Present Status and Physics Prospects of PINGU

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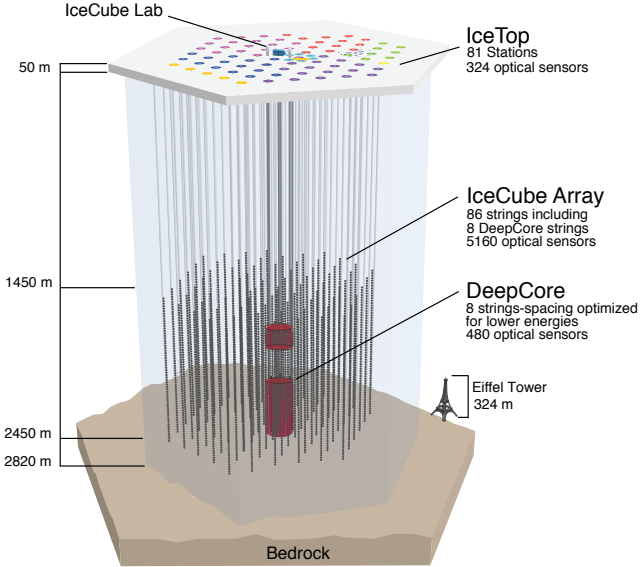
for the IceCube-Gen2 Collaboration

UNIVERSITY OF ALBERTA

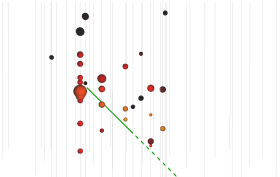
May 30th, 2018

IceCube



- Instrument 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical ν discovered!
- DeepCore
  - $\sim$10 Mton region with denser instrumentation
  - Pushes thresholds down to $\approx$ 5 GeV
  - Surrounding detector used as active veto against atmospheric μ

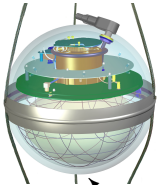
IceCube-DeepCore



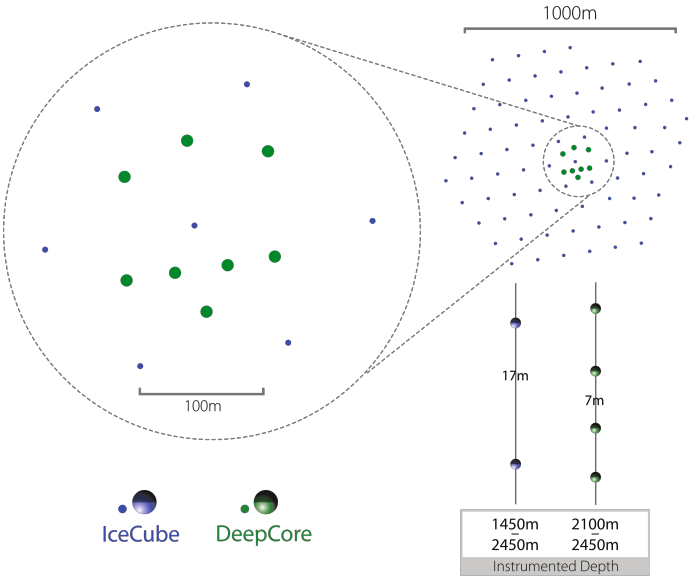
25 GeV ν_μ CC

color → hit time
size → hit charge

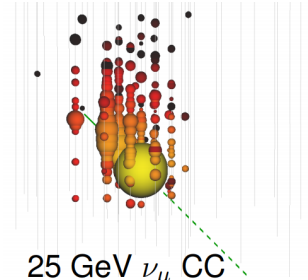
IceCube DOM



10” PMT

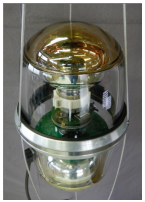


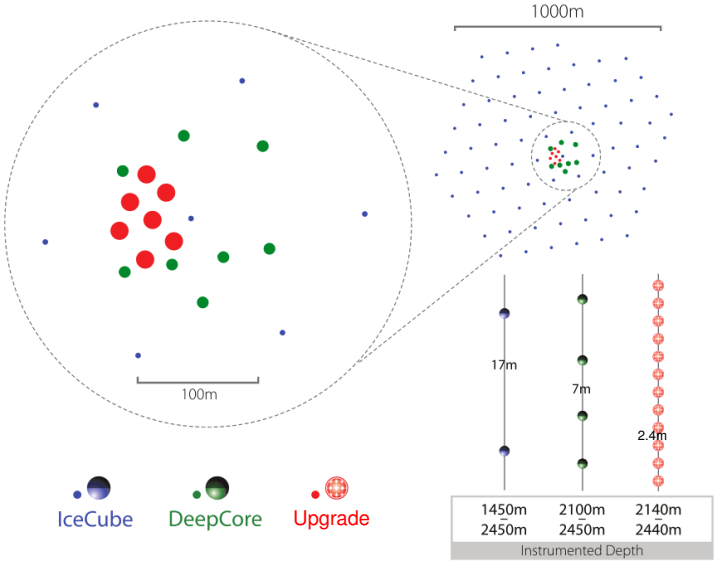
IceCube Upgrade



25 GeV ν_μ CC

color $\rightarrow$ hit time
size $\rightarrow$ hit charge



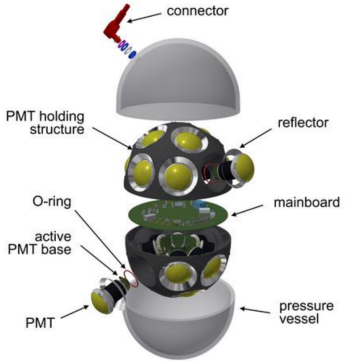


IceCube Upgrade: Hardware

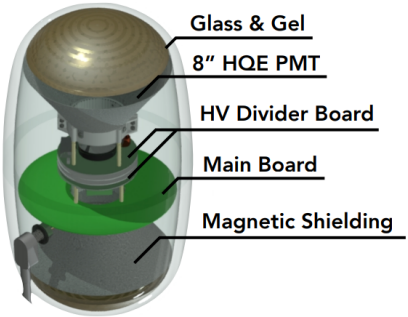
- Seven new strings in DeepCore with inter-string space of $\sim$22m
- Two planned PMT designs:
  - multi-PMTs mDOMs
  - Dual optical sensor in an Ellipsoid Glass for Gen2 (D-Egg)
- Both include new calibration devices to help better understand the ice
  - Onboard LEDs with wider range of angles accessible, including vertically
  - New camera for local ice calibration

IceCube Upgrade: Hardware

- multi-PMTs mDOMs
  - 24 $\times$ 3" PMTs housed in a 14" DOM
  - Double the photocathode area of IceCube DOMs
  - Provides extra directional information of photons



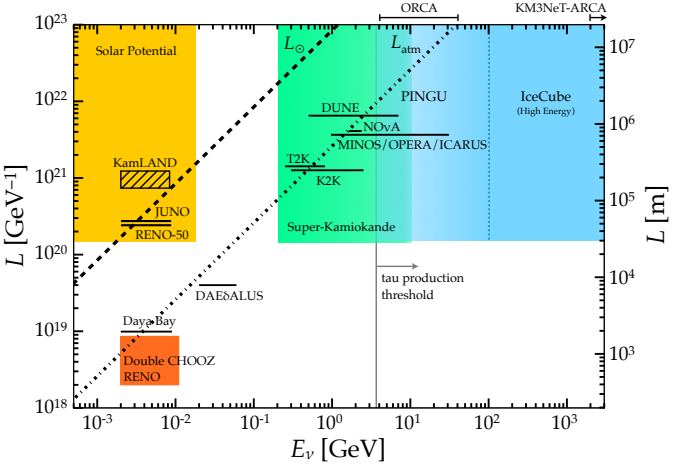
- D-Egg
  - Two 8" PMTs facing back-to-back
  - Ellipsoid glass, optimal shape for glass transparency
  - Single ADC with wide dynamic range



IceCube Upgrade: Science Goals

- ν_τ appearance analysis
  - PMNS unitarity tests
- Precision measurements of $\sin^2(\theta_{23})$ and Δm^2_{32}
  - Octant/Maximal mixing
  - Complementary to LBL experiments
- Neutrino mass ordering at 1.5-2σ in 3 years
- Improvement on eV sterile ν searches, NSI, solar WIMP searches, and other BSM searches
- Better neutrino astronomy at high energies
  - Improved angular resolution and veto performance
  - ν_τ identification
  - Multi-messenger astronomy

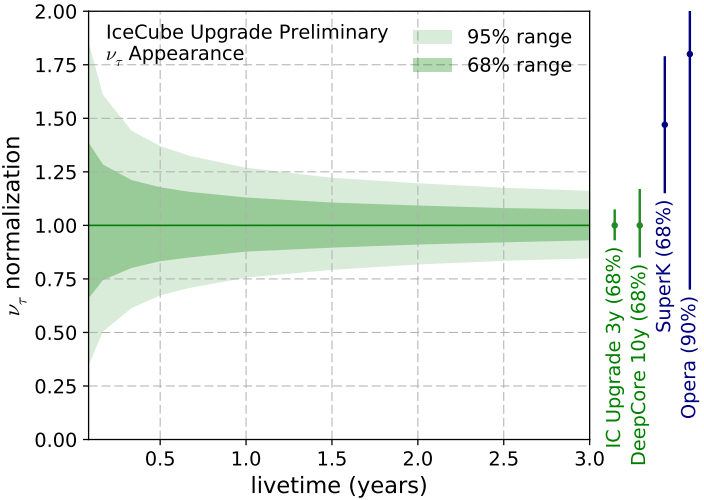
IceCube Upgrade: Oscillation Physics



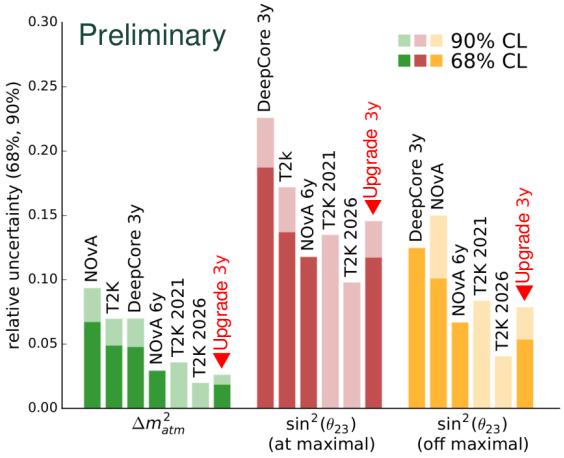
IceCube probes oscillation physics at baselines and energies inaccessible to LBL or reactor neutrino experiments.

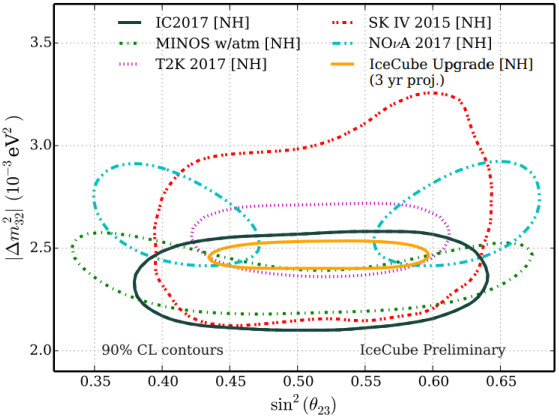
IceCube Upgrade: ν_τ Appearance

- $< 7\%$ precision on the ν_τ normalization after 3 years of data.
- $\sim 10\%$ precision needed for real tests of the unitarity of the PMNS mixing matrix.
- Very few experiments can do this measurement!



IceCube Upgrade: ν_μ Disappearance

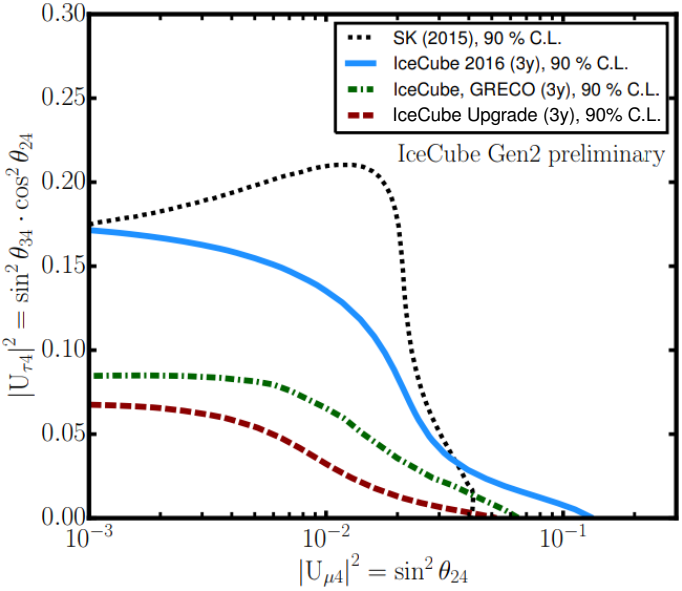




Projected limits on $\sin^2(\theta_{23})$ and Δm^2_{32} competitive with dedicated LBL experiments.

IceCube Upgrade: Sterile Neutrinos

- Higher precision event reconstructions increase sensitivity considerably.
- Upgrade should produce similar improvements in searches for non-standard neutrino interactions (NSI), WIMPs, and other BSM physics - under current investigation.

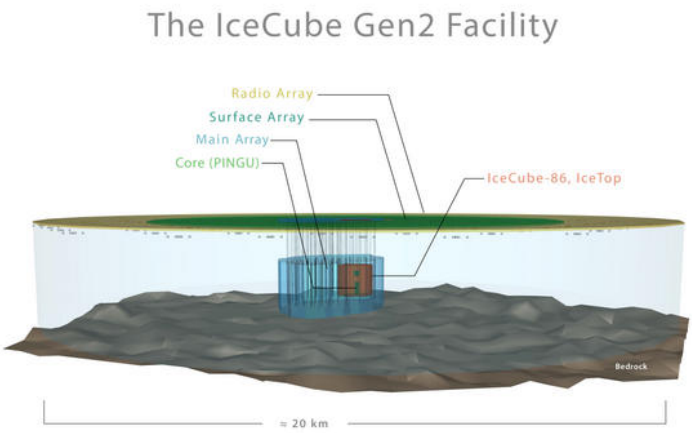


IceCube Upgrade Timeline

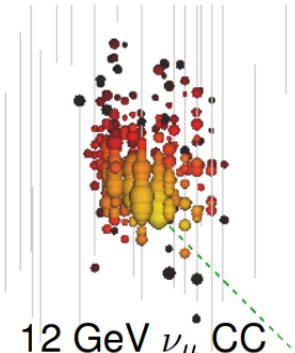
- Project timeline:
  - 2019-Q1: Preliminary Design Review; drill recon season at Pole
  - 2019: Preparation for final design; long lead procurement
  - 2020-Q1: Final Design Review
  - 2020-2021: Drill generators ship to Pole; refurbish drill structures at Pole
  - 2021-2022: Firn drilling
  - 2022-2023: Deploy 7 strings

IceCube-Gen2

- IceCube-Gen2 is a versitile facility for future South Pole physics
- Radio Array
- Surface Array
- High Energy Array
  - 120 strings $\times$ 90 sensors/string
  - $\sim$ 8 km^2 area with wider string spacing
- PINGU
  - Low energy infill
  - 17 strings $\times$ 125 sensors + Upgrade strings
  - 24m inter-string spacing

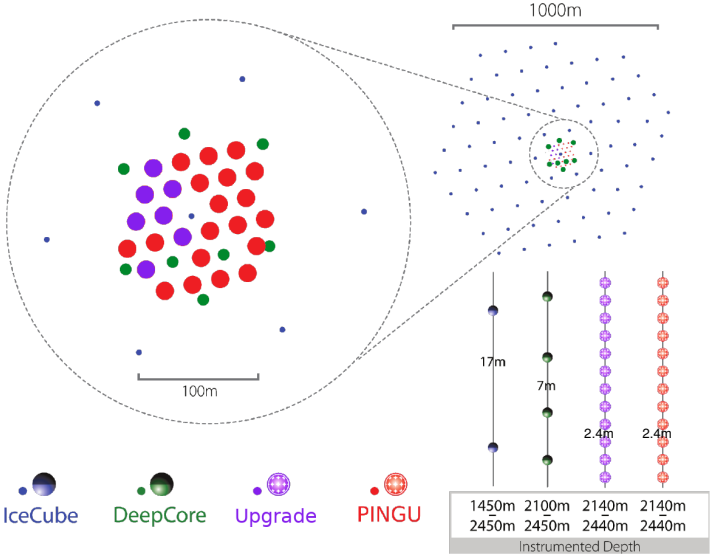


PINGU



12 GeV ν_μ CC

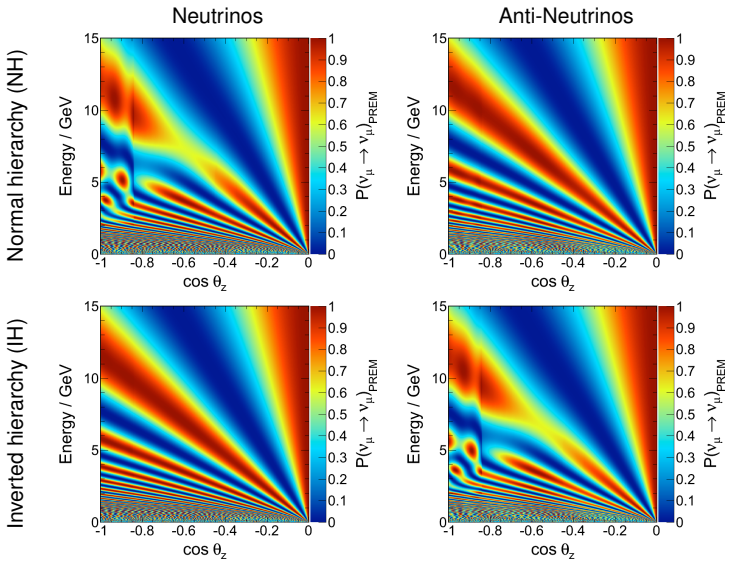
color $\rightarrow$ hit time
size $\rightarrow$ hit charge



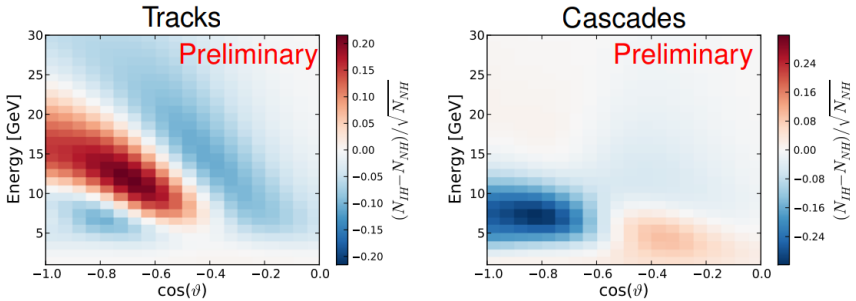
PINGU: Science Goals

- Augmenting the low-energy program of the upgrade.
  - $\sim$ 70k up-going atmospheric neutrinos per year
- Neutrino mass ordering
- ν_τ appearance
- $\sin^2(\theta_{23})$ octant sensitivity
- Wide breadth of other science:
  - Dark matter searches
  - Earth tomography
  - SN
  - ...

PINGU: Neutrino Mass Ordering

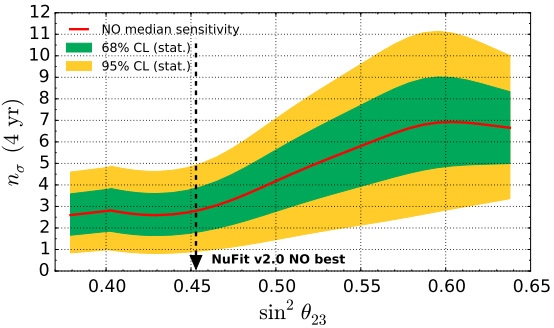


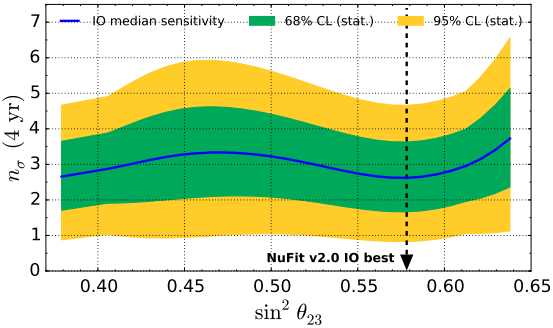
PINGU: Neutrino Mass Ordering



- PINGU cannot differentiate ν and $\bar{\nu}$: rely on difference in flux and cross-section
  - Large statistical samples: $\sim$33k ν_μ + $\bar{\nu}_\mu$ CC per year, $\sim$25k ν_e + $\bar{\nu}_e$ CC per year
- Distinct ordering dependent signatures for tracks (mostly ν_μ CC) and cascades
  - Intensity is statistical significance of each bin with 1 year data
  - Particular expected “distortion pattern” helps mitigate impact of systematics

PINGU: Neutrino Mass Ordering

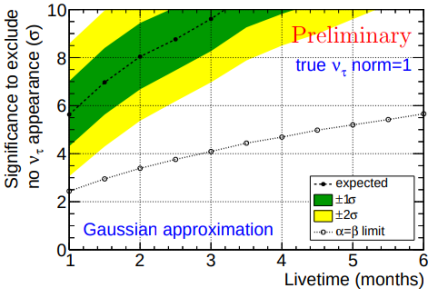


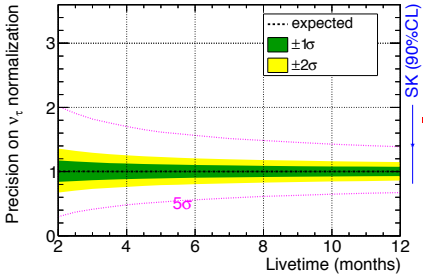


- Sensitivities calculated with 2 different methods (LLR and $\Delta\chi^2$) in agreement
- NMO sensitivity strongly depends on true $\sin^2(\theta_{23})$
- Median sensitivity of $\sim 3\sigma$ with 4 years of data for current best-fit values
  - Current global best fit close to sensitivity minimum for both orderings!

PINGU: ν_τ Appearance

- Expected to reach 5σ exclusion of no ν_τ appearance with a month of data
  - Can even reach 5σ exclusion of no ν_τ appearance within a year if ν_τ normalization is 0.6.
- Can reach Upgrade precision with less than 1 year of data.

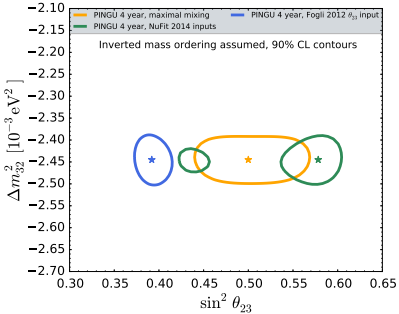


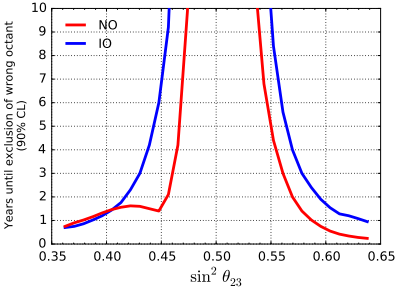


PINGU: ν_μ Disappearance

- Precision of $\sin^2(\theta_{32})$ and Δm^2_{32} measurement is as good as LBL experiments

- 4 year octant sensitivity $\gtrsim 3\sigma$ if:
  - NO: $\sin^2(\theta_{32}) \lesssim 0.38$ or $\gtrsim 0.62$
  - IO: $\sin^2(\theta_{32}) \lesssim 0.38$ or $\gtrsim 0.58$





Conclusion

- IceCube Upgrade proposal is under review
  - Stepping stone towards full IceCube-Gen2 program
  - Anticipated world leading sensitivity to ν_τ appearance
    - ⋆ expected precision better than 7% after 3 years
  - Improvement to wide range of measurements expected
    - ⋆ inparticularly improvements to neutrino astronomy!
- PINGU goes beyond IceCube Upgrade
  - Potential low-energy extension to IceCube-Gen2
  - Rich physics reach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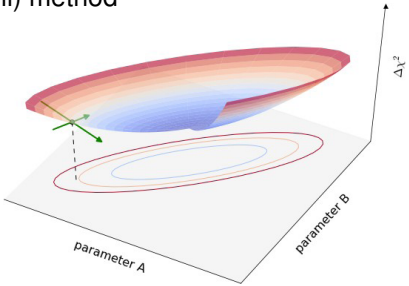
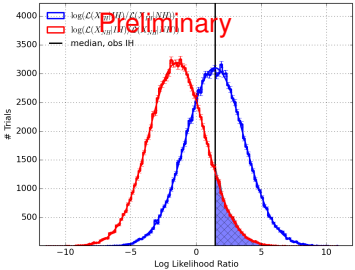
Backup

Methods for estimating sensitivity to the NMH

χ^2 (pull) method



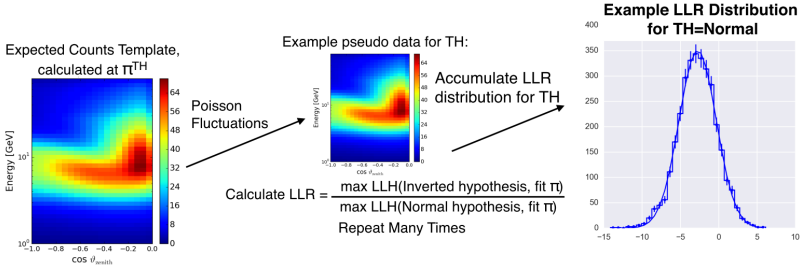
Likelihood Ratio



- Currently two methods used: the χ^2 method and Likelihood Ratio
  - Output of full simulation and reconstruction parametrized and used
  - Analysis done in $E_\nu \times \cos(\text{zenith})$ 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

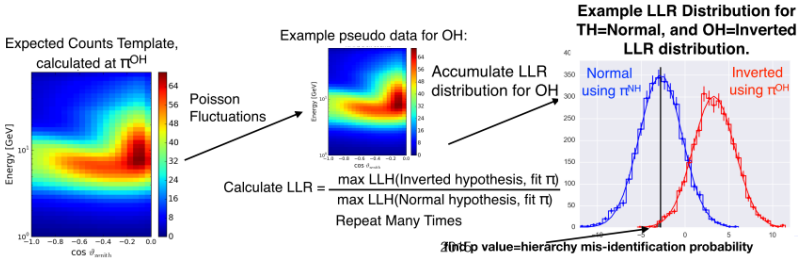
LLR method

- 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:



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.



Systematics for PINGU Studies

	LLR	$\overline{\Delta\chi 2}$	
	*	*	$\Delta m^2_{31} = 2.46 \times 10^{-3}\,\mathrm{eV}^2,\ -2.37 \times 10^{-3}\,\mathrm{eV}^2$ [47]
Oscillation	*	*	$\theta_{23} = 42.3°,\ 49.5°$ [47]
	*	*	$\theta_{13} = 8.5° \pm 0.2°$ [47]
		†	$\delta_{\mathrm{CP}} = 0°$
	*	*	Event rate = nominal
	*	*	ν_e/ν_μ flux ratio = nominal ± 3% [53]
Flux &	*	*	$\nu/\overline{\nu}$ flux ratio = nominal ± 10% [53]
Cross Section	*	*	Atmospheric spectral index = nominal ± 0.05 [53]
		†	Air-shower interactions [53]
		†	Neutrino cross-section (see Sec. Appendix B)
	*	*	Energy scale = 1.0 ± 10% († ± 0.5%)
Detector		†	Individual module efficiency = nominal ±10%
			Ice properties