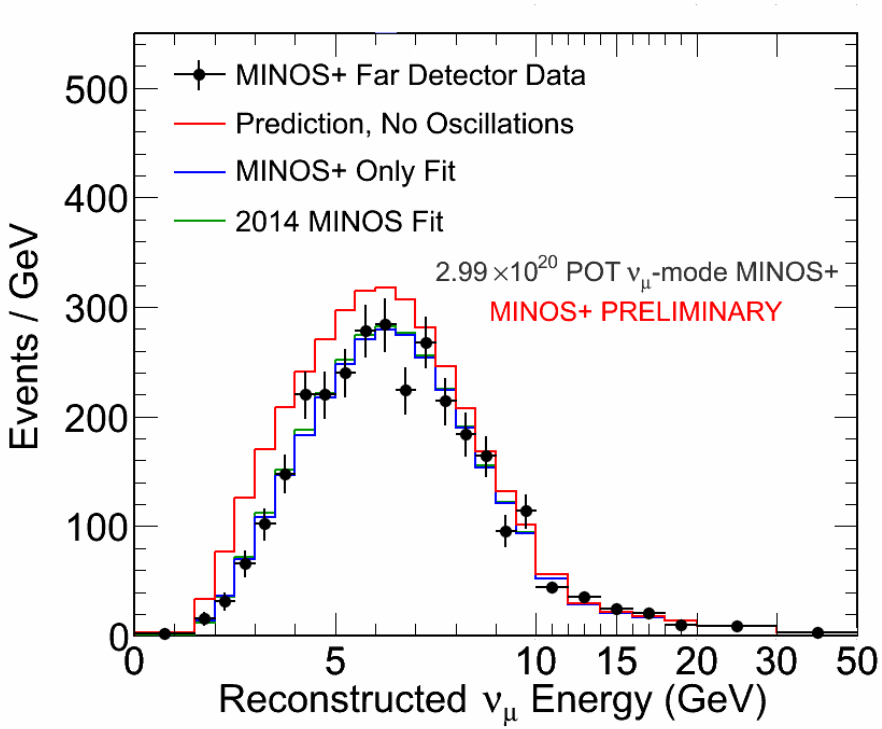
Comparison with T2K

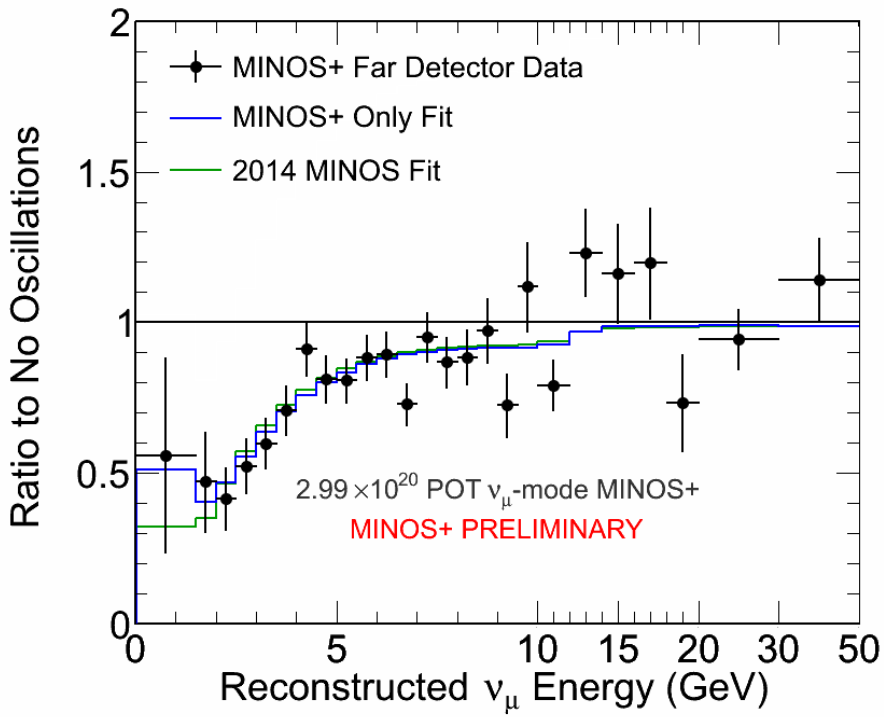
- We continue to improve our sensitivity with more atmospheric neutrino data.
  - We accrue an additional 5 kt-yr each year
- Good agreement with T2K



The MINOS+ Result

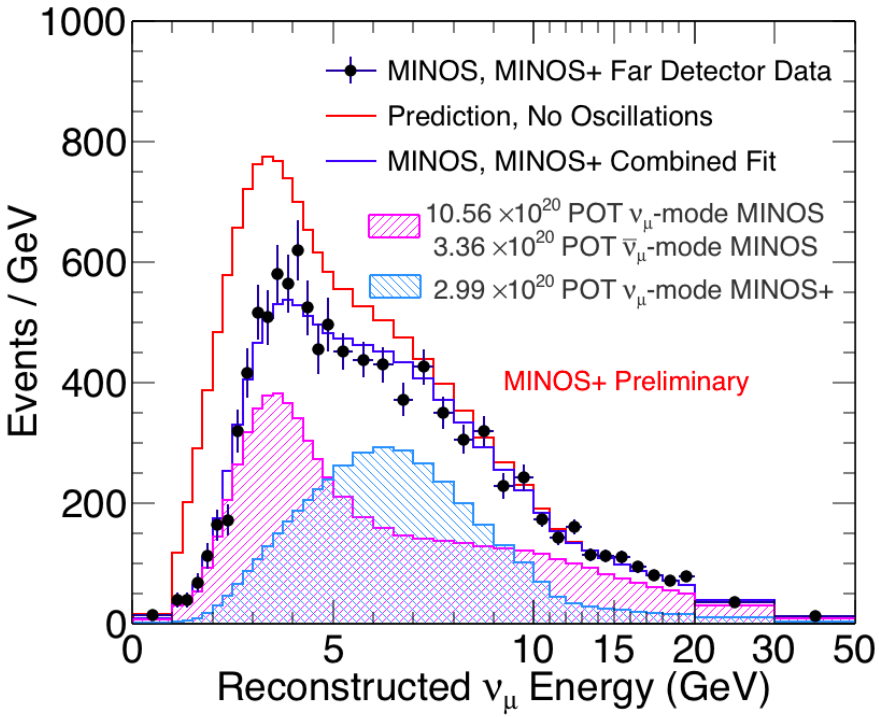
- Updated spectrum for the first 3.0×10^{20} PoT of MINOS+ running.
  - Data accrued from September 2013 to September 2014
- Statistical improvement to rising edge of primary oscillation.
- This data allows us to look for deviations from the standard 3 flavor prediction.
- MINOS+ spectrum consistent with MINOS best fit point:
  - $\Delta\chi^2$ between the 'MINOS+ only fit' and '2014 MINOS fit' is 1.3

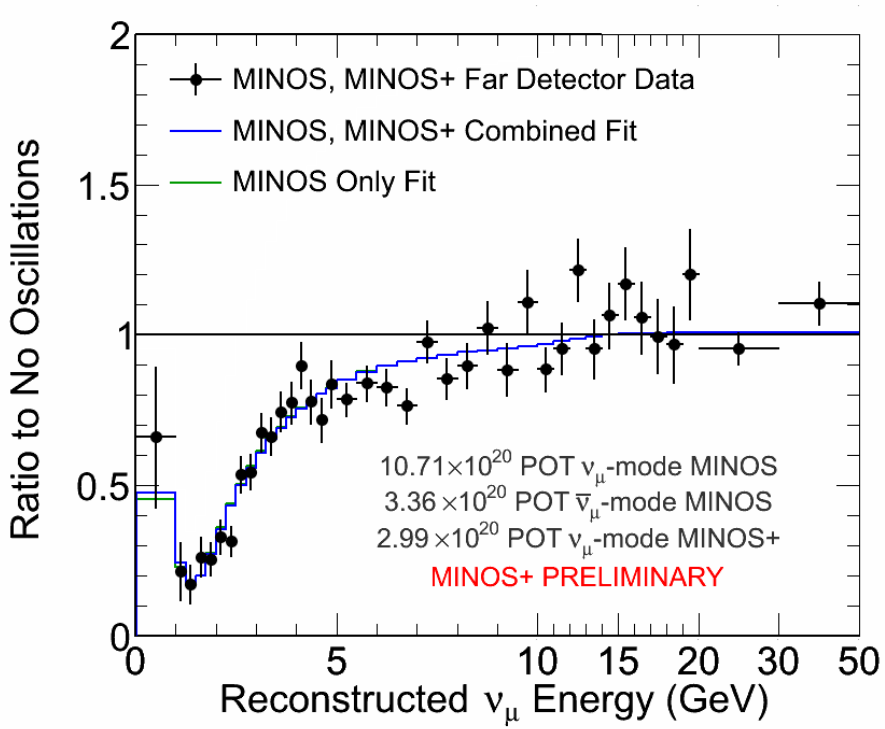




MINOS/MINOS+ Combination

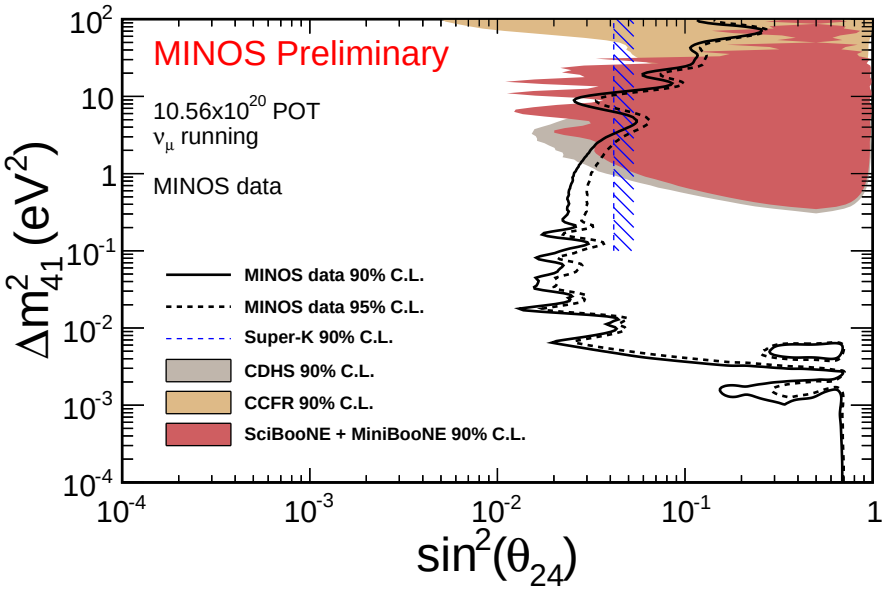
- Robust combination using both MINOS and MINOS+ disappearance samples.

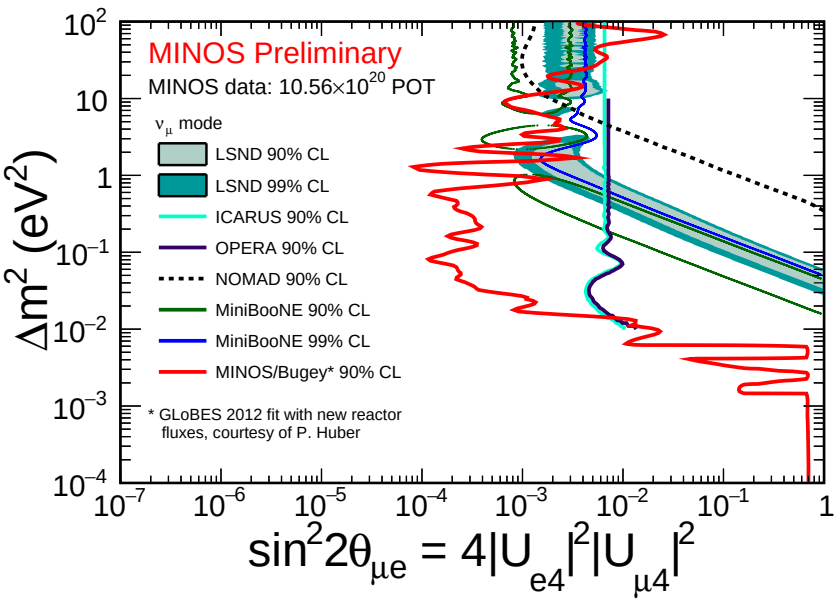




But are there more than 3 flavors???

- The long baseline and broad spectrum of MINOS+ opens up swaths of unexplored parameter space.
- Both ν_μ CC and NC samples are used.
- Combination with the Bugey reactor experiment to set 3+1 sterile mixing limits relevant to $\nu_\mu \leftrightarrow \nu_e$ transitions ($\theta_{\mu e}$).

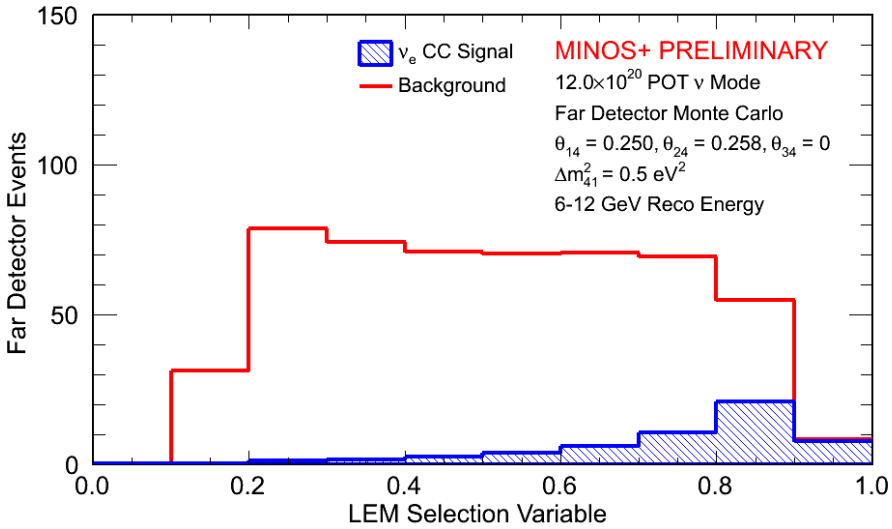


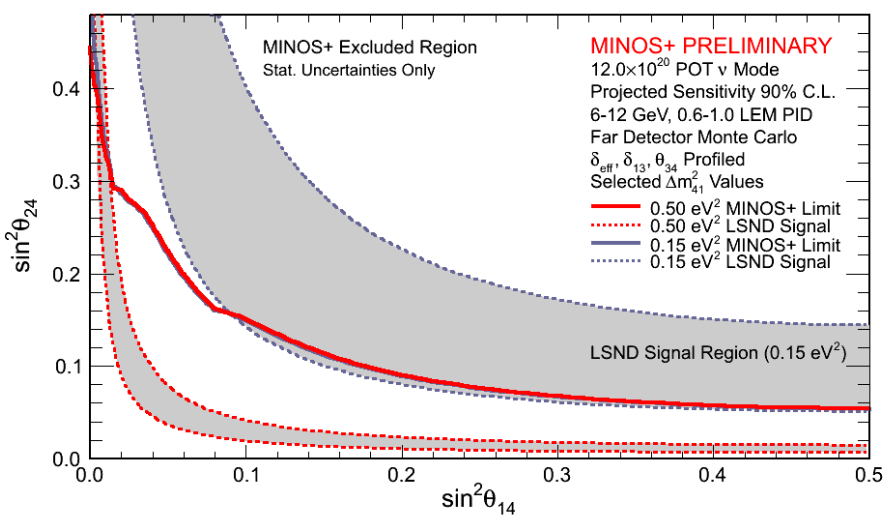


- Combination with Daya Bay in progress.

We also search for steriles with ν_e appearance...

- The medium energy NOνA-era beam allows us to search for ν_e appearance from sterile neutrinos with minimal background from standard $\nu_\mu \rightarrow \nu_e$ oscillations.
- Sensitivity is shown here for two Δm^2_{41} values.





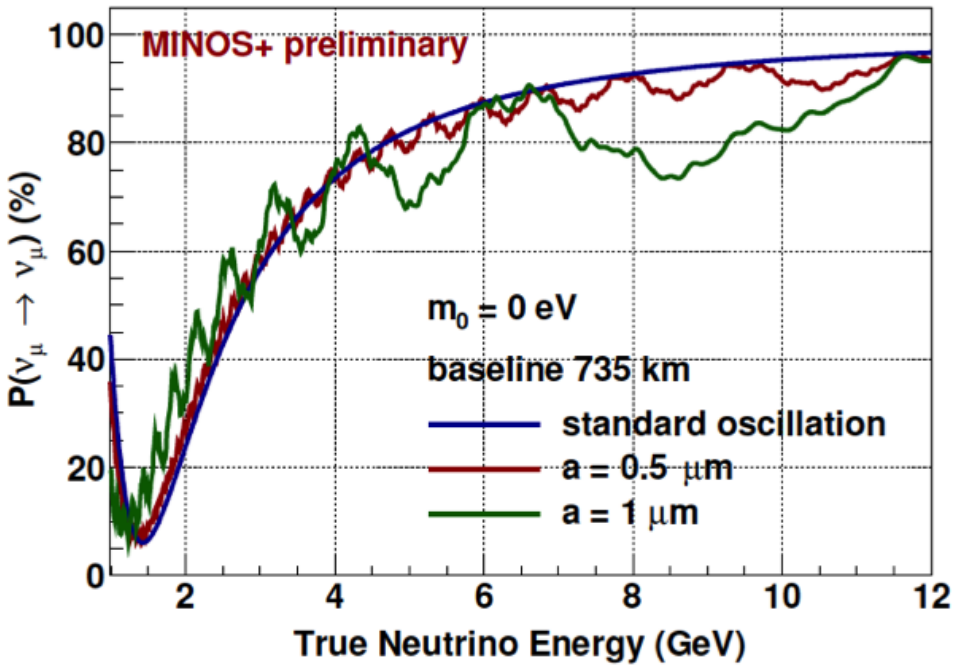
- Library Event Matching technique used to distinguish NC events from ν_e CC events.

LED Sterile Neutrinos

- The oscillation amplitude is given by Arkani-Hamed et al.

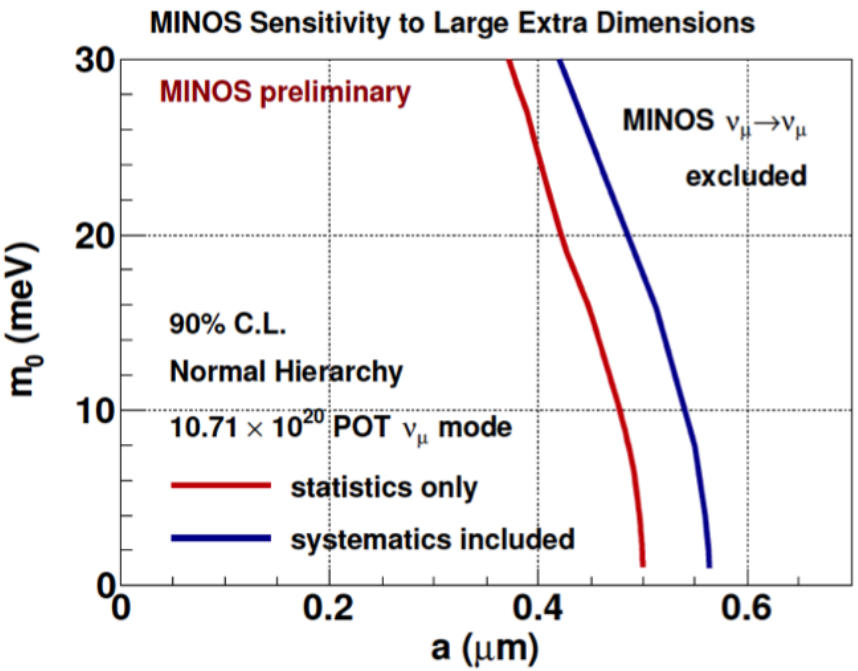
$$A(\nu_\alpha \to \nu_\beta) = \sum_{i,j,k=1}^{3} \sum_{n=0}^{+\infty} U_{\alpha i} U^*_{\beta k} W^{(0n)*}_{ij} W^{(0n)}_{ki} e^{i \frac{(\lambda_j^{(n)}/a)^2 L}{2E}}$$

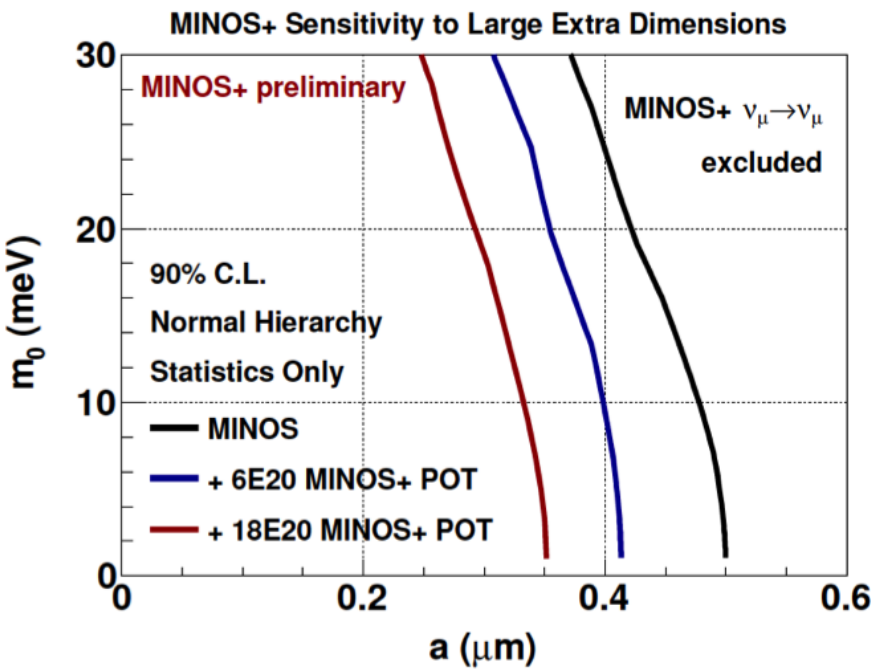
where U and W are mixing matrices for active and Kaluza Klein states, $\lambda_j^{(n)}/a$ is the neutrino mass, m_0 is the smallest mass, and a is the extra dimension size.



LED Sterile Neutrinos

- MINOS+ will be able to achieve a limit on the extra dimension size of 0.4μm!





- Paper in committee - please stay tuned!

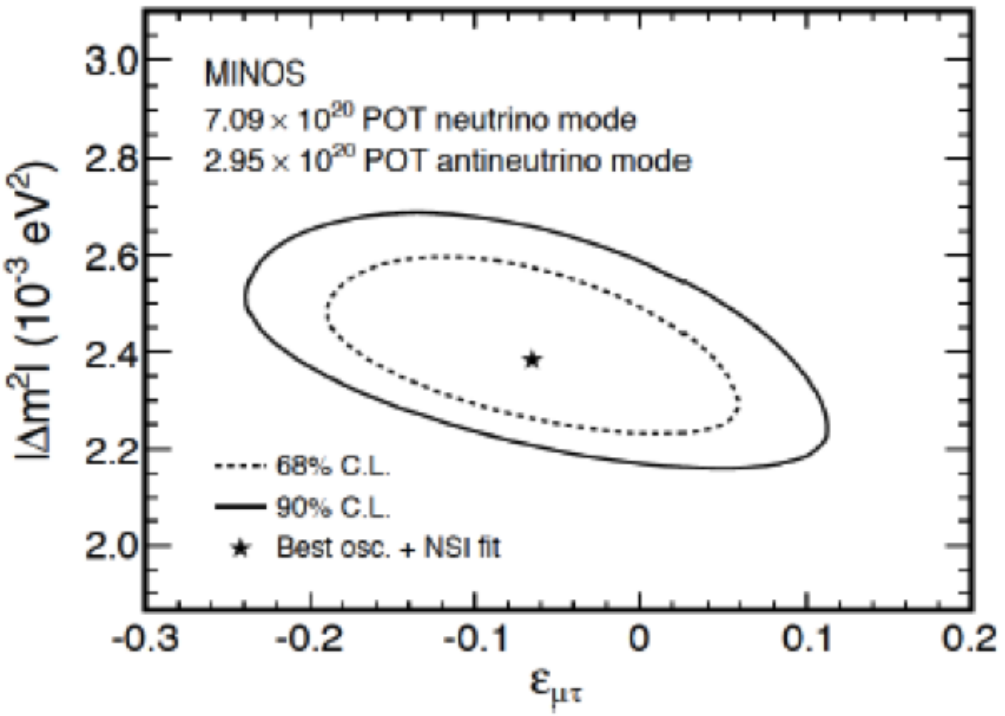
Non-Standard Interactions

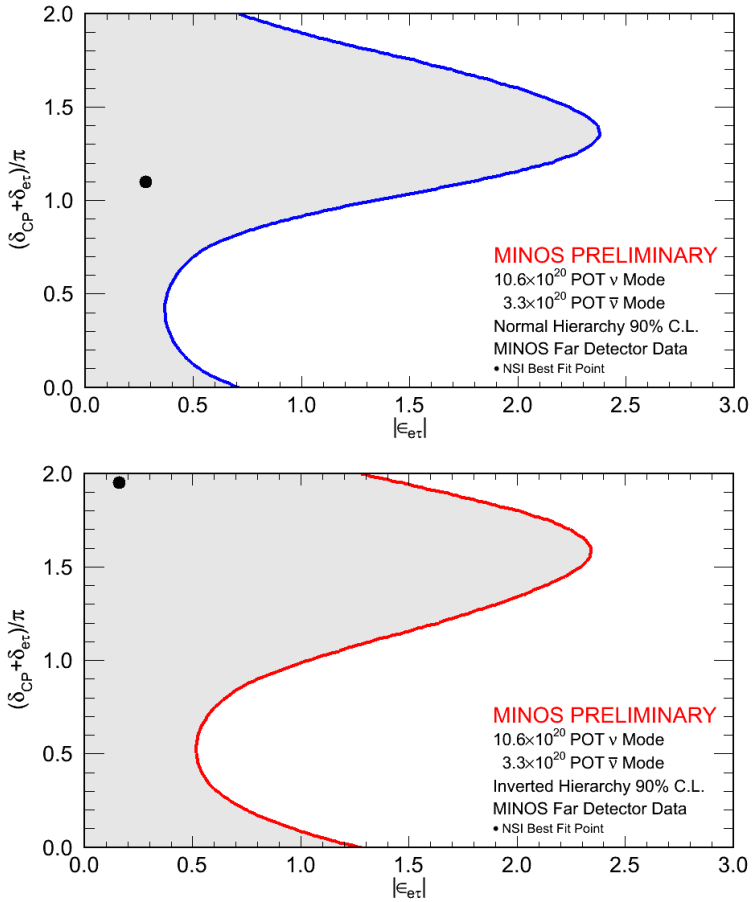
- Neutrinos could interact in a non-standard way
  - Friedland, Lunardini, Maltoni, PRD 70, 111301(2004)
  - Coelho, Kafka, Mann, Schneps, Altinok, PRD 86, 113015 (2012)
- ν_μ disappearance sensitive to $\epsilon_{\mu\tau}$
- ν_e appearance sensitive to $\epsilon_{e\tau}$

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

Non-Standard Interactions

- Disappearance: $-0.20 < \epsilon_{\mu\tau} < 0.07$ (90% CL) (left)
  - PRD 88 072011 (2013)
- Appearance: Sets limits to $\epsilon_{e\tau}$ and δ_{CP} (right)



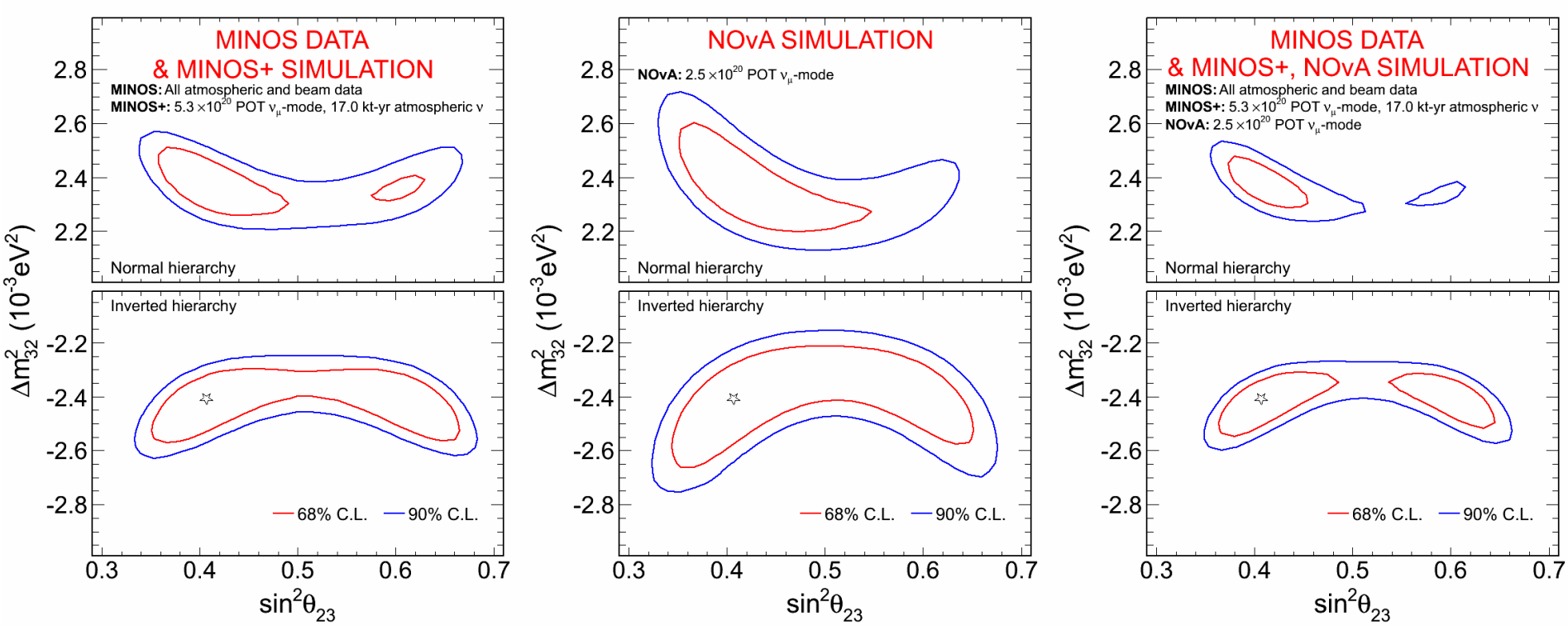


Conclusion

- MINOS+ is testing the 3 flavor paradigm with 7.6×10^{20} PoT
- Our results allow valuable combinations with reactor and other long baseline searches.
- Unique sensitivity to sterile oscillations, large extra dimensions, and non-standard interactions.
- MINOS+ has a goldmine of data for new searches!

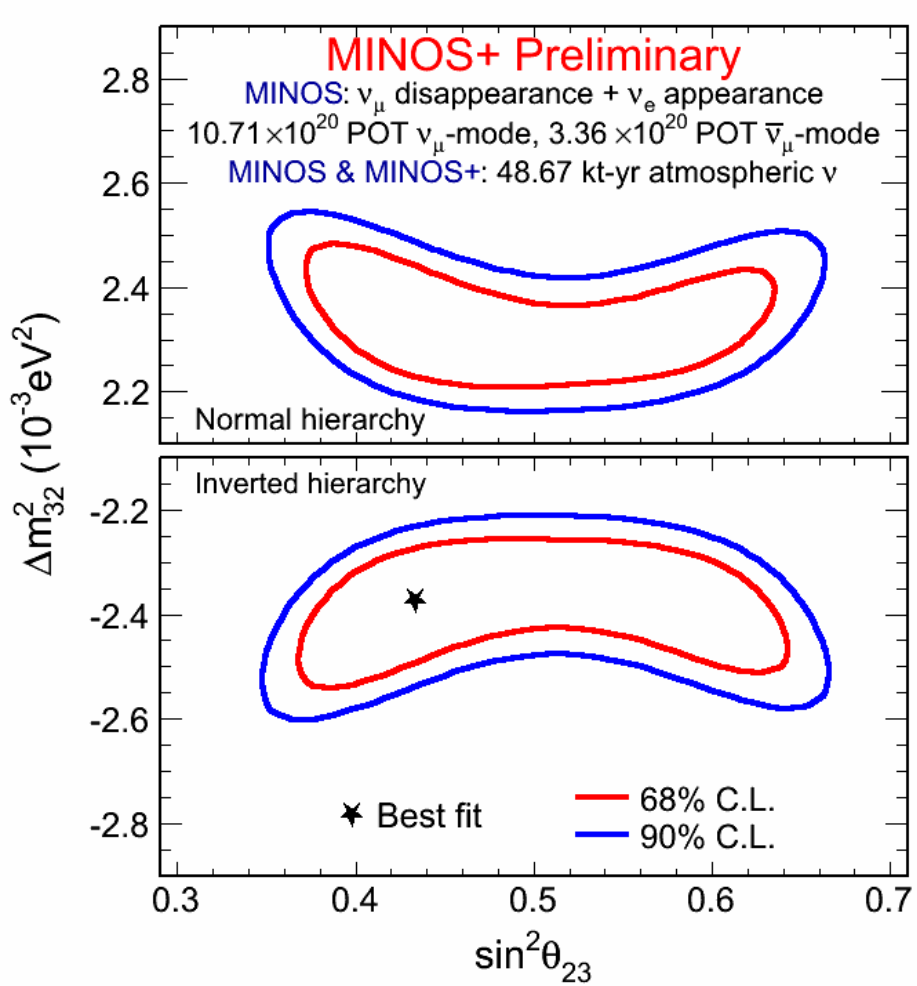
Backup

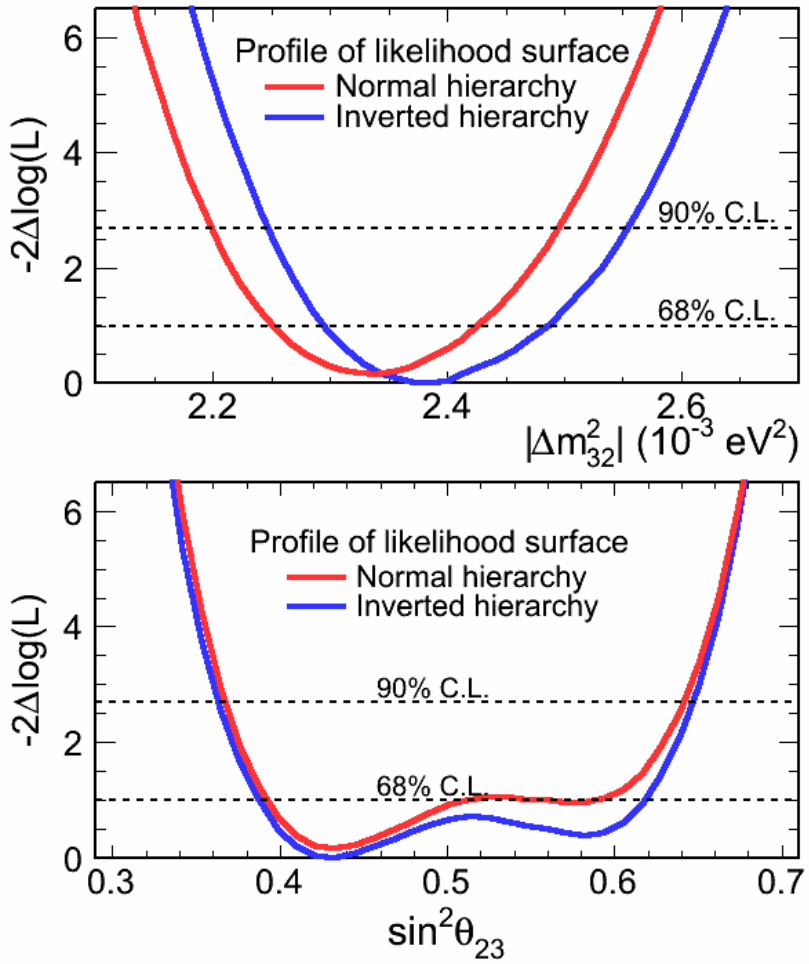
Combination with NOνA



- No published beam oscillation result yet with MINOS+.
- MINOS+ results important for the next few years as NOνA strives to resolve mass θ_{23} quadrant and mass hierarchy

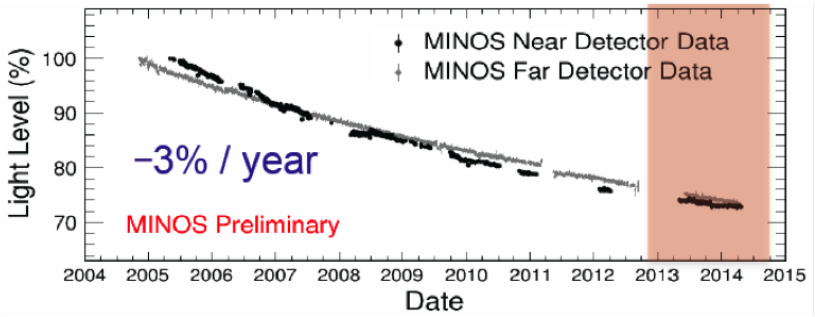
The Latest MINOS+ Atmospheric and Disappearance Result

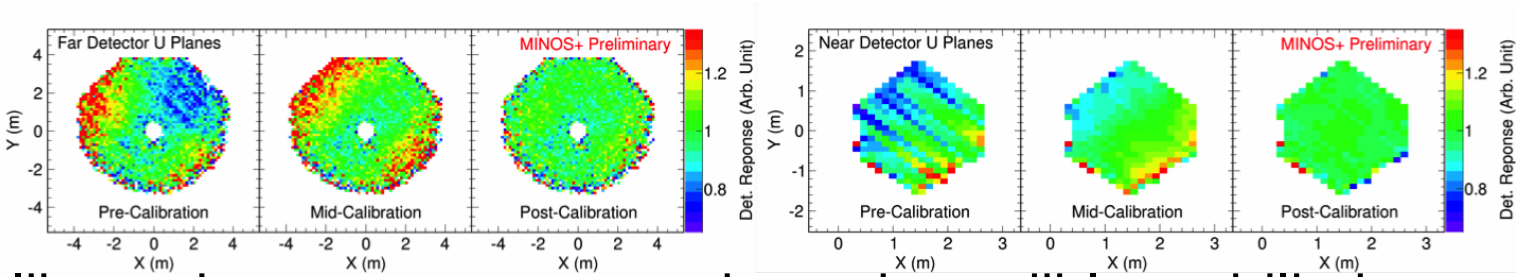




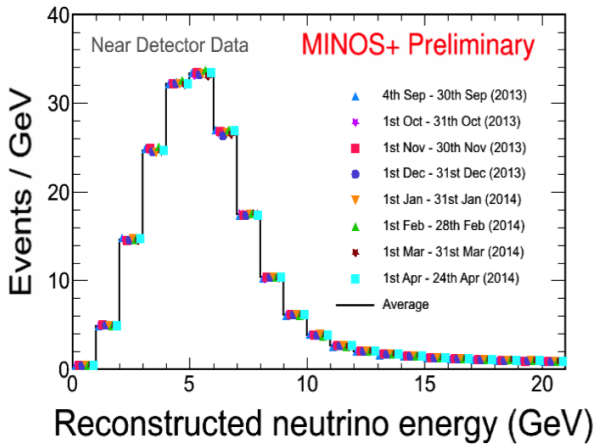
The MINOS Detector - Aging

- Our detector has aged as expected. We've seen > 95% live time!
- We see a consistent decline in light yield which we are able to correct for.



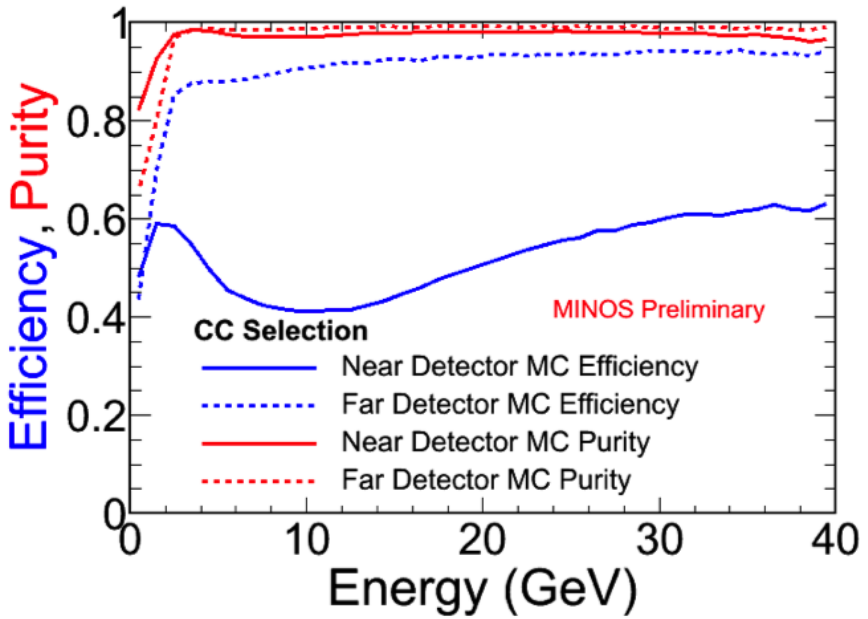


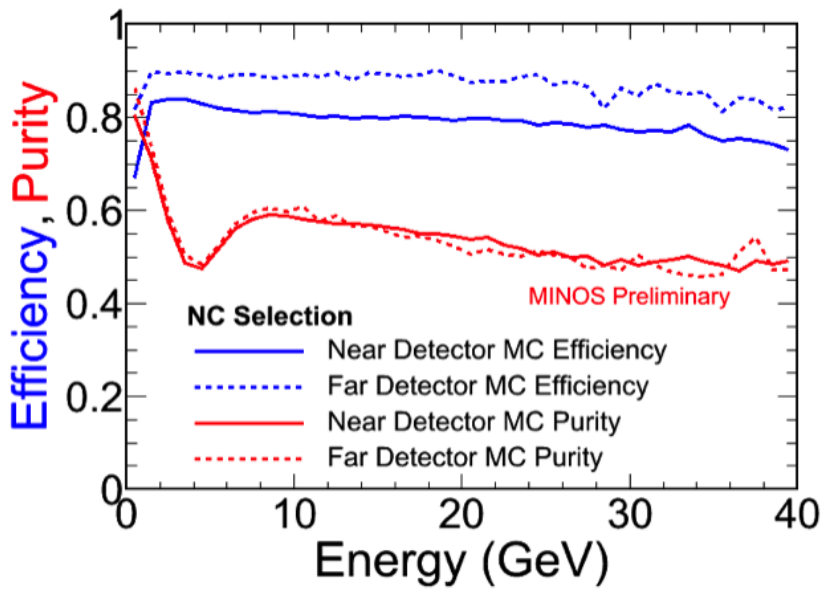
- Calibrated energy spectrum shows incredible stability!



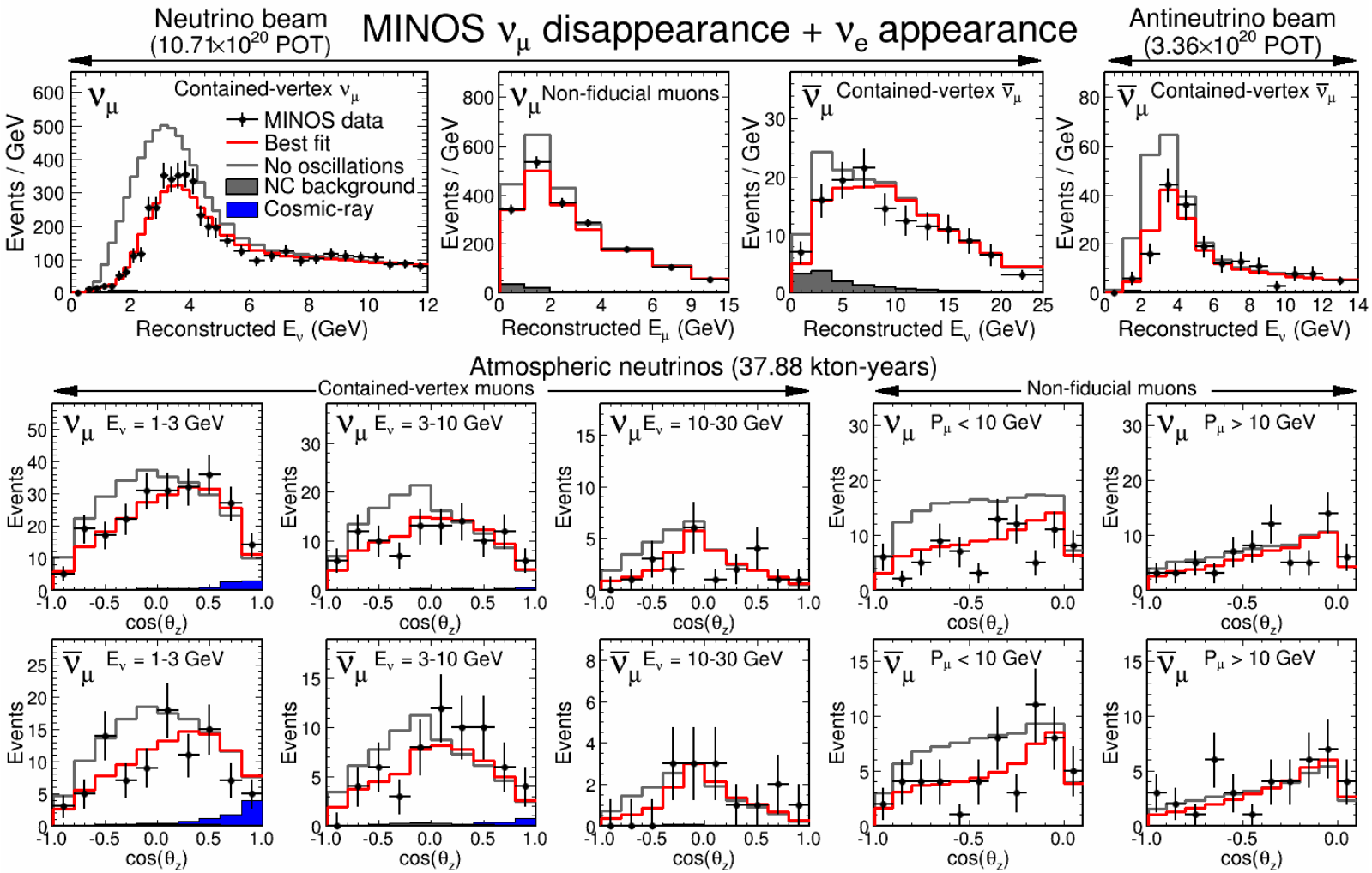
Selection Efficiencies and Purities

- As a steel sampling calorimeter, MINOS is optimized for ν_μ CC selection.
- DIS, ν_e, and NC events are more difficult to disentangle.



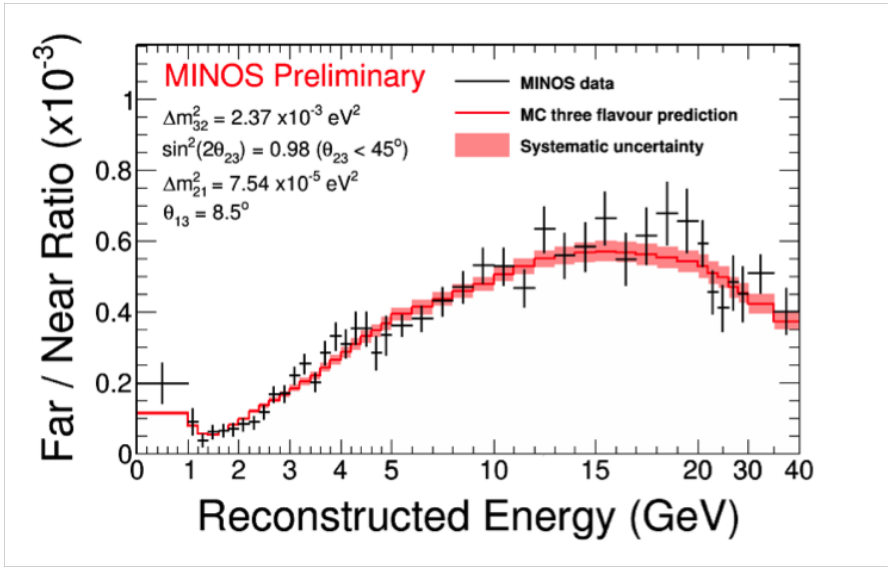


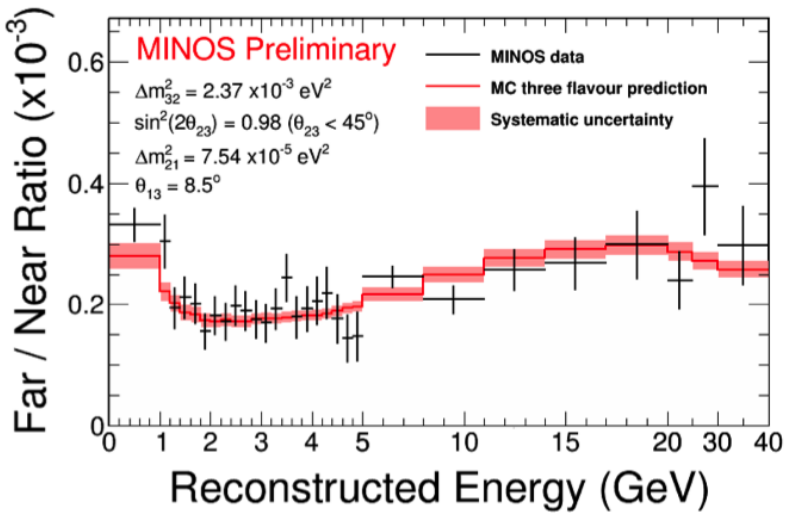
MINOS Combination



Sterile Searches: F/N Ratio

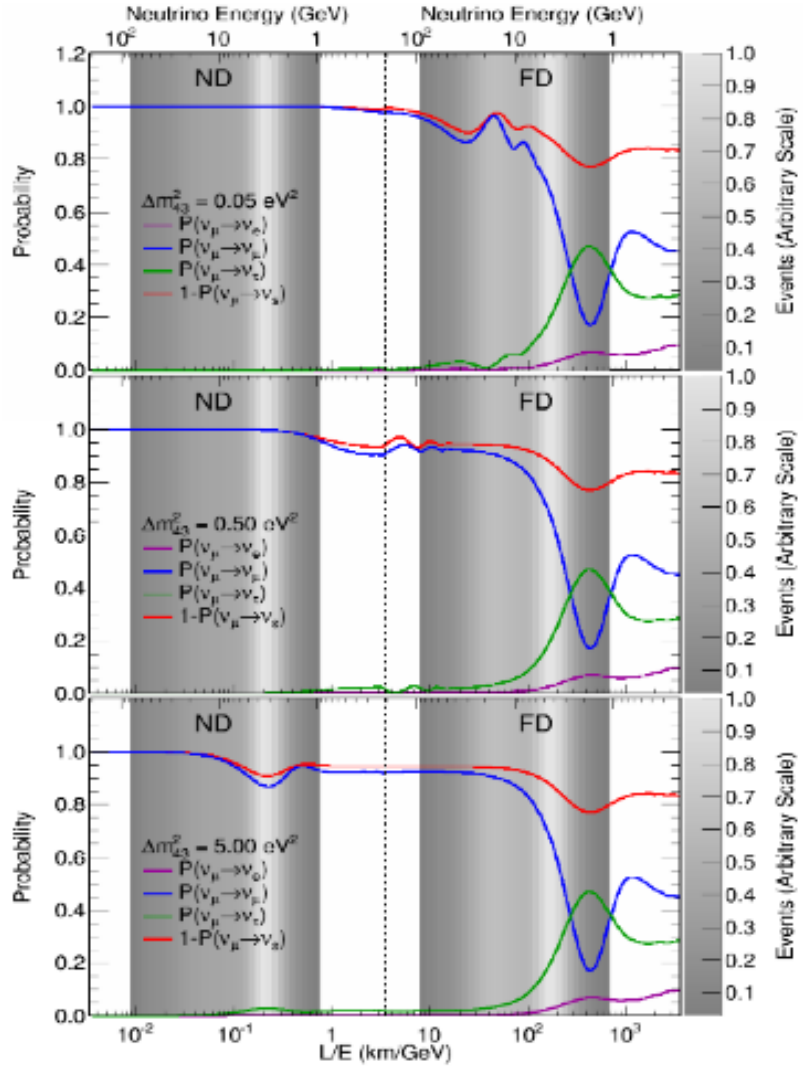
- For sterile searches, the possibility of short baseline oscillations requires a new technique from previous long baseline searches.
  - Far over near ratio employed for both CC and NC samples.





Sterile Searches: F/N Ratio

- Near detector oscillations become non-negligible for large Δm^2_{43}



ν_e Appearance Sterile Search Parameter Space