Neutrino Mass Ordering with Atmospheric Neutrinos in IceCube

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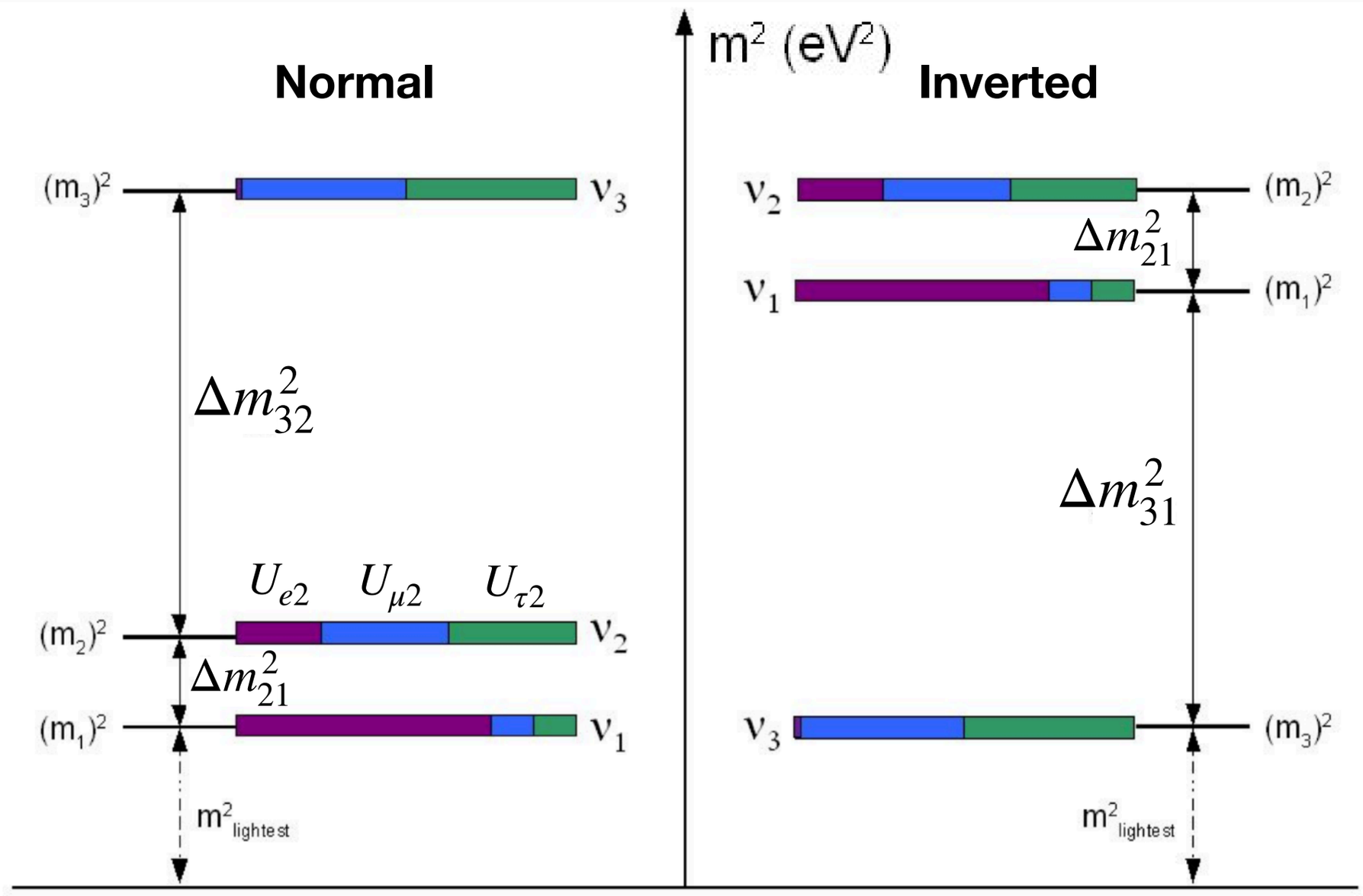
Neutrino Mass Ordering (NMO)



ν_e ν_μ ν_τ

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Looking for the sign of Δm^2_{31}

[1]

$$\Delta m^2_{32} \approx \Delta m^2_{31}$$

MSW Effect

- MSW effect in a two-flavor oscillation case with constant electron density (N_e)
- Effective mass squared difference & effective mixing angle
- Neutrinos (+)
- Anti-neutrinos (-)
- Matter effect introduced by N_e (electron density from surrounding matter)
- Resonance occurs mainly for neutrinos (NO, positive delta m squared) or anti-neutrinos (IO, negative m squared)

$$\Delta m^2 \rightarrow \Delta m^2_m = C \cdot \Delta m^2$$

$$\sin(2\theta) \rightarrow \sin(2\theta_m) = \frac{\sin(2\theta)}{C}$$

$$\textbf{with } C = \sqrt{(\cos(2\theta) - A)^2 + \sin^2(2\theta)}$$

$$A = \pm \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2}$$

Effect is maximal when:

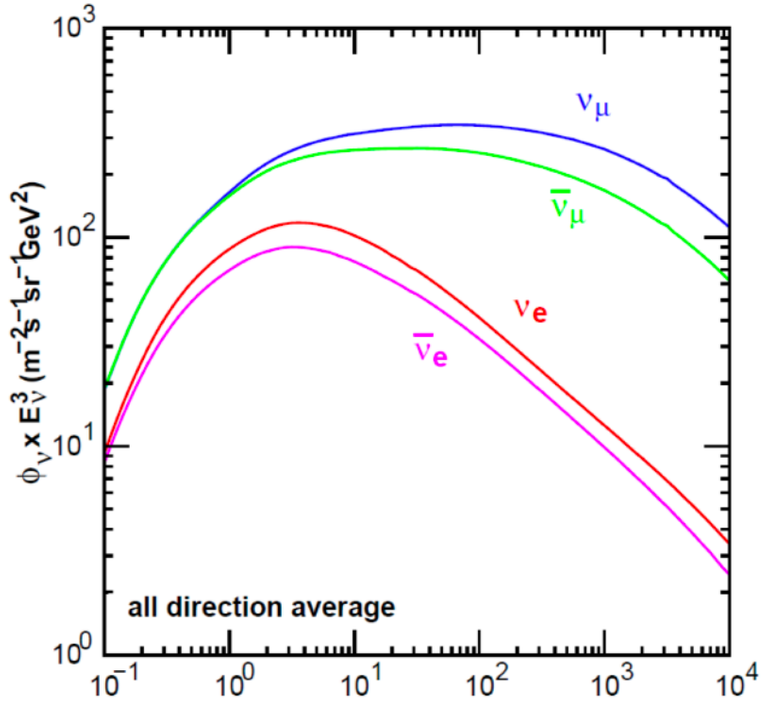
$$\sin(2\theta_m) = 1$$

$$E_\nu = \pm \frac{\Delta m^2}{2\sqrt{2} G_F N_e} \cos(2\theta)$$

For more information: check out link here

Neutrino Flux and Cross Sections

- Neutrino flux at DeepCore energies is higher than anti-neutrino flux
- Total neutrino cross section at DeepCore energies for neutrino-nucleon scattering is about two times greater for neutrinos vs anti-neutrinos



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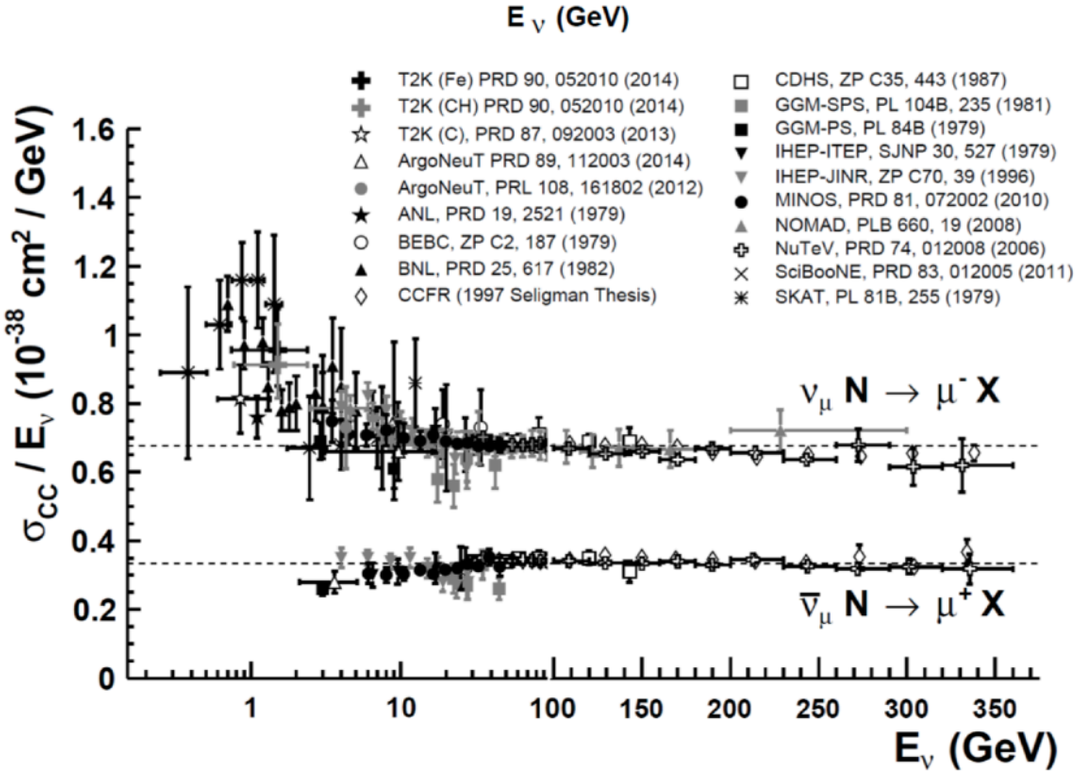
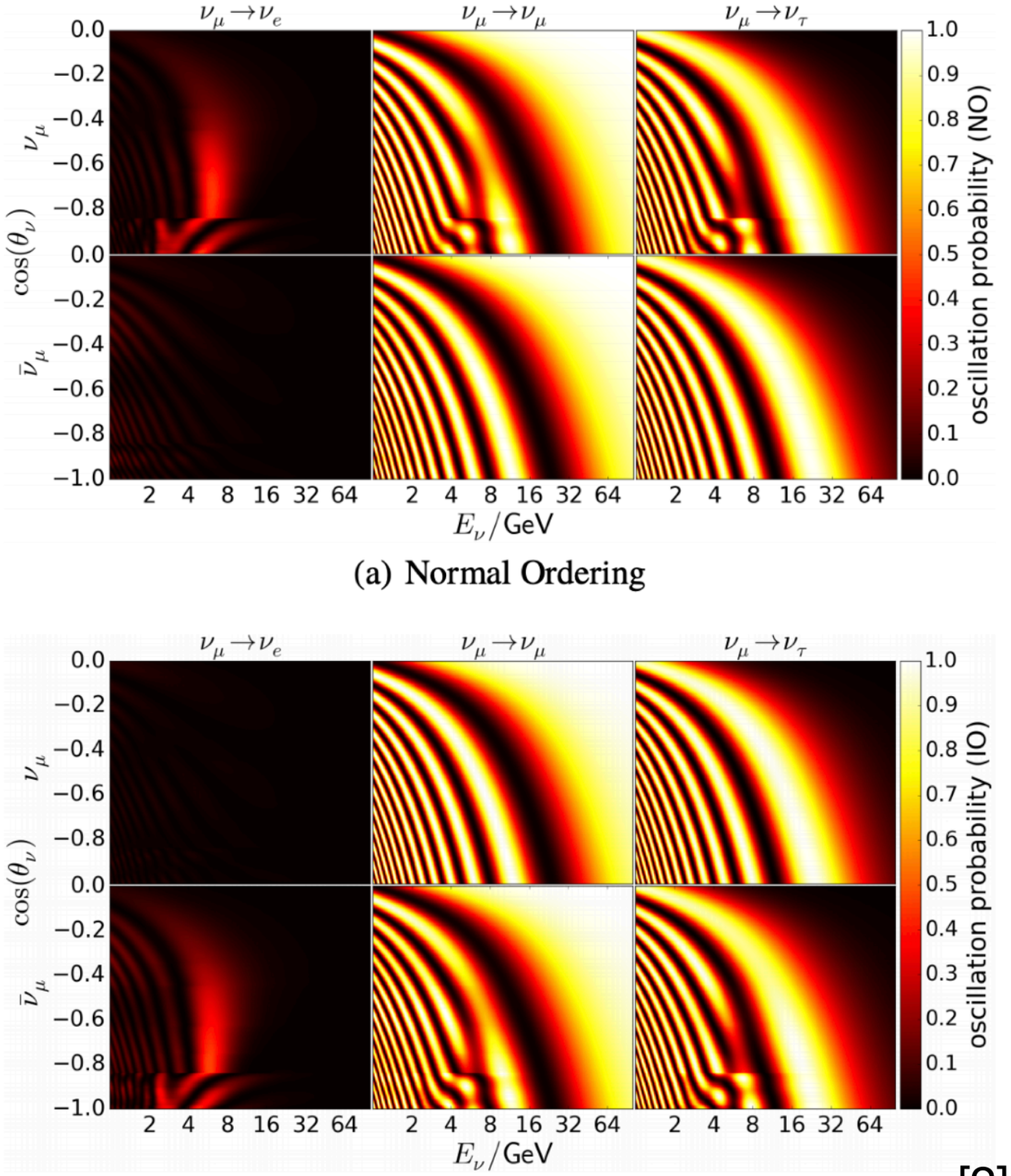


[3]

NMO signal in IceCube

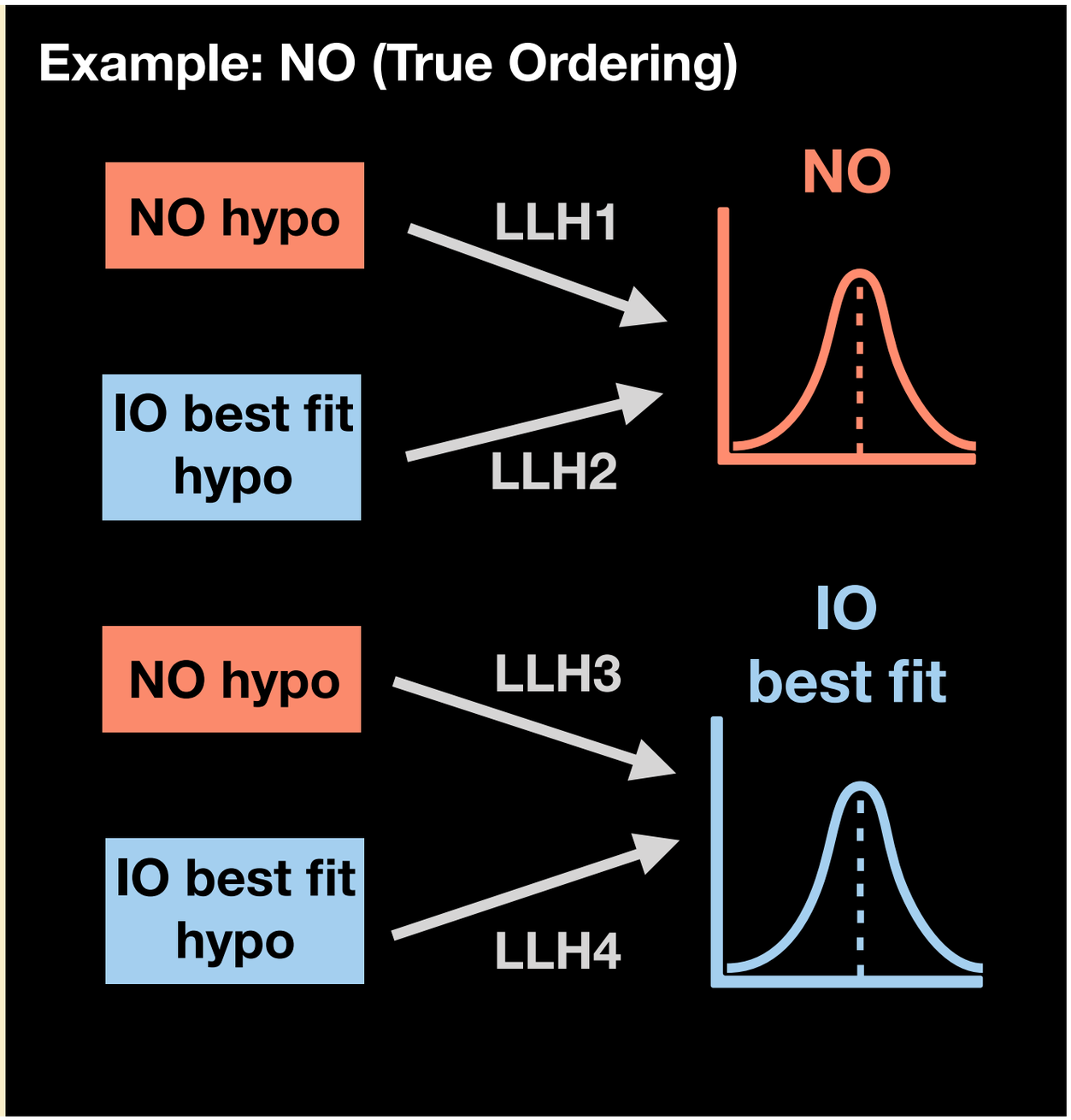
- MSW effect introduces differences in oscillation probabilities between neutrinos and anti-neutrinos for both orderings
- Differences in atmospheric fluxes and cross sections yield higher rate of neutrinos than anti-neutrinos
- For a combined neutrino/anti-neutrino signal (IceCube), matter effects will be stronger in NO signal than in IO signal



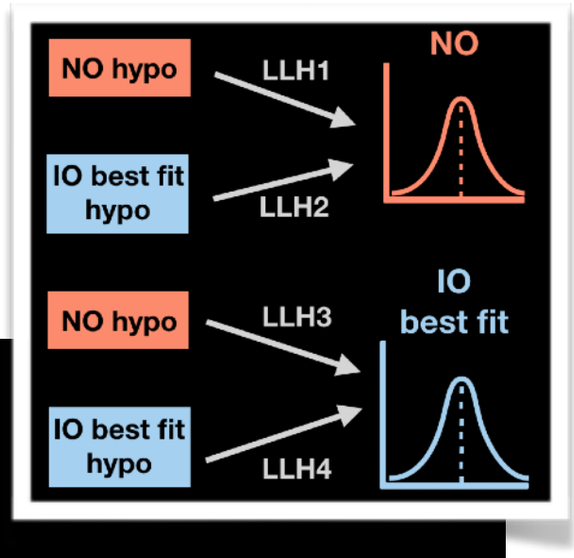
[2]

NMO Analysis in IceCube

- Procedure: (**Pseudotrial Method**)
  - Assume true ordering (TO)
  - Obtain best fit wrong ordering (WO)
  - Fit TO and best fit WO hypotheses to fluctuated TO template
  - Fit TO and best fit WO hypotheses to fluctuated best fit WO template
  - Test Statistic: LLH
  - Goal: Be able to reject even the best fitted case of WO



NMO Analysis in IceCube



- **Asimov Method** assumes $\Delta\mathbf{LLH}_{\mathbf{NO\text{-}IO}}$:
  - Is Gaussian distributed
  - Has a standard deviation related to its mean (for Gaussians):

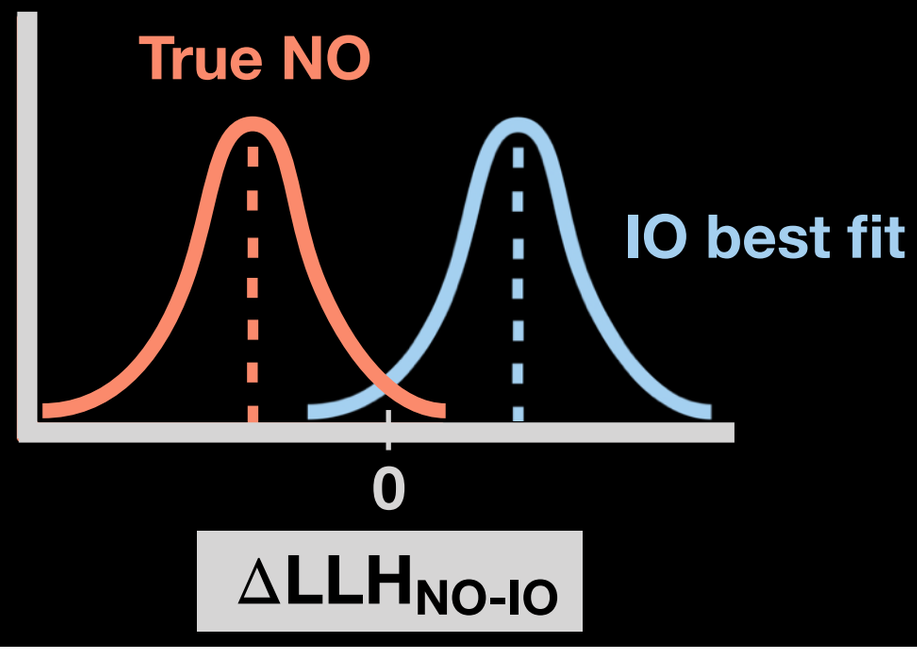
$$\sigma_{\Delta\mathbf{LLH}} = \sqrt{2\overline{\Delta\mathbf{LLH}}}$$

  - Its mean and median should be approx. identical
  - Goal: Obtain approx. mean of distributions to calculate a sensitivity without having to fluctuate any templates

Continued example…

$$\mathbf{LLH1}_i - \mathbf{LLH2}_i = \Delta\mathbf{LLH}_{\mathbf{NO\text{-}IO}_i}$$

$$\mathbf{LLH3}_i - \mathbf{LLH4}_i = \Delta\mathbf{LLH}_{\mathbf{NO\text{-}IO}_i}$$

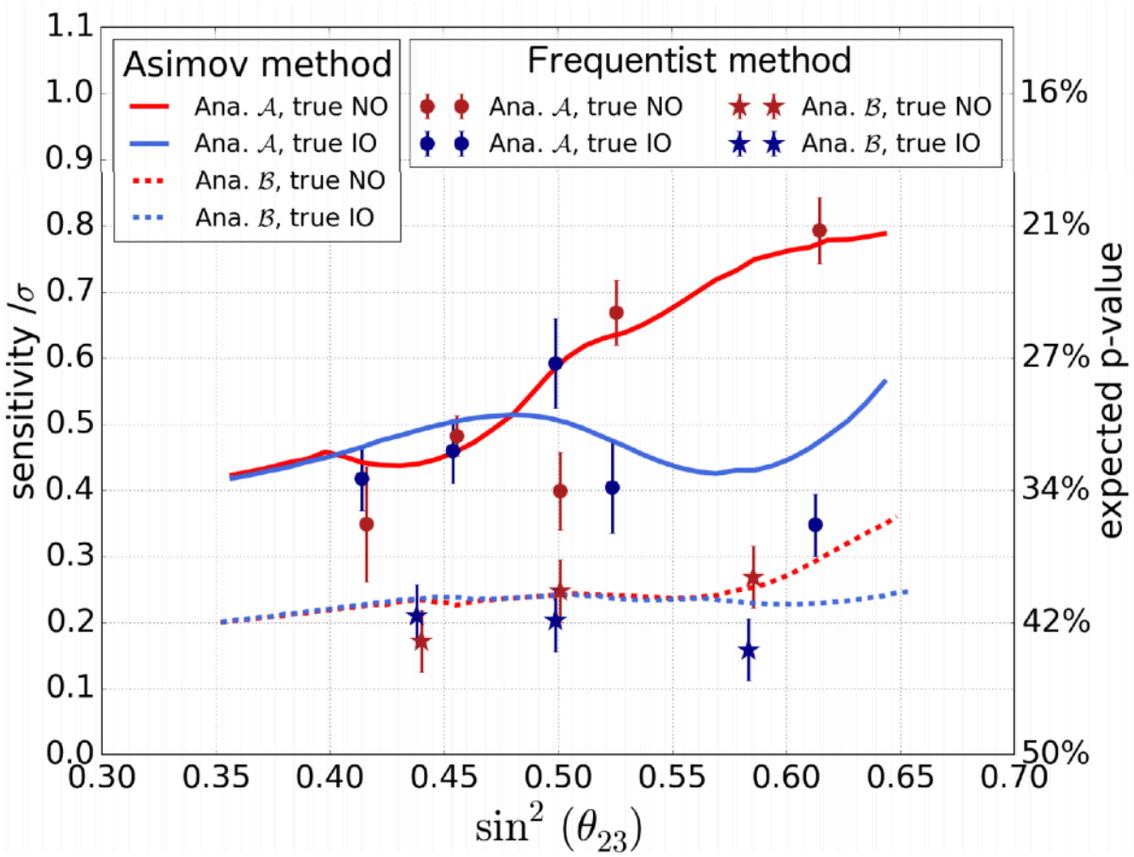


DeepCore Sensitivity

- Three years of IceCube DeepCore data
- Analysis A: Designed to optimize sensitivity; considered main result
- Analysis B: Designed to only use events fully contained inside DeepCore detector; confirmatory result
- Would expect slightly higher sensitivity for NO than for IO at the maximal mixing angle

$$\textbf{Sensitivity NO}/\sigma = \frac{\overline{\Delta\textbf{LLH}}_{\textbf{NO-IO}}(\textbf{NO}) - \overline{\Delta\textbf{LLH}}_{\textbf{NO-IO}}(\textbf{Best fit IO})}{\sqrt{2\overline{\Delta\textbf{LLH}}_{\textbf{NO-IO}}(\textbf{Best fit IO})}}$$

(Red)



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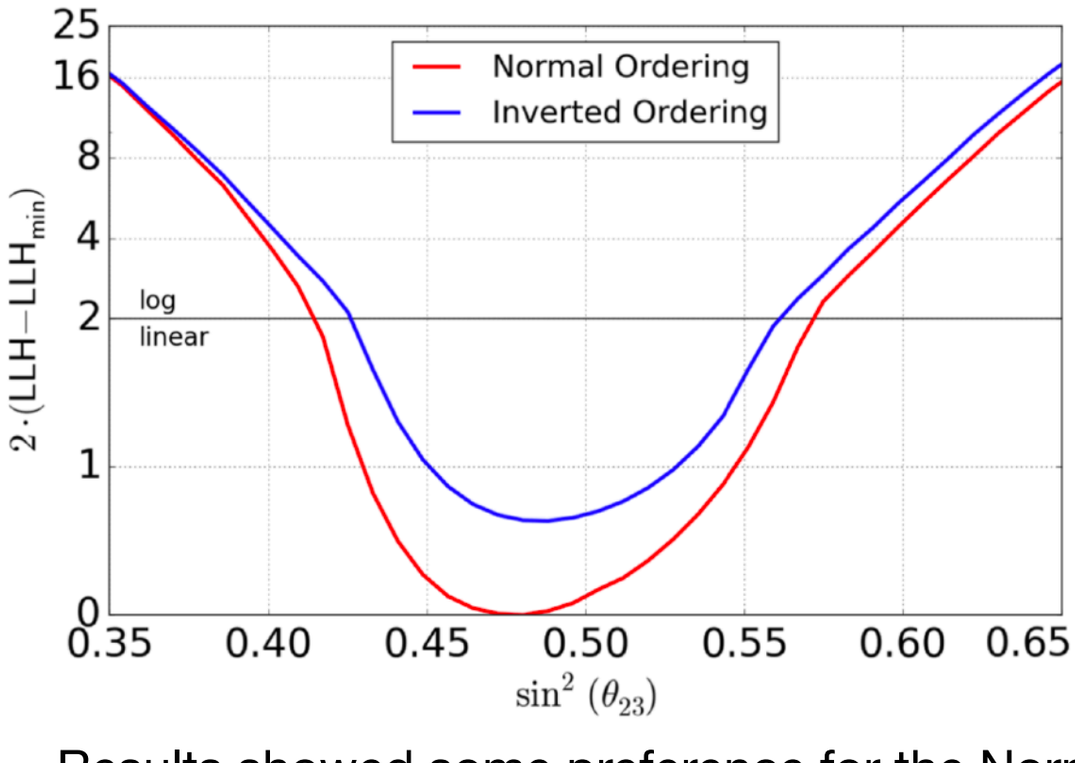
Results

[2]



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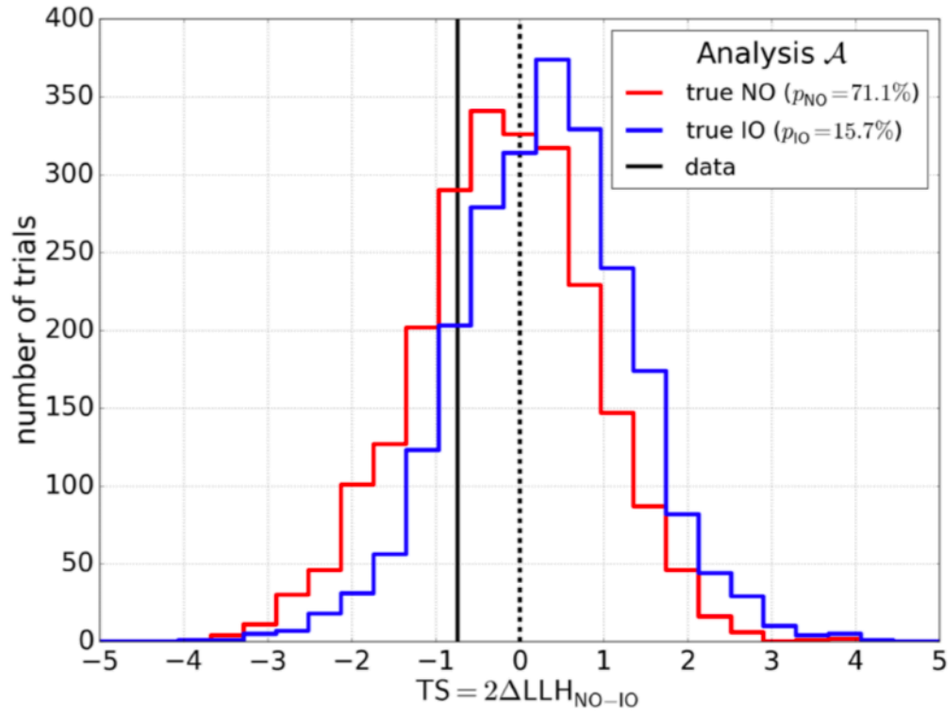

- Results showed some preference for the Normal Ordering vs the Inverted Ordering at a slightly lower mixing angle value than maximal
- Sensitivity was not great to begin with
- Aiming to improve this with a new analysis using 8 years of IceCube DeepCore data (coming soon!) and then improve it even more with the Upgrade
- New analysis will also include improved reconstructions, particle identification, calibrations, systematic uncertainties, etc.
- Idea is for IceCube NMO results to act as a good cross-check at higher energies to results from DUNE and other oscillation experiments

References

[1] https://inspirehep.net/files/3bbc12cc815cca64c67a40ca3010e65a

[2] ArXiv:1902.07771v2 [hep-ex]

[3] https://publications.rwth-aachen.de/record/751704/

files/751704.pdf

Thank you!

Backup Slides

Gaussian Distribution

Chi square function:

$$\chi^2 = \sum_i \frac{(y_i - \tilde{y}_i)^2}{\sigma_i^2}$$

Likelihood function for a Gaussian:

$$L = \prod_i \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(y-\tilde{y})^2}{2\sigma^2}} \propto e^{-x^2}$$

https://www-cdf.fnal.gov/physics/statistics/recommendations/modeling.html

Octant-Dependency of Sensitivity plot