Status of PINGU
measuring the NMH using atmospheric neutrinos

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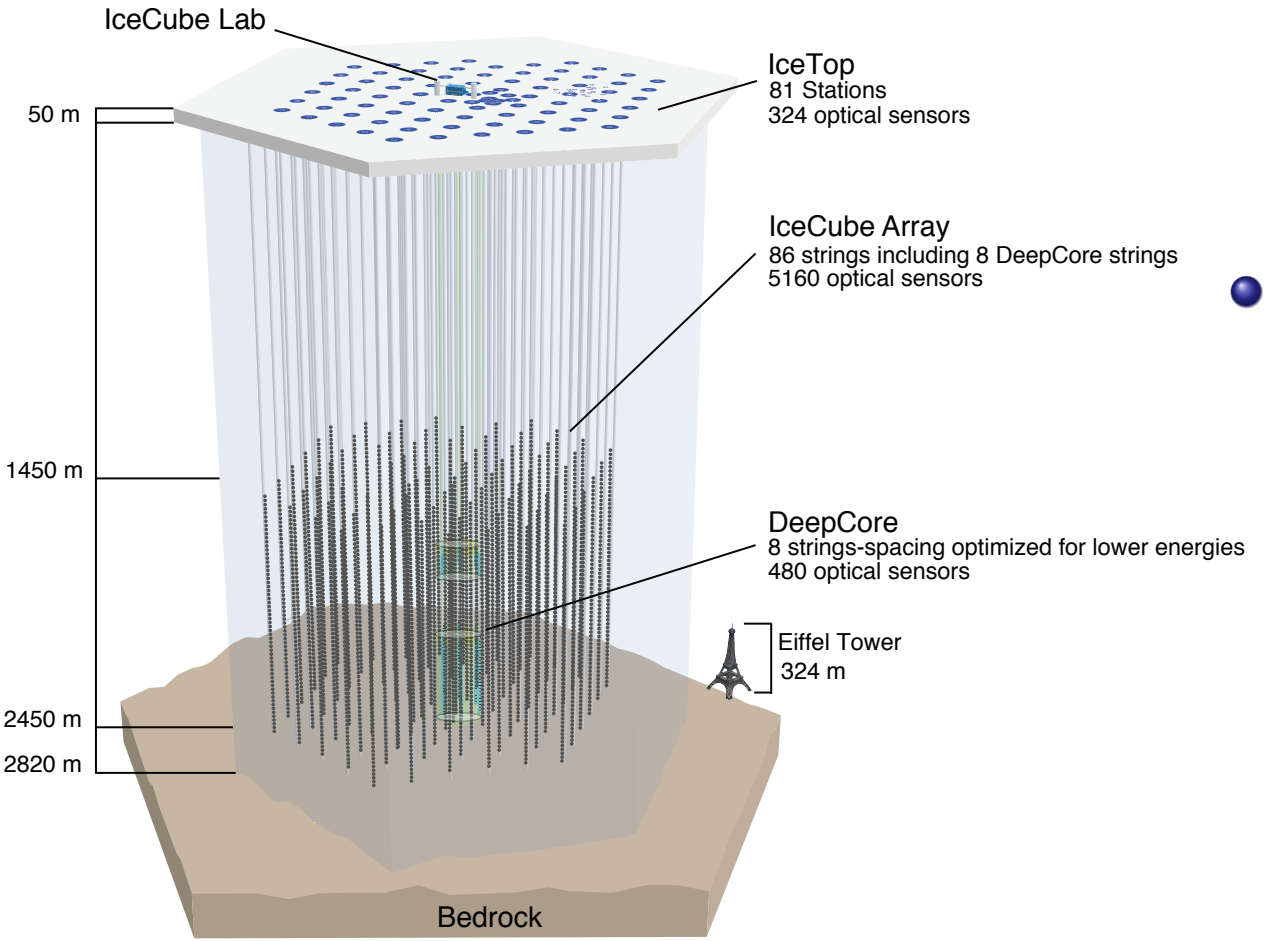
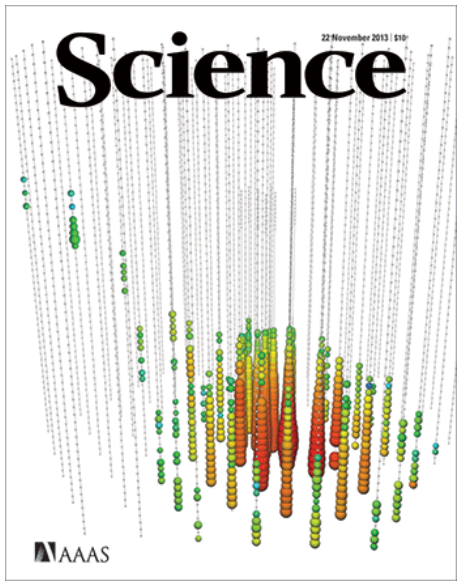
IceCube

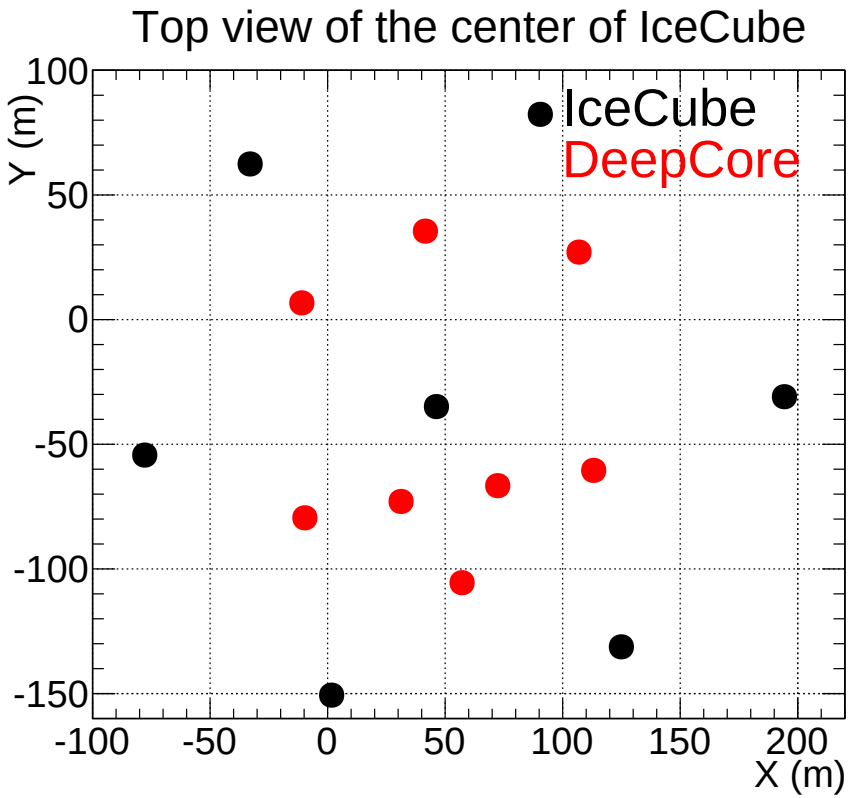


- Without DeepCore:
  78 strings,
  125 m string spacing,
  17 m module z-spacing
- Optimized for (very)
  High Energy neutrinos



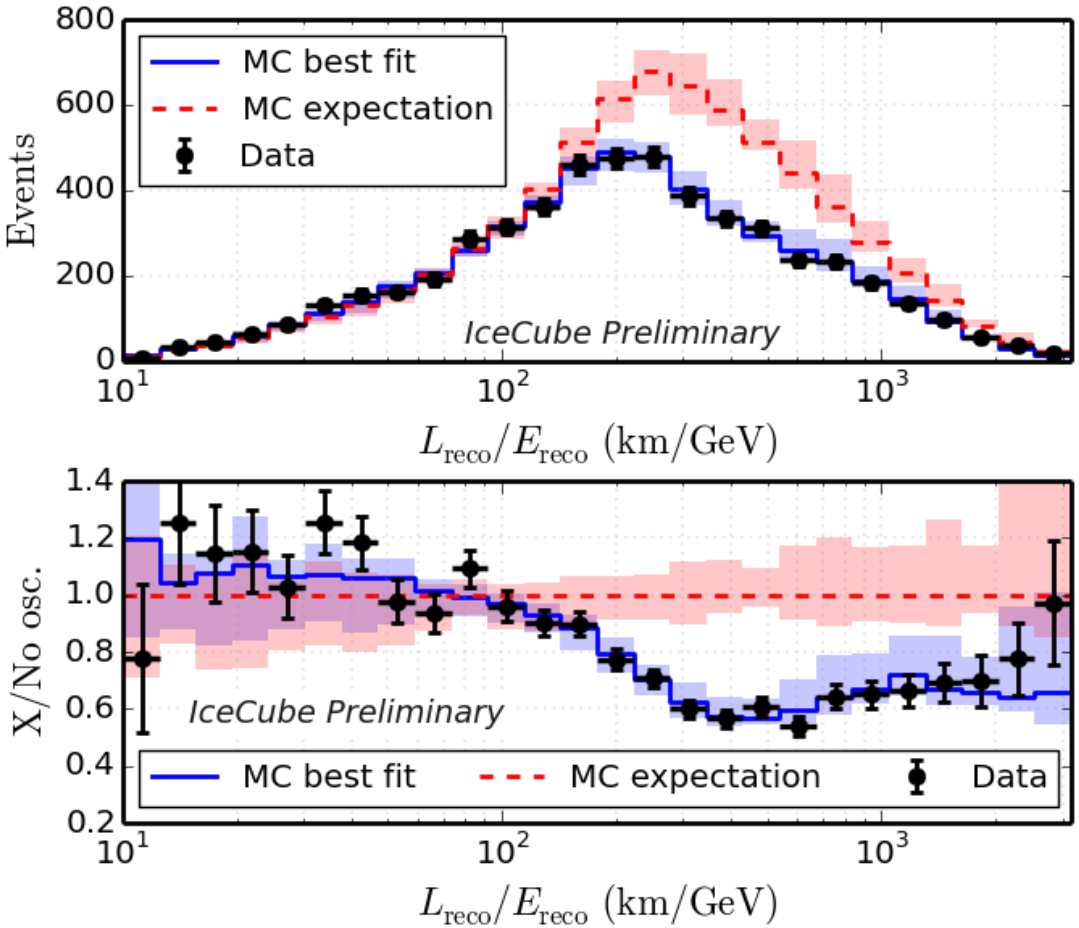
IceCube-DeepCore

- 78 strings, 125 m string spacing
- 17 m modules z-spacing
- 8 strings, 75 m string spacing
- 7 m modules z-spacing



Recent results with DeepCore

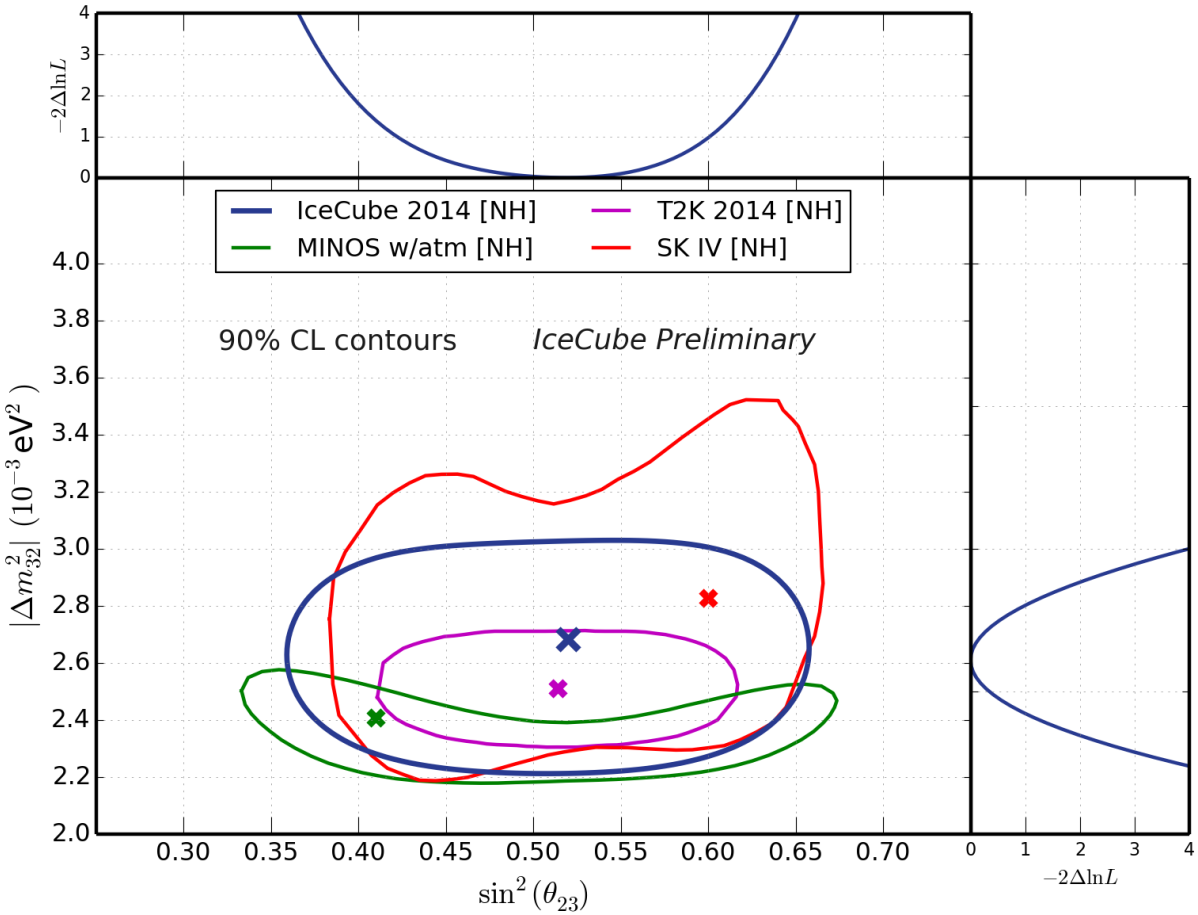
3y ν_μ disappearance oscillation analysis



- Very strong ν_μ disappearance signal
- Good agreement between data and MC

Recent results with DeepCore

3y ν_μ disappearance oscillation analysis



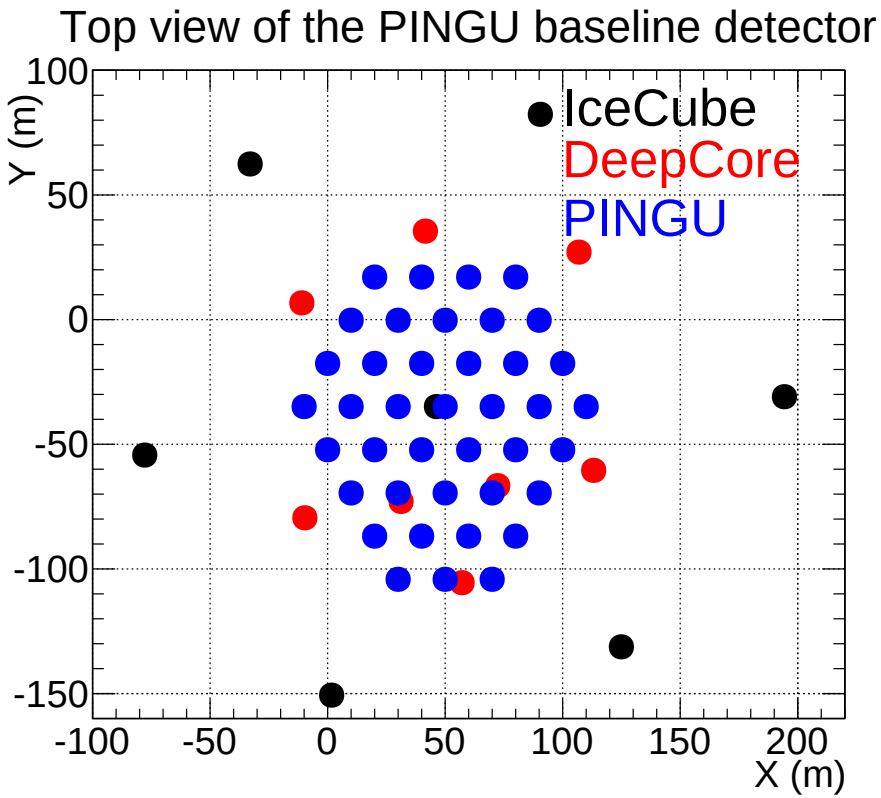
- Result consistent and competitive with other experiments
- Presented at Neutrino 2014, paper being prepared

IceCube-DeepCore-PINGU

- 78 strings, 125 m string spacing
- 17 m modules z-spacing

- 8 strings, 75 m string spacing
- 7 m modules z-spacing

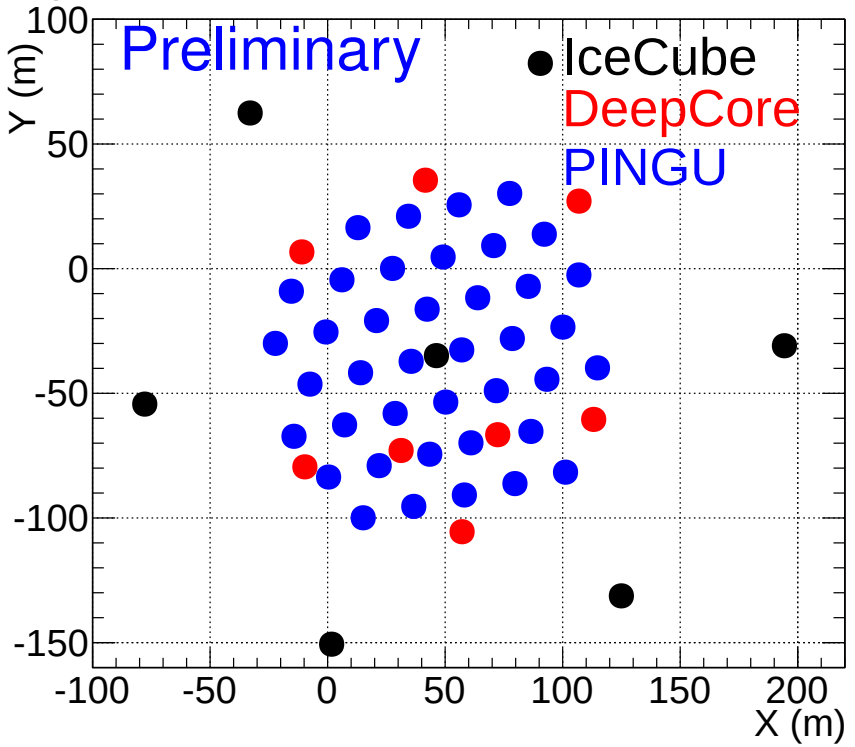
- 40 strings, 20 m string spacing
- 5 m modules z-spacing
- This is not final geometry



IceCube-DeepCore-PINGU

- 78 strings, 125 m string spacing
- 17 m modules z-spacing
- 8 strings, 75 m string spacing
- 7 m modules z-spacing
- 40 strings, 22 m string spacing
- 3 m modules z-spacing
- Improved string placement!
  - This is not the geometry used here but results are similar
  - String placement in this geometry should be feasible!

Top view of the PINGU new candidate detector

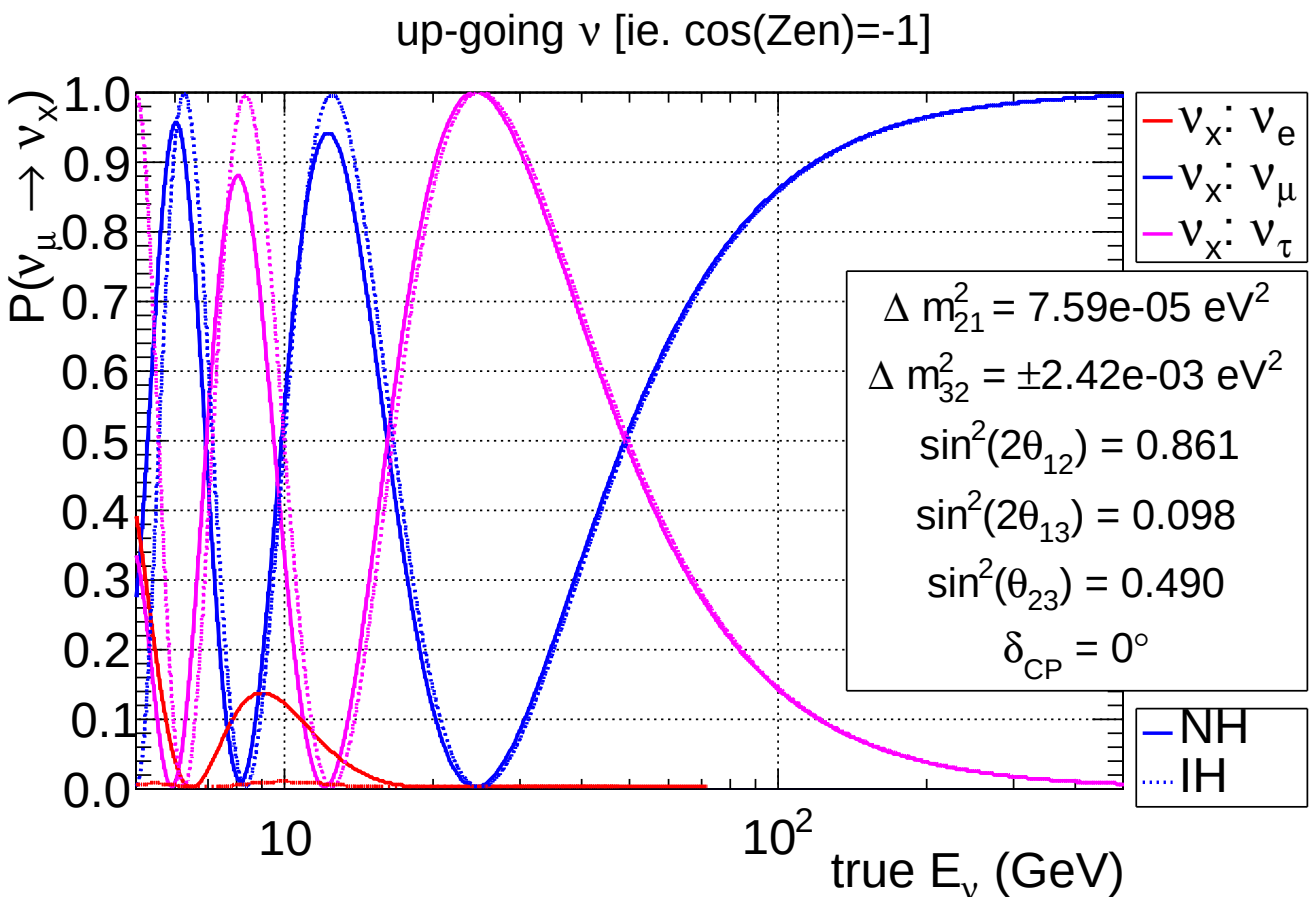


PINGU physics program

- Precision measurements of atmospheric neutrino oscillation at a few GeV with very high statistics
  - Measure Neutrino Mass Hierarchy (NMH)
  - Precise measurement of Δm^2_{23}, θ_{23}
  - High statistics measurement of ν_τ appearance
- Probe lower mass WIMPs
- Increase sensitivity to supernovae ν bursts
- Earth tomography
- For more information refer to our Letter of Intent (arXiv:1401.2046)

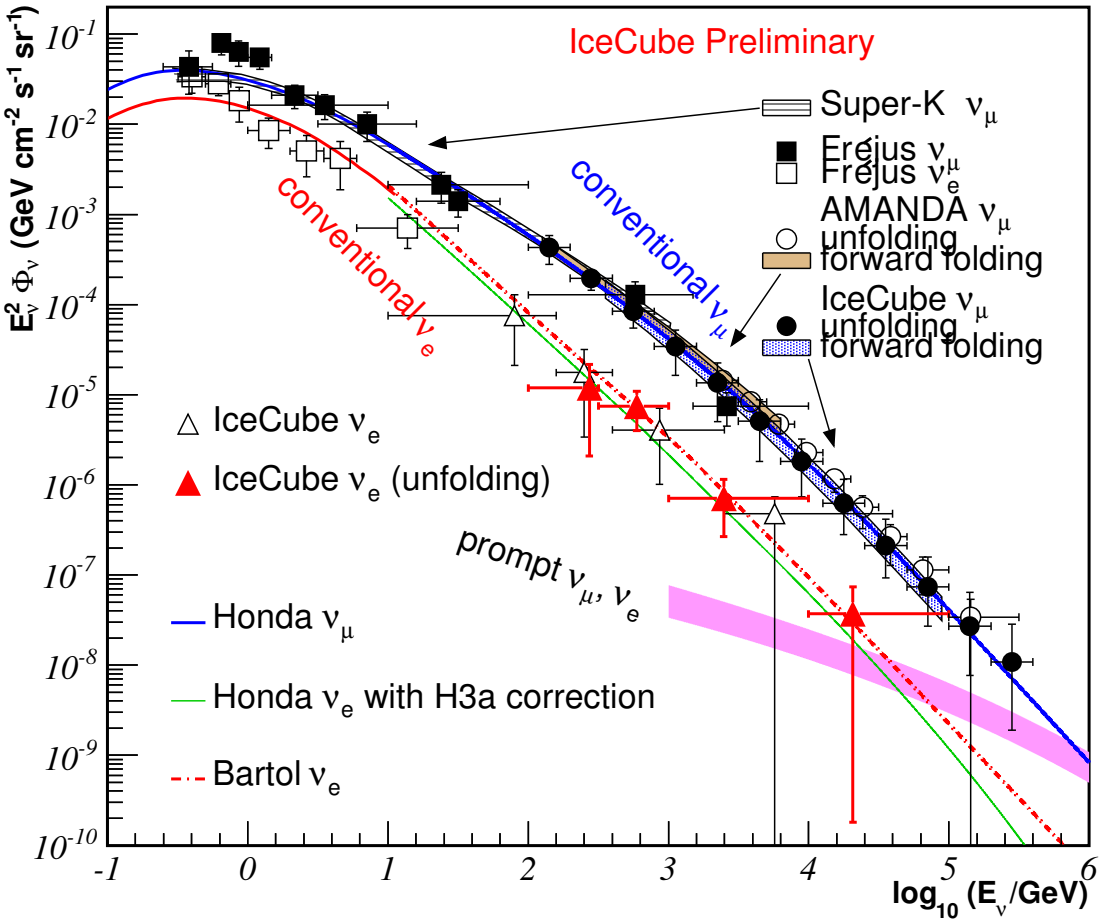
Using atmospheric ν to study ν oscillation

- Neutrinos oscillating through the Earth's diameter have "first" maximum of ν_μ disappearance at 25 GeV
- Hierarchy dependent matter effects below $\sim$12 GeV



Atmospheric neutrinos signal in PINGU

- Large quantity of neutrinos from different baselines and energies

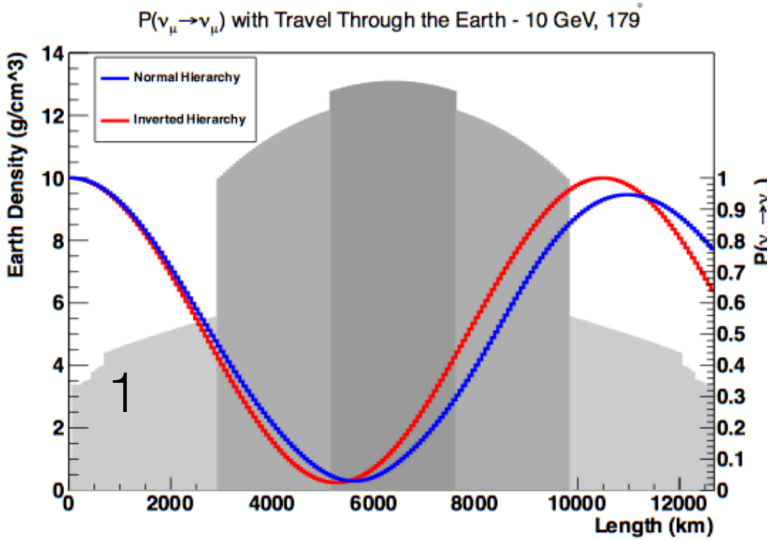


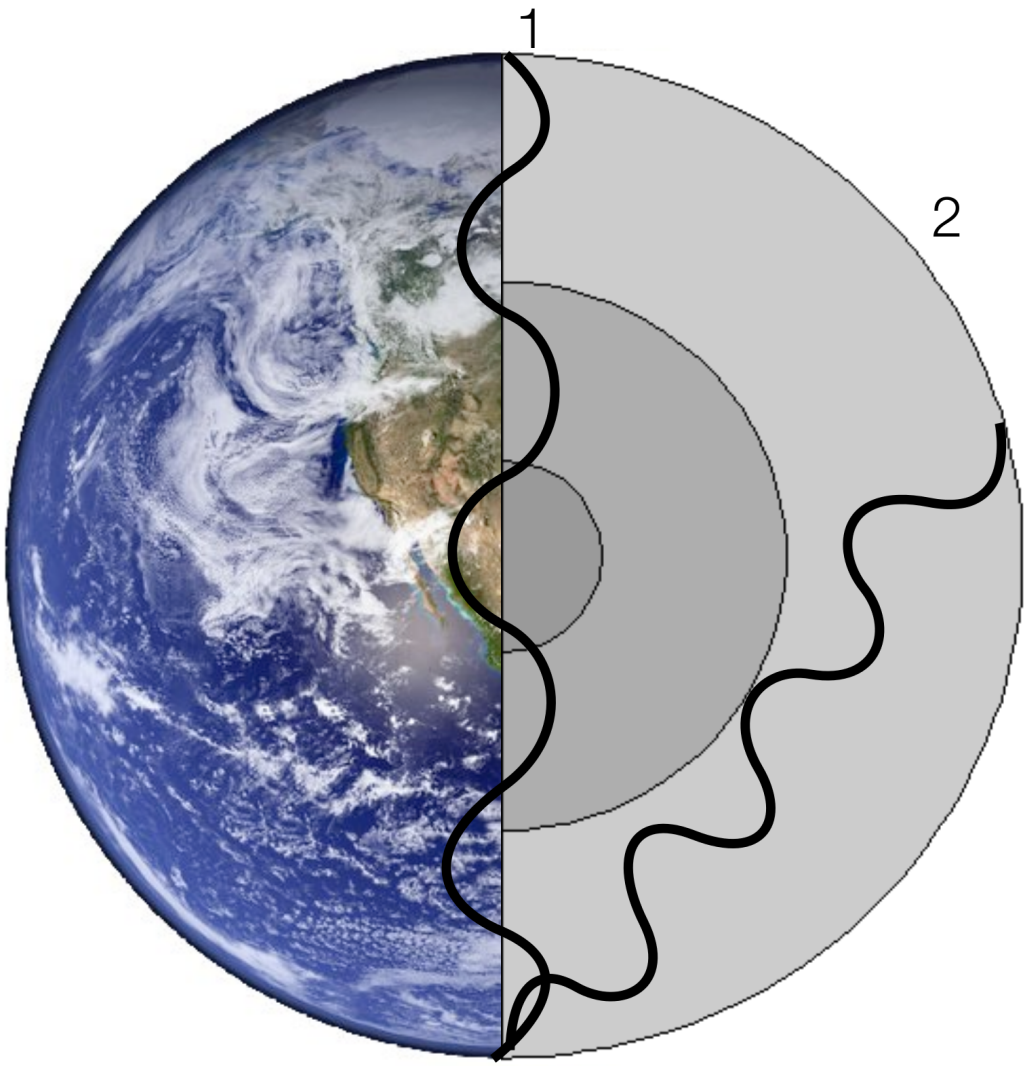
Number of events/year expected:

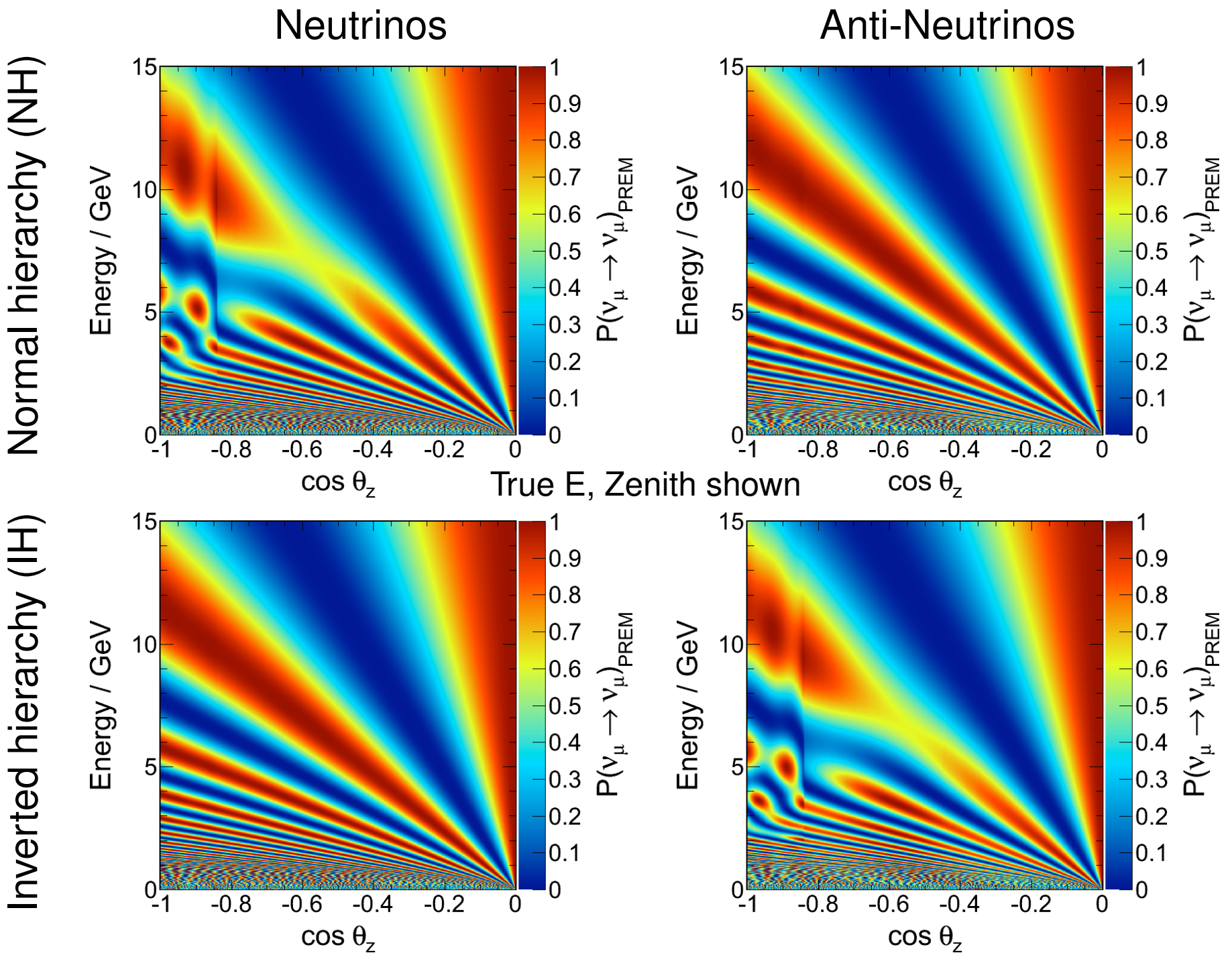
	Trigger detector	Pass analysis cuts
ν_e CC	52k	26k
ν_μ CC	86k	35k
ν_τ CC	6.4k	2.7k
ν NC	17k	7.9k

Measuring the ν Mass Hierarchy with atmospheric ν

- Comparison of different baselines helps control systematics



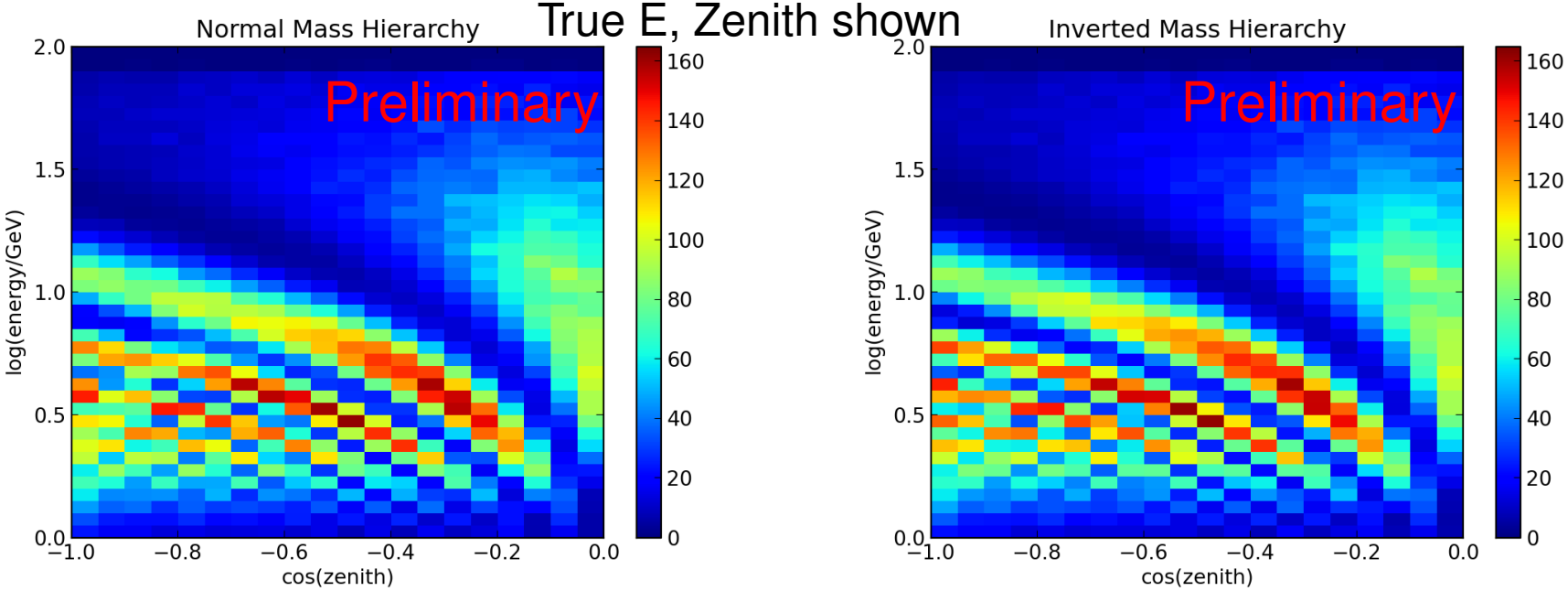



Neutrinos
Anti-Neutrinos
Normal hierarchy (NH)
Inverted hierarchy (IH)
Energy / GeV
cos θz
P(νμ → νμ)PREM
True E, Zenith shown

Pattern from atmospheric oscillation

$\nu_\mu + \overline{\nu}_\mu$ CC only, no detector effects shown

True E, Zenith shown

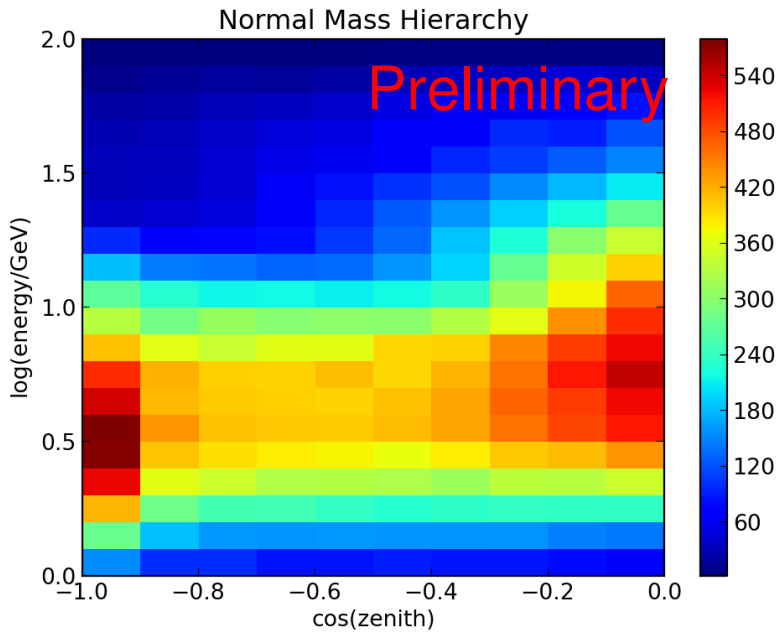


- PINGU cannot distinguish ν and $\overline{\nu}$ directly:
  - rely on natural difference in flux and cross-section
  - to a lesser extent could do statistical separation based on kinematics
- Visible differences at first ν_μ "re-appearance" region
  - WARNING: resolutions not included in this plot!

Expected event rate from atmospheric neutrinos

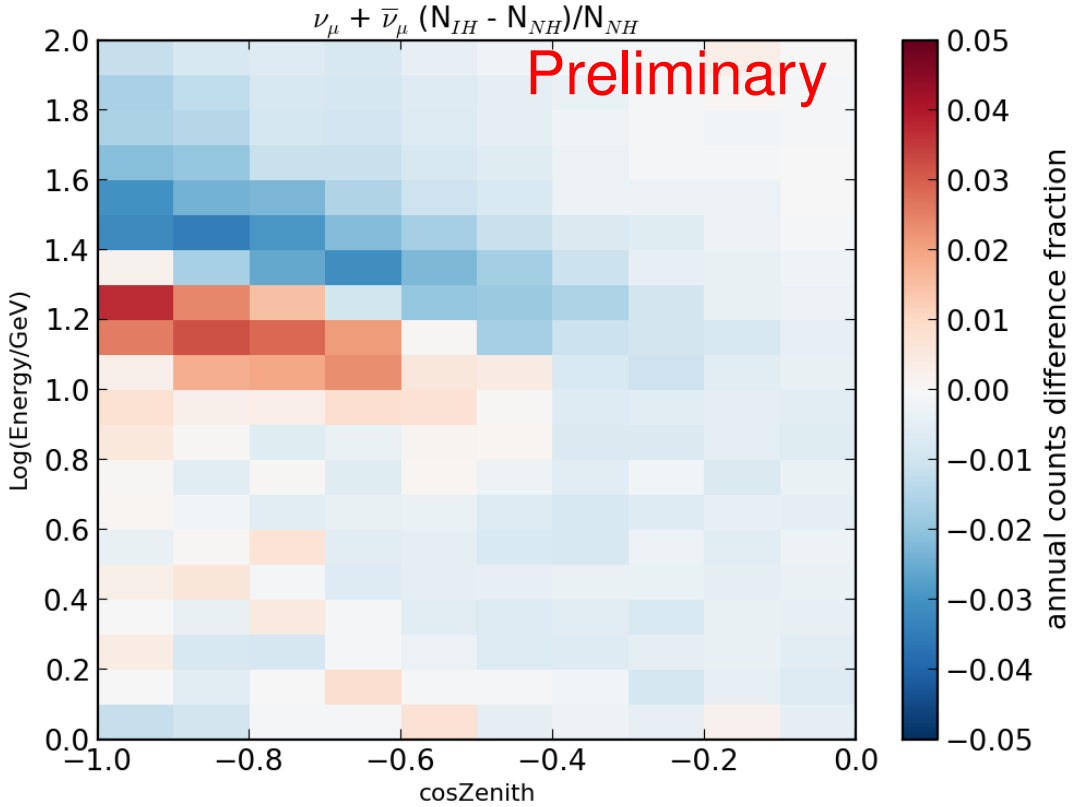
$\nu_\mu + \overline{\nu}_\mu$ CC only, normal hierarchy

- With detector resolutions, signature barely distinguishable by eye:
  - fast oscillation smeared by our resolutions
  - small difference in shape $\rightarrow$ easier to see when comparing difference between normal and inverted mass hierarchy
- To determine sensitivities use full MC simulation using IceCube tools



Expected rate difference between IH and NH

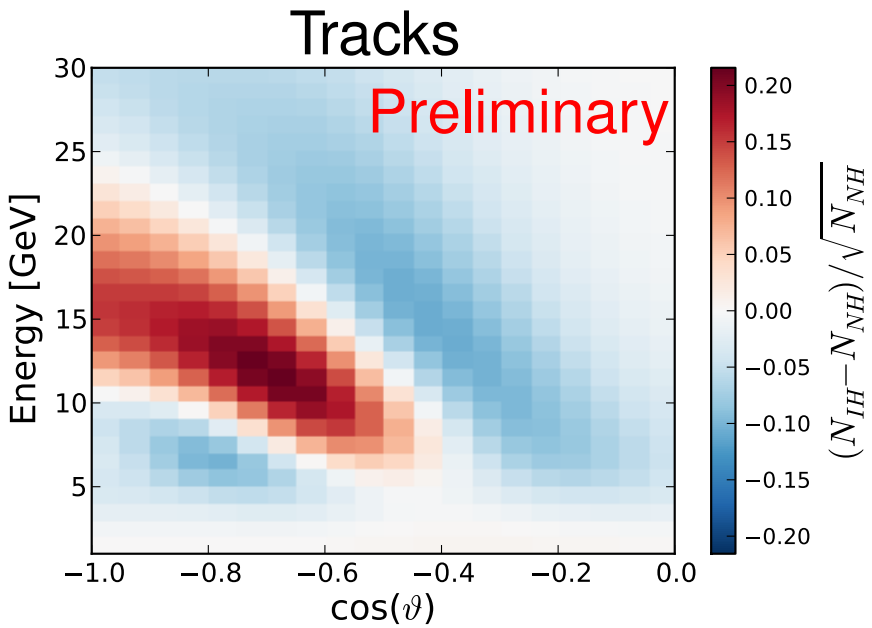
$\nu_\mu + \overline{\nu}_\mu$ CC events only, no particle identification

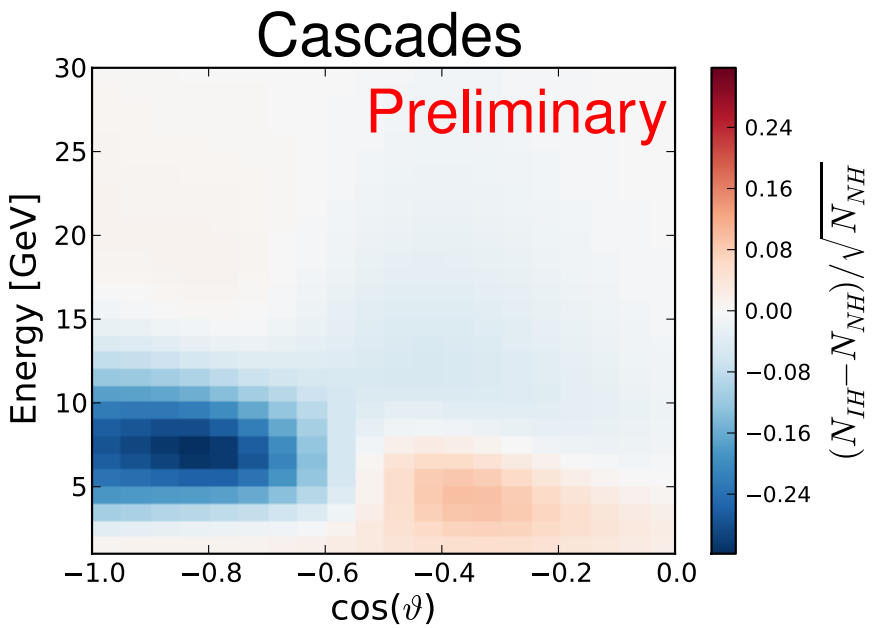


- Shape difference is more visible with a “difference” based metric
  - WARNING: Particle identification not included in this plot
- Pattern measured is important to limit contribution of systematic errors

Bin-by-bin significance of mass hierarchy signature

See arXiv:1401.2046



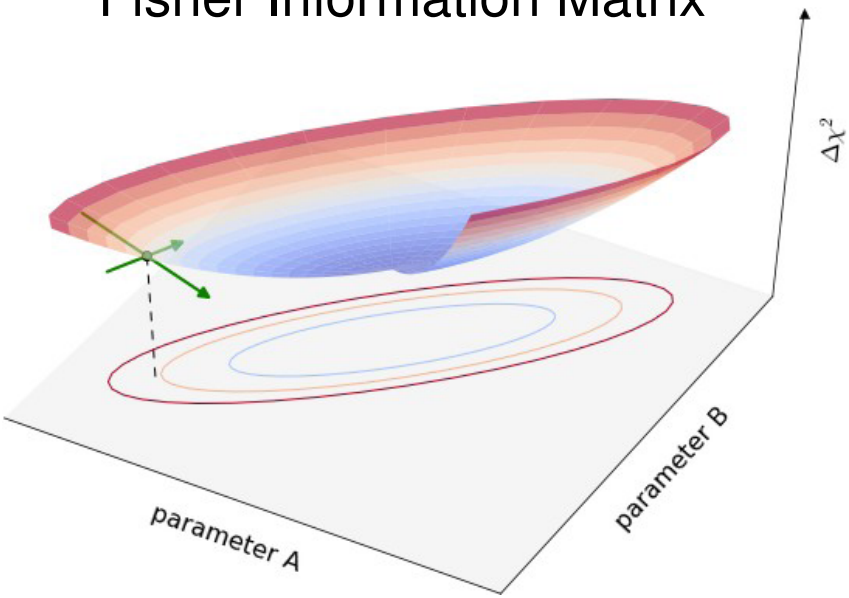


- Distinct hierarchy dependent signatures for tracks (mostly ν_μ CC) and cascades (mostly ν_e CC)
  - Intensity is statistical significance of each bin with 1 year data
  - Uses MC information for detector efficiency, reconstruction and particle identification

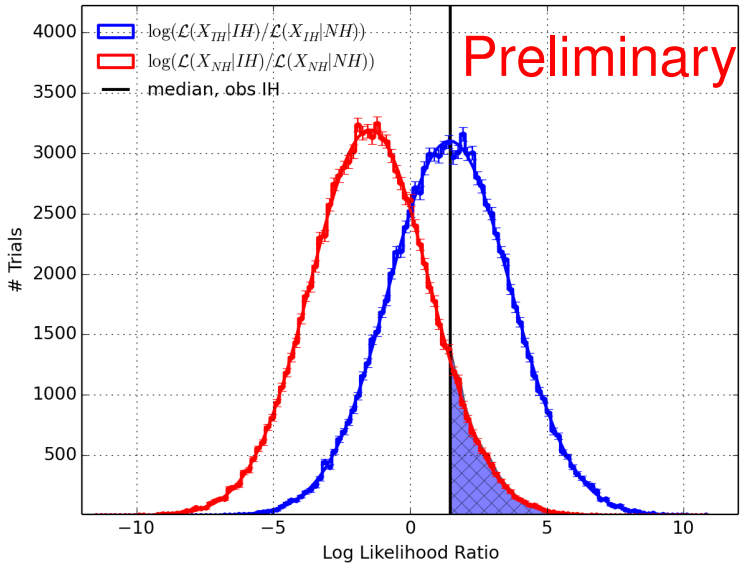
Estimating sensitivity of PINGU to the NMH

methods

Fisher Information Matrix



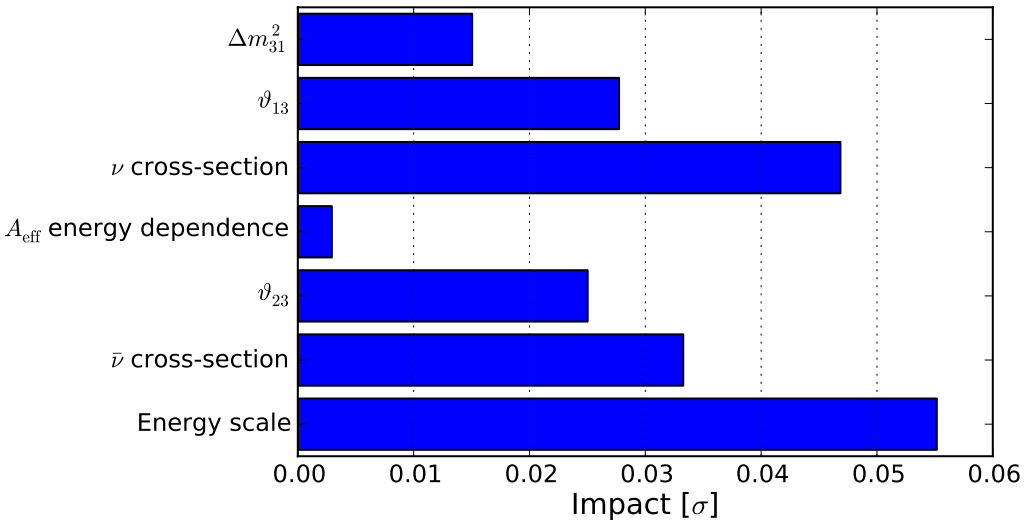
Likelihood Ratio



- Currently two methods used: the Fisher Information Matrix and Likelihood Ratio
  - Output of full simulation and reconstruction used
  - Analysis done in $E_\nu \times$ cos(zenith) space
  - Fisher Information Matrix: Fast evaluation using gradients at each point to fully describe parabolic minimum
  - Likelihood Ratio: Full analysis from pseudo data sets. While method is slower it does not pre-suppose distributions are Gaussian
  - Both methods are in agreement

Estimating sensitivity of PINGU to the NMH

systematics

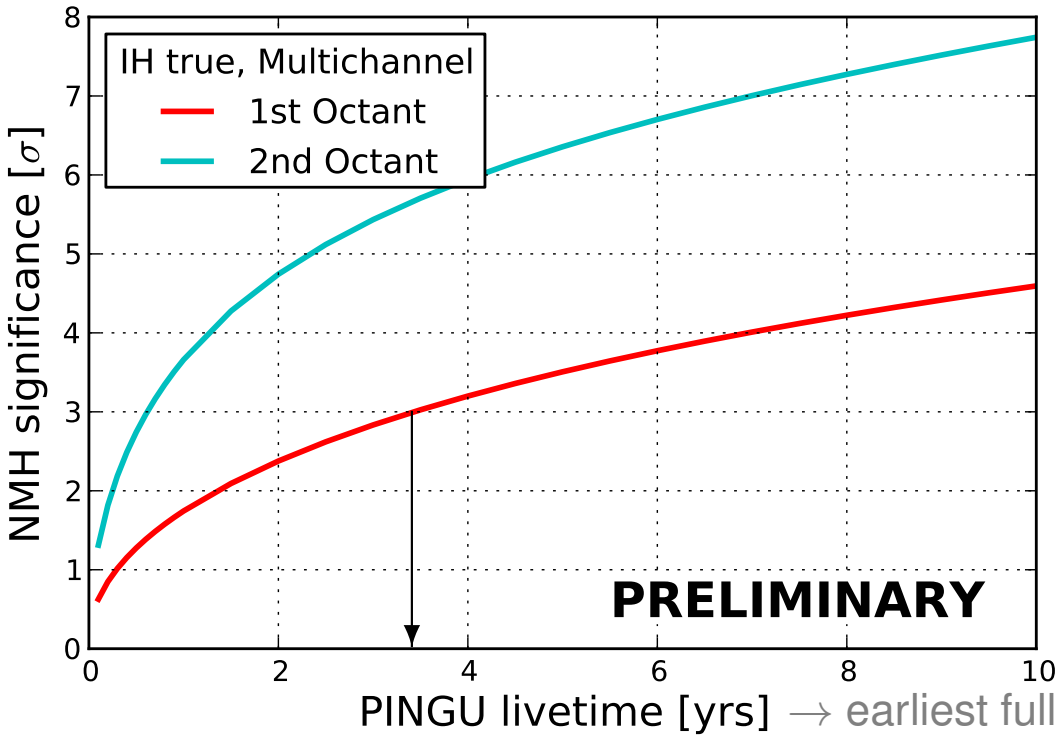


Impact: change to NMH significance if systematic error is assumed perfectly determined by other data

Parameter	Description
Δm^2_{31}, ϑ_{23}, ϑ_{13}	Oscillation parameters
ν / $\bar{\nu}$ cross-section	Cross-section/flux normalization (fully degenerate)
A_{eff} energy dependence	Degenerate with spectral index of atmospheric flux
Energy scale	$E_{\text{reco}}/E_{\text{true}}$

- Main uncertainties are energy scale and ν cross-section
- δ_{CP} has negligible effect
- Additional systematics being incorporated:
  - Particle identification efficiency
  - Cross-section details
  - Ice model

PINGU sensitivity to the NMH



True oscillation parameters	
θ_{12}	$= 33.6°$
θ_{23}	$= 38.7°, 51.3°$
θ_{13}	$= 8.93°$
Δm^2_{21}	$= 7.54 \cdot 10^{-5}$ eV^2/c^4
Δm^2_{31}	$= -2.38 \cdot 10^{-3}$ eV^2/c^4
δ_{CP}	$= 0$

[based on Fogli et al., Phys.Rev. D86 (2012) 013012]

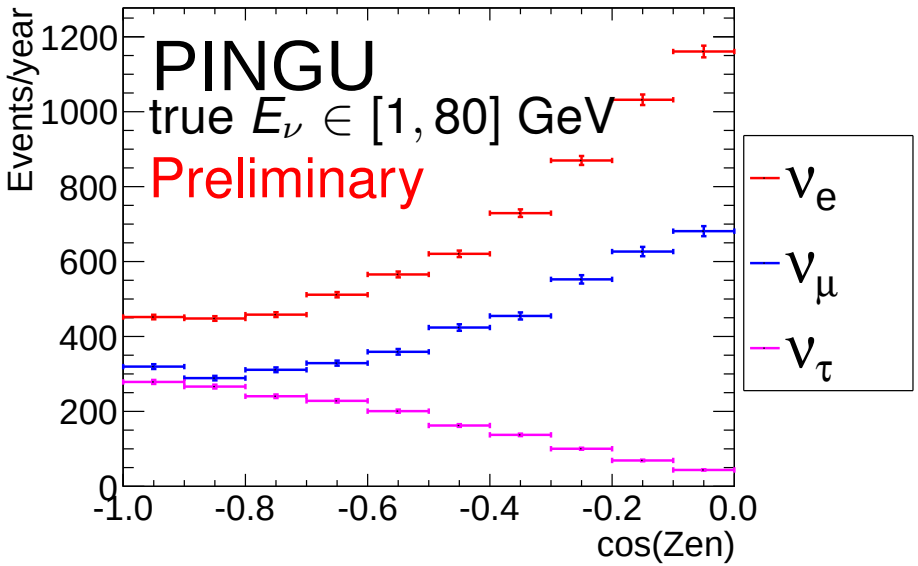
$\rightarrow$ earliest full detector starting date anticipated: 2020

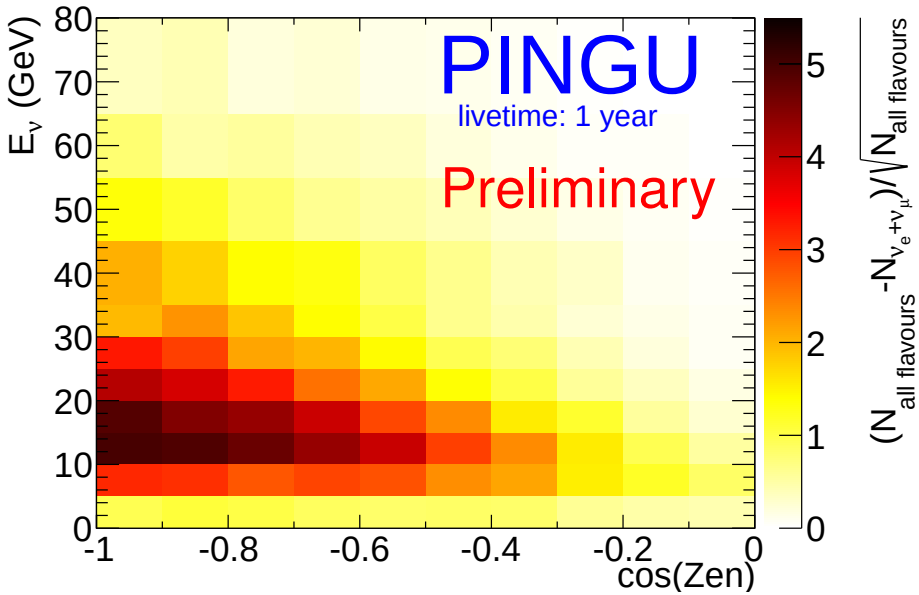
- With baseline geometry, 3 σ determination of mass hierarchy with 3.5 years of data (first octant)
  - Combine track and cascade channels to obtain NMH significance
  - Significance calculated using parametric response of detector from MC
  - Verified to work using Full MC with a limited number of systematics
- Optimization of detector geometry, improvement of analysis and refined treatment of systematics in progress

Other atmospheric measurements: ν_τ appearance

Comparison to NMH analysis

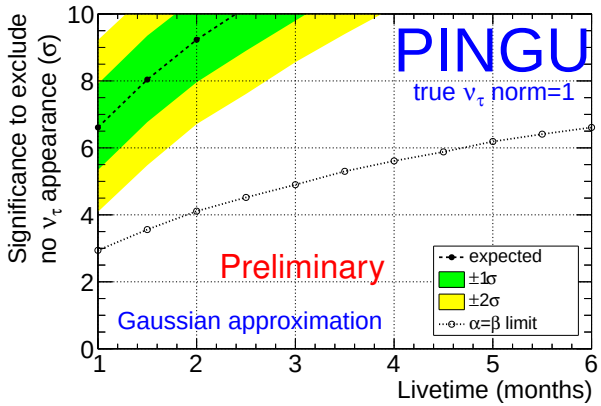
- Uses same event selection as NMH analysis (goal to reject atm. μ)
- Use same BDT training for particle identification as for NMH, however select "pure" cascade-like events (goal to reject ν_μ CC)
- ν_τ statistically significant in final sample

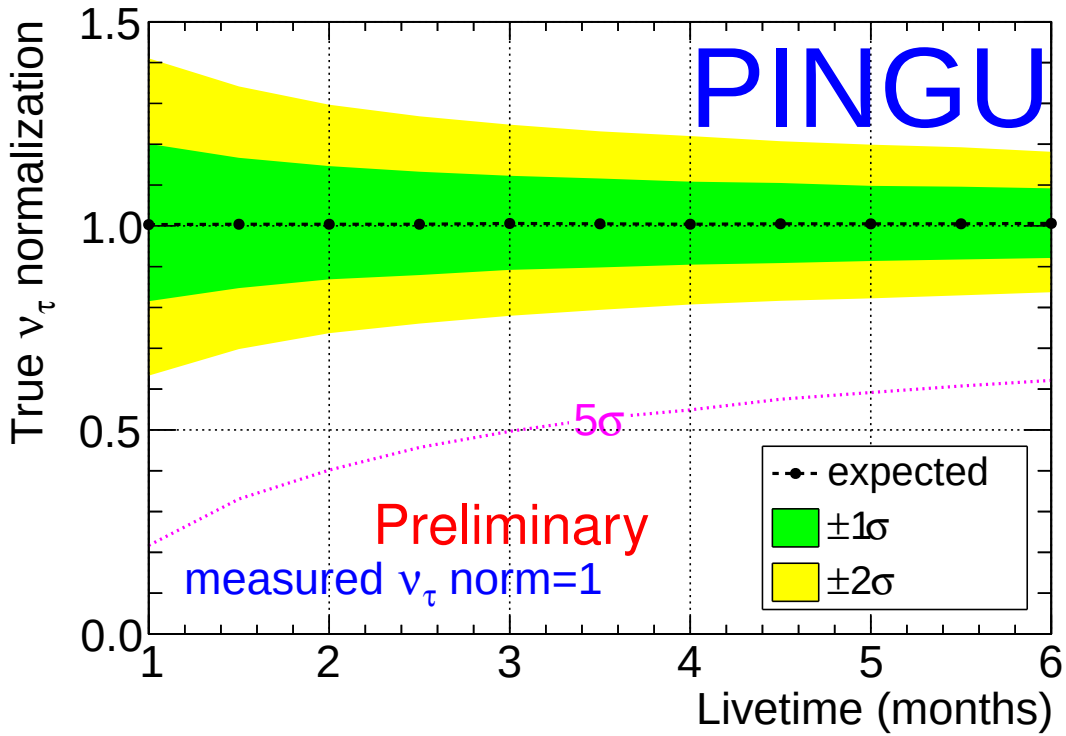




Other atmospheric measurements: ν_τ appearance

Expected sensitivity





- Assumes similar systematics as NMH
- 5σ exclusion of no ν_τ appearance after 1 month of data
- 10% precision in the ν_τ normalization after 6 months
  - Test of the unitarity of the ν mixing matrix

Summary and outlook

- IceCube-DeepCore has shown we can do competitive measurements of neutrino properties

- PINGU is currently being optimized
  - String and optical module placement has fairly broad minimum for the NMH sensitivity
  - However adding detectors (60 $\rightarrow$ 96 modules/string) improves 3 year NMH significance from 2.8 σ to nearly 3.3 σ, for a 10% increase in project cost

- Besides NMH, PINGU can also improve precision on atmospheric parameters, statistically measure ν_τ appearance, increase sensitivity to low-mass indirect WIMP searches, study Earth tomography, ...

- PINGU profits from expertize acquired from IceCube $\Rightarrow$ reduced project risk and potentially quick deployment, dependent on funding

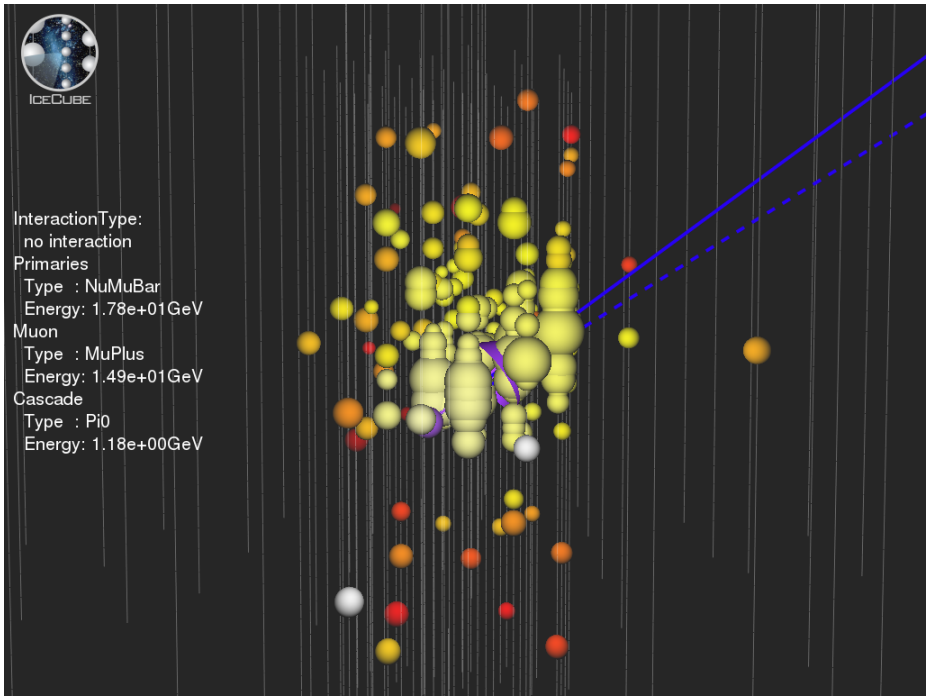
The IceCube–PINGU Collaboration

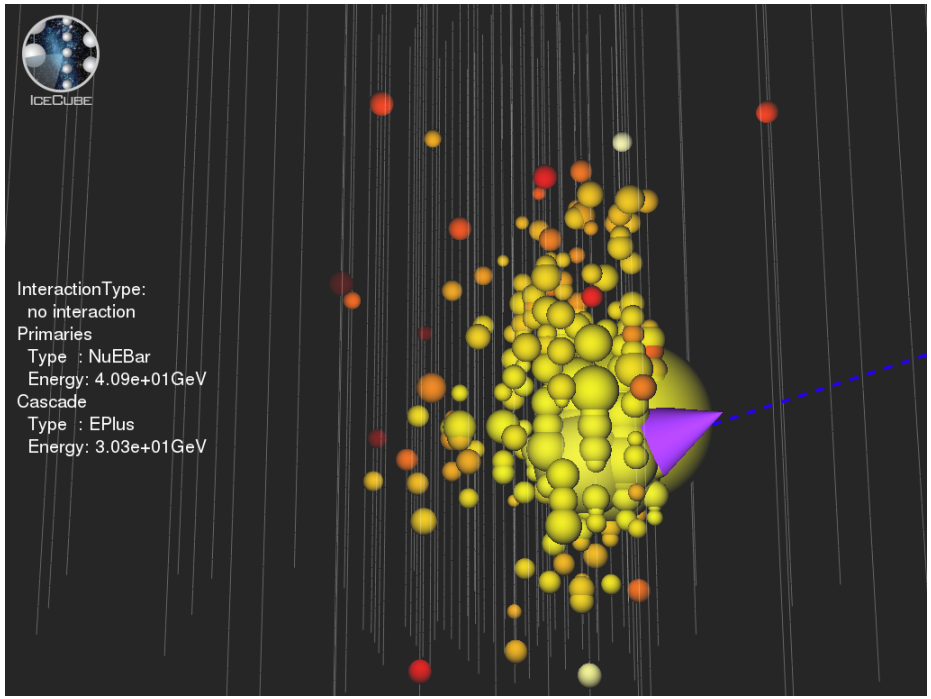
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

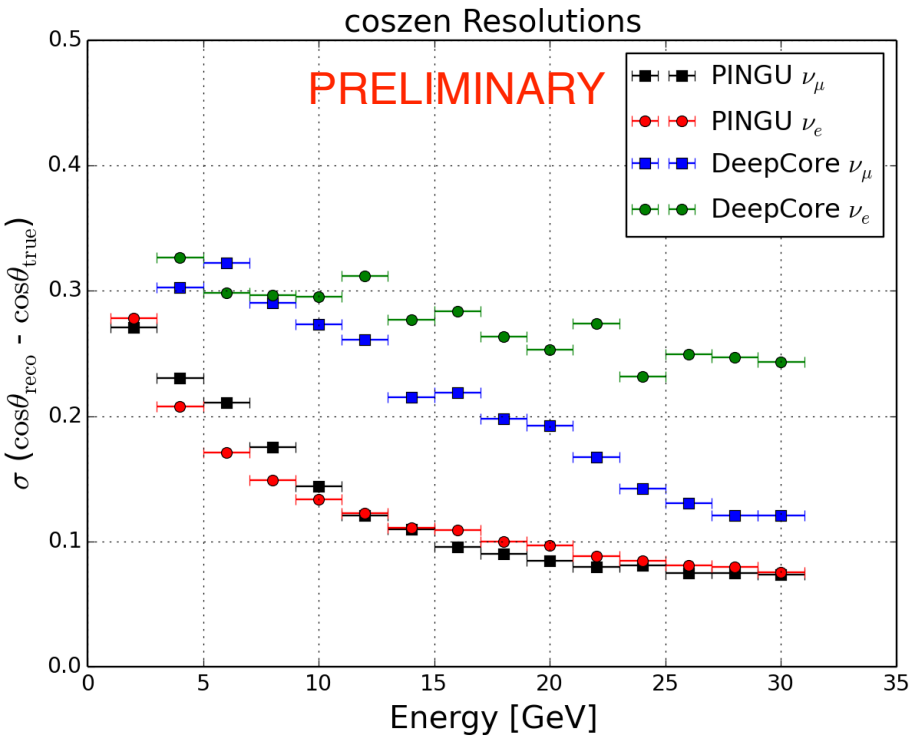
Backup slides

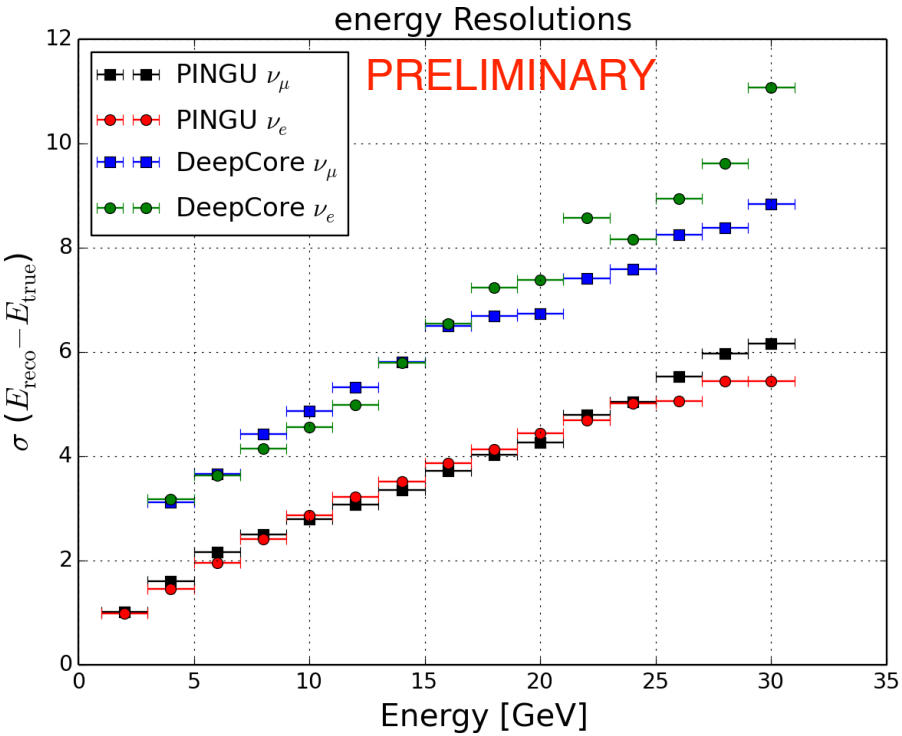
Event display at PINGU



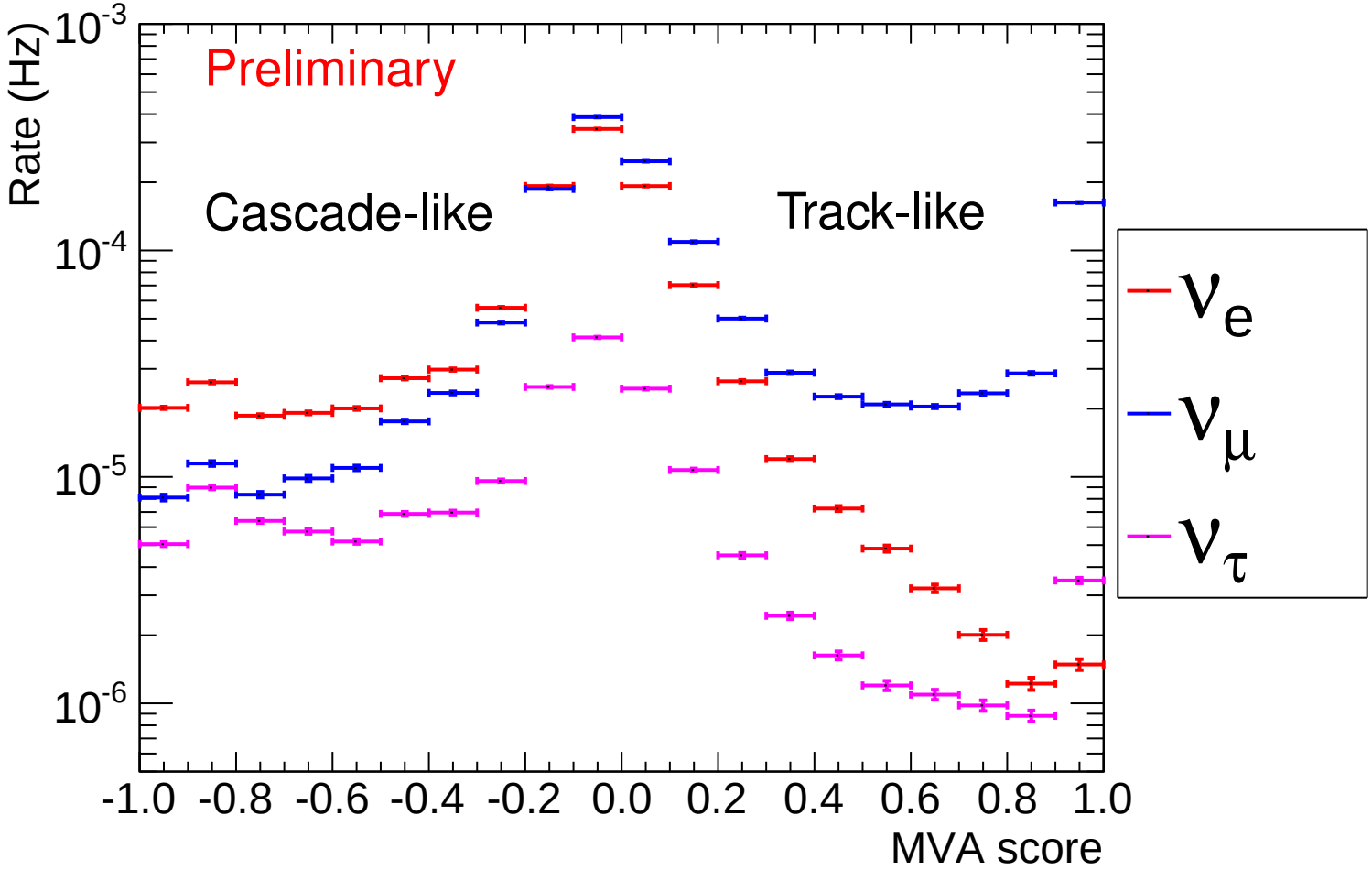


Reconstruction resolutions



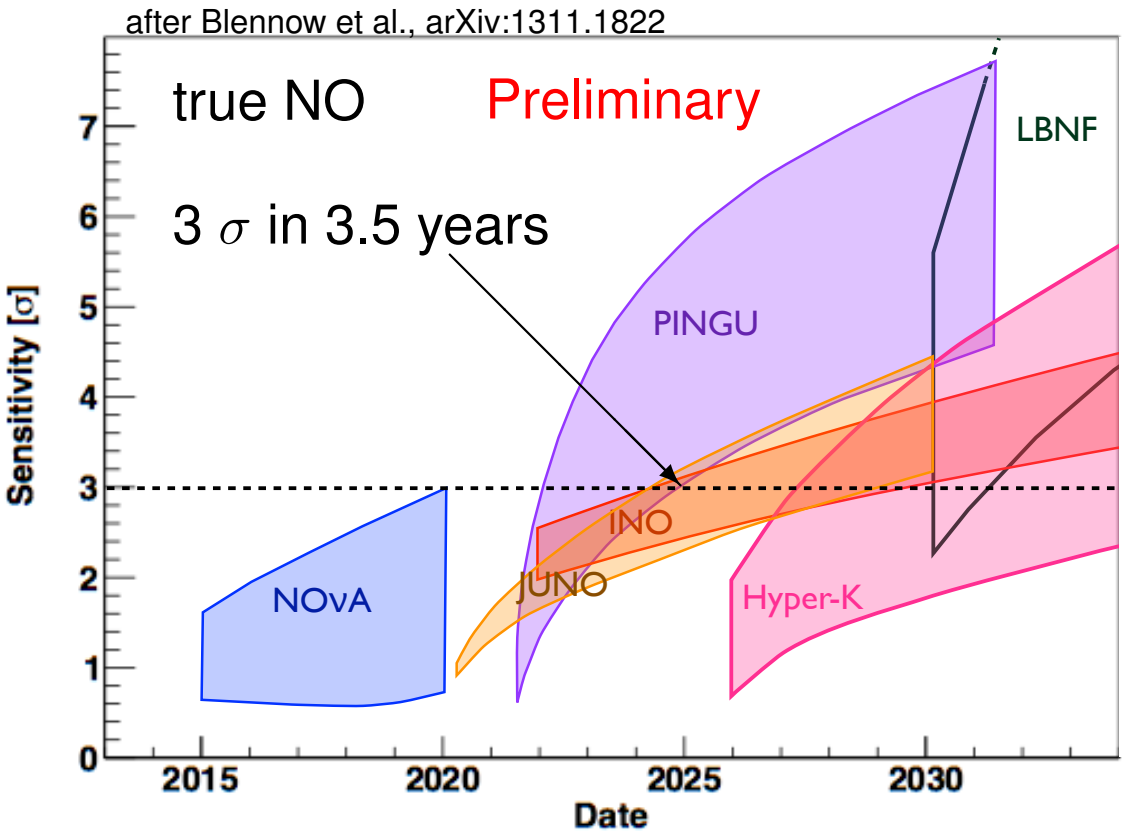


Particle identification



Timeline for the NMH measurement

- Several current and planned experiments have sensitivity to the NMH
- Median sensitivity shown (ie. 50% chance of doing worse and 50% change of doing better than expected)



- Widths indicate main uncertainty:
  - LBNF/NOνA: δ_{CP}
  - JUNO: σ_E (3.0-3.5%)
  - PINGU/INO: θ_{23} (38.7°-51.3°, 39.2°-50.8°)
  - Other projections assume worst case parameters (1st octant)
- PINGU timeline based on agressive (but feasible) schedule
- LBNF from LBNE-doc-8087-v10, Hyper-K from arXiv:1109.3262, INO from arXiv:1406.3689v1, all others from Blennow