Status of atmospheric neutrino oscillation measurements in IceCube and PINGU

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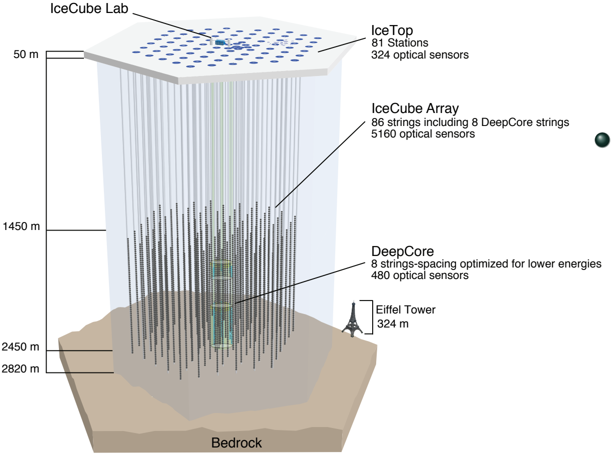
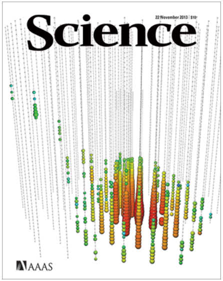
IceCube

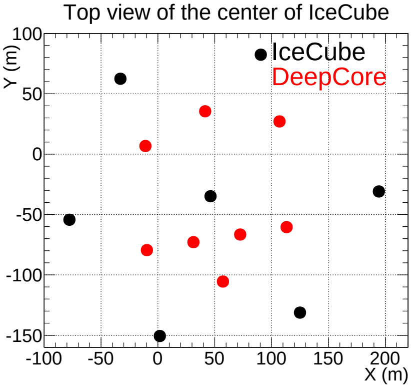


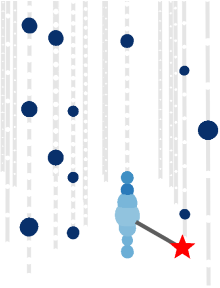
- Without DeepCore:
  78 strings,
  125 m string spacing,
  17 m module z-spacing
- Optimized for (very) High Energy neutrinos



IceCube-DeepCore

- 78 strings, 125 m string spacing
- 17 m modules z-spacing
- 8 strings, 40-75 m string spacing
- 7 m modules z-spacing

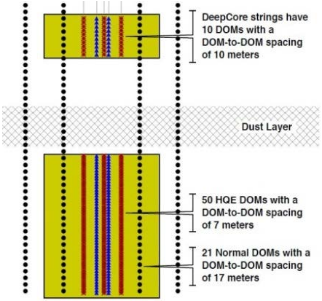

Top view of the center of IceCube



→ Typical LE ν event

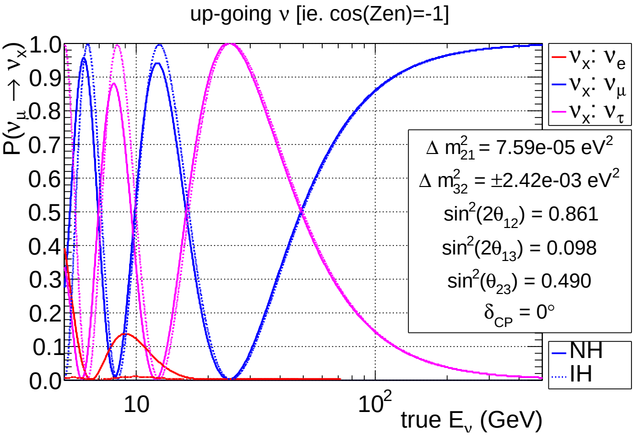
→ $E_{\nu_\mu} = 12$ GeV

(w/ $E_\mu = 8$ GeV)



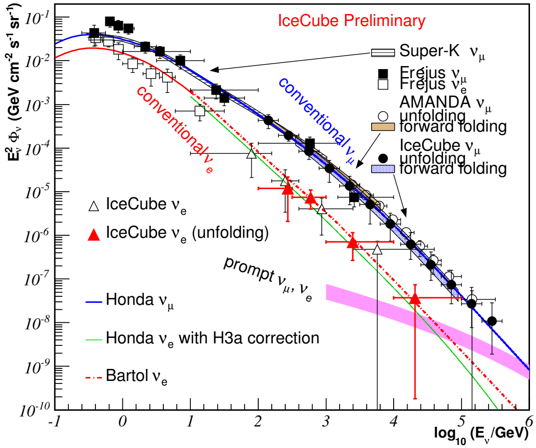
Using atmospheric ν to study ν oscillation

- Neutrinos oscillating through the Earth's diameter have "first" maximum of ν_μ disappearance at 25 GeV
  - signal accessible with DeepCore
- Hierarchy dependent matter effects below ∼12 GeV
  - too low energy for DC, requires higher density of optical modules



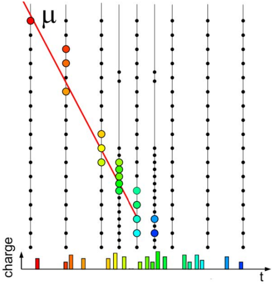
Atmospheric neutrinos signal in DeepCore

- Large quantity of neutrinos from different baselines and energies



- $\sim 10^3 - 10^4\ \nu_\mu$ expected per year at analysis level

Measurement strategies



- Main background is atmospheric μ
  - Use IC as veto to reject atm μ events
- Reconstruct ν energy and direction
  - oscillation distance (L) given by zenith
- Do oscillation measurement!

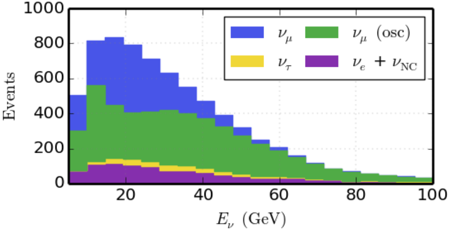
1. Focus on ν_μ CC "golden events" → this presentation
   - Focus on up-going events
   - Clear μ tracks
   - Require several non-scattered γ

   ⇒ Results in PRD 91, 072004 (2015) [arXiv:1410.7227]
2. Relax "golden event" requirements to increase sample size
   - Increased presence of "cascades" (ν NC, ν_e, ν_τ) in sample
   - Requires better understanding of the detector than ①
     - ★ Reconstruction more sensitive to scattering and noise

   ⇒ analysis in progress

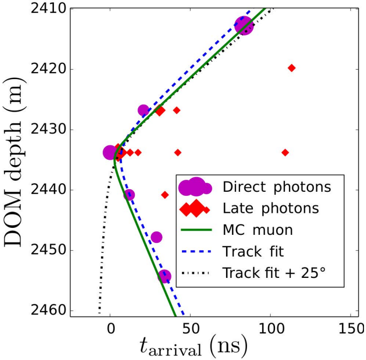
Measurement strategies – focus on "golden events"

- Clear μ tracks
  - Reduce contamination of cascades (mainly ν NC and ν_e CC)



- Require several non-scattered γ

→ select events "easy" to reconstruct
  - 10° resolution in neutrino zenith
  - 25% resolution in neutrino energy

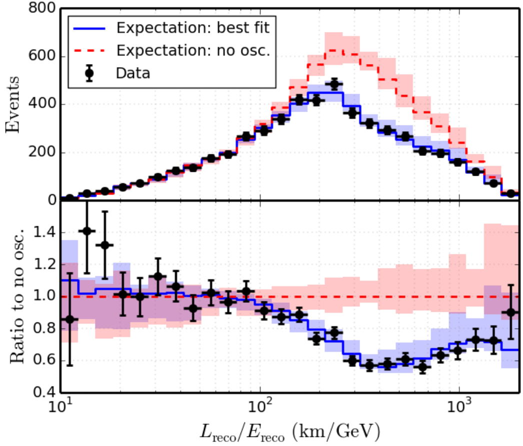


Systematics

- Systematics considered in fit:
  - $\theta_{13} \rightarrow$ prior from PDG
  - event rate/normalization $\rightarrow$ no prior
  - atm. μ contamination rate $\rightarrow$ no prior
  - ν_e/ν_μ ratio $\rightarrow$ 20% prior
  - atm flux spectral index $\rightarrow$ 5% prior
  - DOM overall efficiency $\rightarrow$ 10% prior
  - DOM acceptance (scattering in the hole-ice) $\rightarrow$ prior/values based on fits to flasher data
  - Axial mass $\rightarrow$ prior based on GENIE
- Compared results with 2 bulk ice models, based on different fits to flasher data
- DIS uncertainties considered, and accounted for in flux systematics

3y ν_μ disappearance oscillation analysis

PRD 91, 072004 (2015)

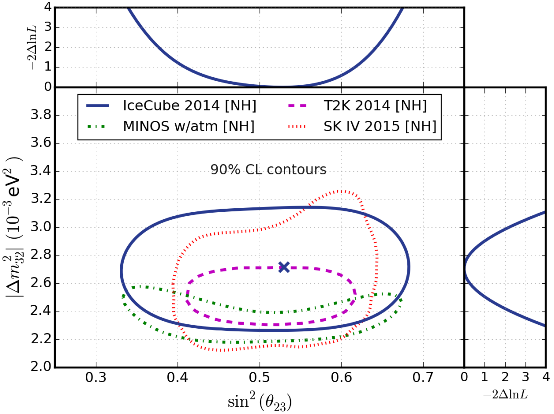


- Using only events with $E_{reco} < 56$ GeV
- Fitting to data done in 2D space (E, θ)
  - $\chi^2/ndf = 54.9/56$
- Observed 5174 events in 953 days

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

3y ν_μ disappearance oscillation analysis

PRD 91, 072004 (2015) with SK result updated



$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} 10^{-3}\mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

- Result consistent with other experiments
  - First time a very large volume ν detector fits in the figure
- This measurement is still statistics limited!
  - Still working on strategy ②: relax “golden event” requirements ⇒ expected increase by an order of magnitude of number ν in sample

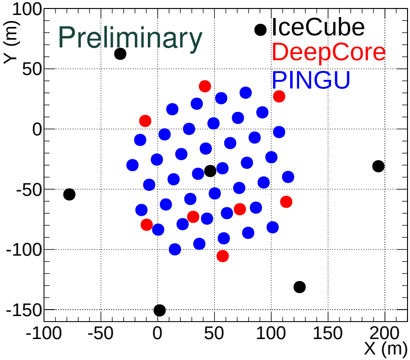
IceCube-DeepCore-PINGU

- 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
    - all optical modules in clearest ice

Top view of the PINGU new candidate detector

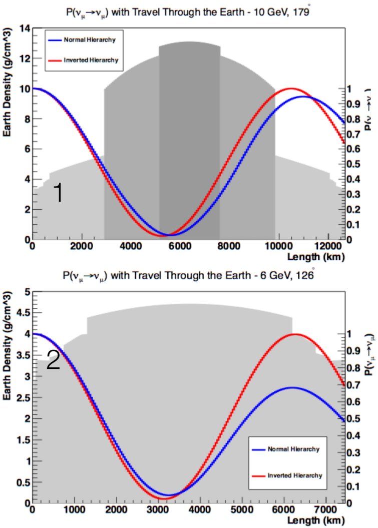


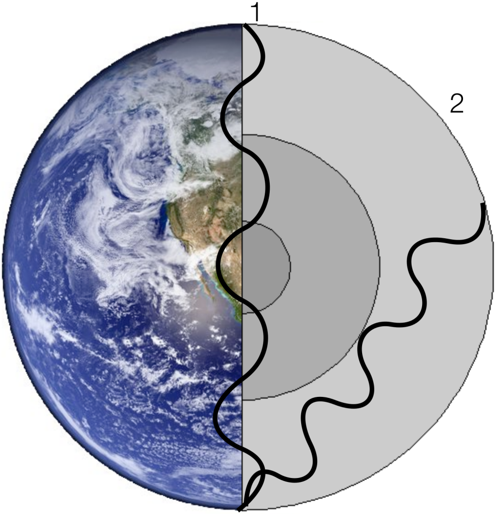
PINGU physics program

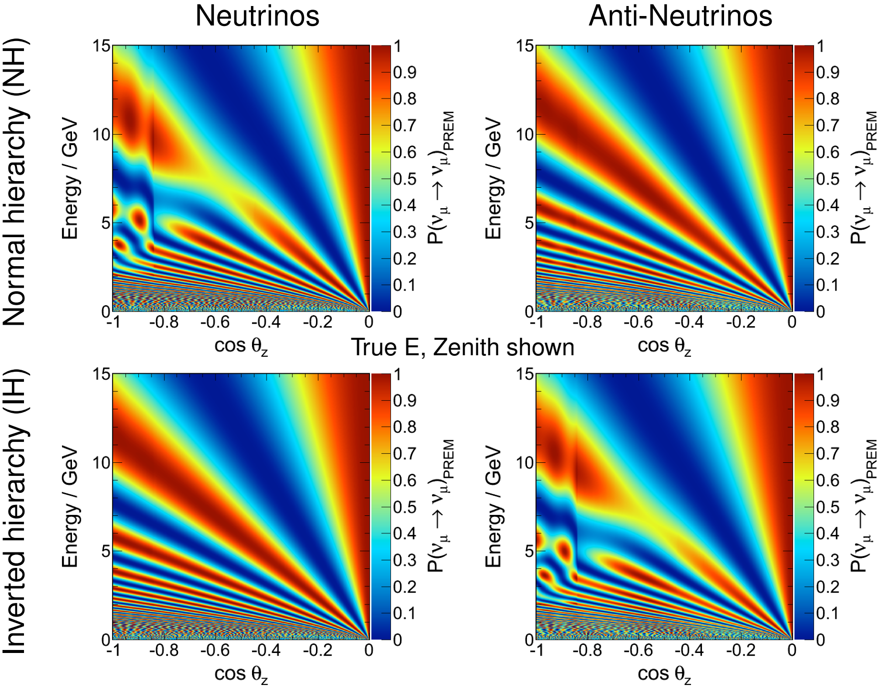
- Precision measurements of atmospheric neutrino oscillation at a few GeV with very high statistics
  - Measure Neutrino Mass Hierarchy (NMH)
  - Precise measurement of Δm^2_{23}, θ_{23}
  - High statistics measurement of ν_τ appearance
- Probe lower mass WIMPs
- Increase sensitivity to supernovae ν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

Measuring the ν Mass Hierarchy with atmospheric ν

- As for DC, large quantity of ν from different baselines and energies
- Comparison of different baselines helps control systematics





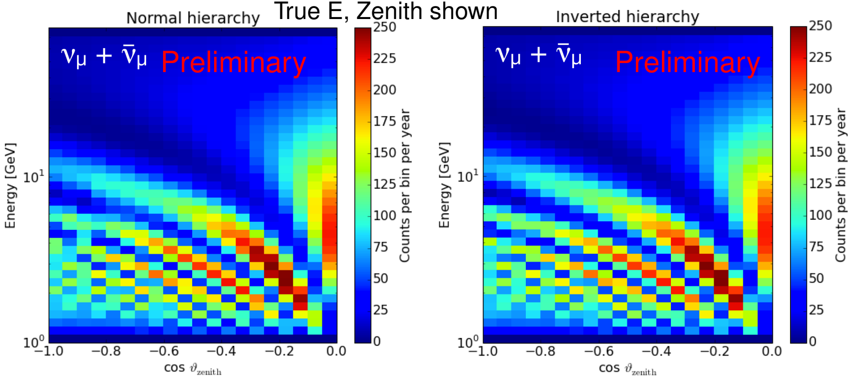


True E, Zenith shown

Pattern from atmospheric oscillation

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

True E, Zenith shown

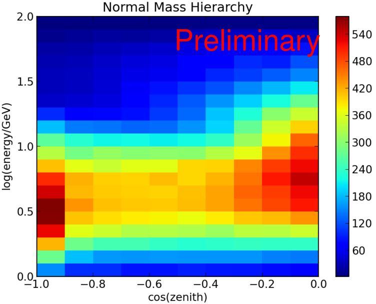


- PINGU cannot distinguish ν and $\overline{\nu}$ directly:
  - rely on natural difference in flux and cross-section
  - to a lesser extent could do statistical separation based on kinematics
- Visible differences at first ν_μ “re-appearance” region
  - $\sim$ 50k $\nu_\mu + \bar{\nu_\mu}$ per year, $\sim$ 38k $\nu_e + \bar{\nu_e}$ per year
  - WARNING: resolutions not included in this plot!

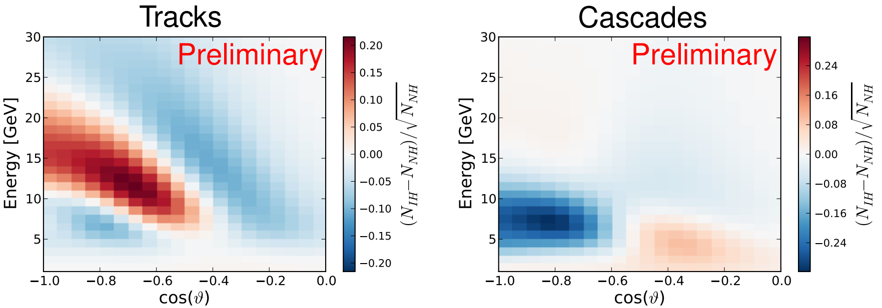
Expected event rate from atmospheric neutrinos

$\nu_\mu + \overline{\nu}_\mu$ 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



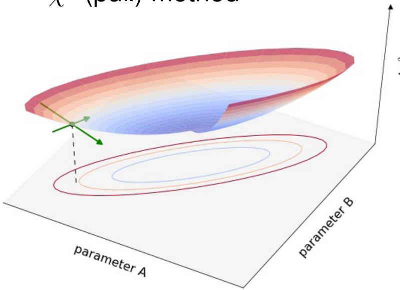
Bin-by-bin significance of mass hierarchy signature



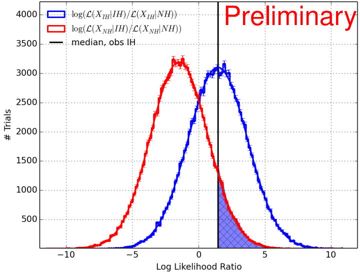
- Distinct hierarchy dependent signatures for tracks (mostly ν_μ CC) and cascades (mostly ν_e CC)
  - Intensity is statistical significance of each bin with 1 year data
  - Uses parametrized MC information for detector efficiency, reconstruction and particle identification

Methods for estimating sensitivity to the NMH

χ^2 (pull) method



Likelihood Ratio



- Currently two methods used: the χ^2 method and Likelihood Ratio
  - Output of full simulation and reconstruction parametrized and used
  - Analysis done in $E_\nu \times$ cos(zenith) space in 2 PID bins
  - χ^2 method: Relatively fast evaluation by scanning nonlinear parameters and propagating error for linear parameters and minimizing the $\Delta\chi^2$
  - Likelihood Ratio: Full analysis from pseudo data sets. While method is slower it does not pre-suppose any shapes
  - "Other" hierarchy parameter chosen to minimize distinguishability

Systematic uncertainty impact to measure the NMH

- Oscillation parameters (based on nu-fit.org values [1])

	NH	IH		
$\Delta m^2_{31}(10^{-3}\mathrm{eV}^2)$	2.46	-2.37	θ_{13} (w/prior)	$(8.5 \pm 0.2)^\circ$
$\theta_{23}(^\circ)$	42.3	49.5	Δm^2_{21} (fixed)	$7.50 \cdot 10^{-5}\mathrm{eV}^2$
δ_{CP} (fixed)	0		θ_{12} (fixed)	33.48°

    - Most important systematics (Δm^2_{31} and θ_{23}) used with no prior
- Detector/flux/cross-section related systematics
    - event rate/normalization → no prior
    - energy scale → 10% prior
    - ν_e/ν_μ ratio → 3% prior [2]
    - $\nu/\bar{\nu}$ ratio → 10% prior [2,3]
    - atm flux spectral index → 5% prior [2]
- Also studied only with fast method:
    - detailed x-sec systematics from GENIE [3]
    - detailed atmospheric flux uncertainties [2]

Type	3yr σ (NMH)	3yr σ (IMH)
stat. only	4.84	4.82
flux only	4.55	4.56
det. only	4.06	3.99
θ_{23} only	3.52	3.26
osc. only	2.96	2.53
All	2.90	2.51

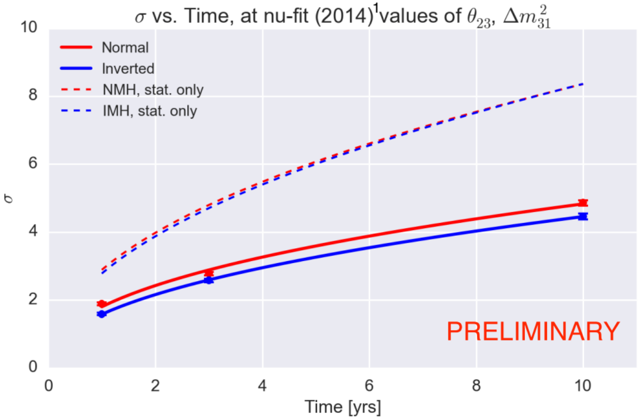
Preliminary

[1] M.C. Gonzales-Garcia et al., *JHEP 11 052* (2014)

[2] G.D. Barr, T.K. Gaisser et al., *Phys.Rev.D 74 094009* (2006)

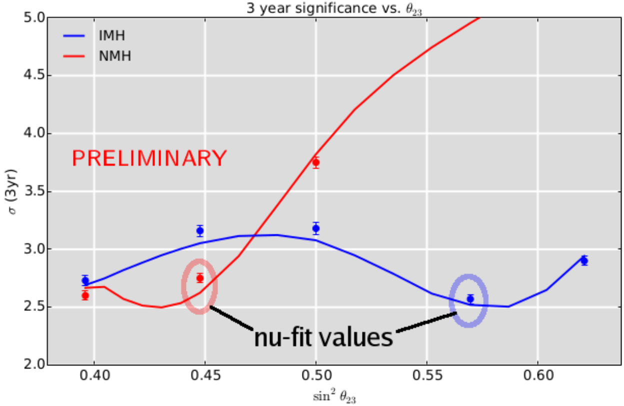
[3] C. Andreopoulos et al., *Nucl.Instrum.Meth.A 614 87-104* (2010)

PINGU sensitivity to the NMH as a function of time



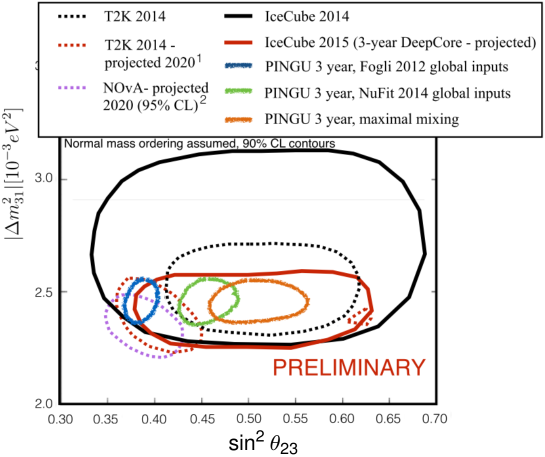
- 3 σ determination of mass hierarchy with 3-4 years of data
  - Combined track and cascade channels to obtain NMH significance
  - Does not include DeepCore only or partial detector data

PINGU sensitivity to the NMH as a function of θ_{23}



- Lines from χ^2 method and points from LLR method
  - Both methods are in reasonably good agreement
- NMH sensitivity strongly dependent on true value of θ_{23}
- Current global best fit θ_{23} close to sensitivity minimum for both hierarchies

PINGU sensitivity to θ_{23}



- Expected constraints of precision comparable to NOνA and T2K (projected)

[1] L. Abe et al. (T2K collaboration), arXiv:1409.7469

[2] `http://www-nova.fnal.gov/plots` and `figures/plot` and `figures.html`

Summary and outlook

- IceCube-DeepCore has capability to measure ν oscillations
  - Result obtained on same scale as other experiments
  - Progress being made towards improved results by using more of the currently existing data

- PINGU will greatly enhance reach of existing DC physics program
  - 3σ determination of the NMH in 3-4 years with full detector
  - Good precision to measure of atm. oscillation parameters
  - Enhanced sensitivity to ν_τ apperance, low-mass indirect WIMP searches, earth tomography, ...

- PINGU profits from expertize acquired from IceCube $\Rightarrow$ reduced project risk and potentially quick deployment
  - PINGU is first component to be deployed of the IceCube-Gen2 multipurpose observatory (white paper: arXiv:1412.5106)
  - full PINGU detector could be complete 4-5 years after approval
  - improved version of PINGU LoI available soon including new geometry, updated statistical analysis methods, more studies with detailed systematics

The IceCube–PINGU Collaboration

Canada
University of Alberta–Edmonton
University of Toronto

USA
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
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University of California, Irvine
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Universität Bonn
Technische Universität Dortmund
Universität Mainz
Universität Wuppertal

Université de Genève, **Switzerland**

University of Adelaide, **Australia**

University of Canterbury, **New Zealand**

International Funding Agencies

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German Research Foundation (DFG)
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Inoue Foundation for Science, Japan
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NSF–Physics Division
Swedish Polar Research Secretariat
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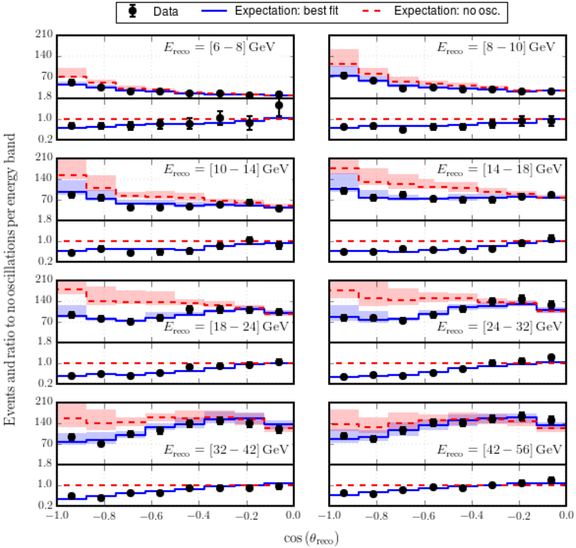
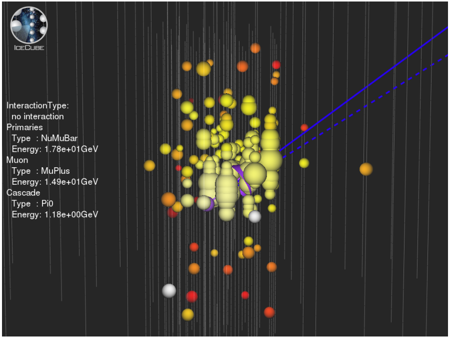
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Backup slides

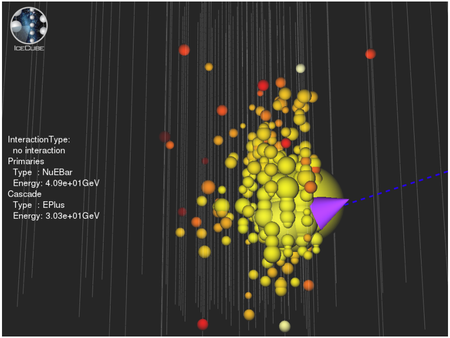
Agreement between data and MC in fitted parameter space for DC



Event display at PINGU



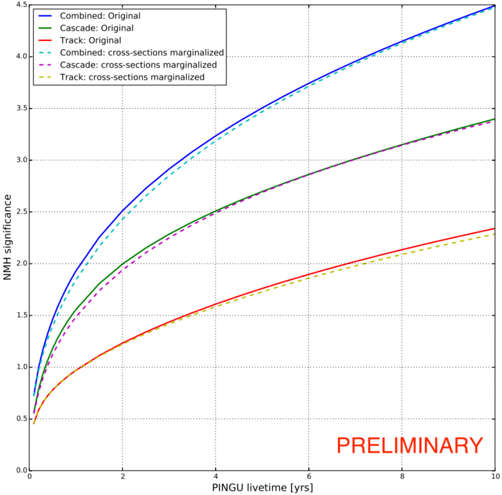
InteractionType:
no interaction
Primaries
Type : NuMuBar
Energy: 1.78e+01GeV
Muon
Type : MuPlus
Energy: 1.49e+01GeV
Cascade
Type : Pi0
Energy: 1.18e+00GeV



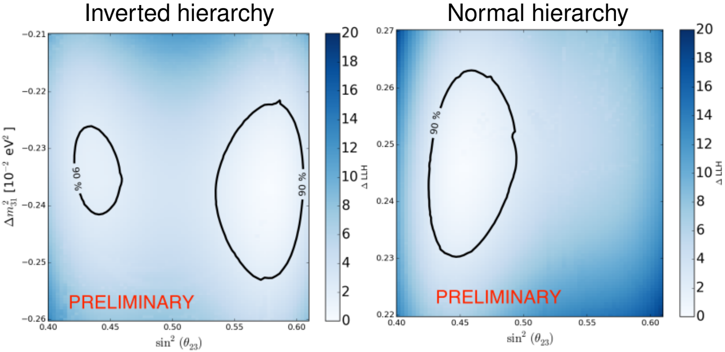
InteractionType:
no interaction
Primaries
Type : NuEBar
Energy: 4.09e+01GeV
Cascade
Type : EPlus
Energy: 3.03e+01GeV

Neutrino interaction cross-section uncertainties

- x-sec uncertainties from GENIE
- strongest impact:
  - axial mass parameters for CCQE and hadron resonance production
  - Bodek-Yang higher twist parameters for DIS
- small additional effect compared to existing systematics

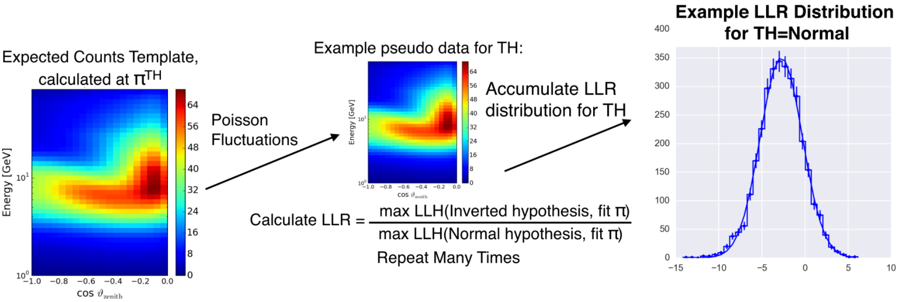


Atmospheric mixing parameters determination



LLR method

- Greatly improved statistical analysis method since LoI
  - Ability to include many more systematics (from 2 → ~10) by using a minimizer to find optimal LLH fit rather than grid scan
  - Run optimizer twice to search for solutions in both octants of θ_{23}.
- To test for significance of true hierarchy (TH)/rejection of other hierarchy (OH)
  - pull pseudo data from template of TH, with parameters: $\pi^{TH} = (\Delta m^2_{31}|^{TH}, \theta_{23}|^{TH}, \theta_{13}|^{TH},$ *all other params at nominal*)
  - Then following procedure is performed:



Expected Counts Template, calculated at π^{TH}

Poisson Fluctuations

Example pseudo data for TH:

Accumulate LLR distribution for TH

Example LLR Distribution for TH=Normal

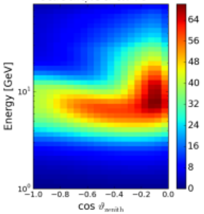
Calculate LLR = $\dfrac{\text{max LLH(Inverted hypothesis, fit } \pi)}{\text{max LLH(Normal hypothesis, fit } \pi)}$

Repeat Many Times

LLR method

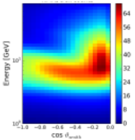
- Greatly improved statistical analysis method since LoI
  - Ability to include many more systematics (from 2 → ~10) by using a minimizer to find optimal LLH fit rather than grid scan
  - Run optimizer twice to search for solutions in both octants of θ_{23}.
- To test for significance of true hierarchy (TH)/rejection of other hierarchy (OH)
  - Next: parameters in OH that fit best to TH are found: $\pi^{OH} = (\Delta m^2_{31}|^{OH}, \theta_{23}|^{OH})$
  - Find LLR distribution at these parameters, π^{OH}, to find probability of mis-identifying OH as TH.
    - p value then converted to significance of rejecting OH.

Expected Counts Template, calculated at π^{OH}



Poisson Fluctuations

Example pseudo data for OH:

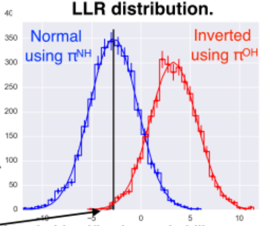


Accumulate LLR distribution for OH

Calculate LLR = $\dfrac{\text{max LLH(Inverted hypothesis, fit } \pi)}{\text{max LLH(Normal hypothesis, fit } \pi)}$

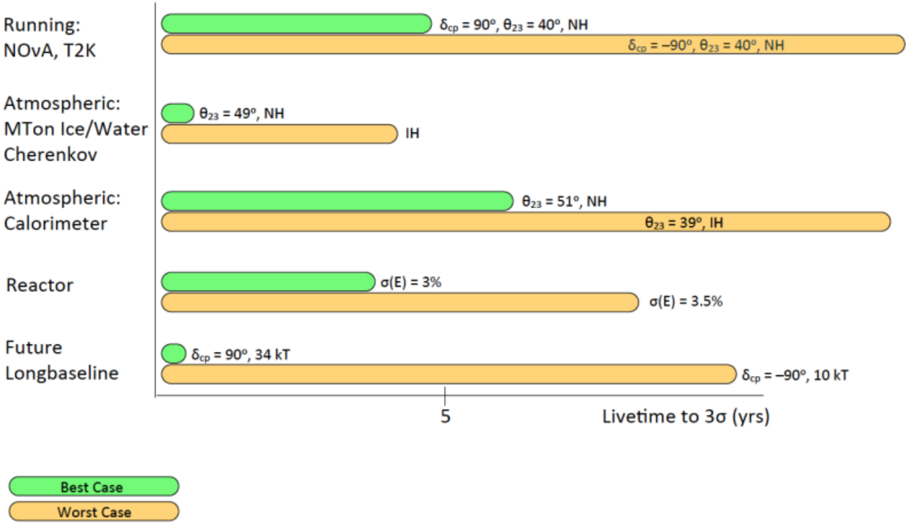
Repeat Many Times

Example LLR Distribution for TH=Normal, and OH=Inverted LLR distribution.



find p value=hierarchy mis-identification probability

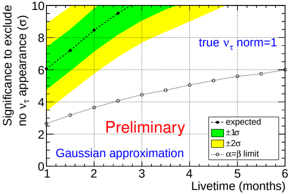
Sensitivity to the NMH for various techniques

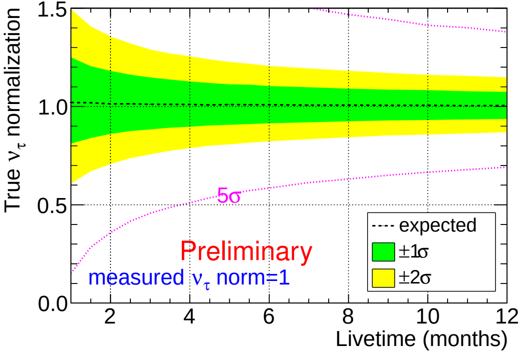


Sources: arXiv:1311.1822, arXiv:1401.2046v1, arXiv:1406.3689v1, Neutrino 2014, LBNE-doc-8087-v10

Other atmospheric measurements: ν_τ appearance

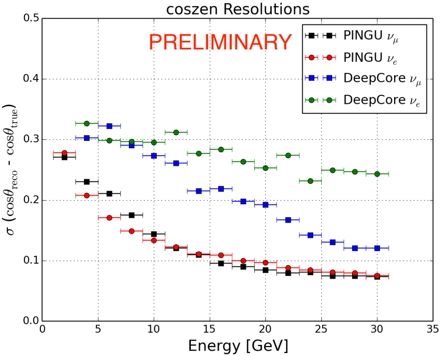
Expected sensitivity

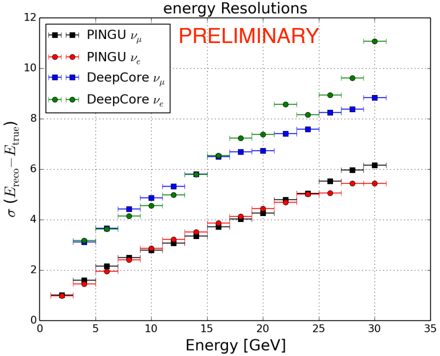




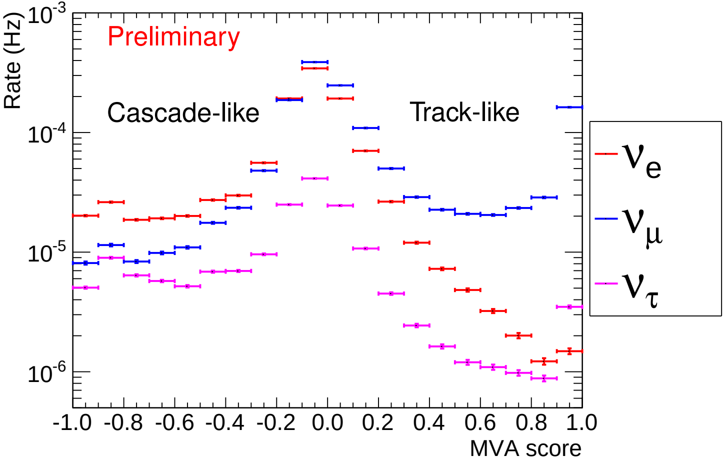
- Assumes similar systematics as NMH
- 5σ exclusion of no ν_τ appearance after 1 month of data
- 10% precision in the ν_τ normalization after 6 months
  - Test of the unitarity of the ν mixing matrix

Reconstruction resolutions





Particle identification



PINGU Cost

- Primary US funding source for IceCube-Gen2 would be NSF
  - Total cost comparable to IceCube
  - Many items common to PINGU and other elements
  - Marginal cost of PINGU withing IceCube-Gen2 is $88 M, with anticipated non-US contributions of $25 M

Cost for PINGU component

Hardware	$48 M
Logistics	$23 M
Contingency	$16 M
Expected non-US contributions	$25 M
Total US Cost	$63 M