Current Status of MINOS+

The Legend Continues....

Paul Sail

University of Texas at Austin
On behalf of the MINOS+ collaboration

The 49th Annual Fermilab Users Meeting
16 June 2016

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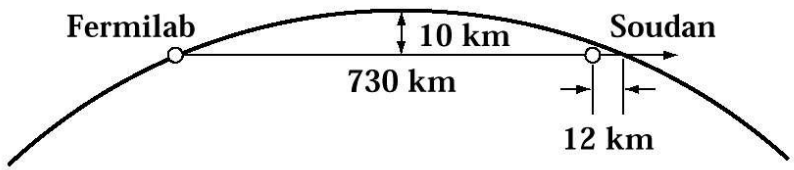


EXPERIMENT OVERVIEW

THE PHYSICS OF MINOS(+)

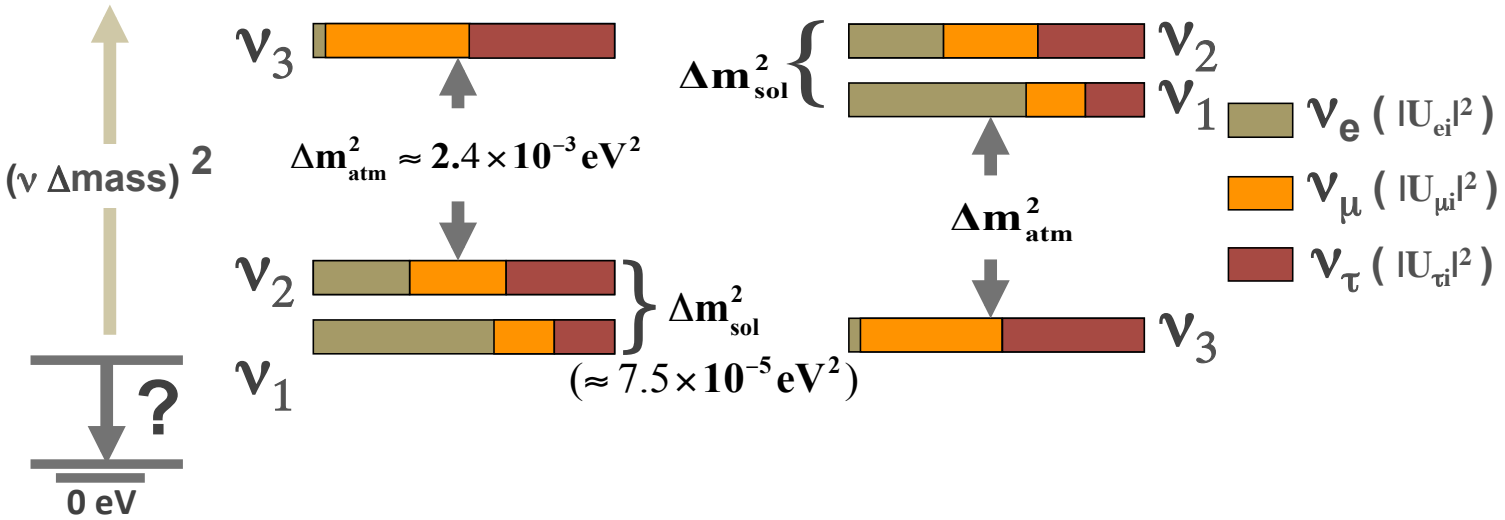
- **M**ain **I**njector **N**eutrino **O**scillation **S**earch Experiment.
- Designed to make precision measurements of "atmospheric" parameters.

STANDARD THREE FLAVOUR

- $P(\nu_\mu \rightarrow \nu_\mu)$ (θ_{23}, Δm^2_{32}).
- $P(\nu_\mu \rightarrow \nu_e)$ (θ_{13}, δ_{CP}, MH).
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ (θ_{23}, CPT).

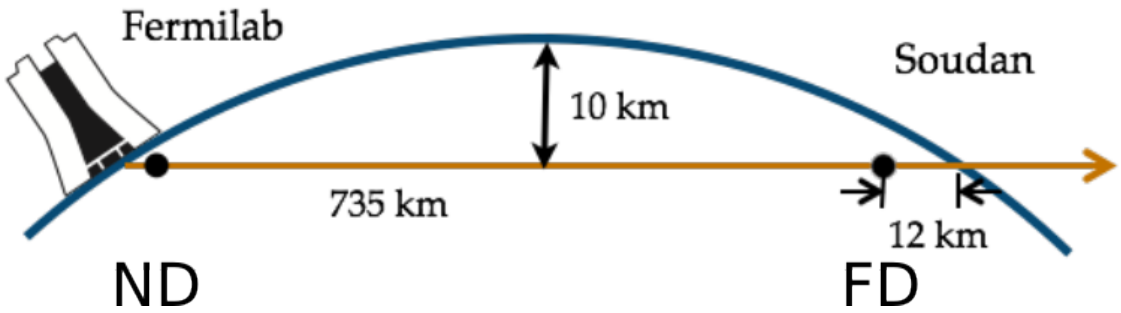
EXOTIC PHENOMENA

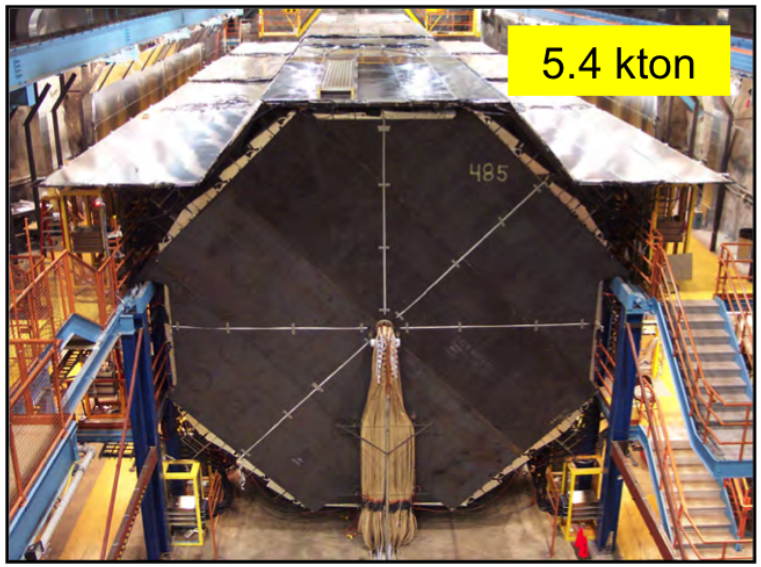
- Sterile neutrinos (3+1).
- Large Extra Dimension (LED).
- Non-Standard Interactions (NSI).



THE MINOS DETECTOR

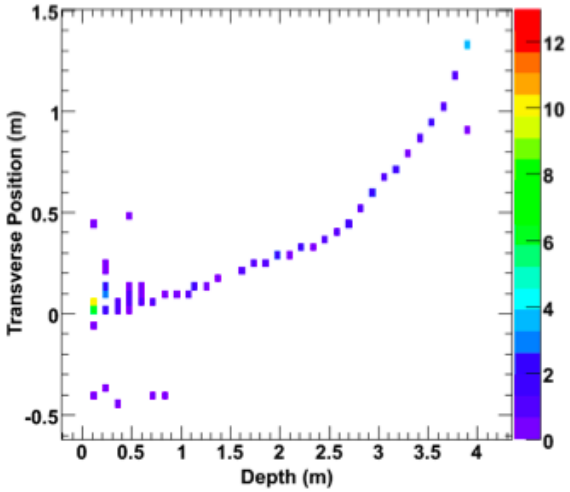
- Long-baseline neutrino oscillation experiment.
- Two functionally similar magnetized steel-scintillator sampling calorimeters.
- Compare event spectra between detectors to study neutrino oscillations.



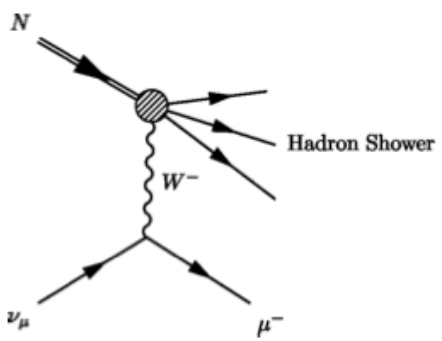


MINOS EVENT TOPOLOGIES

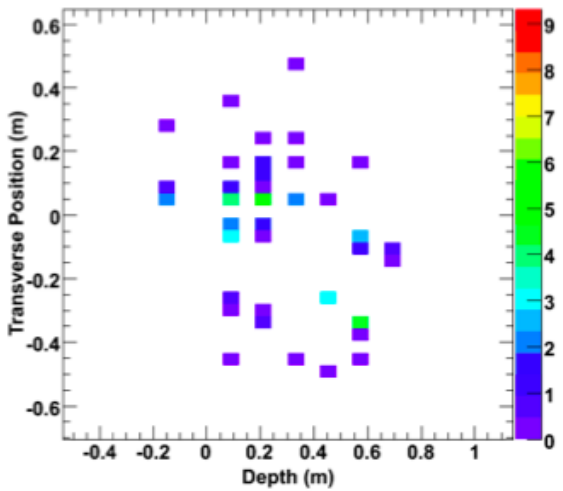
ν_μ Charged Current (CC)



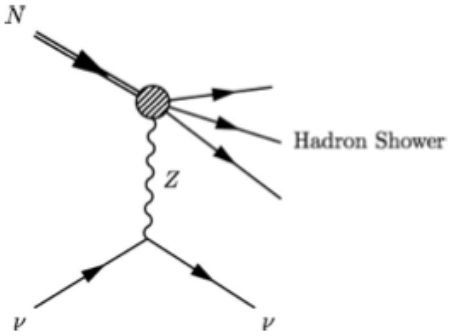
$$\nu_\mu + N \rightarrow \mu^- + X$$



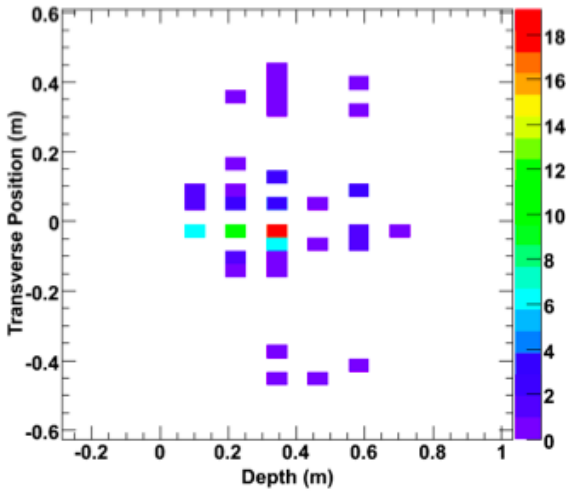
Neutral Current (NC)



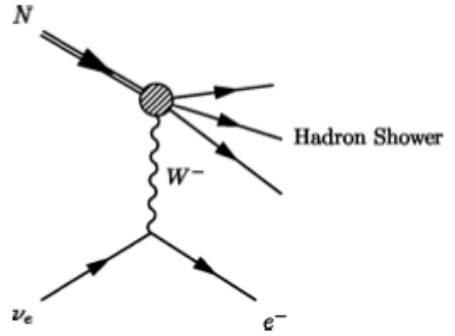
$$\nu + N \rightarrow \nu + X$$



ν_e CC

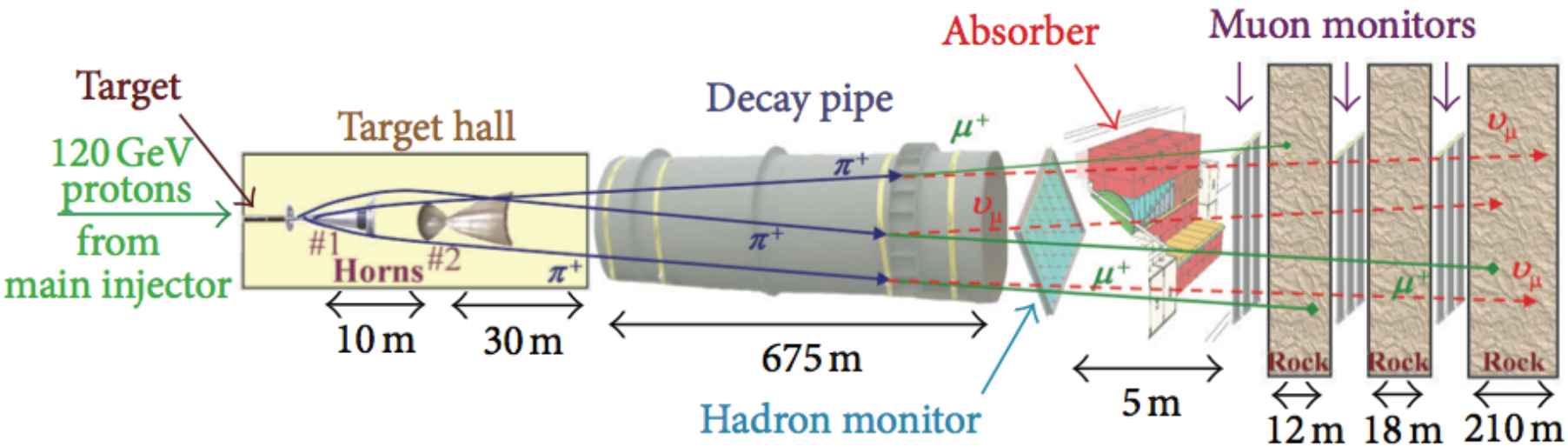


$$\nu_e + N \rightarrow e^- + X$$



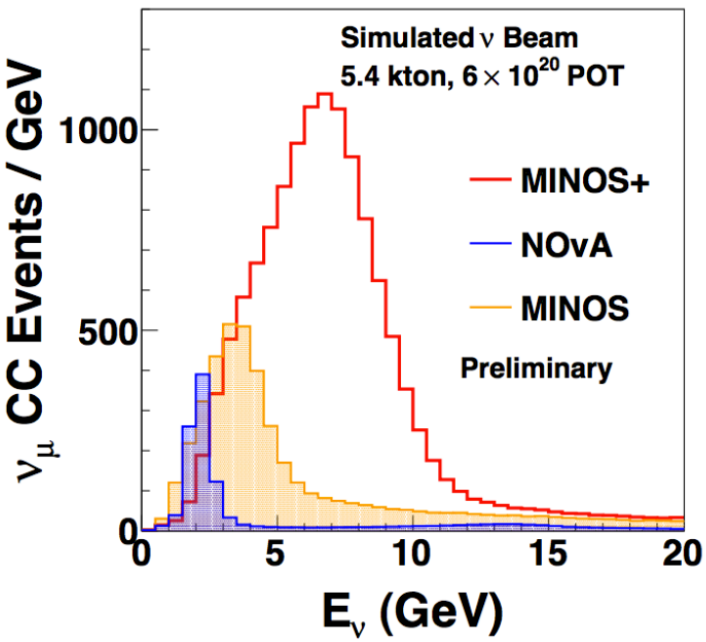
THE NUMI BEAM

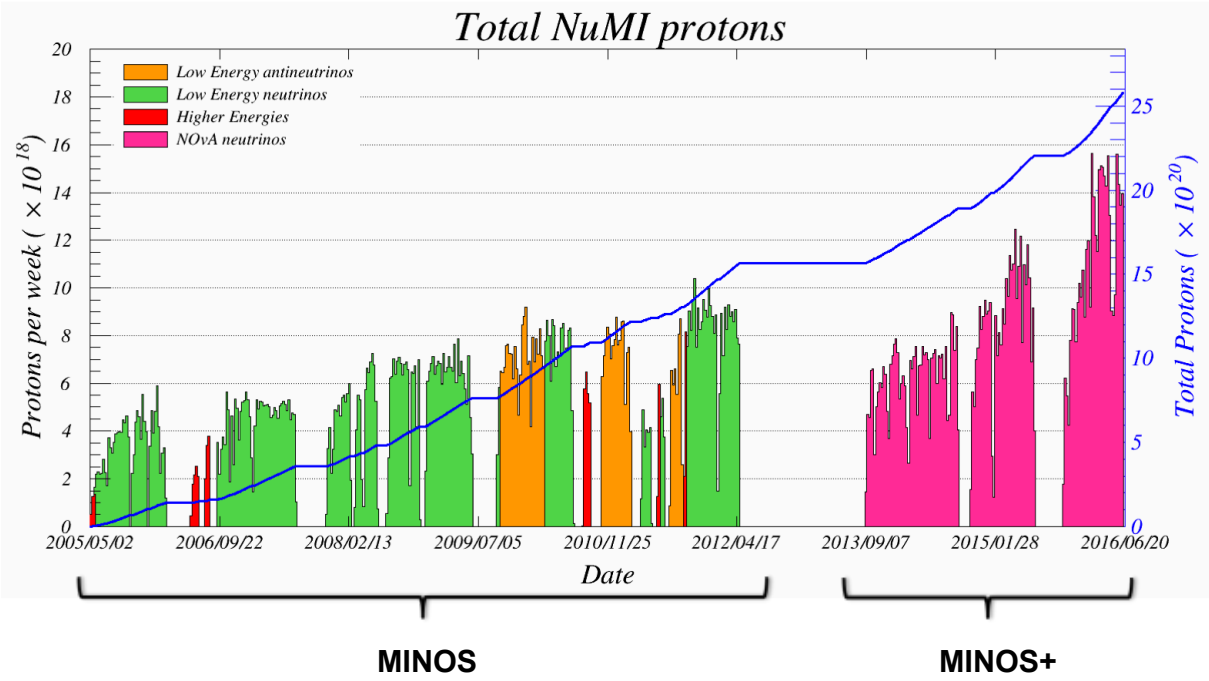
- Protons at 120 GeV are directed at graphite target producing charged hadrons.
- Magnetic horns focus positive/negative charged particles based on beam type.
- Neutrino beam 91.7% ν_μ and anti-neutrino beam 39.9% $\bar{\nu}_\mu$.



BEAM PERFORMANCE

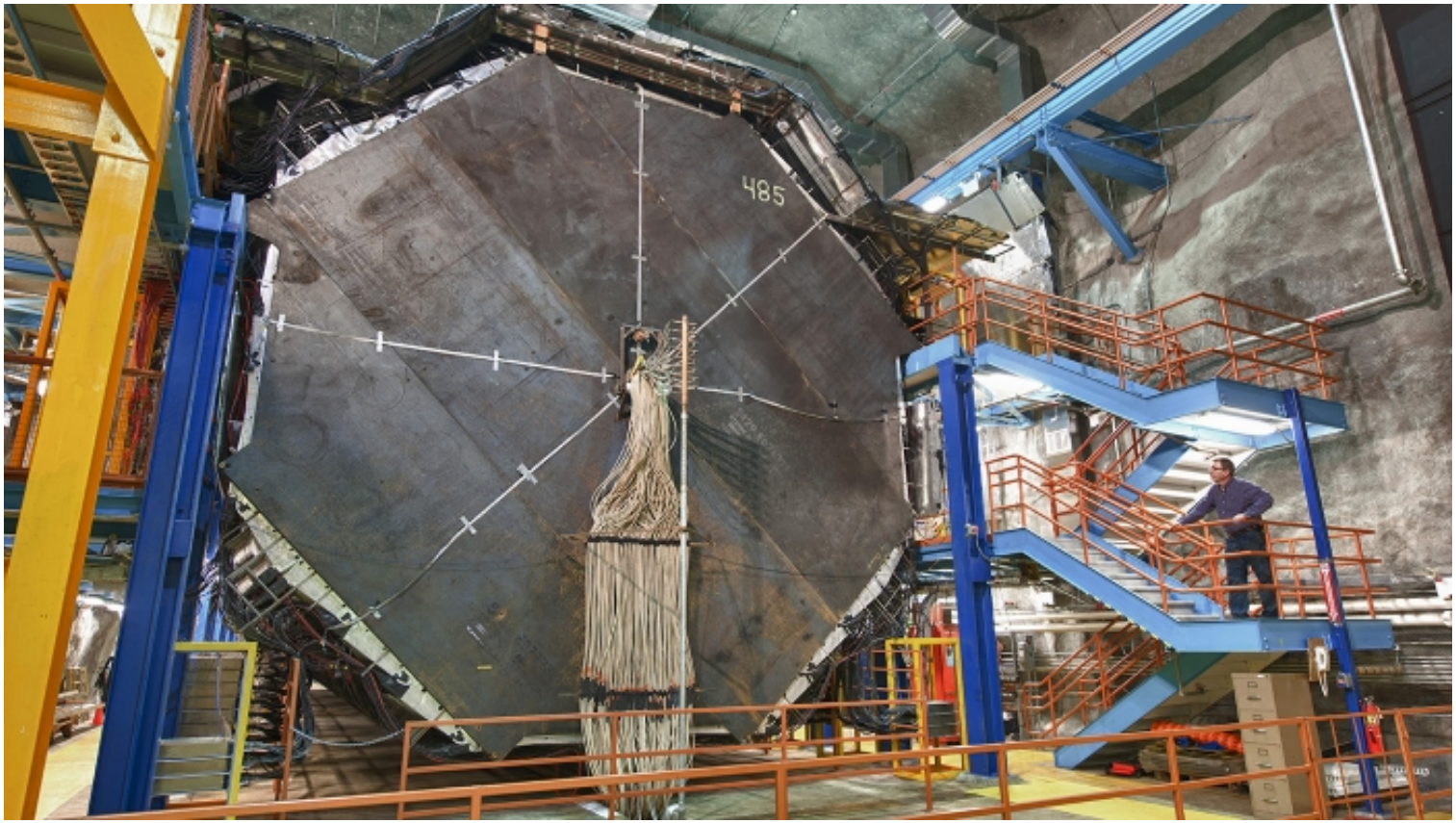
- MINOS: low energy (2005-2012), MINOS+: medium energy (2013-2016).
- MINOS beam peaks at 3 GeV with MINOS+ peaking at 6 GeV.
- MINOS PoT: 10.56×10^{20} in ν_μ mode and 3.36×10^{20} in $\bar{\nu}_\mu$ mode.
- MINOS+ PoT: $\sim 10.0 \times 10^{20}$ in ν_μ currently recorded.





THE END OF AN ERA

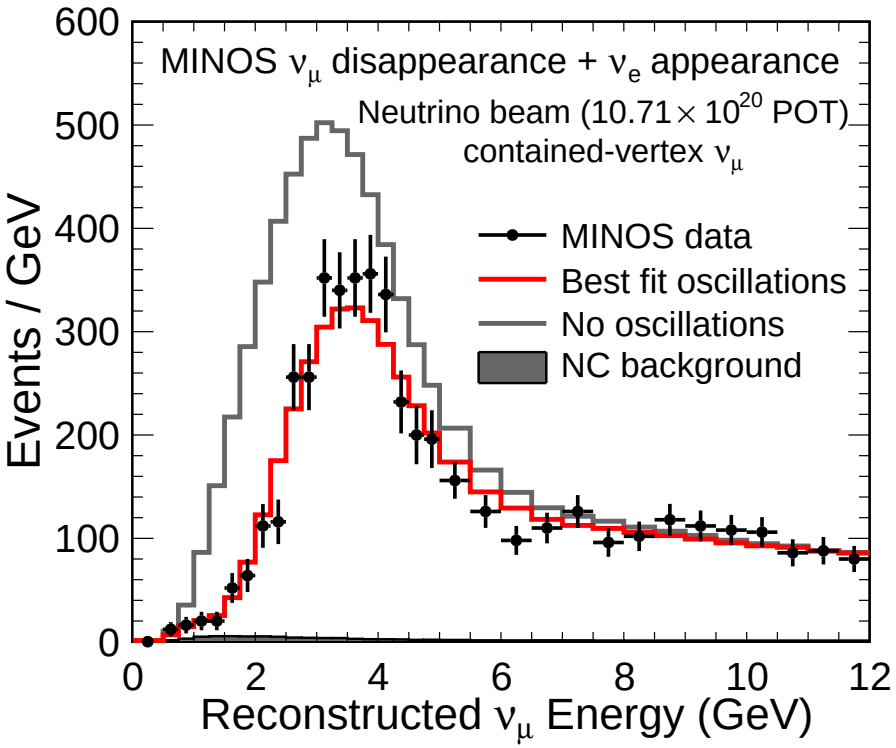
- MINOS+ data taking to conclude over the summer.
- Pioneered the long baseline, two detector experiment method.
- MINOS results have contributed hugely to understanding of neutrinos.
- MINOS+ to follow.....

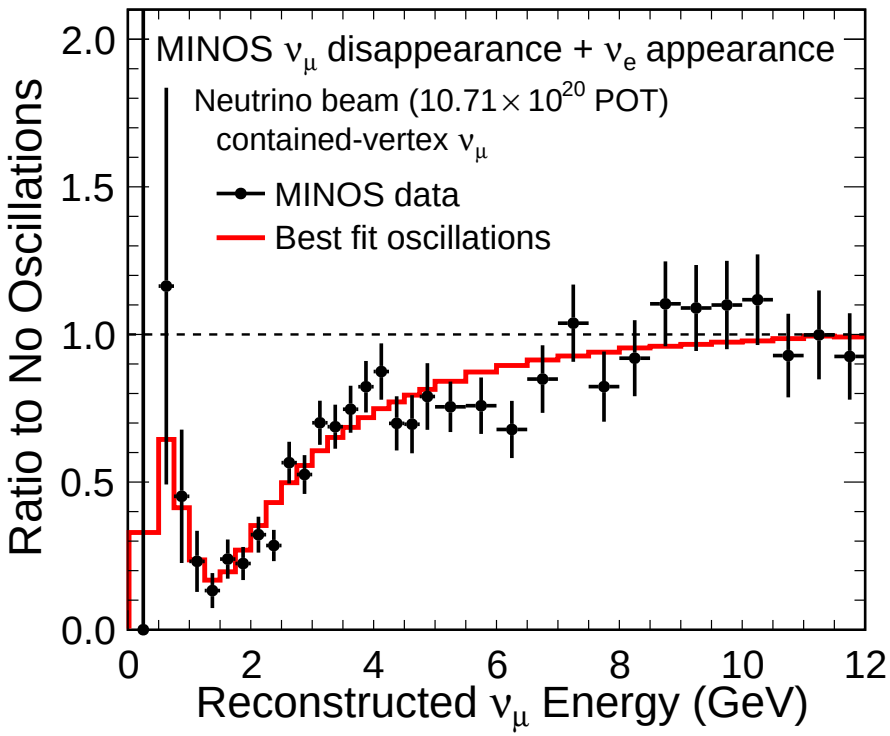


STANDARD THREE FLAVOUR

MINOS ν_μ DISAPPEARANCE (PRL 110, 251801 2013)

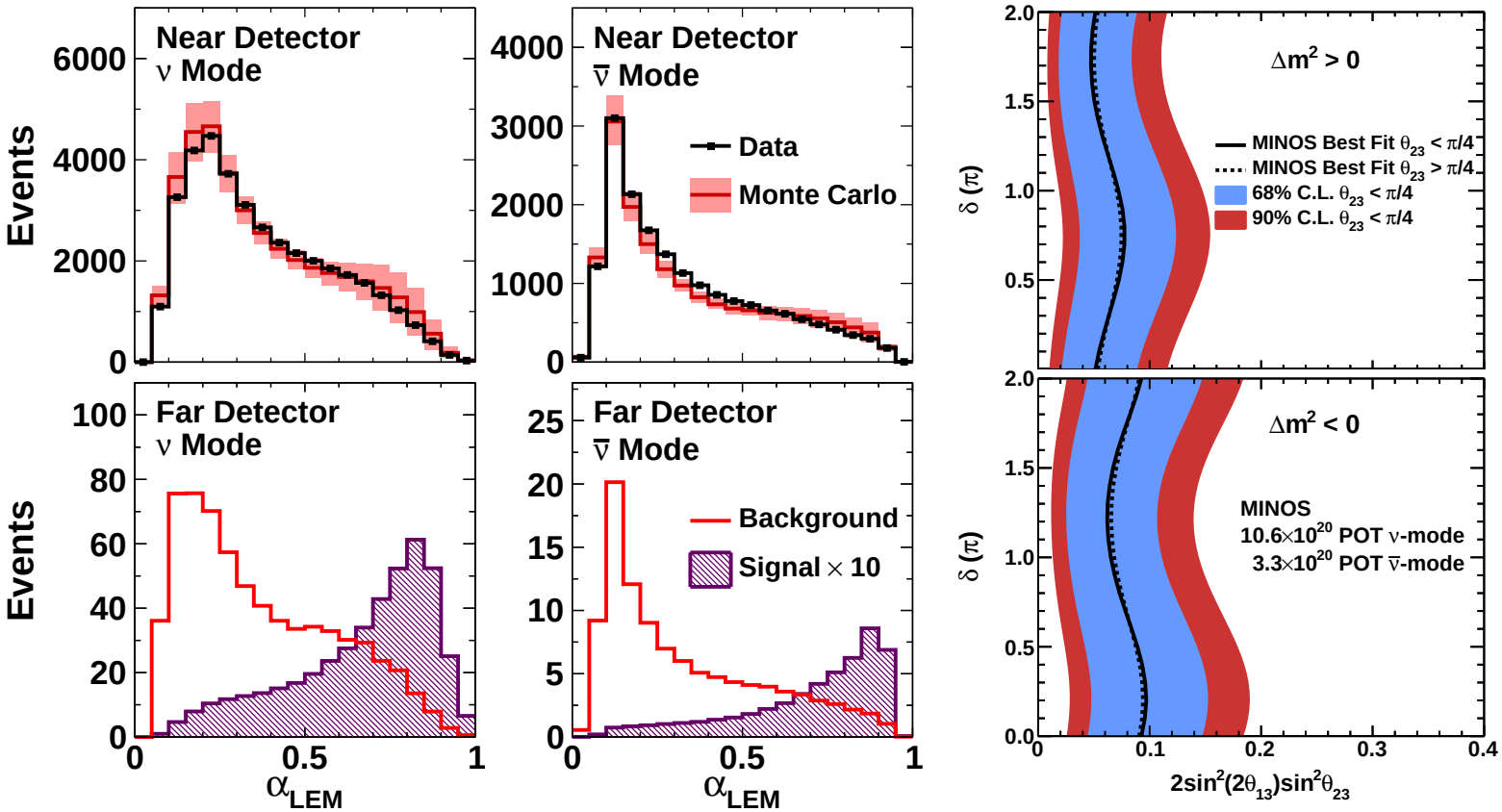
- Analyse beam and atmospheric ν_μ to get θ_{23} and Δm^2_{32}.
- ND ν_μ energy spectrum used to predict FD spectrum.
- Results: $|\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3} eV^2$ and $\sin^2 2\theta = 0.950^{+0.035}_{-0.036}$





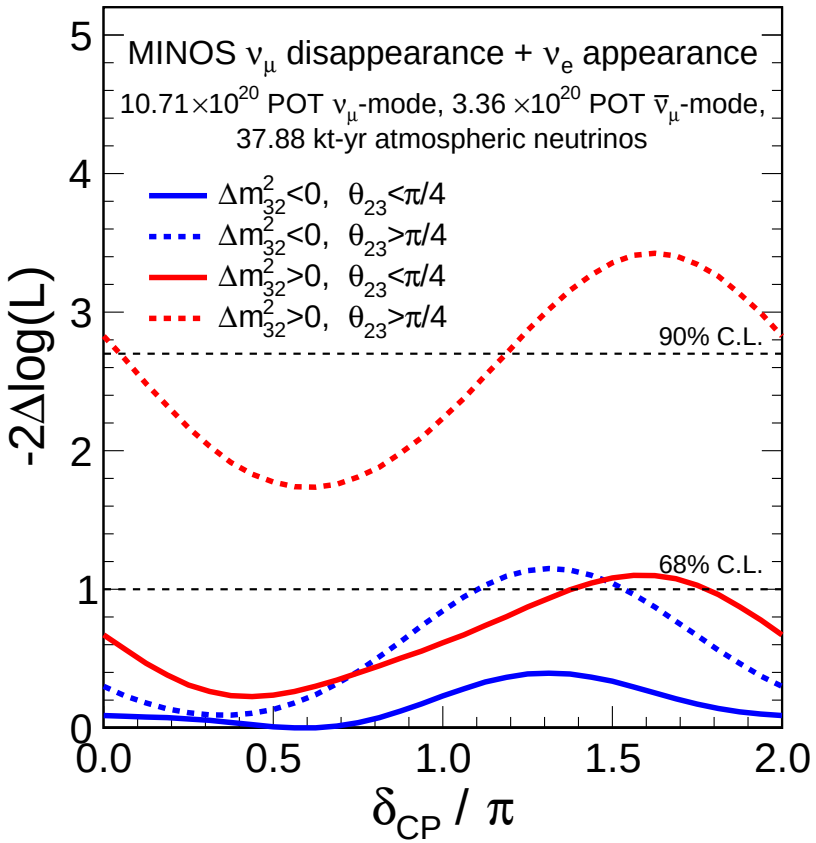
MINOS ν_e APPEARANCE (PRL 110, 171801, 2013)

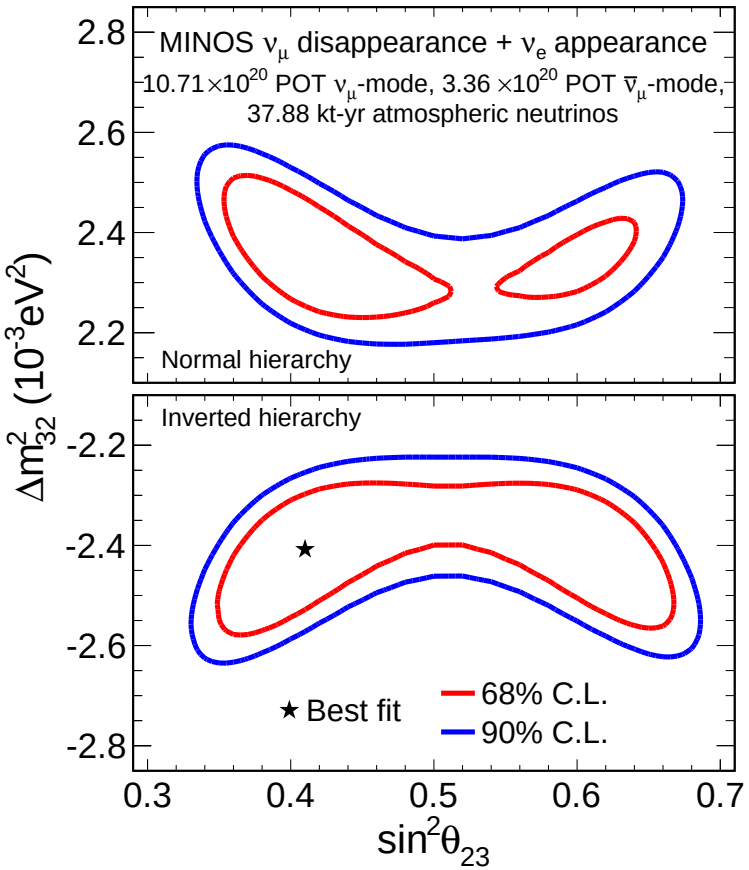
- Search for ν_e in ν_μ beam enables measurement of θ_{13}, δ_{CP} and MH.
- **L**ibrary **E**vent **M**atching (**LEM**) used to identify ν_e from NC events.
- First constraint on δ_{CP} and $\bar{\nu}_e$ appearance search in long baseline $\bar{\nu}_\mu$ beam.
- NH: $2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$, IH: $2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$.



MINOS $\nu_\mu + \nu_e$ COMBINATION (PRL 112, 191801, 2014)

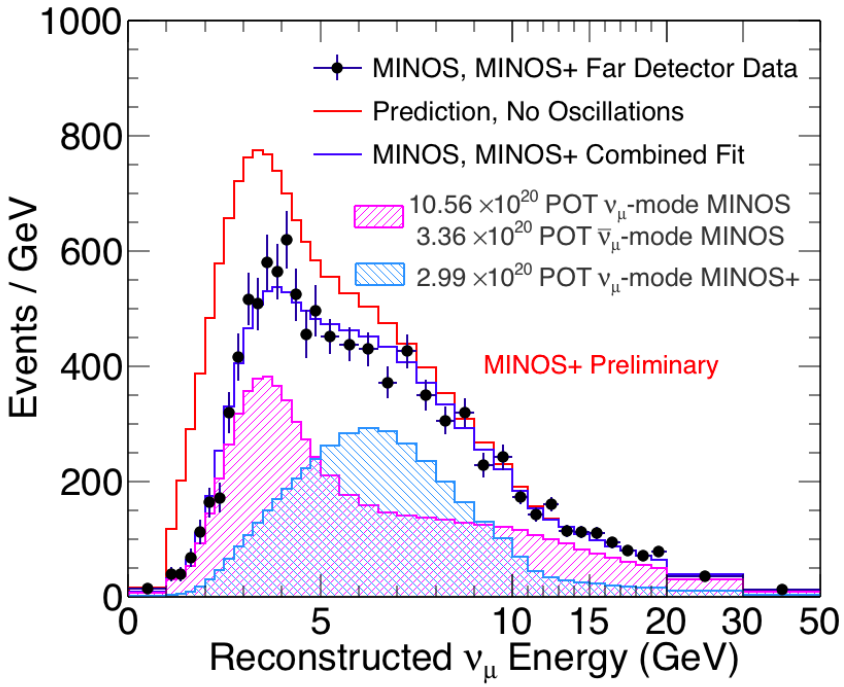
- Combined fit of ν_μ and ν_e atmospheric and beam data.
- Improved limits on δ_{CP} and precision on Δm^2_{32} and $\sin^2\theta_{23}$.
- NH: $|\Delta m^2_{32}| = |2.28 - 2.46| \times 10^{-3} eV^2$ (68% C.L.) and $\sin^2\theta_{23} = 0.35 - 0.65 (90\% C.L.)$
- IH: $|\Delta m^2_{32}| = |2.32 - 2.53| \times 10^{-3} eV^2$ (68% C.L.) and $\sin^2\theta_{23} = 0.34 - 0.67 (90\% C.L.)$

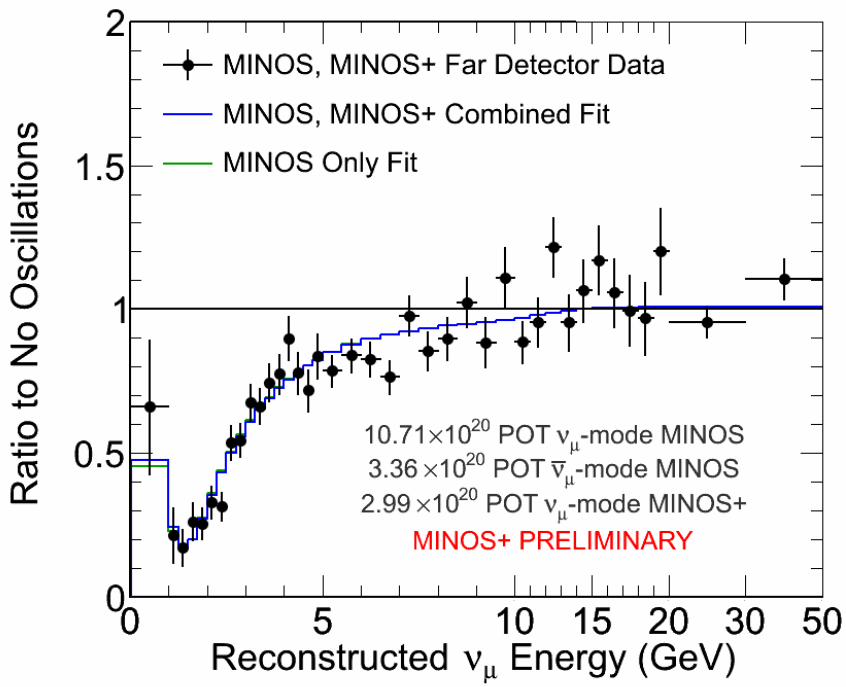




MINOS AND MINOS+ ν_μ DISAPPEARANCE

- Combine MINOS and MINOS+ data (first year).
- Good test of oscillation theory away from maximum with improved stats in primary rising edge of oscillation.
- Combined fit is consistent with MINOS best fit parameters.

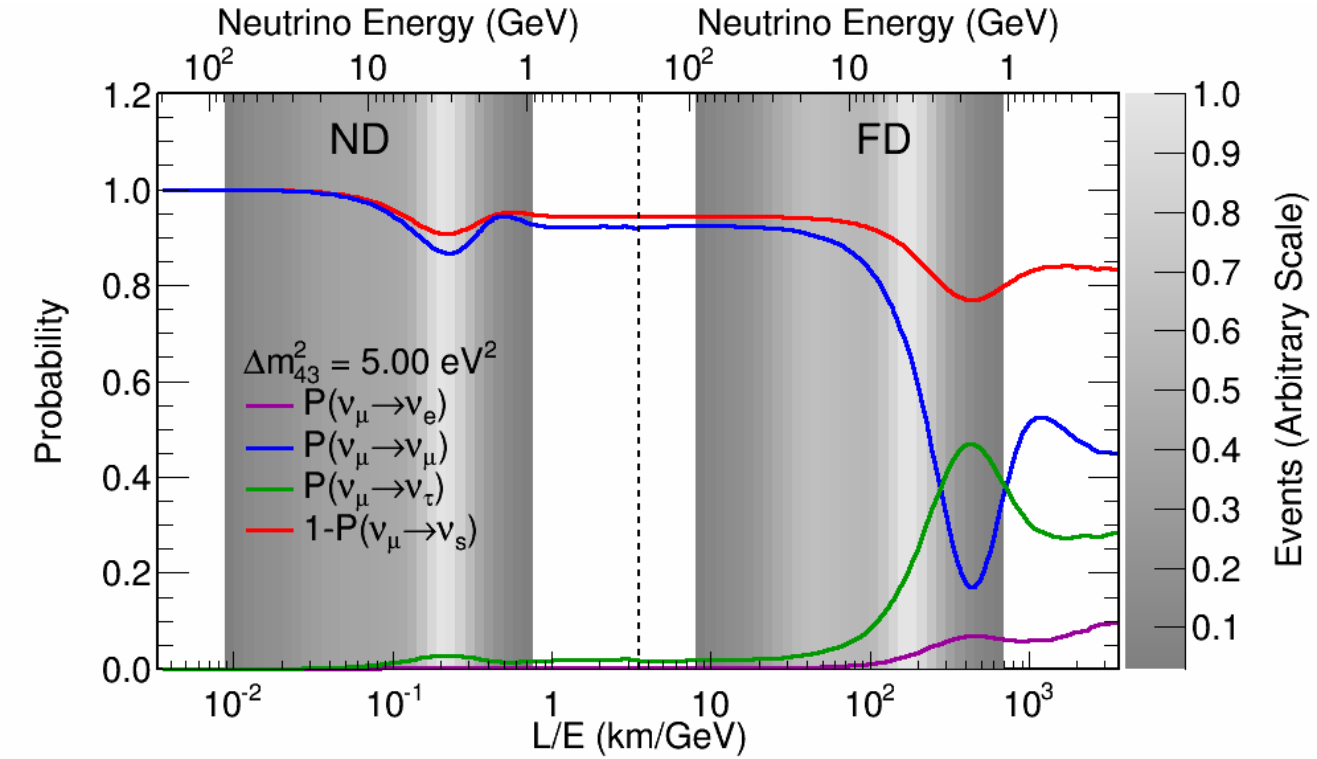




EXOTIC PHENOMENA

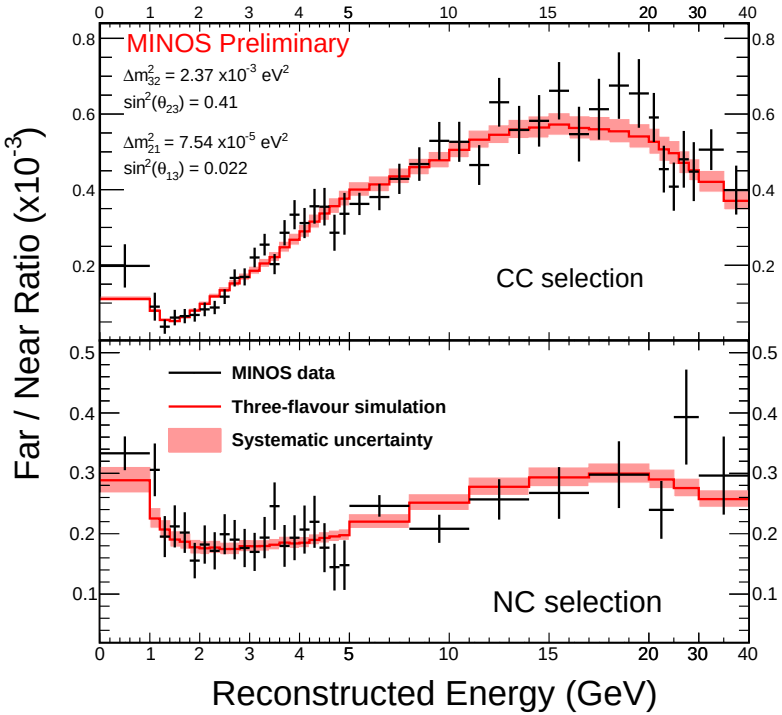
SEARCHES FOR ADDITIONAL NEUTRINO FLAVOURS

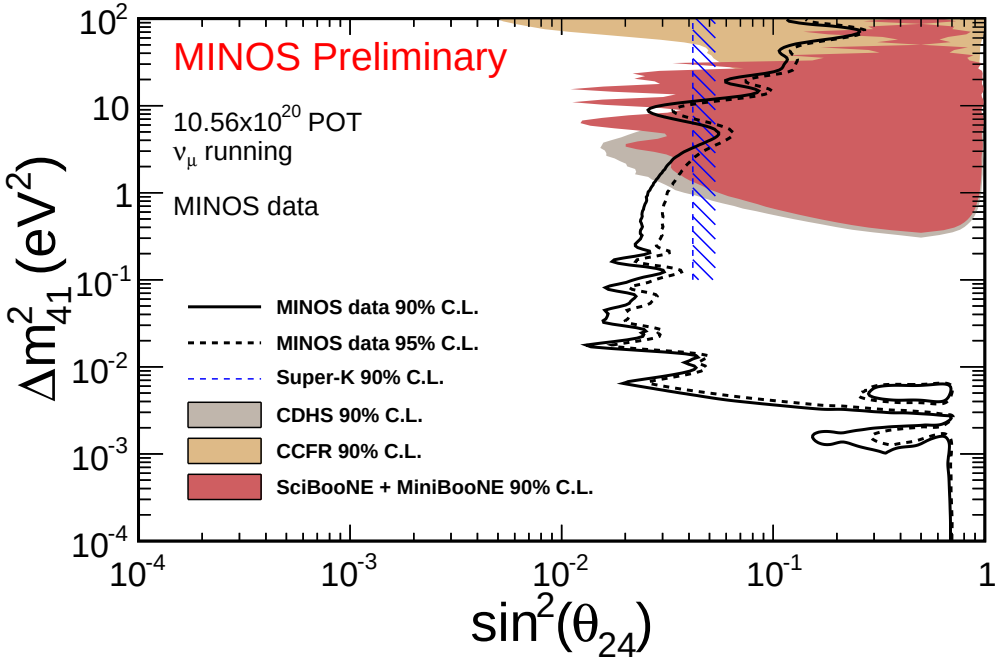
- Anomalous results observed in short baseline experiments - LSND, MiniBooNE.
- Energy dependent reduction in event rate affecting CC and NC.
- MINOS mostly sensitive to Δm^2_{41} and θ_{24}.
- Observe different spectral distortion based on the size of Δm^2_{41}.



MINOS 3+1 MODEL

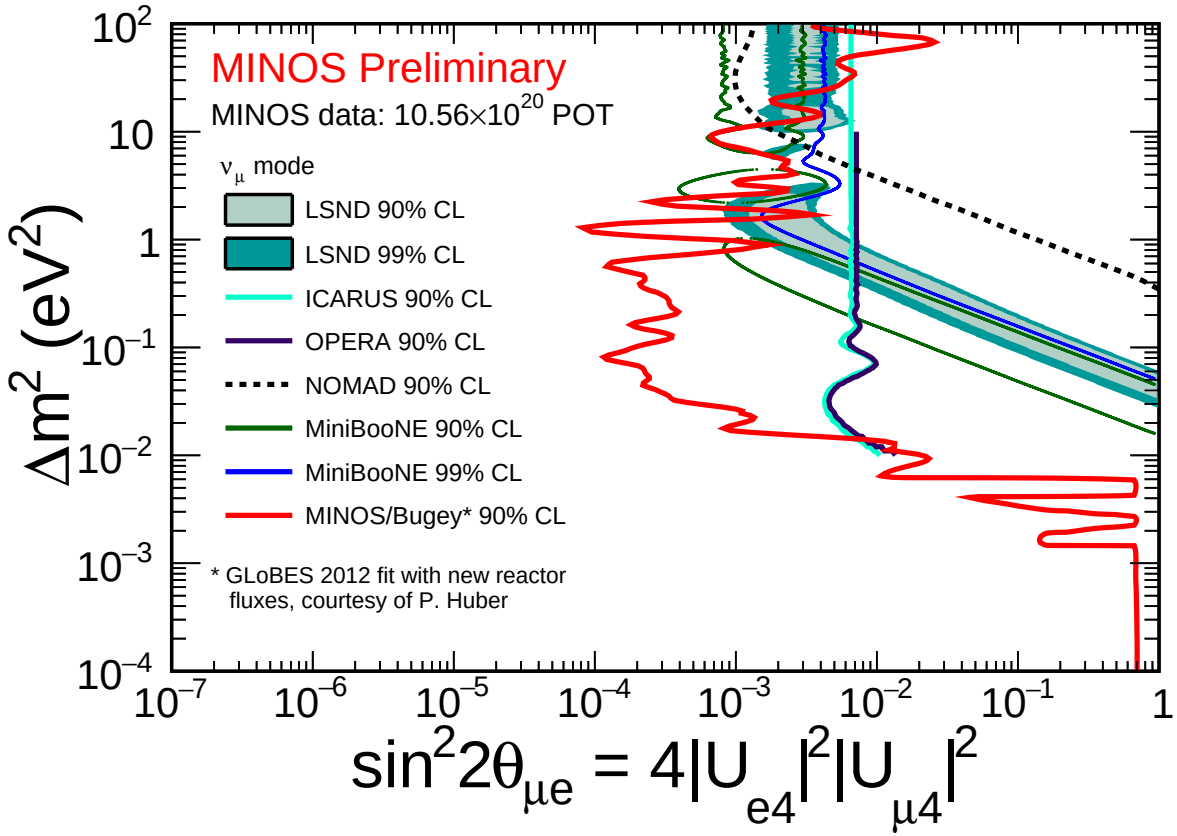
- Use predicted Far/Near ratio to fit Far/Near data ratio.
- Strong constraint in the $\Delta m^2_{41} < 1 eV^2$ region of phase space.
- Results using MINOS only data due shortly.





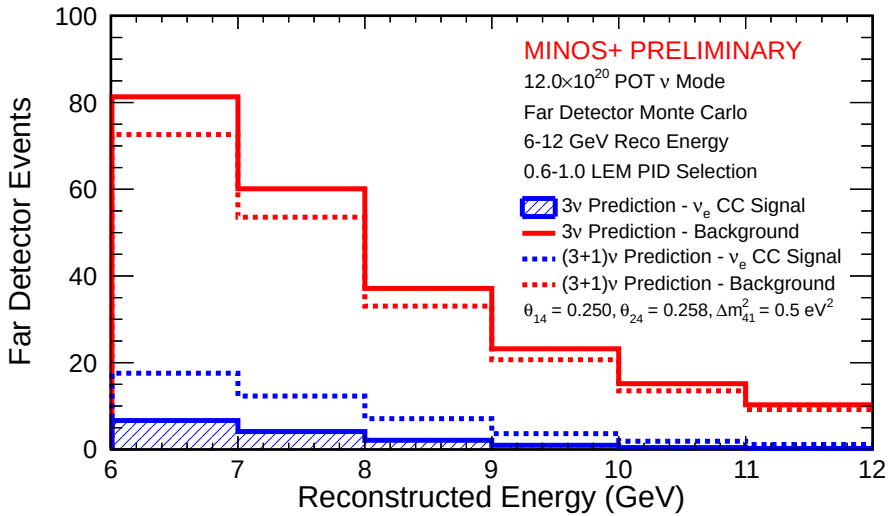
STERILE 3+1 COMBINATION

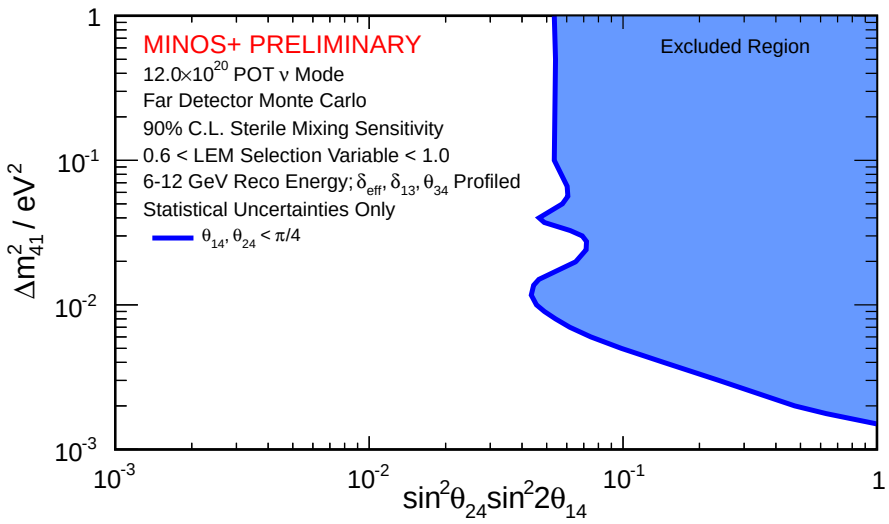
- Combination of MINOS with Bugey reactor experiment data.
- Bugey is short baseline and sensitive to θ_{14} through ν_e disappearance.
- Possible due to largely uncorrelated systematics.
- Can be compared directly with LSND contours.



STERILES THROUGH ν_e APPEARANCE

- Search for modified ν_e appearance signal due to steriles in MINOS+.
- Select events with energy above 6 GeV as signal could be enhanced.
- Sensitive to θ_{24} and θ_{14}.
- Sensitivity to exclude the LSND signal region below $0.15 eV^2$ at 90% CL.



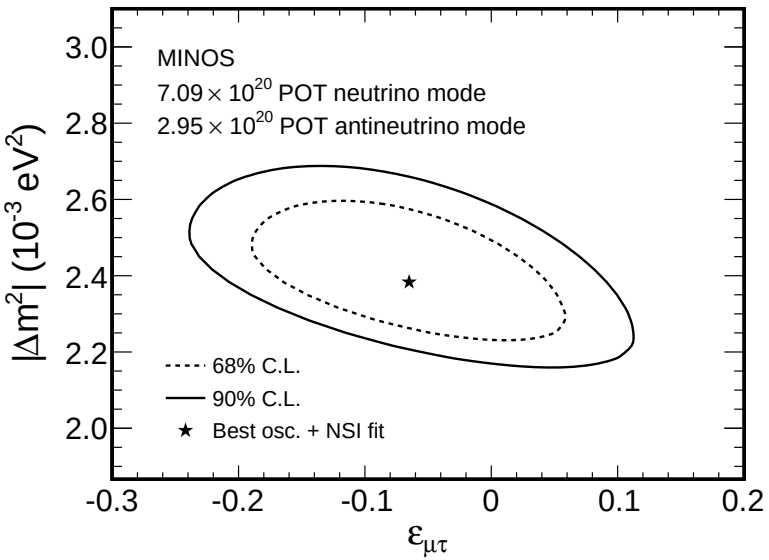


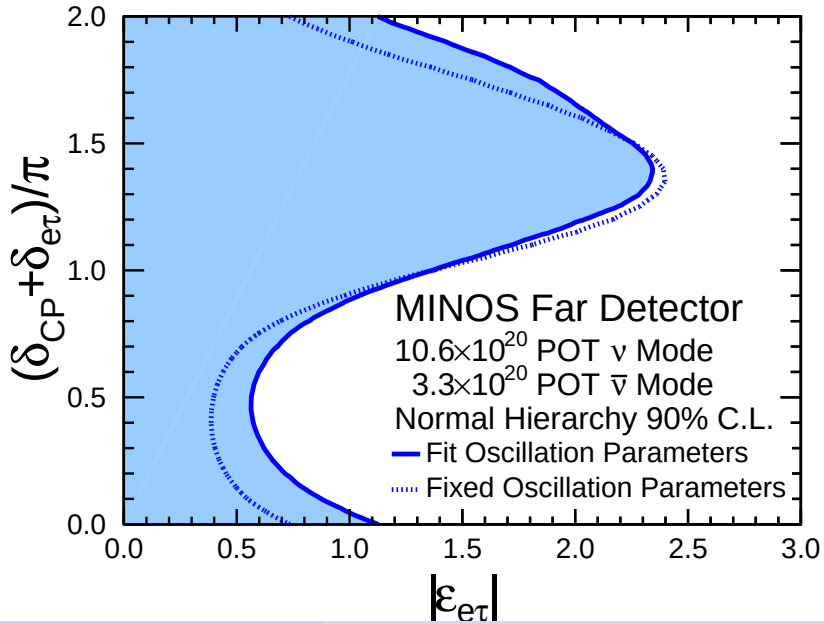
NON-STANDARD INTERACTIONS (NSI) (PRD 88, 072011, 2013)

- Neutrinos may interact in non-standard ways.

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

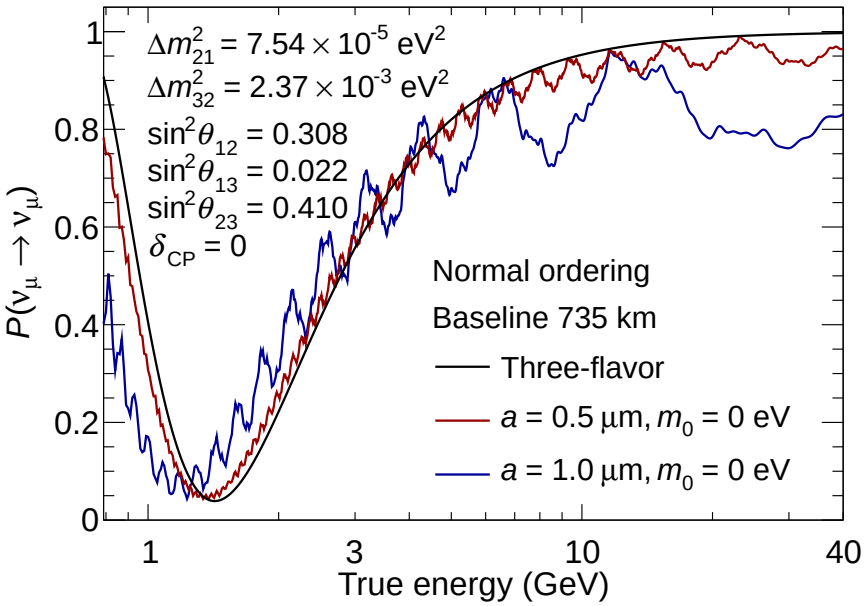
- ν_μ disappearance - $-0.20 < \epsilon_{\mu\tau} < 0.07$, ν_e appearance - $\epsilon_{e\tau}$ and δ_{CP}

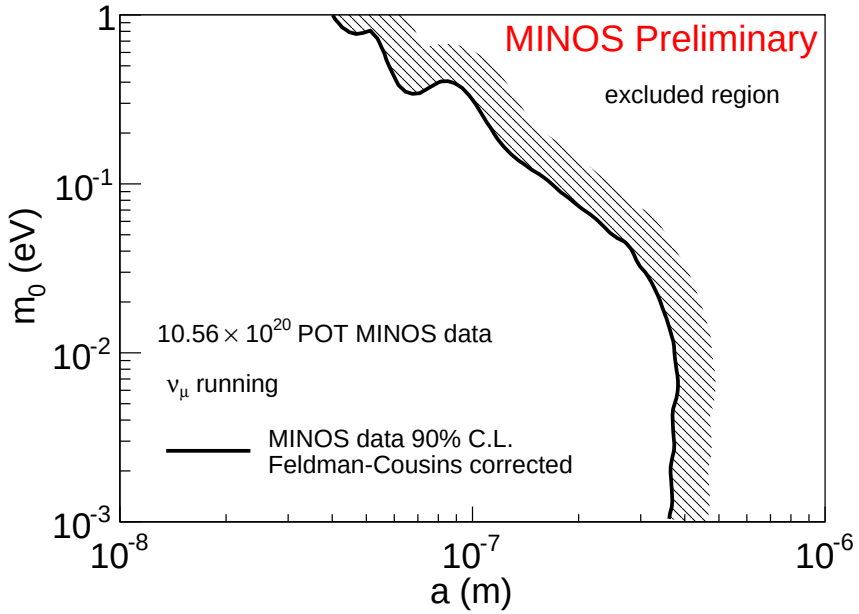




LARGE EXTRA DIMENSIONS (LED)

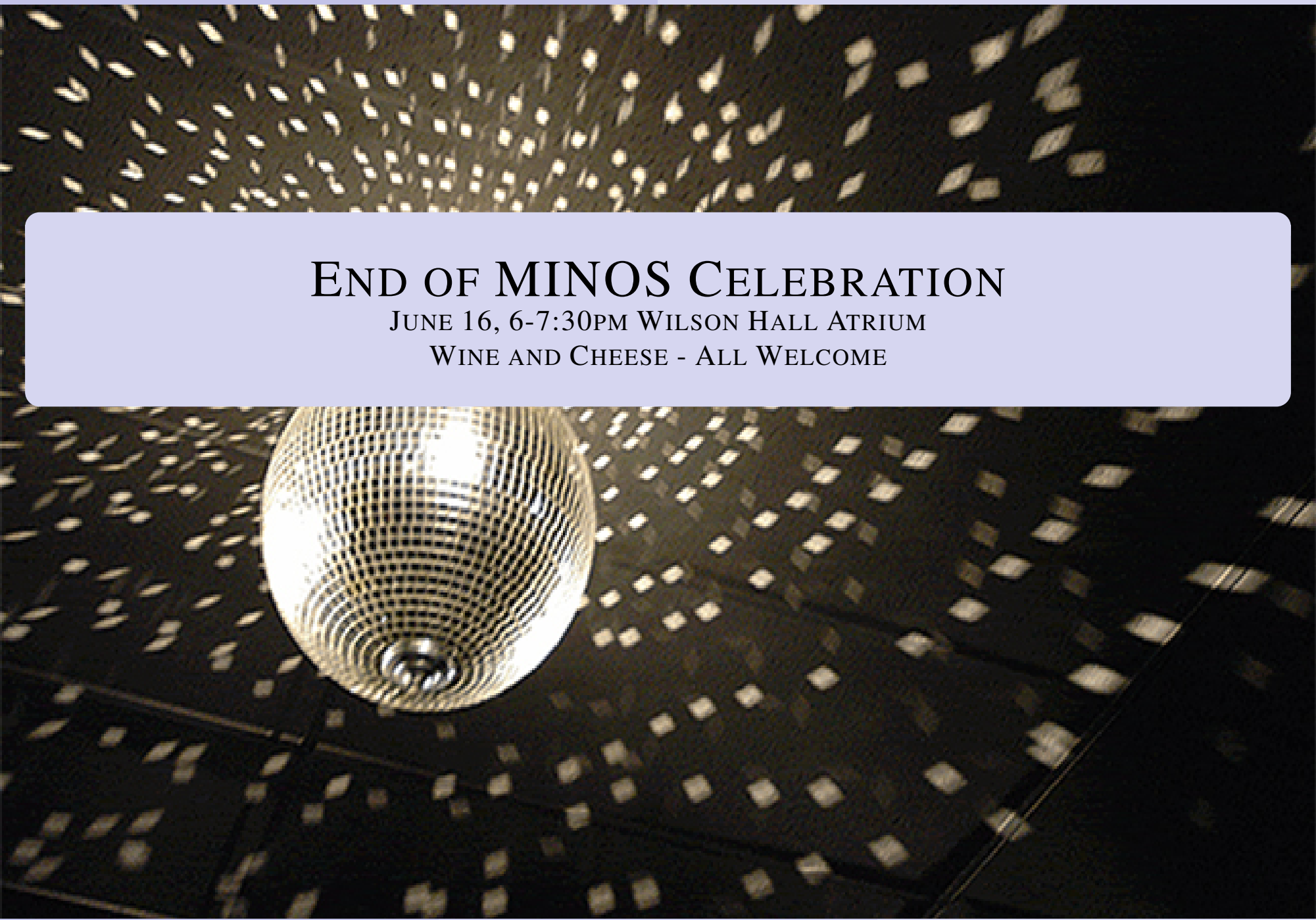
- Another way to search for steriles is to assume they exist in LEDs.
- a = extra dimension size, m_0 = lightest active neutrino mass.





SUMMARY

- MINOS has set some of the most stringent limits in the three flavour paradigm.
- MINOS+ is still collecting data that is still to be analysed.
- Many physics searches still ongoing:
  - Standard 3 flavour updates.
  - Sterile neutrinos (ν_μ and ν_e).
  - LED and NSI analyses.
- MINOS+ results to be shown at Neutrino 2016.



End of MINOS Celebration

June 16, 6-7:30pm Wilson Hall Atrium

Wine and Cheese - All Welcome