Searching for the Neutrino Mass Hierarchy Using Atmospheric Neutrinos in MINOS and DUNE

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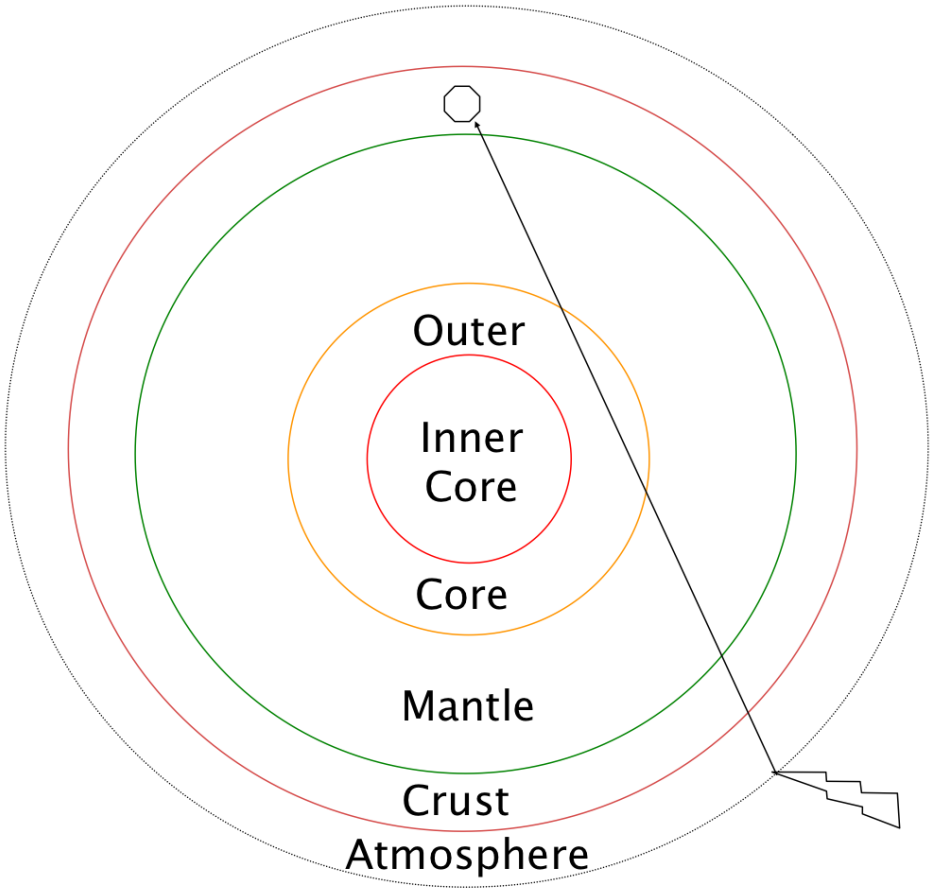
Motivation

- Cosmic rays impinging on the atmosphere produce cascades of particles, including neutrinos
- L/E varies across 4 orders of magnitude
- Mass Hierarchy affects oscillation probabilities via MSW effect.
- ν and $\overline{\nu}$ oscillations affected differently
- Distinct from CP violation.



MINOS Data Set

- We use the data collected at the MINOS far detector from the beginning of the experiment (August 2003) until March of 2011.
- Only data collected with both the main detector and the veto shield fully operational are used in the analysis. This data set corresponds to 2553 live-days, an exposure of 37.9 kton-years.
- Two classes of atmospheric neutrino events
  - Contained-vertex μ, where the event vertex is within the fiducial volume of the detector (406 events)
  - Neutrino-induced muons (NIM), where the neutrino interacts in the rock beneath the far detector and the muon enters the detector from outside (237 events)

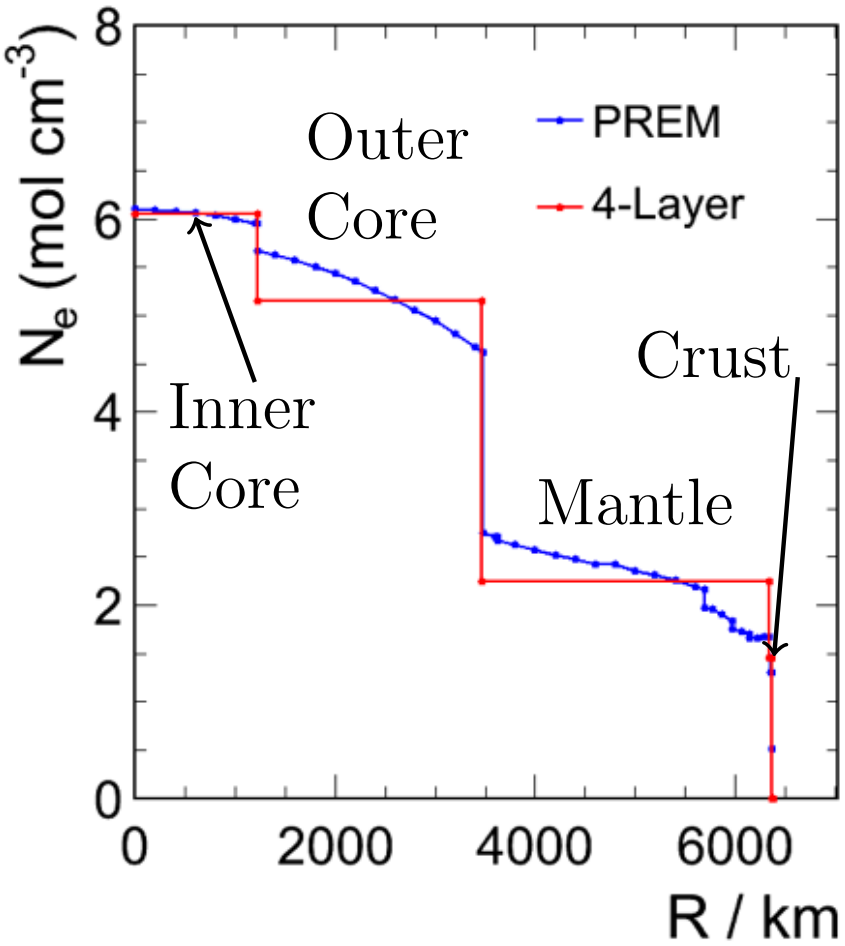
Simulated Data Set

- Generate a simulated data sample equivalent to 193240 kton-yrs simulated exposure for contained vertex events and 325200 kton-yrs for NIM events.
- From half of simulated sample, generate pseudo-experiments for the values of mixing parameters
- For each pseudo-experiment we calculate the χ^2 value against normal mass hierarchy (χ^2_{NH}) and inverted mass hierarchy (χ^2_{IH}). Use these to determine probability as a function of the χ^2 difference.
- Use remaining half for comparison with data to measure hierarchy preference

$$|\Delta m^2_{32}| = 2.32 \times 10^{-3}\,\mathrm{eV}^2 \quad \sin^2(2\theta_{12}) = 0.87 \quad \delta_{\mathrm{CP}} = 0$$
$$\Delta m^2_{21} = 7.59 \times 10^{-5}\,\mathrm{eV}^2 \quad \sin^2(2\theta_{23}) = 1.00 \quad \sin^2(2\theta_{13}) = 0.10$$

Propagation through Earth

- Use four-layer model of Earth's interior based on the PREM model, plus atmosphere.
- Flat neutrino production height of 15 km
- Uncertainties in the Earth model have small impact on the results, so this is a sufficient approximation.



Dziewonski & Anderson, *Physics of the Earth and Planetary Interiors* **25**, 297 (1981)

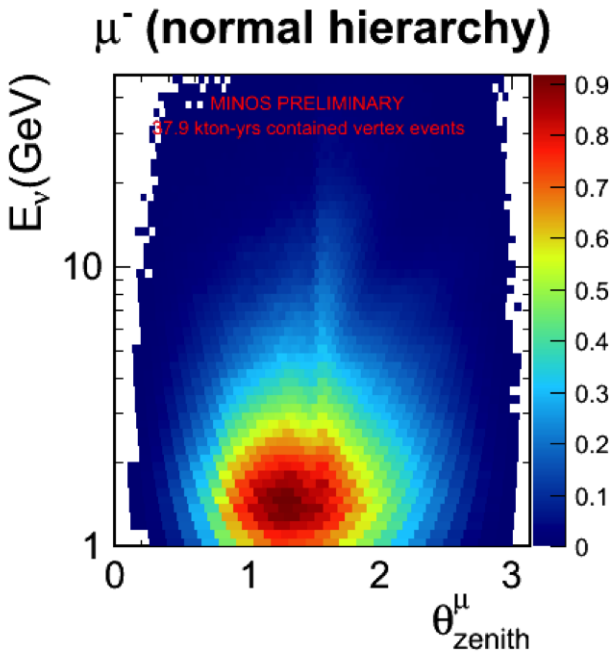
χ^2 Comparison and Systematic Uncertainties

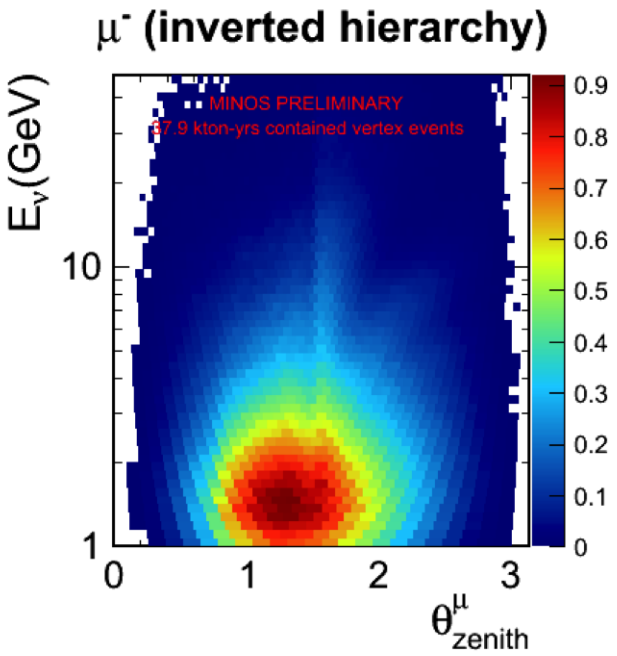
$$\chi^2 = 2\sum_{i=1}^{N}\left[y_i - n_i + n_i \ln\left(\frac{n_i}{y_i}\right)\right],$$

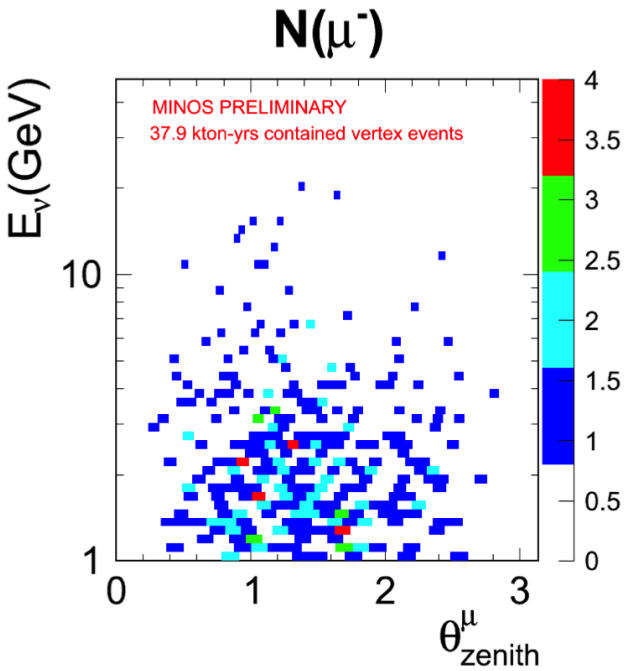
where N is the number of bins (in energy and angle) y_i is the predicted number of events, and n_i is the number of data events.

- Major systematic uncertainties: atmospheric ν flux normalization, the $\nu_\mu/\overline{\nu}_\mu$ ratio, and flux vs. energy.
- Most systematic uncertainties taken from the main MINOS atmospheric ν analysis[1]
- For our estimated uncertainty on a systematic parameter, we create PDFs which we sample with pseudo-experiments.
- We plot the distribution of the χ^2 values of that parameter as take the RMS width as the systematic uncertainty.

[1] Phys. Rev. D **86**, 052007 (2012)







- Bin y-axis $(0 \leq \log_{10}(E_\nu) \leq 1.68)$ into 56 bins of equal width in $\log_{10}(E_\nu)$.
- Bin x-axis, $(0 \leq \theta_{\text{zenith}} < \pi)$ into 24 – 99 bins, depending on E_ν
- Plots are for CV μ^- events.
- Color scale number of evts. (data) and expected number of evts. (simulation)

Results

Table : $\chi^2_{\mathrm{NH}} - \chi^2_{\mathrm{IH}}$

	CV	NIM
μ^+	1.350	0.005
μ^-	-1.598	0.377
All μ	-0.248	0.382
All Data	**0.134**	

- Slight preference for IH ($\chi^2_{\mathrm{IH}} < \chi^2_{\mathrm{NH}}$)
- Proven that the technique is viable with a magnetized iron detector.
- Could be used for significant results and contribution to global determination in an experiment like INO or MIND.

DUNE Proposed Methods

- The plots (and most of the methods) of this section are taken from §2.2.7 and 4.6 of the LBNE Science Book[2]
- Most significant difference is that DUNE FD will not be magnetized
- This requires other methods of distinguishing ν from $\overline{\nu}$
- DUNE will be able to detect ν_e (and $\overline{\nu}_e$) in addition to ν_μ and $\overline{\nu}_\mu$
- Current studies have only considered contained vertex events
- The heart of the analysis is again a comparison of data to expectations for each of the hierarchies

[2] https://sharepoint.fnal.gov/project/lbne/LBNE%20at%20Work/LBNE%20Science%20Program/SitePages/Home.aspx

Expected Data Set

Parameter	Value
$\Delta m^2 = 1/2(\Delta m^2_{32} + \Delta m^2_{31})$ (NH)	$+2.40 \times 10^{-3}$ eV^2
$\sin^2\theta_{23}$	0.40
Δm^2_{21}	7.54×10^{-5} eV^2
$\sin^2\theta_{12}$	0.307
$\sin^2\theta_{13}$	0.0242
δ_{CP}	0

Table : Atmospheric-neutrino event rates including oscillations in 100 kton-years with a LArTPC, fully or partially contained in the detector fiducial volume.

Sample	Event rate
fully contained electron-like sample	4,015
fully contained muon-like sample	5,958
partially contained muon-like sample	1,963

Reconstruction and $\nu/\overline{\nu}$ Separation

- For low-multiplicity events, protons occur preferentially in neutrino interactions; assume protons are tagged with 100% efficiency if their kinetic energy is greater than 50 MeV.
- Decay electrons are assumed to be 100% identifiable and are assumed to occur 100% of the time for μ^+ and 25% of the time for μ^-, based on the $\mu^\pm$ capture probability on ^{40}Ar.
- A Fast MC runs on simulated (Bartol) four-vectors, placing events into containment and flavor categories.
- Identify $e^\pm$ with 90% probability
- Misidentify π^0, γ, etc. as $e^\pm$ with 5% probability
- Muons are identified with 100% probability
- With these assumptions, the purities of the flavor-tagged samples are 97.8% for the FC electron-like sample, 99.7% for the FC muon-like sample, and 99.6% for the PC muon-like sample.

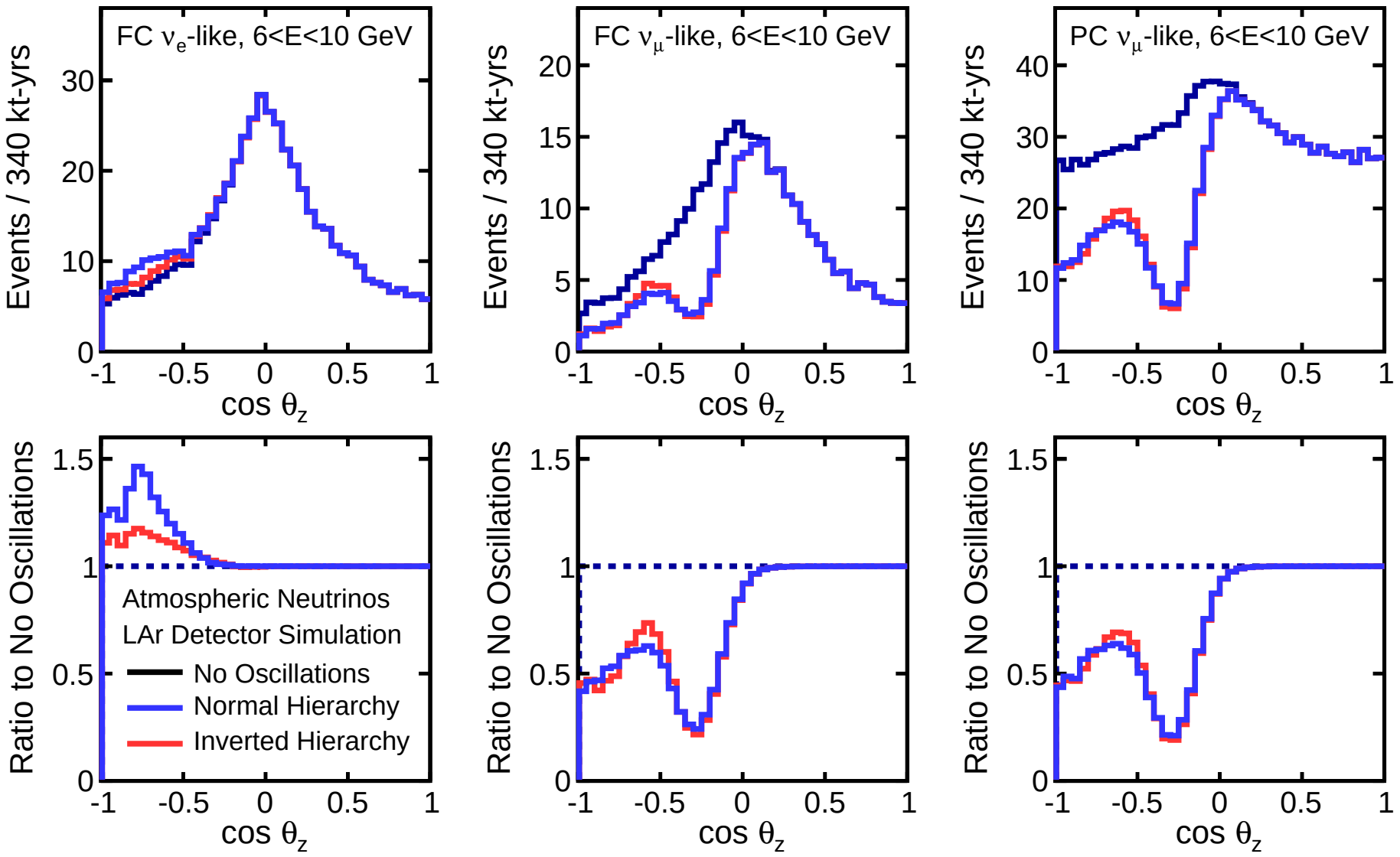


Figure : Reconstructed zenith angle distributions for events of 6-10 GeV. Compare inverted (red) and normal (blue) hierarchy

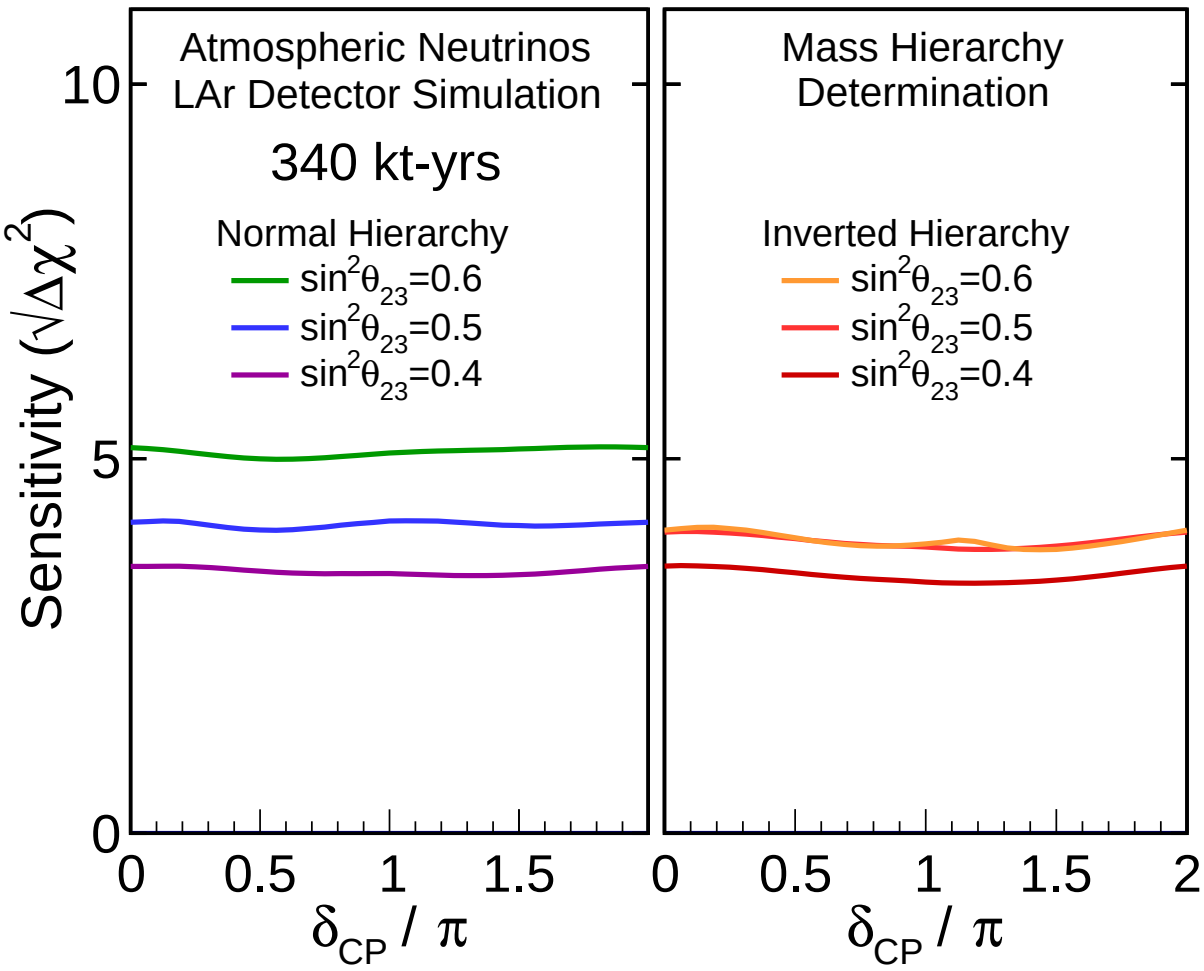
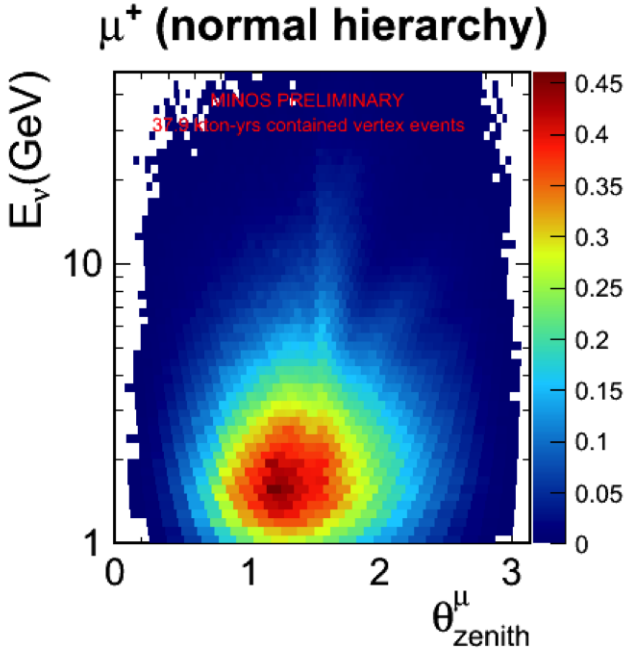
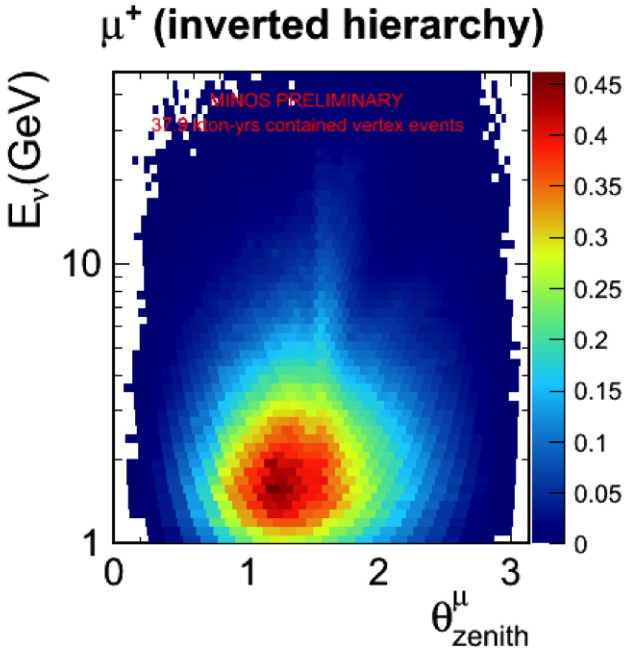


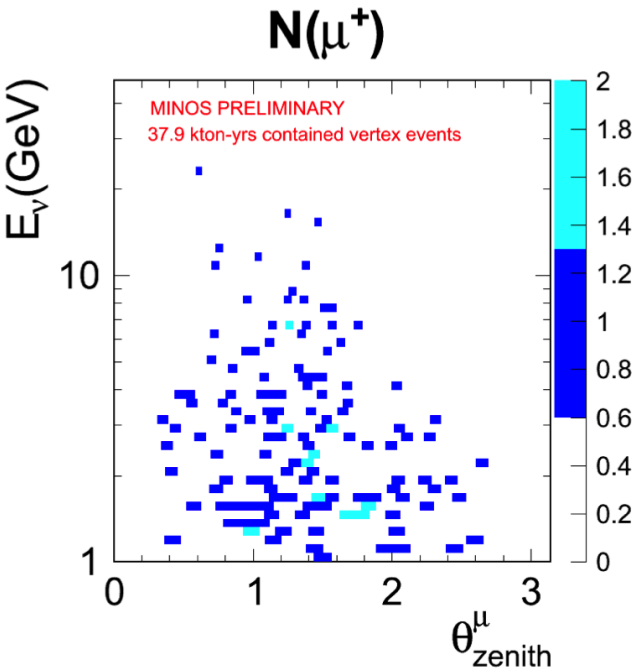
Figure : Sensitivity of 340 kton-yrs of atmospheric neutrino data to MH as a function of $\delta_{\rm CP}$for true normal (left) and inverted (right) hierarchy and different assumed values of $\sin^2\theta_{23}$.

Conclusion

- The MINOS results were inconclusive but proved the technique viable.
- We hope this will be of use to future magnetized iron neutrino detectors, such as INO
- This method holds great promise in DUNE if sufficient $\nu/\overline{\nu}$ discrimination can be achieved
- Simulations and software development toward that end are well underway.
- Probably no single experiment will determine the hierarchy; it will likely be the combination of several that yields the answer







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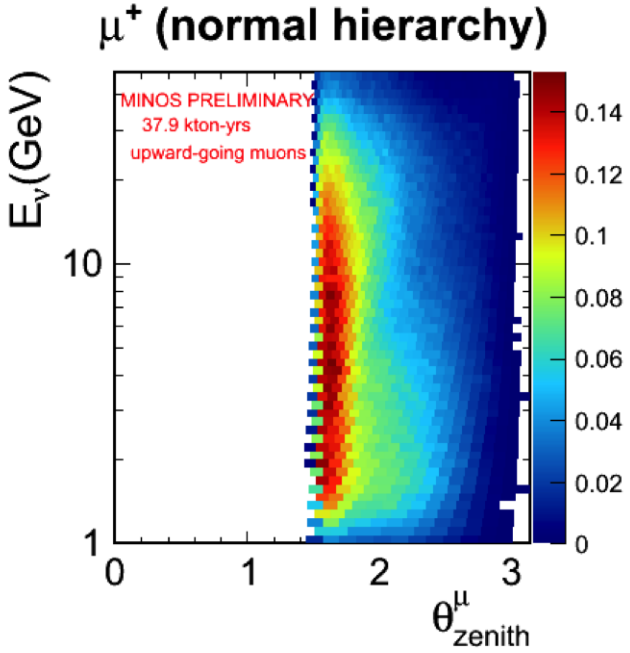
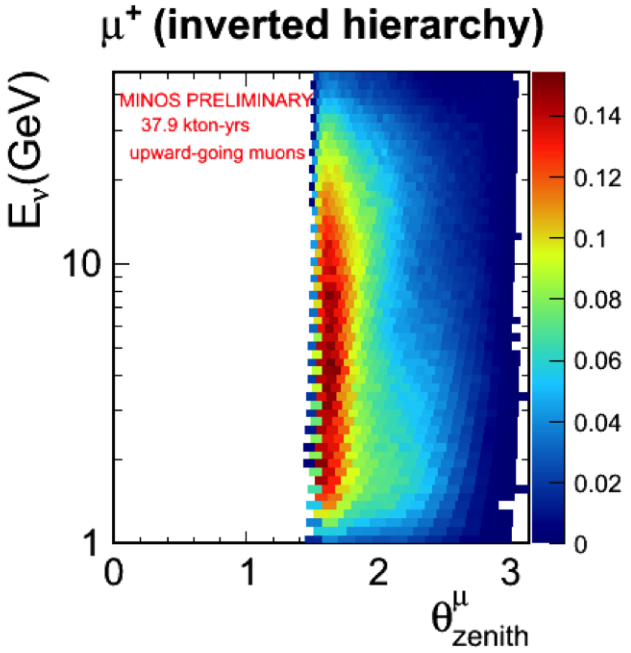
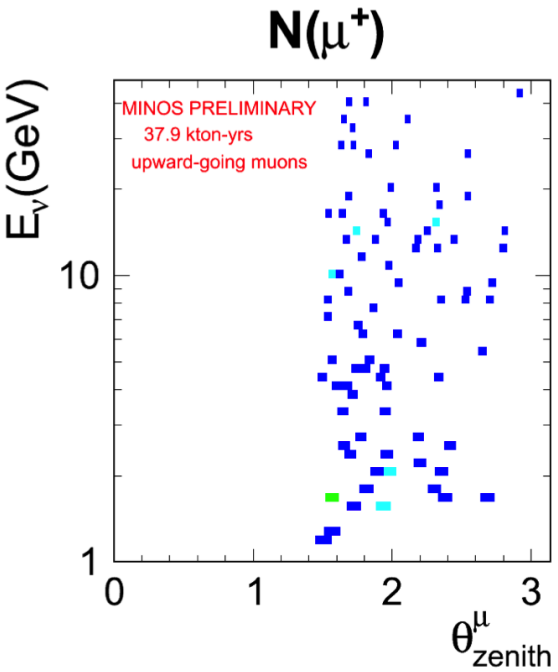
- Color scale is number of events for data and expected number of events for simulation







- Plots are for NIM μ^+ events.
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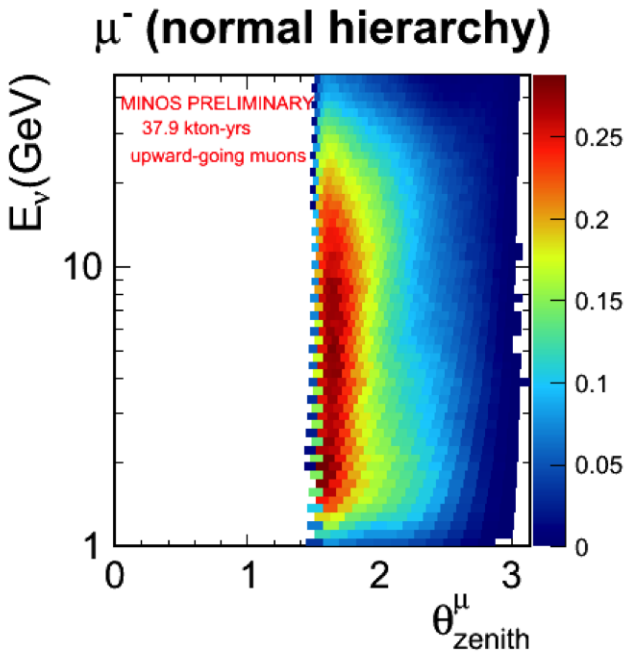

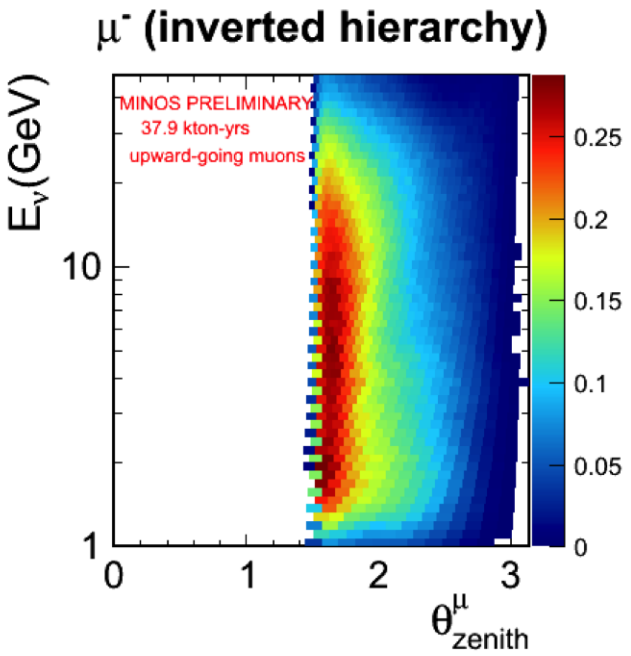

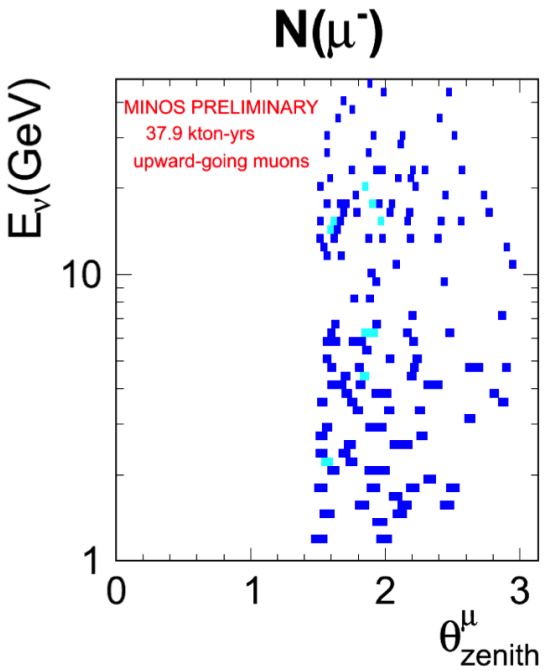

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