IceCube

RWTH AACHEN UNIVERSITY

PINGU Precision for Atmospheric Oscillation Parameters

Kai Krings

MANTS 2013
Garching, 14th Oct. 2013

HELMHOLTZ | GEMEINSCHAFT

Allianz für Astroteilchenphysik

Bundesministerium für Bildung und Forschung

Introduction to PINGU

→ *Precision IceCube Next Generation Upgrade*

- 20 to 40 additional strings are filled into the DeepCore volume
- Baseline geometry, 40 strings
  inter-string spacing: 20 m
  inter-DOM spacing: 5 m
- Denser spacing
  → ν detection threshold of a few GeV

Main Physics Goal

Measurement of the **neutrino mass hierarchy**

$\Delta m^2_{32} > 0$ (normal hierarchy)
$\Delta m^2_{32} < 0$ (inverted hierarchy)

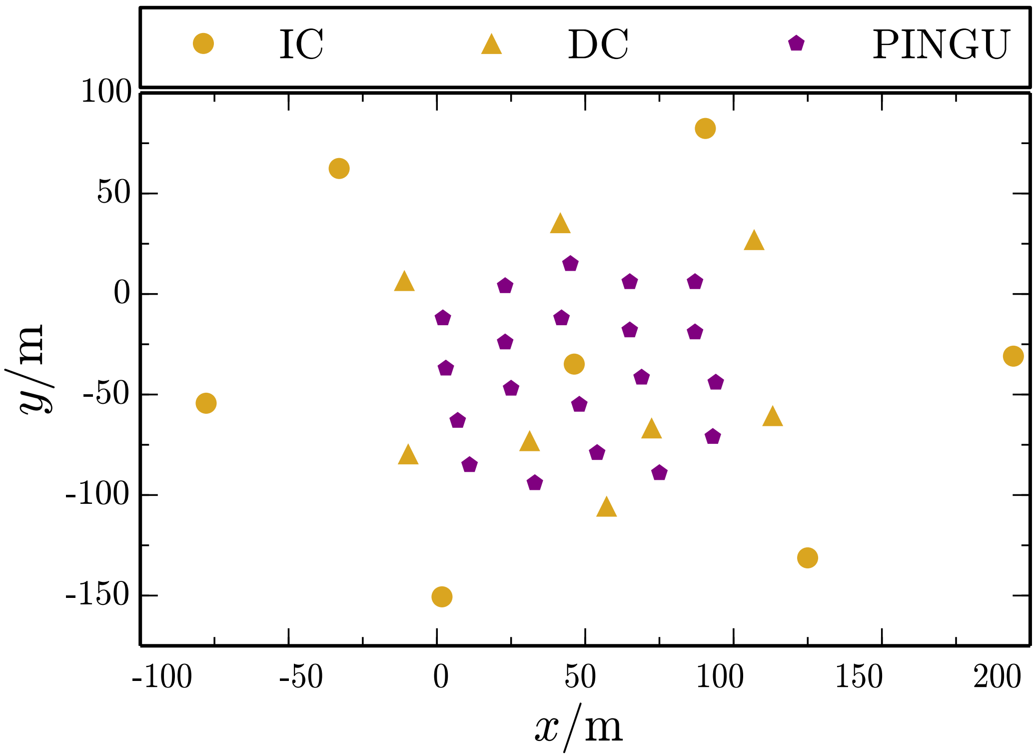
In principle, a measurement of the atmospheric mixing parameter Δm^2_{32} (and Θ_{23}).

→ Need to know these parameters very precisely.

→ **ν_μ disappearance analysis**

Goal of this Analysis

Geometry Version 6 (Dozier)



- 20 strings
- 26 m inter-string spacing
- 5 m inter-DOM spacing

Analysis Goal

Precise measurement of the atmospheric neutrino mixing parameters with PINGU using DeepCore as a benchmark.

Generated Datasets

- High-statistic ν_μ and ν_e datasets generated with GENIE/NuGen
- Energy range
  GENIE: 1–100 GeV
  NuGen: 50 GeV-10 TeV
- Energy spectrum: E^{-2}
- SPICE Mie and PPC*

*Hadronic light yield not correct below 10 GeV.

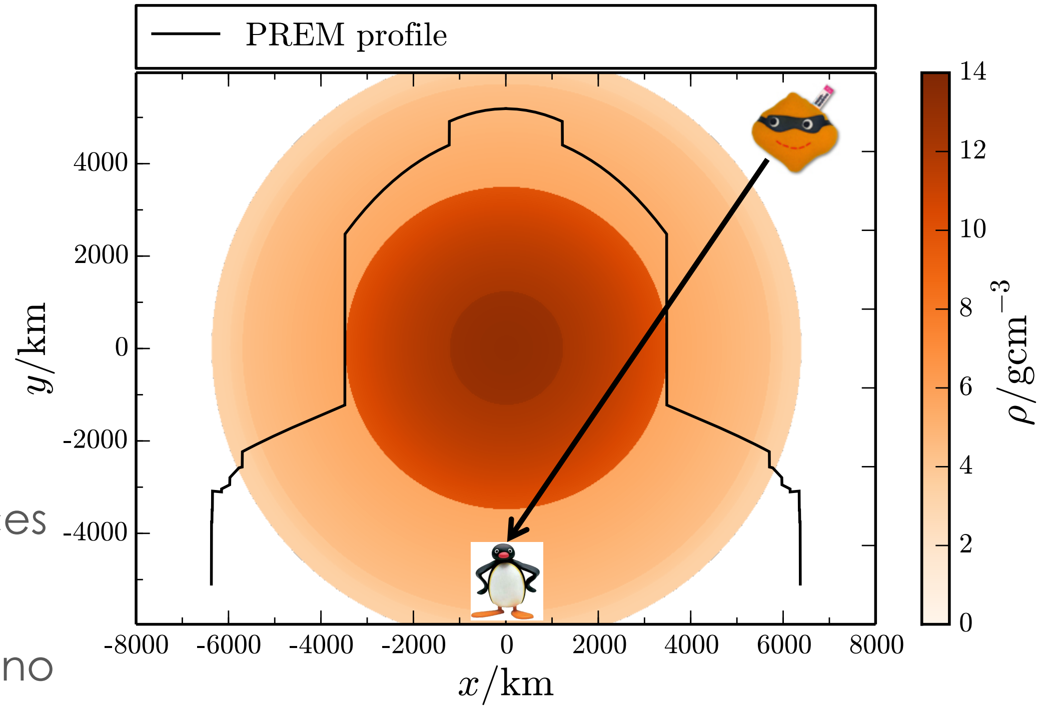
Atmospheric Neutrino Oscillations

- Mixing between flavor and mass eigenstates of neutrinos

$$|\nu_l\rangle = \sum_i U_{li}^* |\nu_i\rangle \quad l = e, \mu, \tau \quad i = 1,2,3$$

$$|\nu_i\rangle \propto \exp\left(-i \cdot m_i^2 \frac{L}{2E}\right)$$

- Mixing matrix *U* can be parameterized with rotation matrices → **mixing angles θ_{ij}**
- The probability to measure a neutrino of flavor *l* can oscillate because of the **different squared masses m^2_i**



measured indirectly over zenith angle θ_ν

Two-flavor Approximation

$$P_{\nu_\mu \to \nu_\mu}(E_\nu, L) \approx 1 - \sin^2(2\theta_{23})\sin^2\left(1.27 \frac{\Delta m_{32}^2}{eV^2} \frac{L/km}{E_\nu/GeV}\right)$$

For the analysis: *

- Three-flavor oscillations
- Matter effects

* calculated with nuCraft, http://nucraft.hepforge.org

Adapted Event Selection from IC79

IC79 DeepCore Analysis
by Sebastian Euler

- Background rejection of atm. muons
- Use the outer string layers of IceCube as a veto
- **~10 000** ν_μ events per year

Veto Region (RTVeto)
All IceCube DOMs besides

PINGU DOMs
DeepCore DOMs
DOMs on central IceCube string

(below the dust layer)

→ **Larger veto than for IC79.**

Veto Cuts	Directional Cuts
$^*Q_{tot}$(RTVeto) < 3PE	$\cos(\Theta_{\text{LineFit, imp.}}) < 0.2$
$^*Q_{tot}$(L7Veto) < 5PE	$\cos(\Theta_{\text{SPEFit4}}) < 0.2$
	$\cos(\Theta_{\text{SPEFit32}}) < 0.0$

Containment Cuts	Quality Cuts
N_{Ch}(SRT, PINGU) ≥ 10	$N_{Dir} \geq 3$, $L_{Dir} > 20$m
*1st HLC inside fid. volume	PLogL$3.5 < 8$
Vertex(finiteReco) inside fid. volume	ΔLogL(MPEFit, BayesFit) < -17

Fiducial Volume
Right cylinder

radius: 80 m
height: 288 m

➕ **Correlated Noise**
NoiseEngine
TopologicalSplitter

*introduced by Juan-Pablo Yanez

Expected Number of ν Events

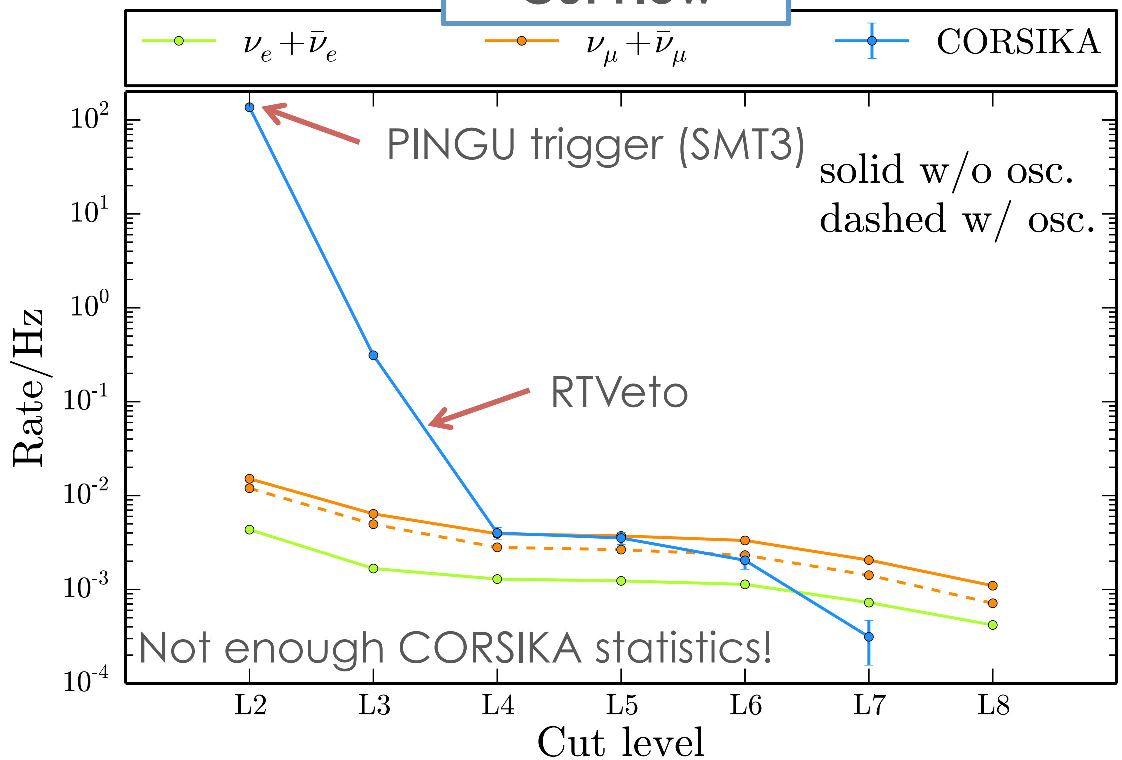
Number of Events

- Electron neutrinos: ~14,000 events/year
- Muon neutrinos: ~34,000 events/year **~22,000** events/year (osc.)

~12,000 'signal' events (disappeared neutrinos)

- At least twice as much statistics than for IC79
- μ contamination at L7: ~13 % → down to a few % at L8

Cut Flow



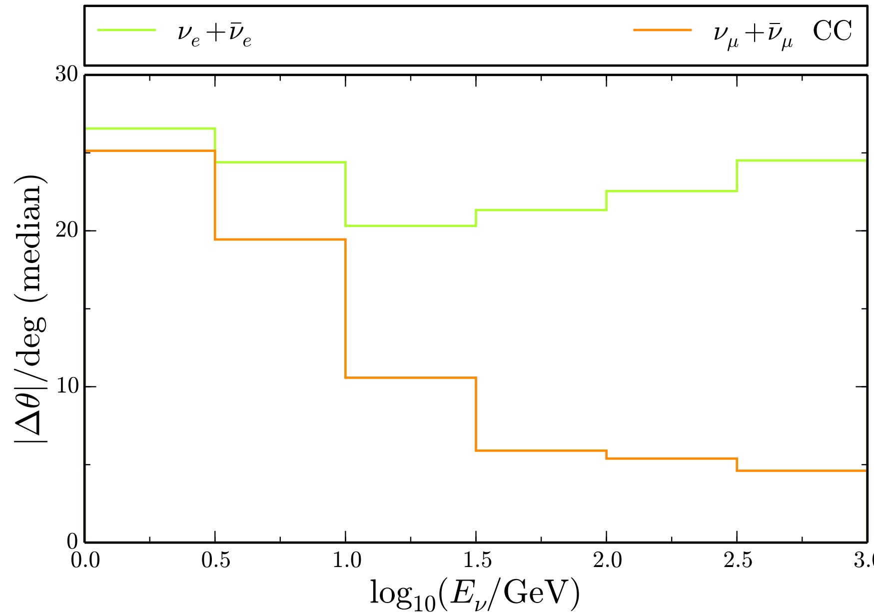
Rate/mHz	ν_μ w/o osc.	ν_μ w/ osc.	ν_e w/ osc.
Level 8	1.10	0.71	0.42
Efficiency	*21 %	*21 %	10 %

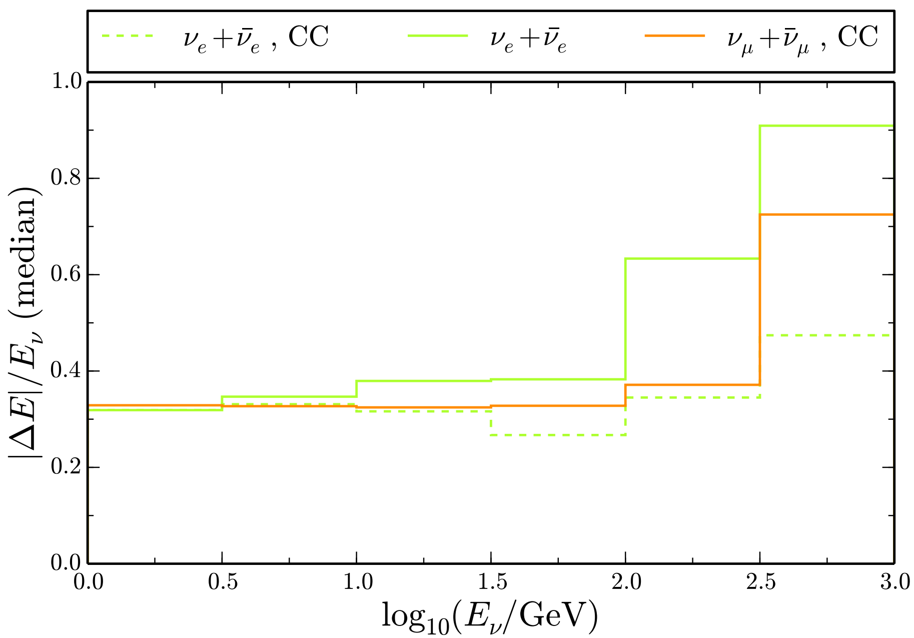
* w.r.t. up-going CC events, 1-30 GeV

Energy and Zenith Angle Estimators

Zenith Angle Estimator

- Use muon track reconstructions developed for IceCube.
- Median zenith angle resolution $< 25\,°$ for (anti-) muon neutrinos, CC





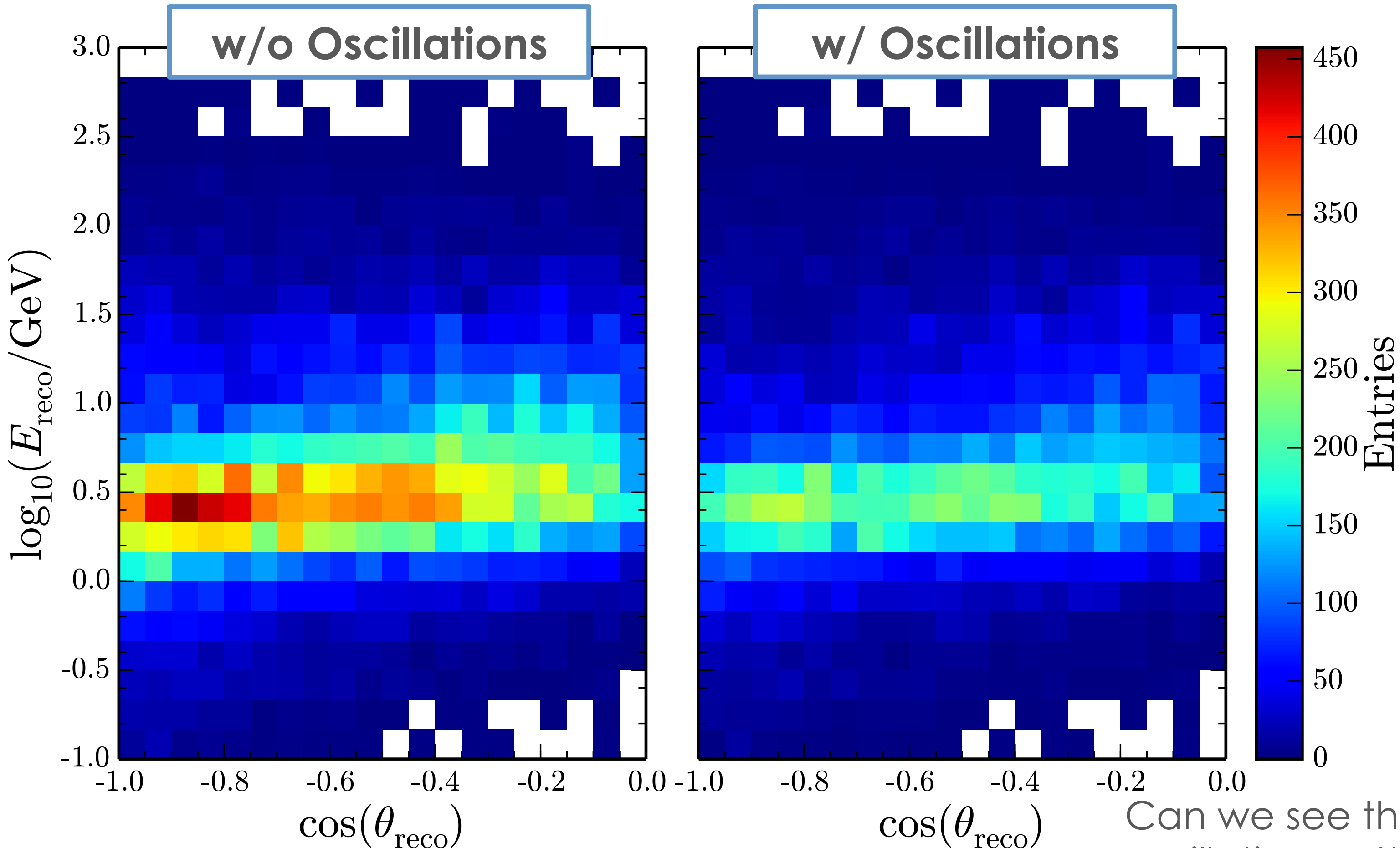
Energy Estimator

- Combine reconstructed muon track length and had. cascade energy as introduced by Andrii Terliuk

$$E_\nu^{reco} = E_{cascade}^{reco} + l_{track}^{reco} \,/\, 4.5\,mGeV^{-1}$$

- Median energy resolution ~35 % below 20 GeV

Detector Response to ν Oscillations

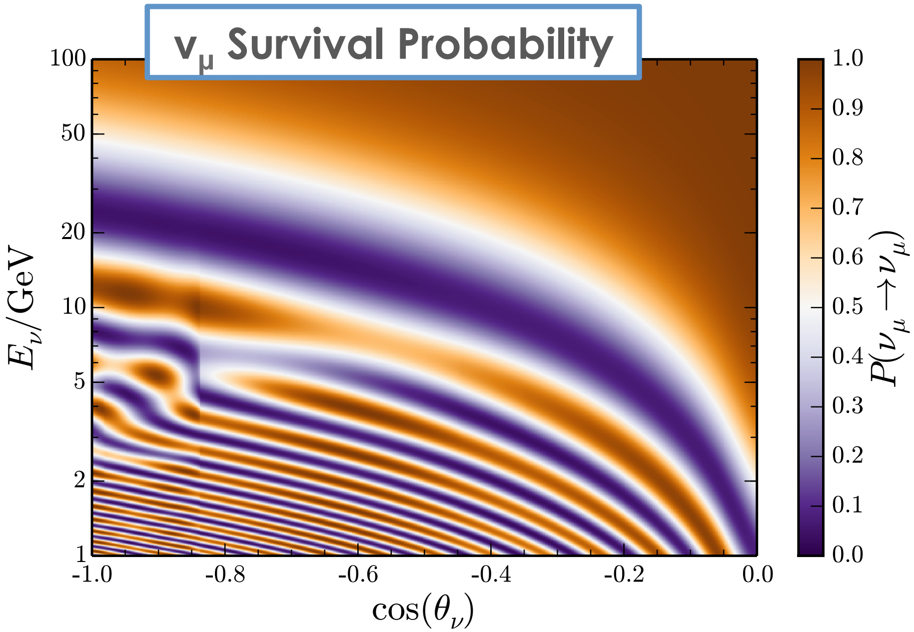


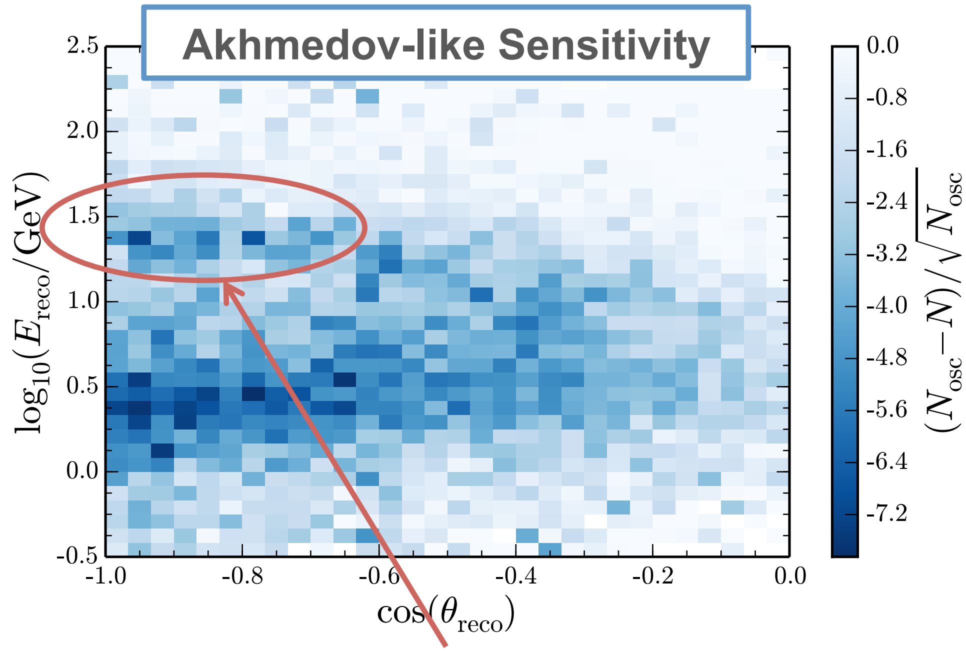
Can we see the oscillation pattern?

- Histogram reconstructed energy and zenith angle
- Oscillations effects are visible

Next slide

Detector Response to ν Oscillations



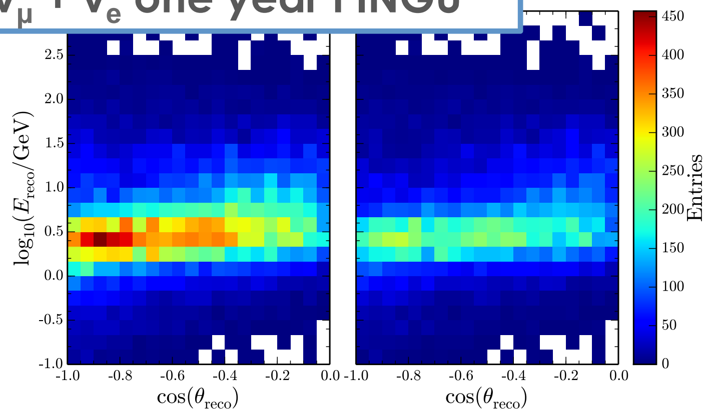


- Current DeepCore analyses measure the minimum at ~25 GeV ($\Theta_\nu = \pi$).
- PINGU is able to resolve the full minimum, including the rising edge.

- 1st minimum in the ν_μ survival prob.
- Effect of further minima/maxima at lower energies
- Both regions are separated.
  - Sensitive to the 1st maximum at about 10 GeV.
  - Yields strong constraints on Δm_{32}^2.

MC Analysis Method

ν_μ + ν_e one year PINGU



Reweighting

$$N_k \propto \sum_i \left(\sum_{l \in \{e,\mu\}} c_l \Phi_i^{\nu_l} P_{\nu_l \to \nu_\mu} \left(E_\nu, \theta_\nu \right) \right)$$

Mixing Parameters

Δm^2_{32}, θ_{23}, *and* θ_{13},

Δm^2_{21}, θ_{12}, δ_{cp} (fixed)

Flux Normalizations

c_e, c_μ

RANDOM

Likelihood Matching

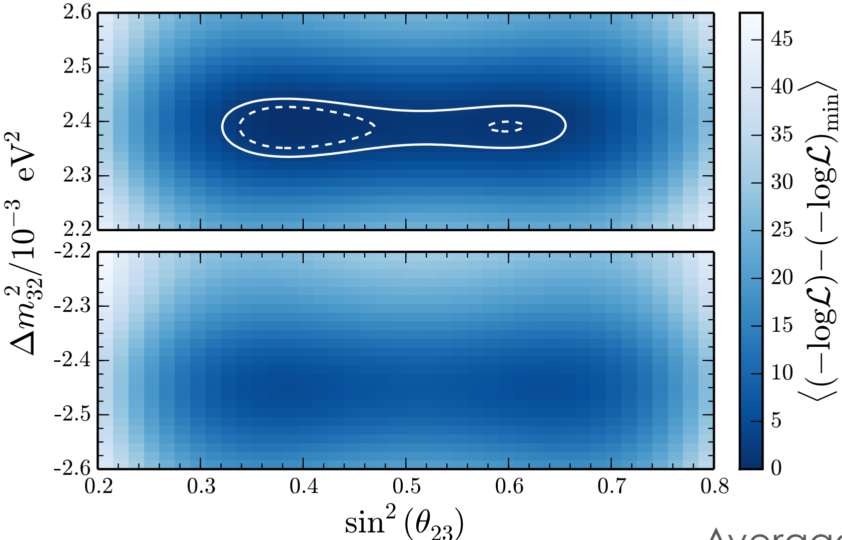
$$L = \prod_{i,j} L_{Poisson} \left(s_{ij} \mid \{ \Delta m^2_{32}, \sin^2(\theta_{23}) \}, \{ q_k \} \right)$$

$$\times \frac{1}{\sqrt{2\pi\sigma_{\theta_{13}}}} \exp\left(- \frac{\left(\theta_{13} - \langle \theta_{13} \rangle \right)^2}{2\sigma^2_{\theta_{13}}} \right)$$

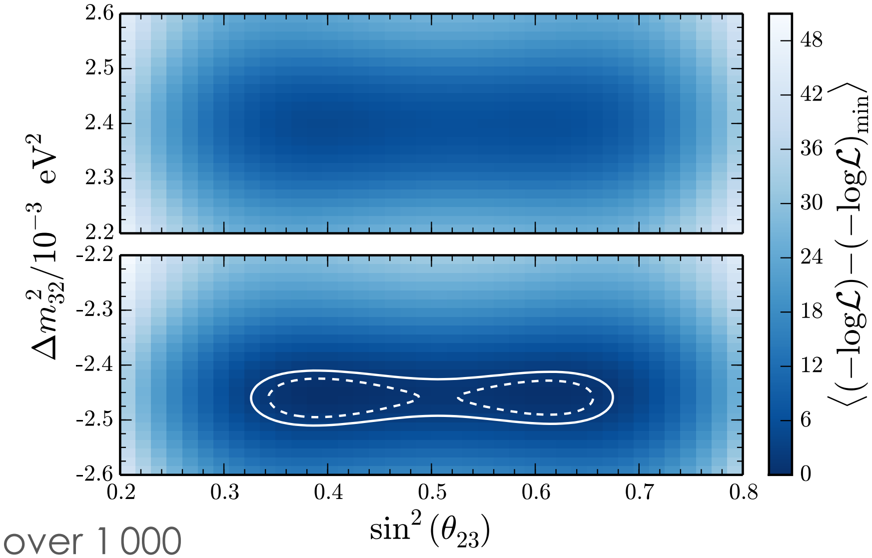
- Use Poisson statistics to create 1000 pseudo experiments
- Compare pseudo experiments with reweighted MC histograms via likelihood matching to find the best set of parameters
- Treat flux normalizations as continuous nuisance parameters
- Treat Θ_{13} as a discrete nuisance parameter (with Gaussian prior)

LLH Scan in Δm^2_{32} *and* $\sin^2(\theta_{23})$

Normal Hierarchy



Inverted Hierarchy



Input

$\Delta m^2_{21} = 7.54\times10^{-5}\,eV^2\,(fixed)$

$\Delta m^2_{32} = 2.39\times10^{-3}\,eV^2\,(NH)$

$\sin^2(\theta_{12}) = 3.07\times10^{-1}\,(fixed)$

$\sin^2(\theta_{13}) = 2.41\times10^{-2}$

$\sin^2(\theta_{23}) = 3.86\times10^{-1}$

Fogli et al.

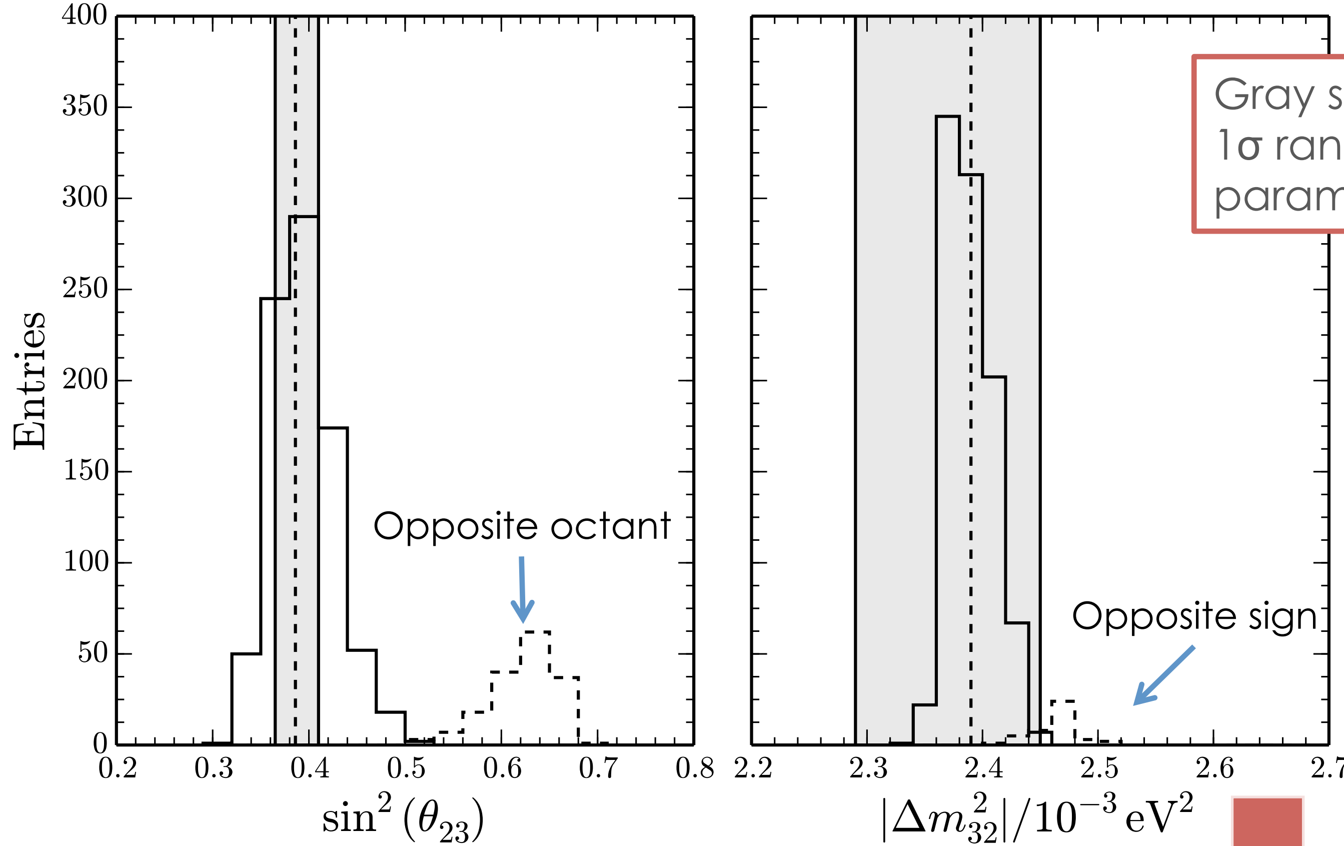
$c_e = 1.0 \quad c_\mu = 1.0$

Averaged over 1 000 pseudo-experiments

- c_e and c_μ fitted in each scan point
- $\sin^2(\theta_{13})$ 'fitted' in each scan point
- Depending on the hierarchy, PINGU shows sensitivity to the octant of Θ_{23} .

Further investigations needed.

Best Fit Values for Δm^2_{32} & $\sin^2(\theta_{23})$

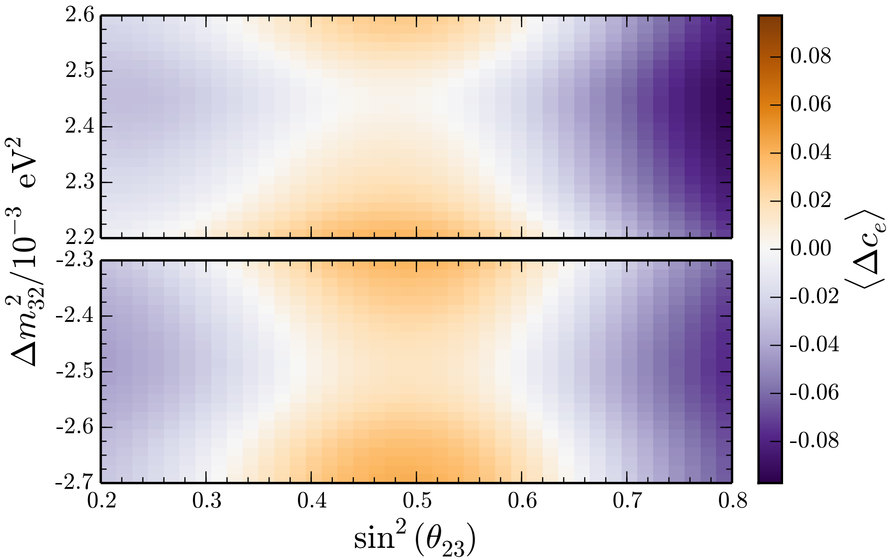


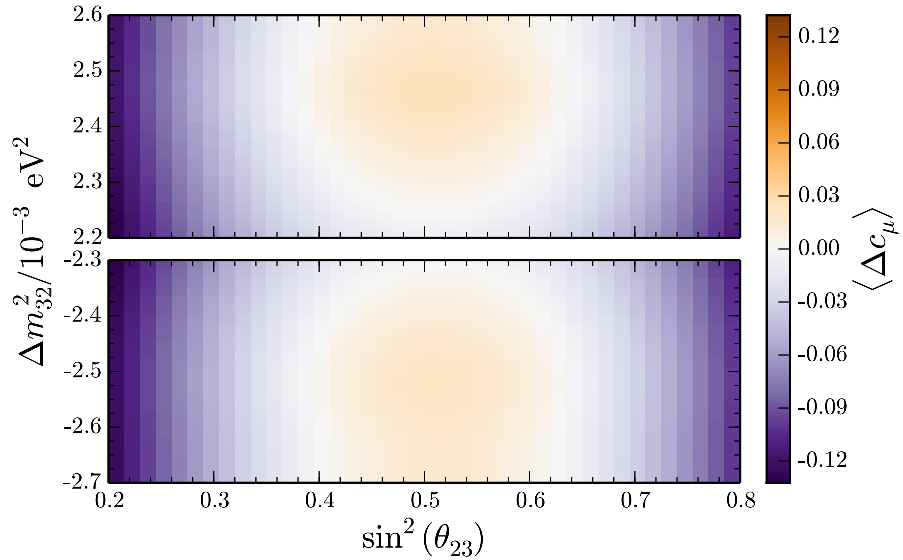
Gray shaded:
1σ range of input parameters

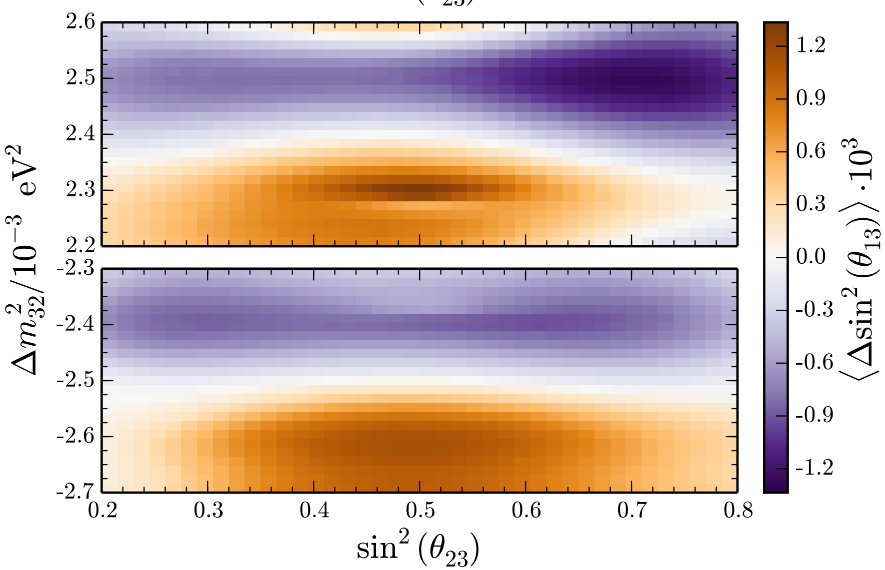
- Opposite octant for 17% of the pseudo-experiments
- Opposite sign in Δm^2_{32} for 4% of the pseudo-experiments

PINGU can measure Δm^2_{32} more accurately than the World's best fit value.

Nuisance Parameters on the LLH Map







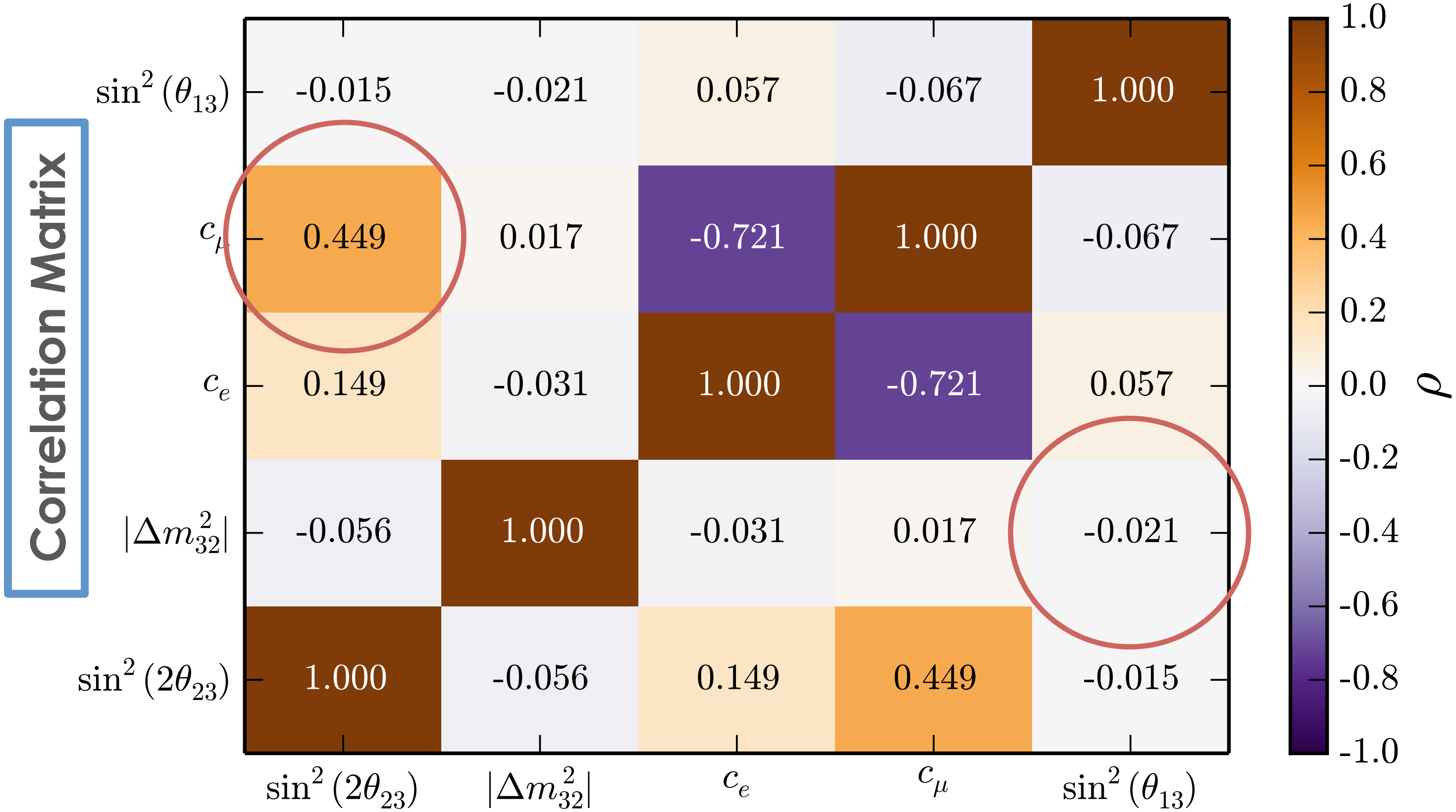
- Degeneracy between c_μ and $\sin^2(\theta_{23})$
- Degeneracy between $\sin^2(\theta_{13})$ and Δm^2_{32} ($\sim\Delta m^2_{31}$)

↕

MSW resonance

$$G_F N_e E_\nu \propto \cos(2\theta_{13})\Delta m^2_{31}$$

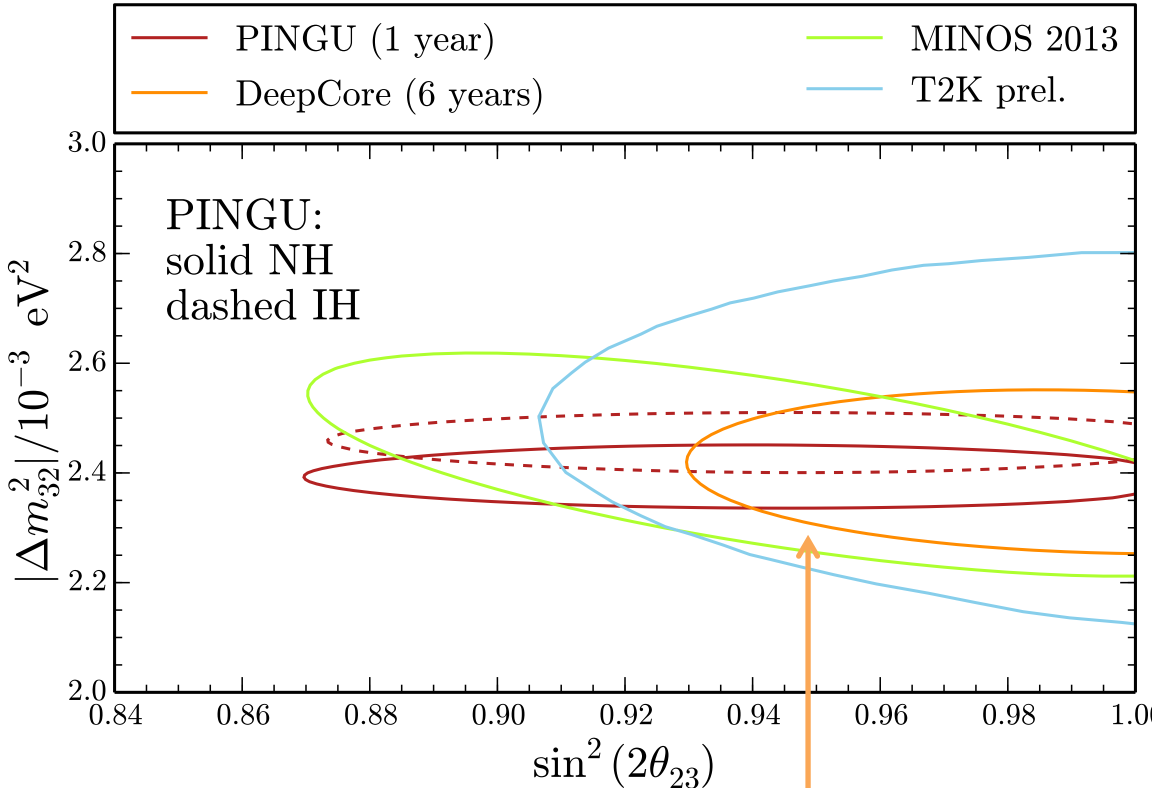
Degeneracy with Nuisance Params.



- No correlation between the best fit values of Δm^2_{32} & $\sin^2(\theta_{13})$
- Correlation between c_μ and $\sin^2(2\theta_{23})$ inhibits a more precise measurement of θ_{23}.

Comparison to other Experiments

- Compare PINGU's 90 % contour to MINOS, T2K and DeepCore



Conclusions:

- PINGU will be competitive after the first year of data.
- PINGU has the potential to set the World's best constrains on $\Delta m_{32}{}^2$.

Caveats:

- Neutrino rate below 10 GeV is overestimated.
- Energy-dependent systematics are not included yet.
- MC statistics correspond only to 1 year of data.

Julia Leute et al.:

Expected sensitivity for DeepCore after 6 years of data.

Extension to Neutrino Mass Hierarchy

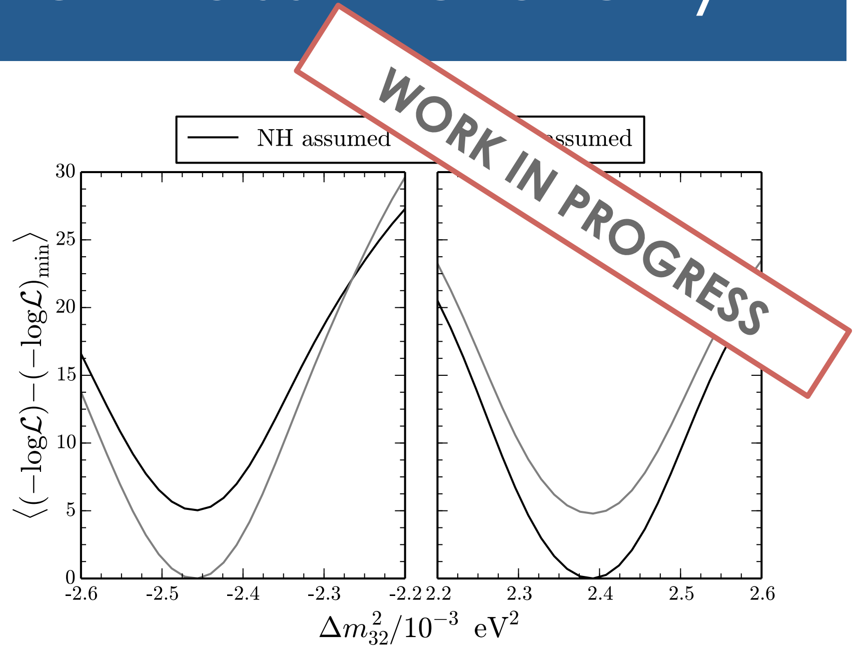
Question:
Assume a certain hierarchy. At which confidence level is PINGU able to exclude the opposite hierarchy?

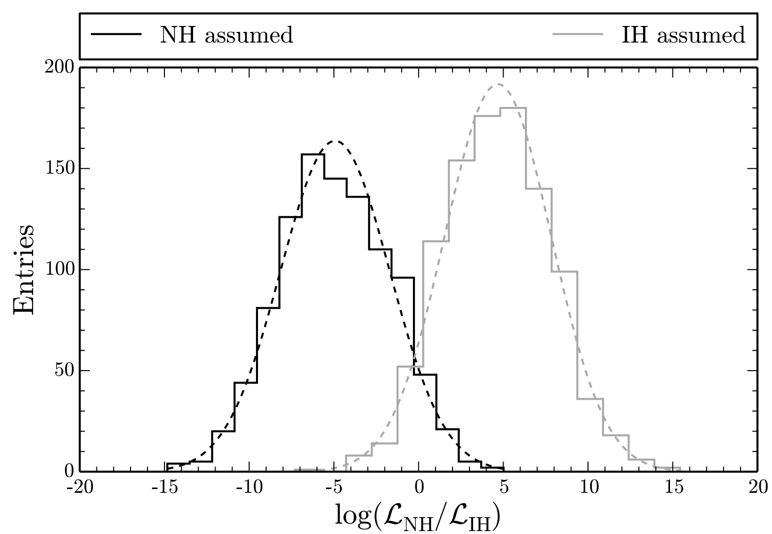
Method

- Marginalize over $\sin^2(\Theta_{23})$:
  For each row in $\Delta m_{32}{}^2$, choose the minimum negative log-likelihood.
- Evaluate significance to NMH via two methods:
  - Based on Wilks' theorem
  - Based on hypothesis test → test statistic

$$\log\left(L_{NH} / L_{IH}\right)$$

Visible separation between both neutrino mass hierarchies.





Summary and Outlook

Summary

- Next IceCube Upgrade: PINGU
→ Measurement of the neutrino mass hierarchy
→ ν_μ disappearance is the first step
- Adapt event selection from I79 DeepCore analysis:
→ Defined a larger veto region.
→ μ contamination expected to be below 10 %
- Fit of mixing parameters:
→ Competitive results already after the 1st year of data
→ High sensitivity to Δm^2_{32}
- Extension of analysis to the neutrino mass hierarchy
→ Significance can be extracted from the LLH map.
→ Test statistic shows a visible separation between both hierarchies.

Outlook

- Switch to 40-string geometry.
- Implement missing systematics.

Summary and Outlook

Summary

- Next IceCube Upgrade: PINGU
→ Measurement of the neutrino mass hierarchy
→ ν_μ disappearance is the first step

- Adapt event selection from I79 DeepCore analysis:
→ Defined a larger veto region.
→ μ contamination expected to be below 10

- Fit of mixing parameters:
→ Competitive ... year of data
→ Hi...

...alysis to the neutrino mass hierarchy
...gnificance can be extracted from the LLH map.
→ Test statistic shows a visible separation between both hierarchies.

Thank you for your attention.

Outlook

- Switch to 40-string geometry.
- Implement missing systematics.