Results from Testing the Neutrino Mass Ordering with Three Years of IceCube DeepCore data

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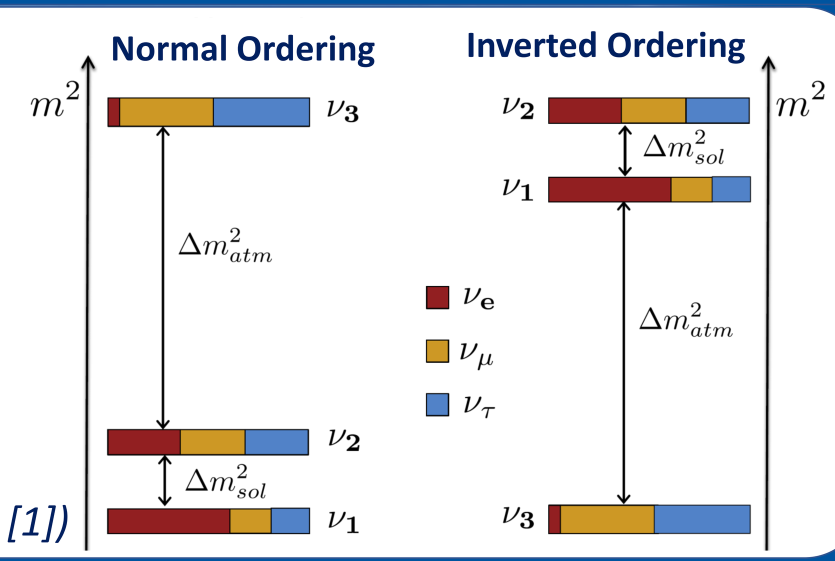
Abstract

The **measurement of the Neutrino Mass Ordering (NMO), i.e. the ordering of the three neutrino mass eigenstates, is a major goal of many future experiments**. One strategy to measure the NMO is observing matter effects in the oscillations of atmospheric neutrinos as proposed for the Precision Next Generation Upgrade (PINGU) of the IceCube Neutrino Observatory.

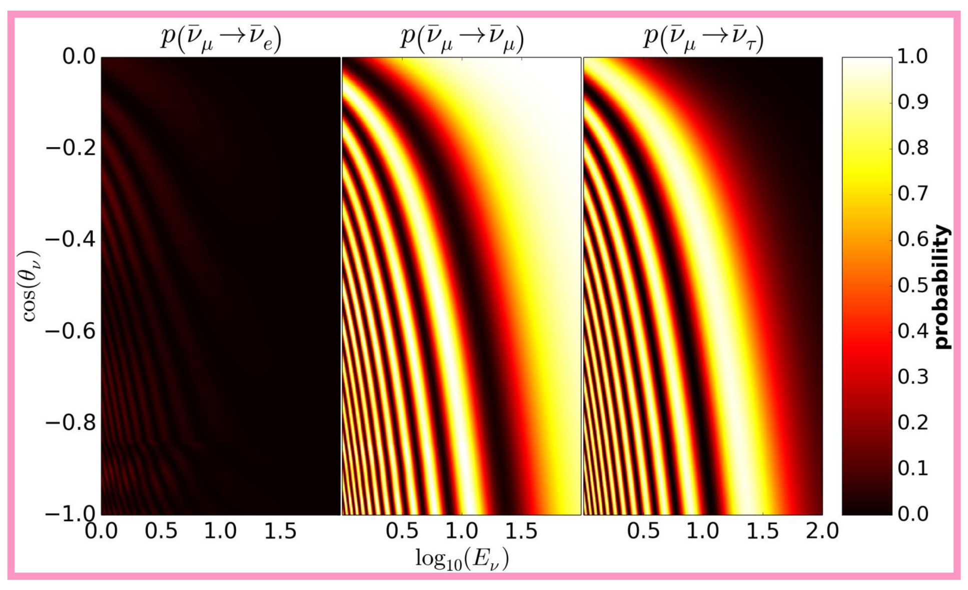
This type of measurement **can already be explored with the currently running IceCube DeepCore detector**. Albeit with lower significance, such a measurement contributes to the current understanding of the NMO. Moreover, it prototypes future analyses with PINGU.

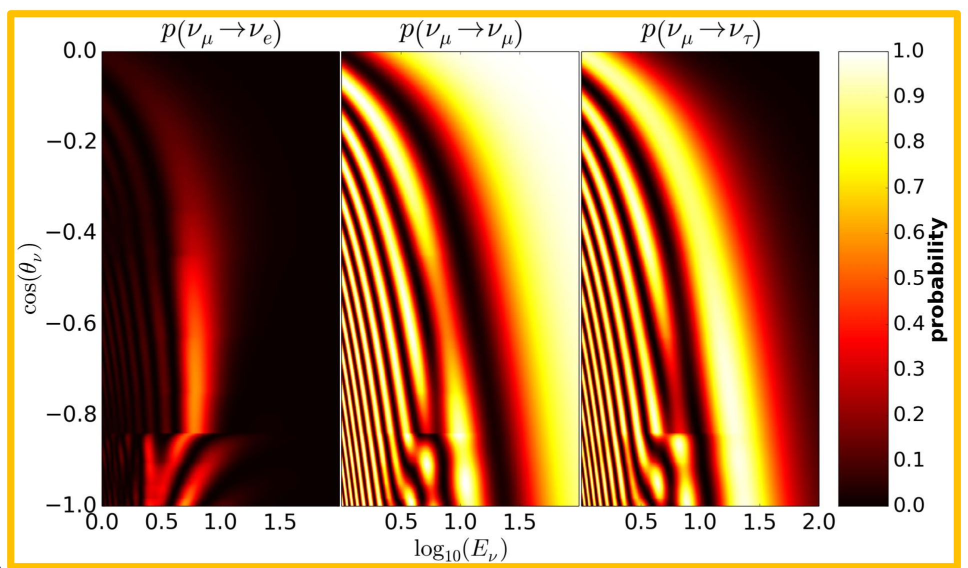
We present results from two likelihood analyses measuring the NMO with three years of data from IceCube DeepCore. In the more sensitive one, **we observe a slight preference for Normal Ordering in the first octant, close to maximum-mixing, with a p-value of p_{IO}=15.3% (CL_s=53%) for Inverted Ordering.**



(plot from [1])

Matter Effects in Atmospheric ν-Oscillations





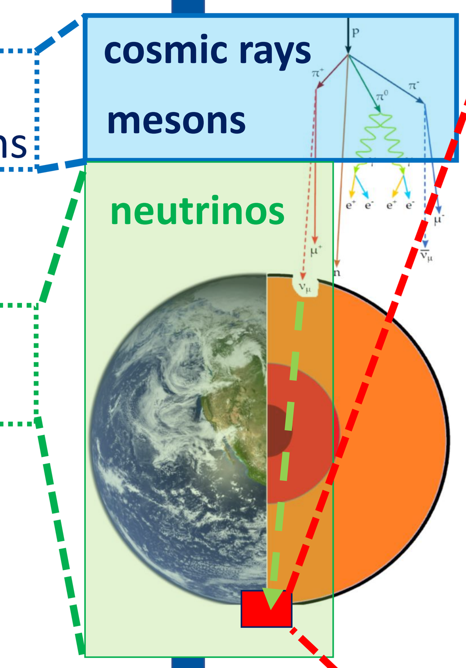
Atmospheric Neutrino Oscillations:

- $\nu_{e/\mu}$ generated in atmosphere by meson decays
- Propagate through Earth undergoing ν-oscillations
- **Vacuum oscillations** identical for ν and $\bar\nu$

Matter Effects:

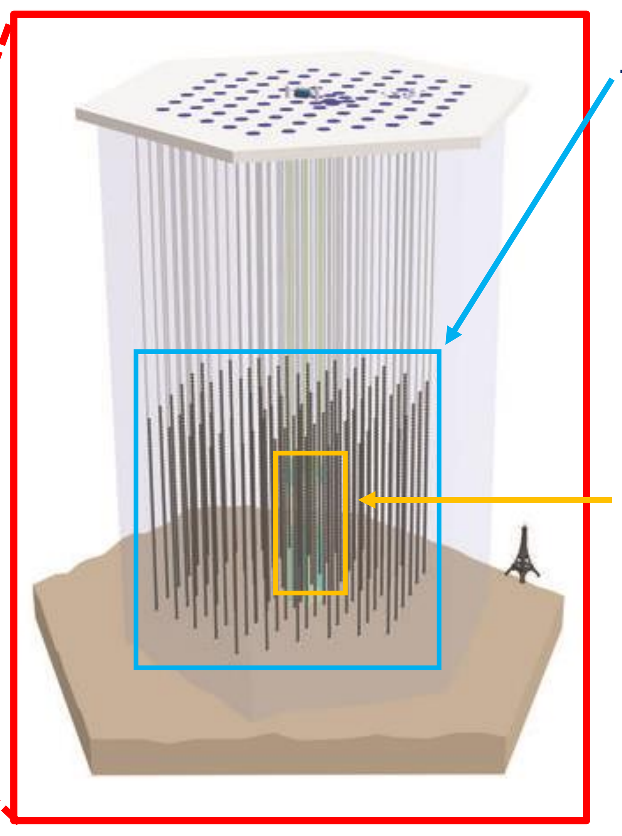
- modify oscillation pattern by ν-e-interactions (MSW effect [2], Parametric Enhancement [3])
- **Matter effects** arise in ν- or $\bar\nu$-channel for NO and IO, respectively:

	NO	IO
neutrinos	$\nu_e \to \nu_\alpha$ $\nu_\mu \to \nu_\alpha$	$\nu_e \to \nu_\alpha$ $\nu_\mu \to \nu_\alpha$
anti-neutrinos	$\bar\nu_e \to \bar\nu_\alpha$ $\bar\nu_\mu \to \bar\nu_\alpha$	$\bar\nu_e \to \bar\nu_\alpha$ $\bar\nu_\mu \to \bar\nu_\alpha$
overall signature	high matter effects	low matter effects



Idea: measure NMO via strength of matter effects

The IceCube DeepCore Detector



IceCube Detector [4]:

- ~1 km^3 Cherenkov detector at Geographic South Pole
- 86 vertical strings carrying ~ 5100 Optical Modules
- detects ν and $\bar\nu$ above E_ν ~ 100 GeV

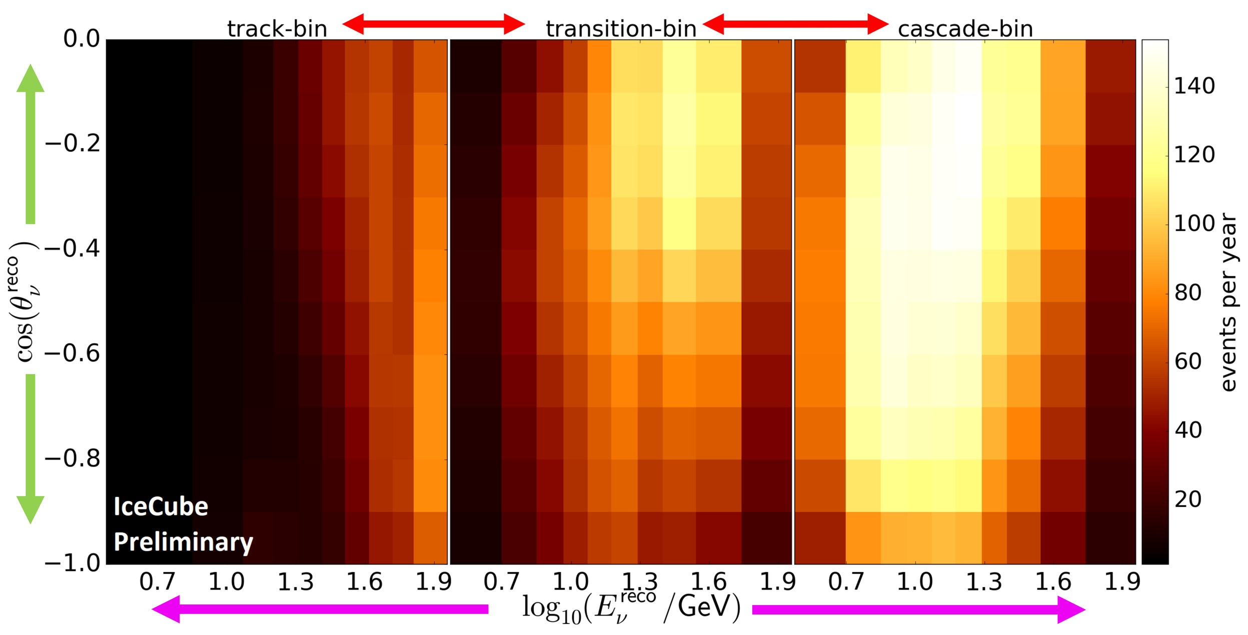
DeepCore Detector [4]:

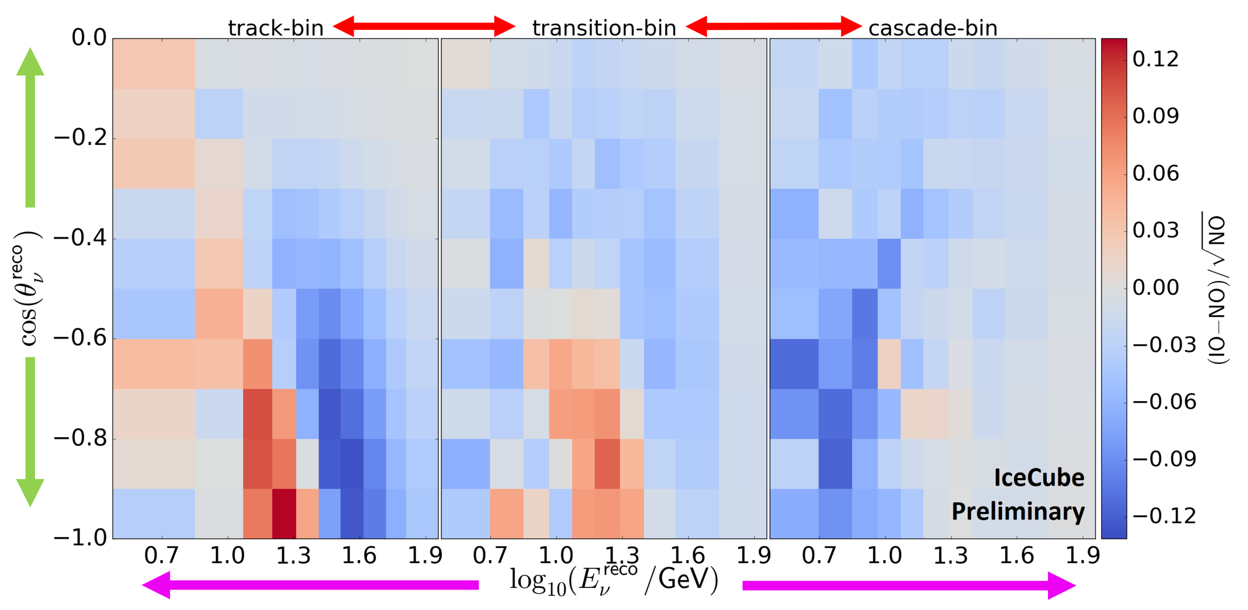
- 8 strings, denser spacing
- High quantum-efficiency Optical Modules
- detects ν and $\bar\nu$ above E_ν ~ 5 GeV

- Partial flavor separation ⇒ tracks (CC ν_μ) and cascades (rest)
- No separation of ν and $\bar\nu$ on event-by-event level
- BUT more ν than $\bar\nu$ due to production + detection cross-sections

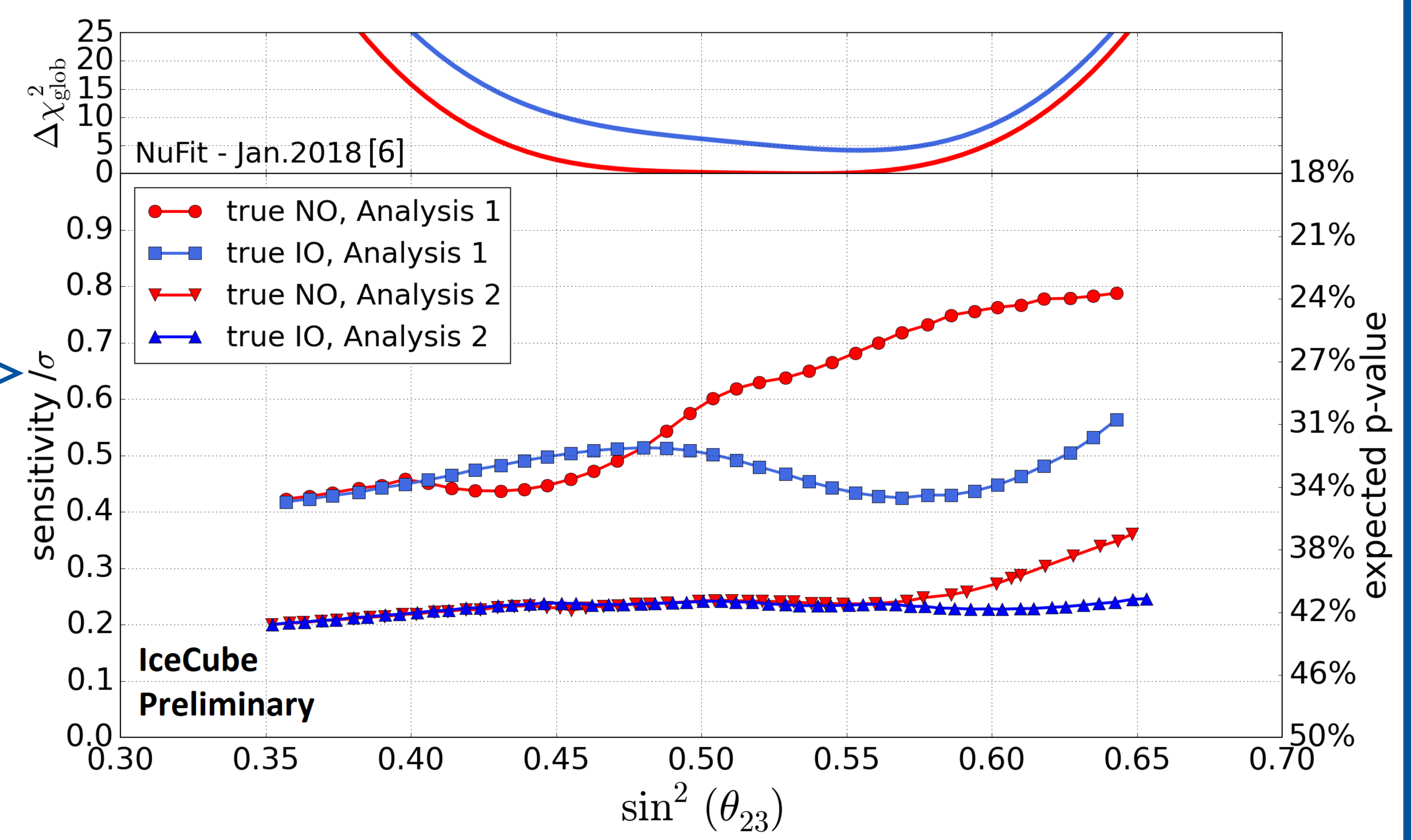
⇒ Visible net-effect of matter effects depends on NMO

Likelihood Analyses





- Reconstruct E_ν, θ_ν and a flavor separating variable (PID)
- Likelihood fit on 3D histograms
- $\Delta LLH_{NO-IO} = LLH(\mathcal{H}_{NO}) - LLH(\mathcal{H}_{IO})$ used as test statistic for separation
- Asimov method for sensitivity [5]
- Parametrize and fit nuisance parameters for systematic uncertainties (15 total):
  - Normalizations
  - Atmospheric fluxes
  - Atmospheric oscillations
  - Detector response
  - ν-nucleon interactions

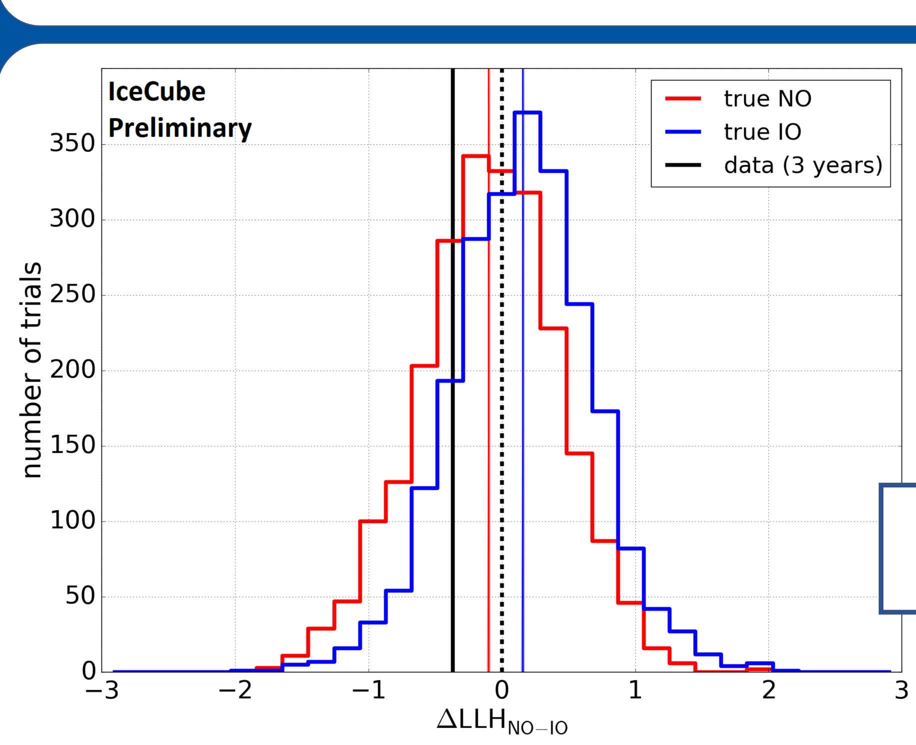


Two Independent Analyses:

1. Sensitivity optimized analysis
2. Benchmark PINGU analysis [1]

Analysis	Selection Focus	Energy Range	Binning (E_ν, θ_ν, PID)	Total Events (2012-14)	Background Description	Template Generation
1	high statistics	4 – 90 GeV	(10, 10, 3)	~ 43,000	simulation	KDEs
2	high quality	5 – 80 GeV	(10, 5, 2)	~ 23,000	data	histograms

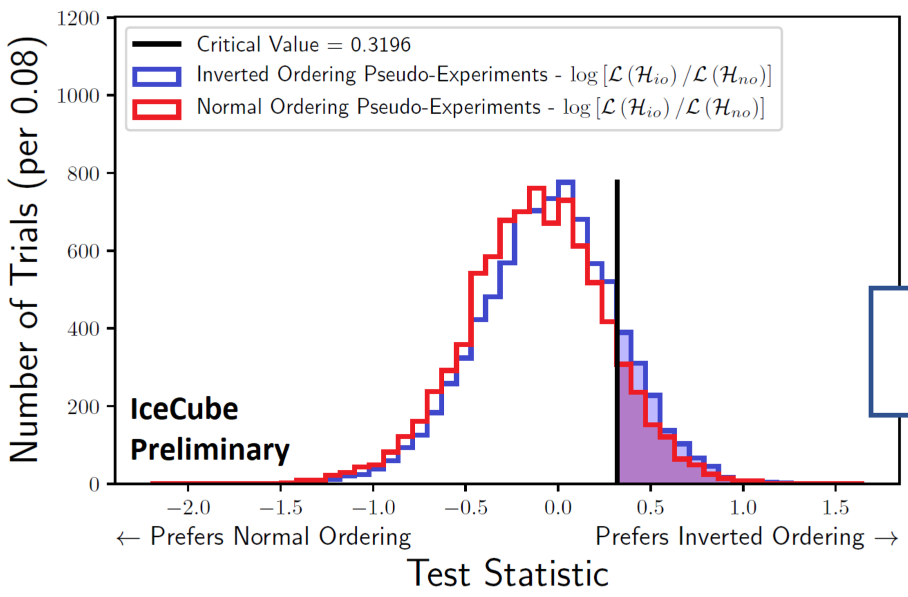
Results on Neutrino Mass Ordering



Analysis 1

Fit prefers NO over IO in first octant:

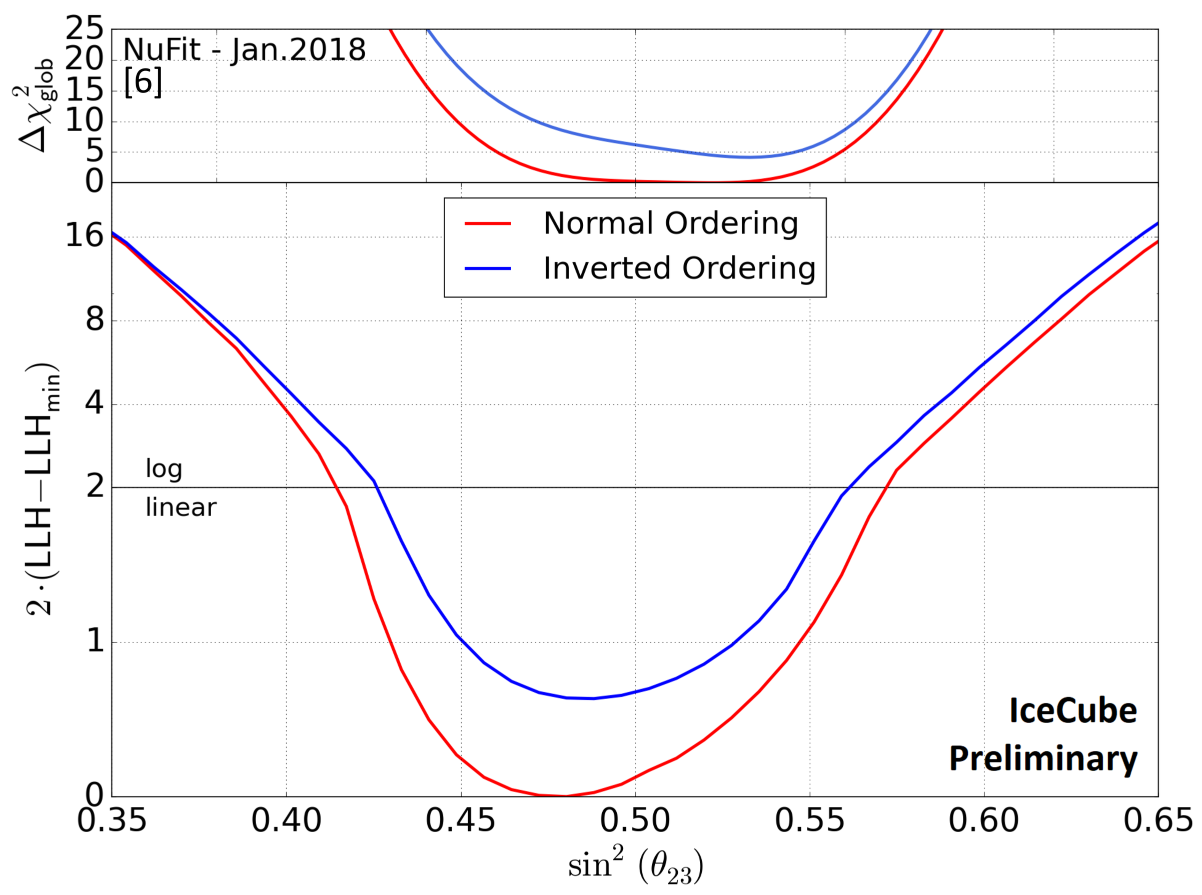
$$p(\mathcal{H}_{NO}) = 71\%$$
$$p(\mathcal{H}_{IO}) = 15\%$$
$$CL_s(\mathcal{H}_{NO}) = 83\%$$
$$CL_s(\mathcal{H}_{IO}) = 53\%$$



Analysis 2

Fit prefers IO over NO in second octant:

$$p(\mathcal{H}_{NO}) = 15\%$$
$$p(\mathcal{H}_{IO}) = 89\%$$
$$CL_s(\mathcal{H}_{NO}) = 73\%$$
$$CL_s(\mathcal{H}_{IO}) = 96\%$$



- Preference for NO over IO visible in LLH scan for all values of $\sin^2(\theta_{23})$
- Observed NO preference and oscillation parameter consistent with global fits (NuFit Jan. 2018 [6])

Conclusion

- Matter effects in atmospheric ν-oscillations can be used to determine the NMO
- DeepCore capable to test the NMO with existing data
  - More sensitive analysis prefers Normal over Inverted Ordering at $p(\mathcal{H}_{IO}) = 15\%$, $CL_s(\mathcal{H}_{IO}) = 53\%$ in the first octant, close to maximum mixing
  - Results consistent with global fit of oscillation parameters [6]
- Prototype analysis and proof of principle for future IceCube-Gen2 extension and PINGU [1]

References:

[1] The IceCube-PINGU Collaboration, Letter of Intent (2017), arXiv:1401.2046v2
[2] I. Mocioiu and R. Shrock, AIP Conf. Proc. 533 (2000), p. 74-79, DOI: 10.1063/1.1361725
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[4] The IceCube Collaboration, JINST 12 (2017), no. 3, p. 03012
[5] E. Ciuffoli, J. Evslin, X. Zhang, JHEP 1401 (2014) , p. 095
[6] I. Esteban *et al.*, NuFIT 3.2 (2018), www.nu-fit.org