Neutrino Mass Hierarchy with PINGU

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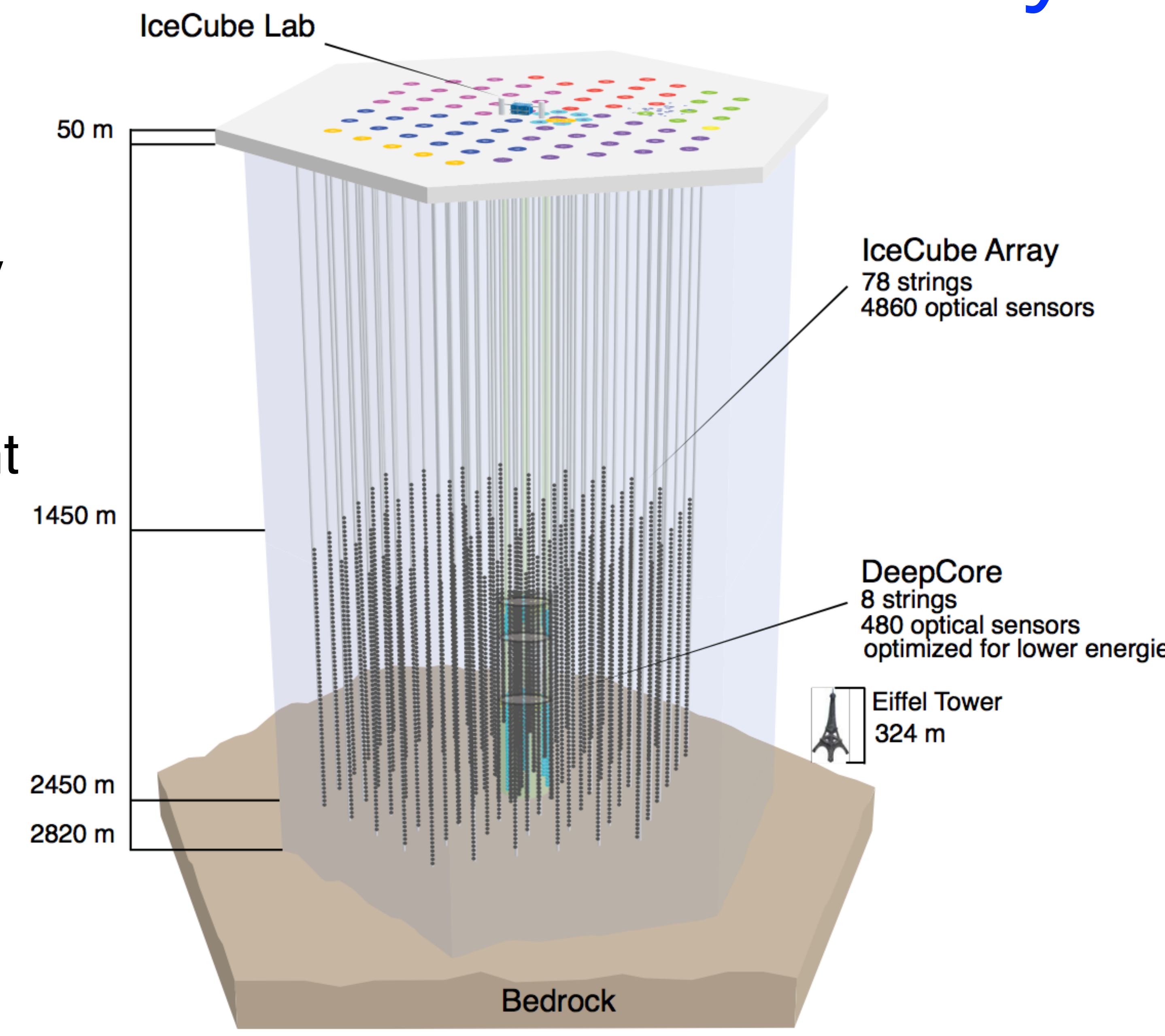
The IceCube Neutrino Observatory

IceCube:

- 78 strings, 125 m/17 m spacing
- Energy range: ~ 100 GeV to ≳ 10 PeV
- 1 km^3 volume of south pole ice as ν target, and medium for Cherenkov light production.



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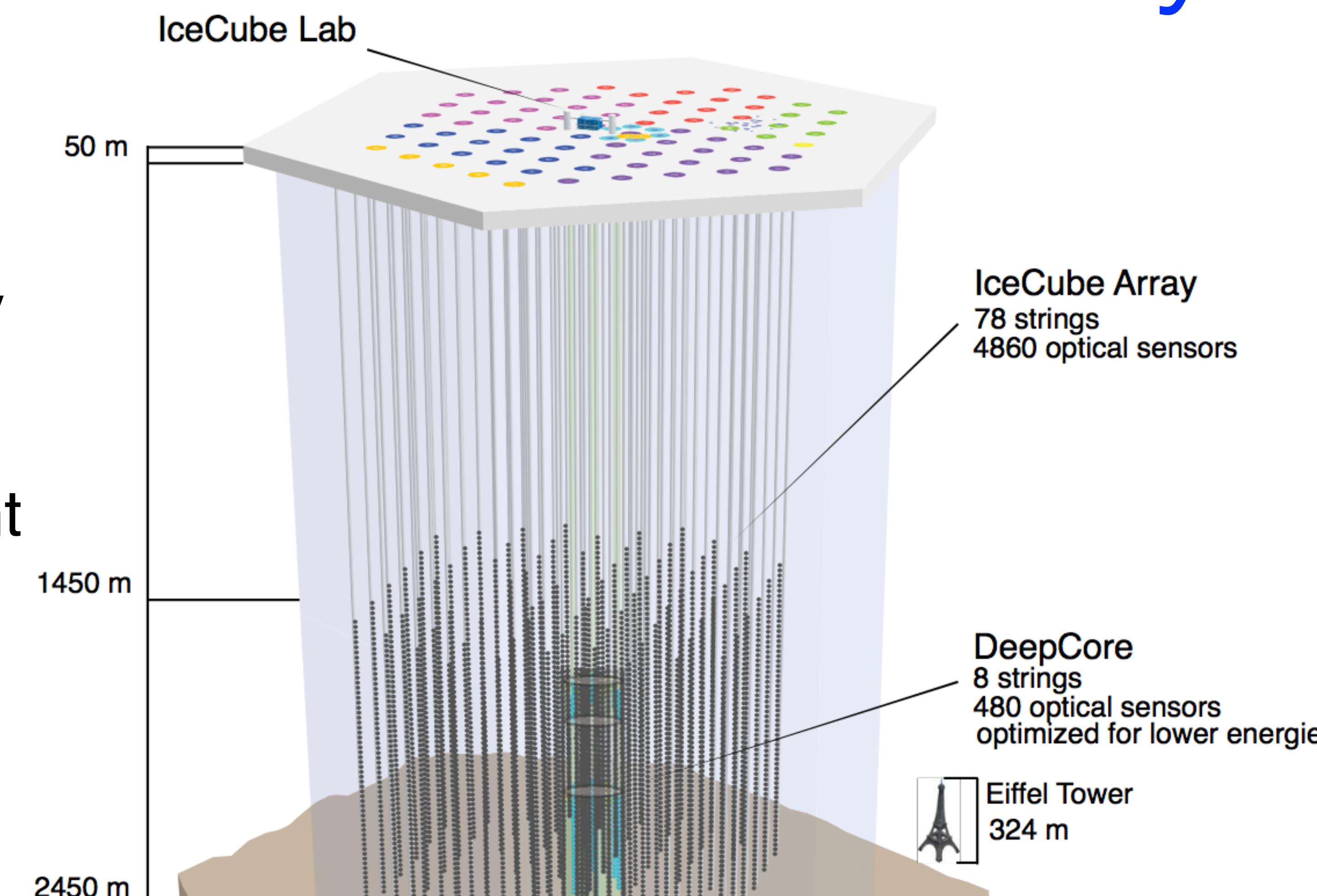
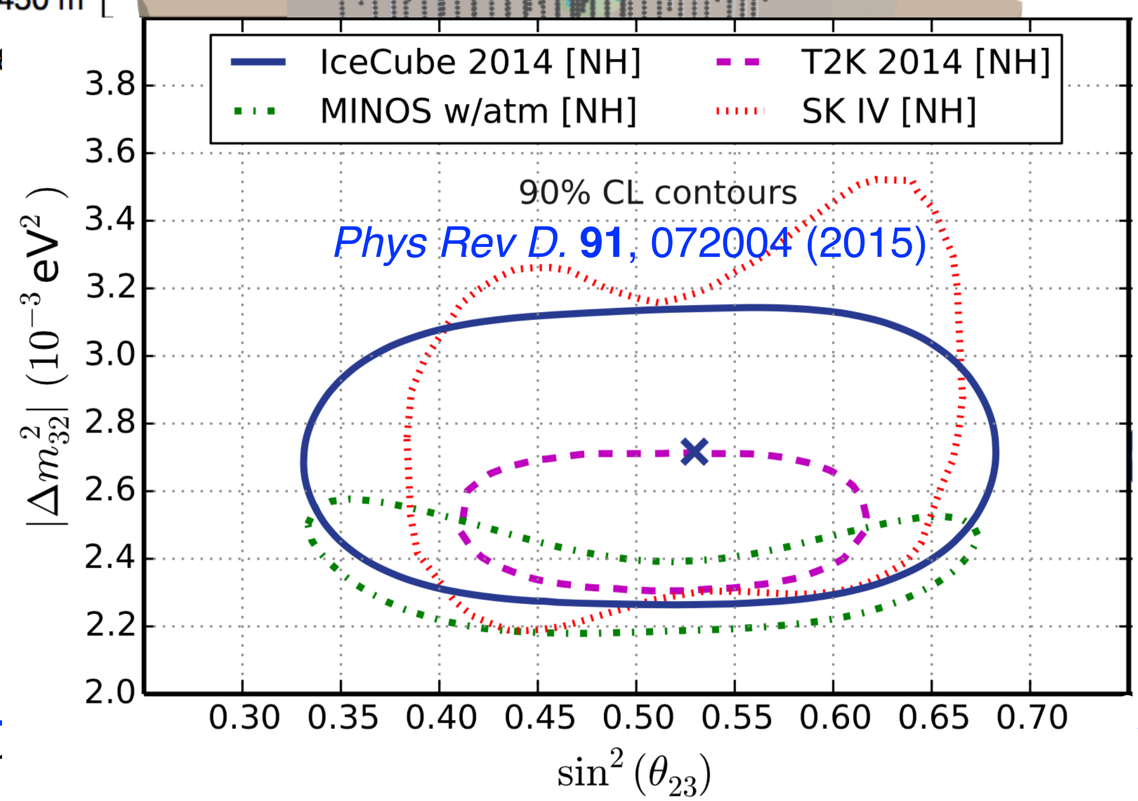
DeepCore:

- 8 additional strings, ~ 40 - 70 m / 7 m spacing
- Spans ~ 10 - 100 GeV
- Targets atmospheric ν oscillations and dark matter searches

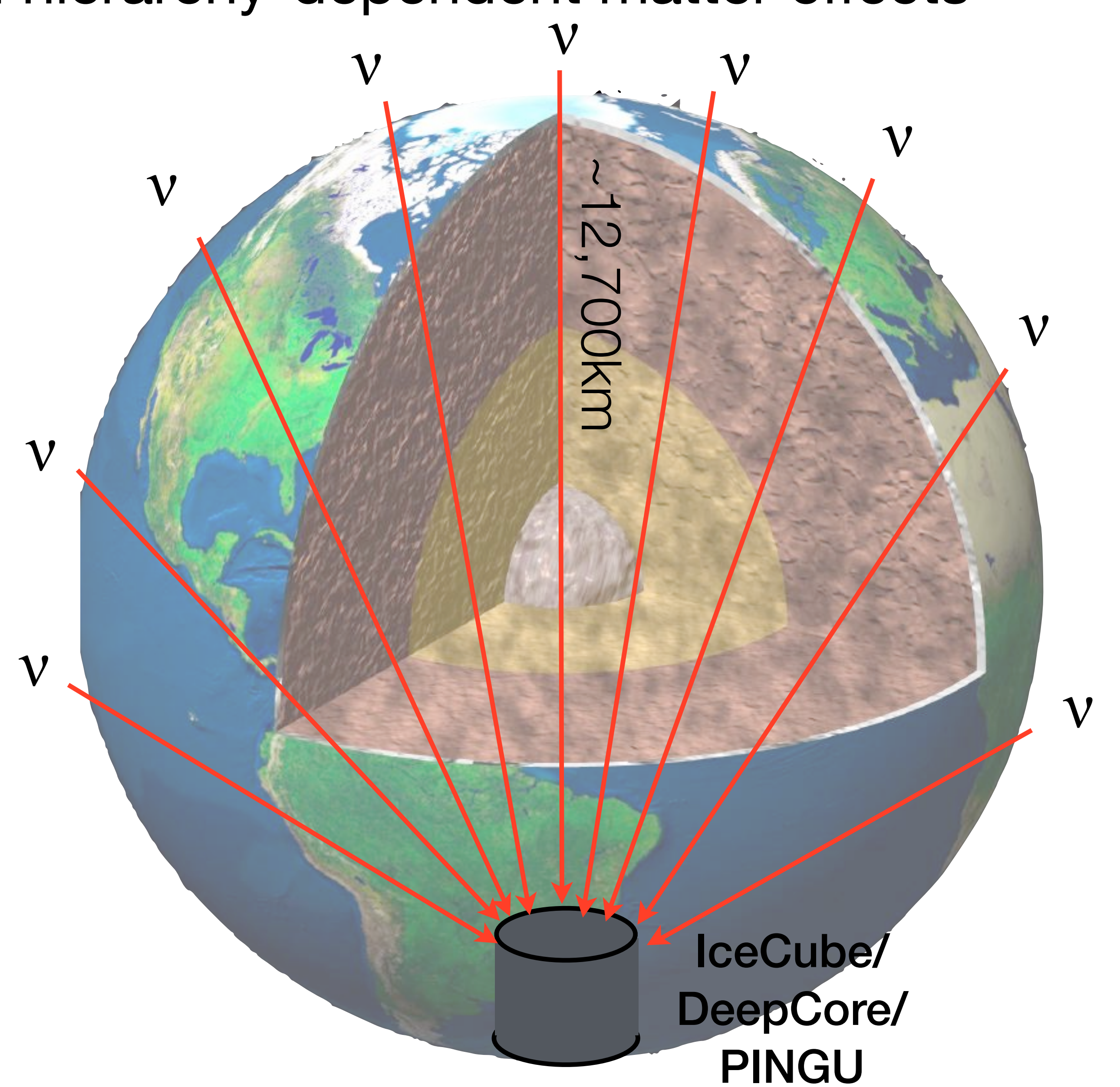




Atmospheric Neutrino Oscillations

- Neutrinos available over a wide range of energies and baselines
  - ✦ Oscillations produce a distinctive pattern in energy-angle space
  - ✦ ν_μ 1st survival minimum ~ 25 GeV, and hierarchy-dependent matter effects below ~ 12 GeV.
- Large detector required to provide sufficient statistics to make this approach feasible
  - ✦ DeepCore event rates

type	triggered	analysis level
ν_μ	~70 k/yr	~1-10 k/yr
ν_e	~10 k/yr	~0.1-3 k/yr

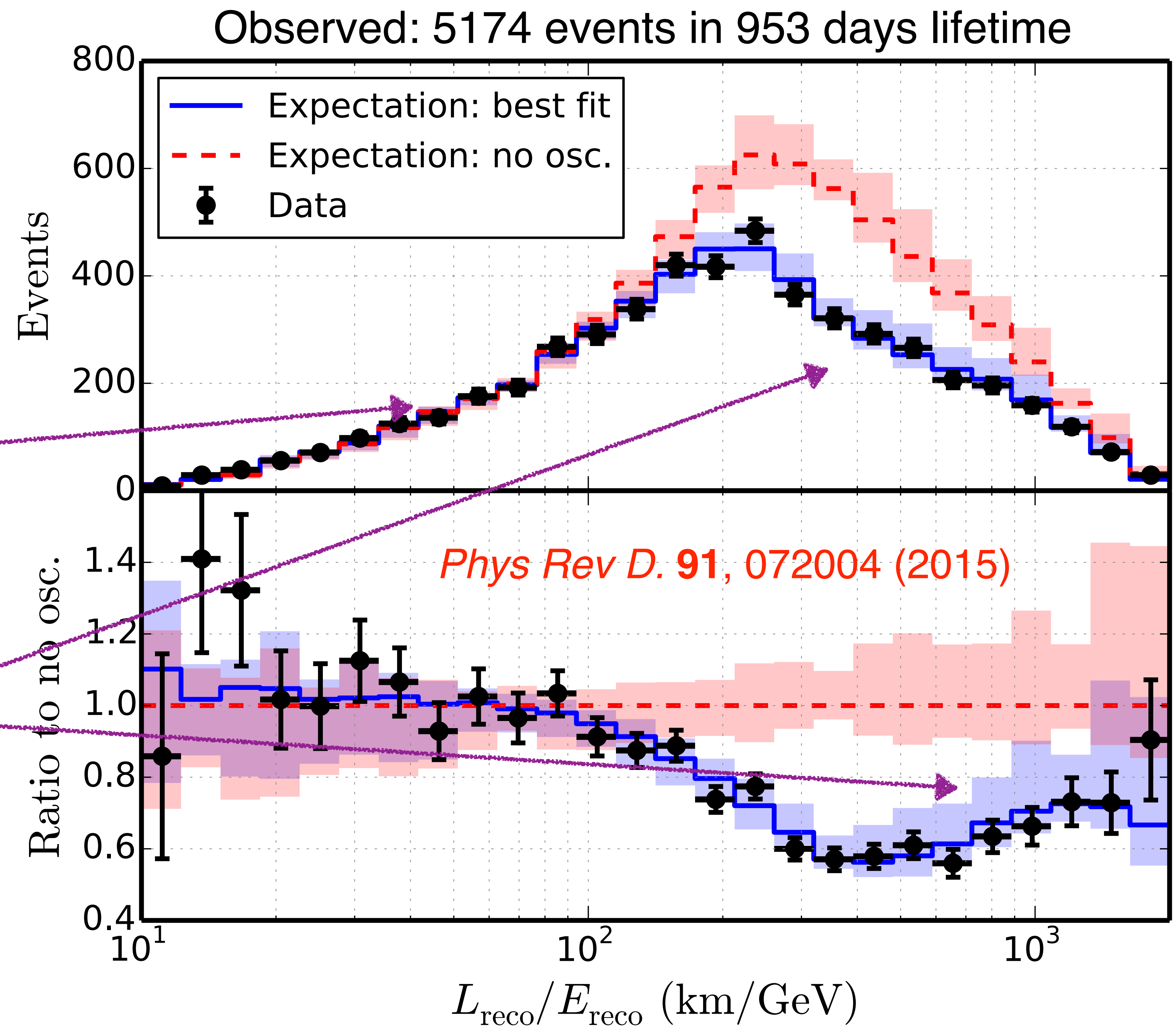


Atmospheric Oscillations with IceCube-DeepCore

- Projection onto reconstructed L/E_ν for illustration purposes
- Shaded range shows allowed systematics with constraints from current data

Good agreement in control region

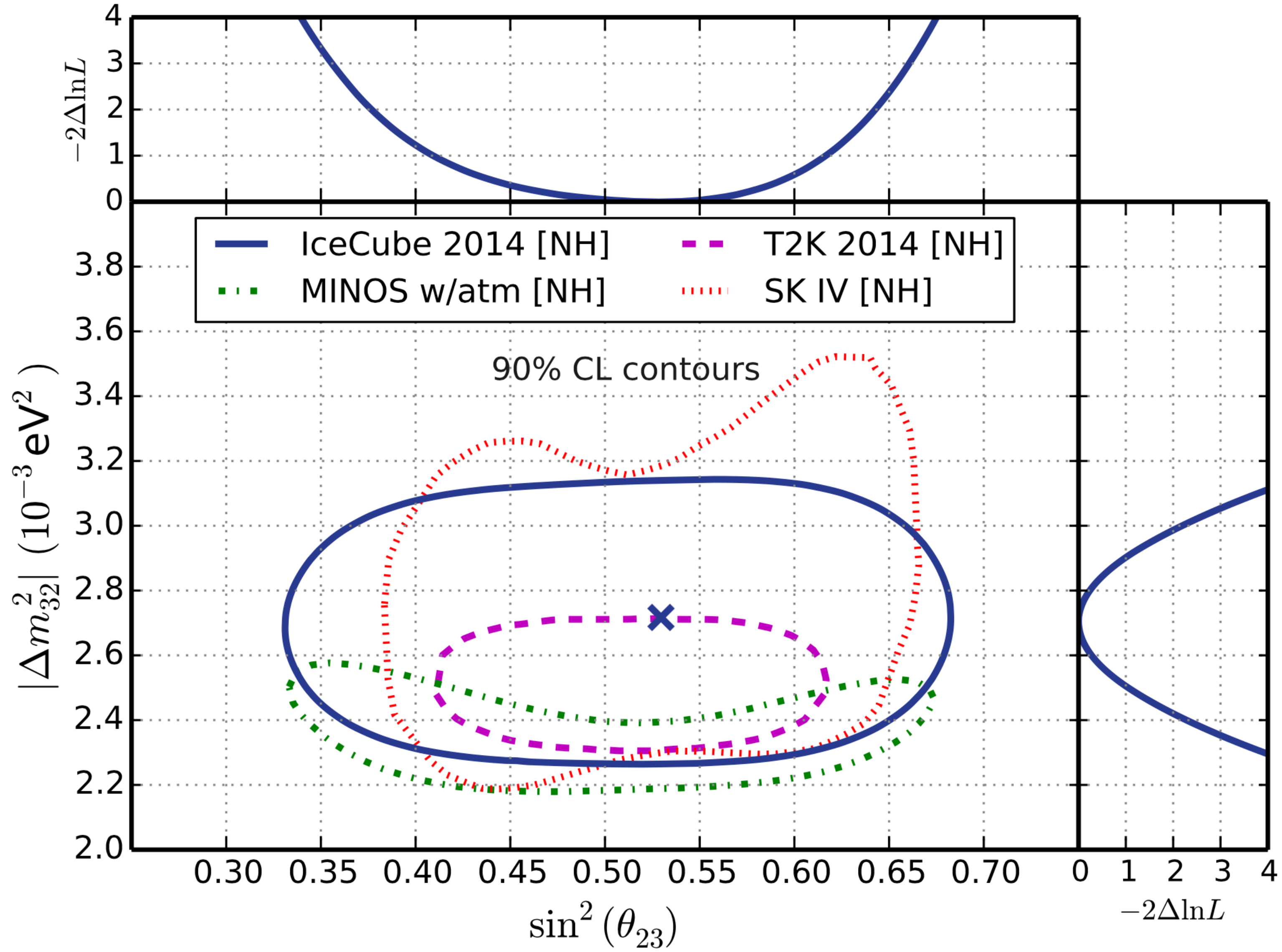
Good description of oscillation region



IceCube-DeepCore Constraints

- Very competitive constraints
- 3 years of DeepCore data
- Analysis improvements are ongoing, extending to:
  - Higher statistics
  - Extend to both track and cascade channel

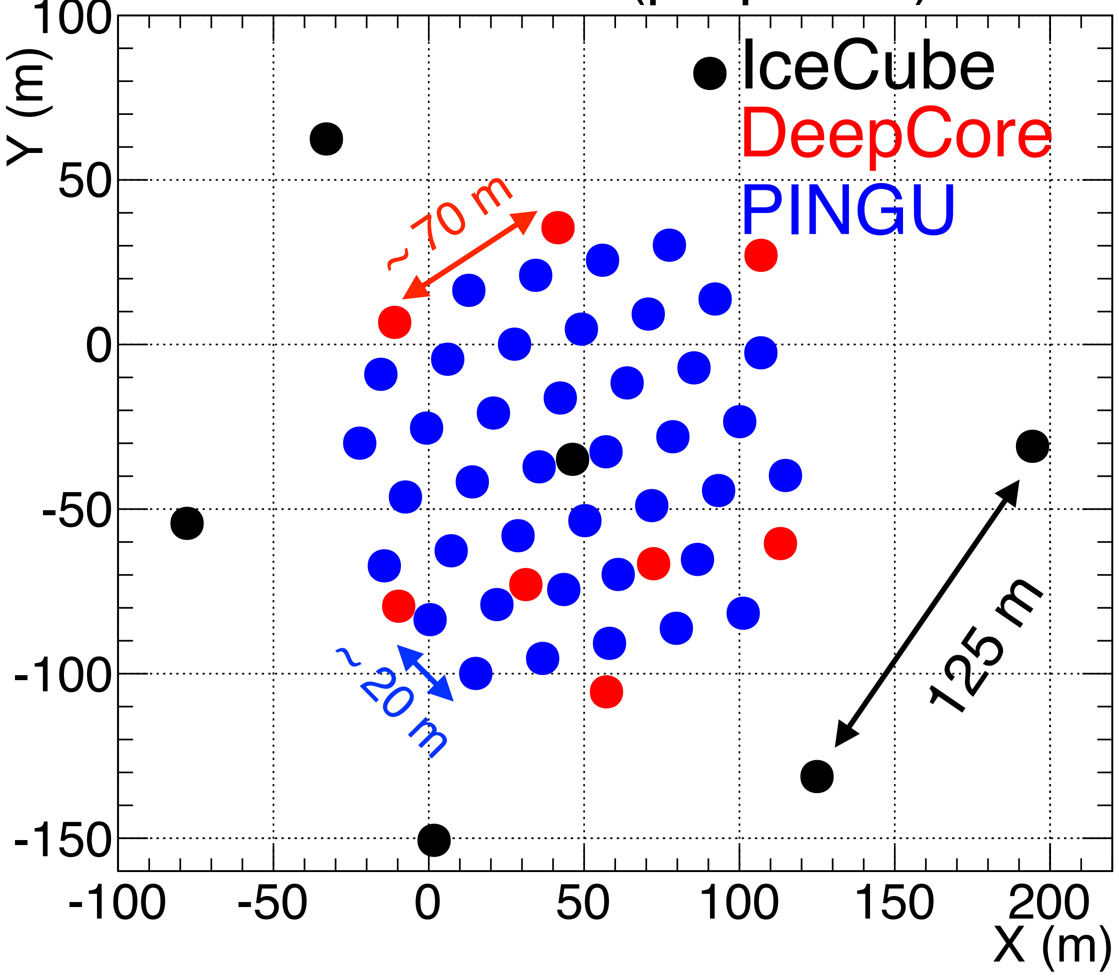
Phys Rev D. **91**, 072004 (2015)



PINGU: Beyond DeepCore

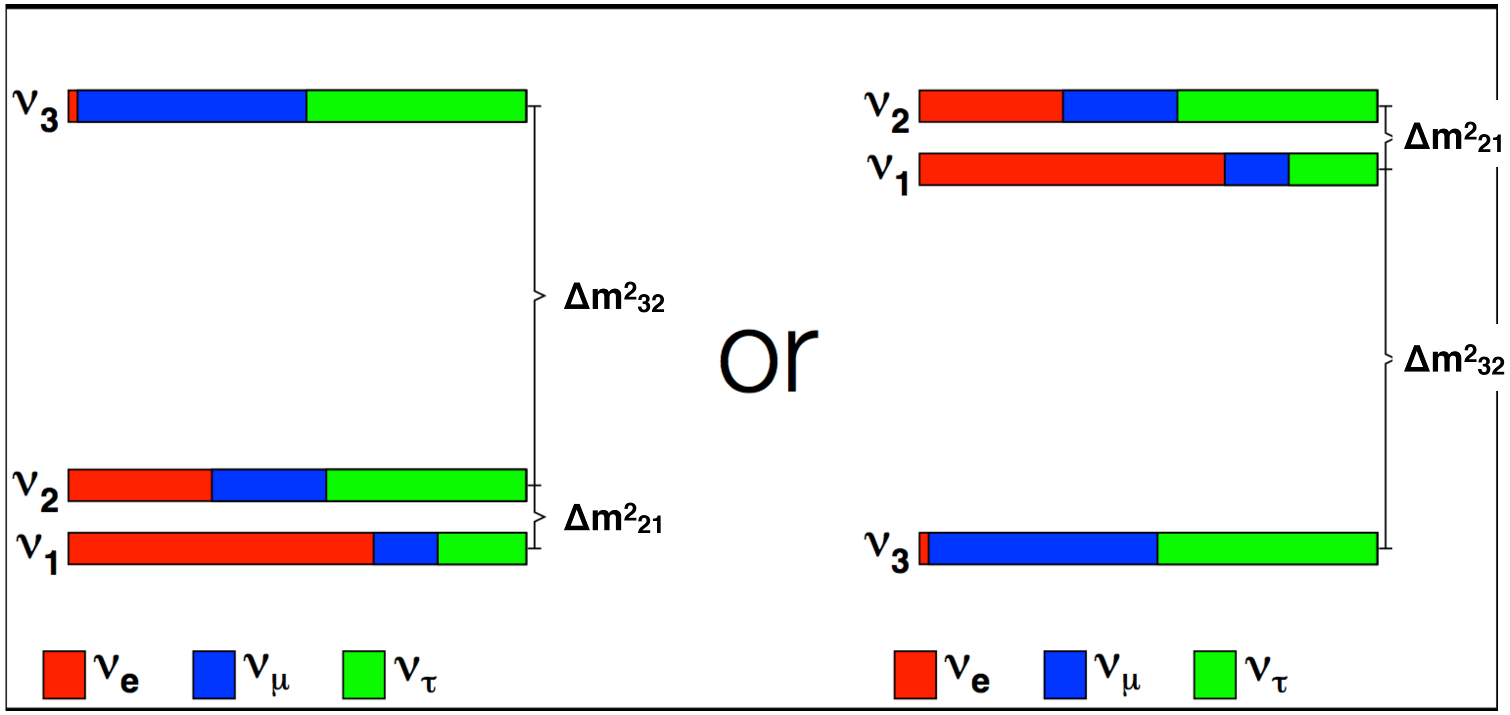
- Baseline detector described in LoI- arXiv:1401.2046
  - ✦ 40 additional strings
  - ✦ 60 DOMs per string
    - Deployed within DeepCore volume
- Since then:
  - ✦ Geometry optimization performed
  - ✦ Low marginal cost to increase DOMs/string
    - Final version: ~ 50 % more DOMs/string
  - ✦ 20 - 22 m string spacing
    - ~25x higher photocathode density vs DC
  - ✦ Additional in situ calibration devices to better control systematics

Top Down View of IceCube/DeepCore (operational) and PINGU (proposed)



Neutrino Mass Hierarchy (NMH)

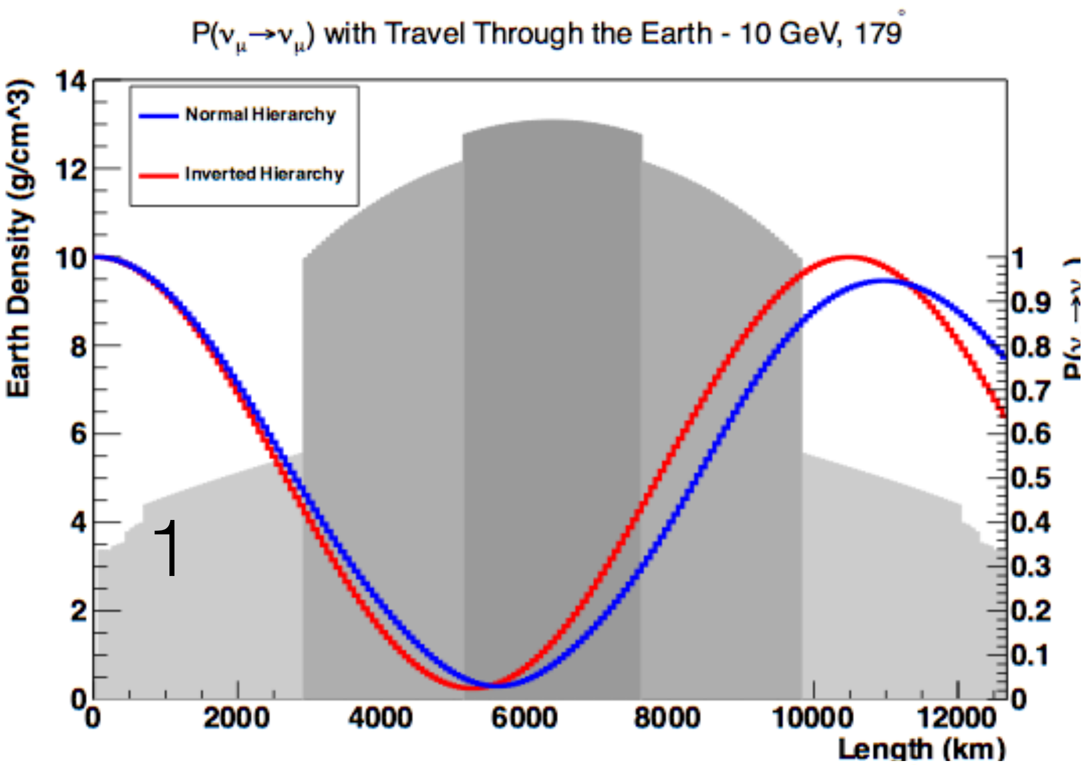
- One important outstanding question in neutrino physics:
  - sign of the atmospheric mass splitting: Δm^2_{32} (mass hierarchy)

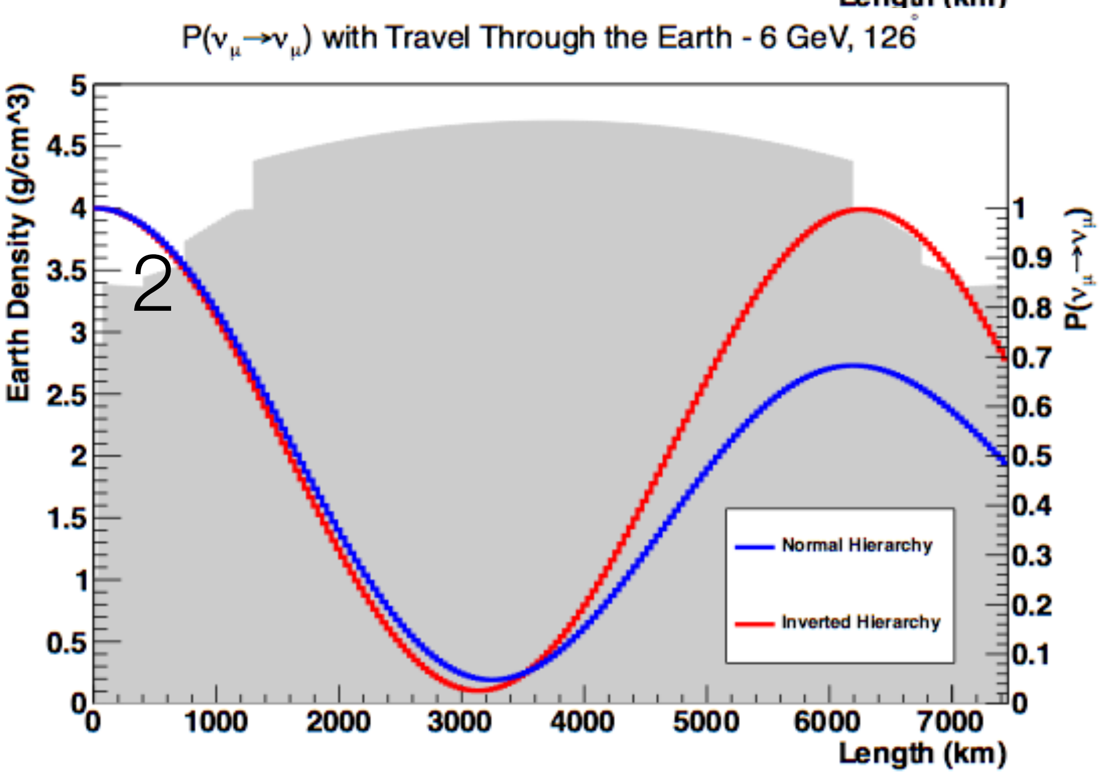


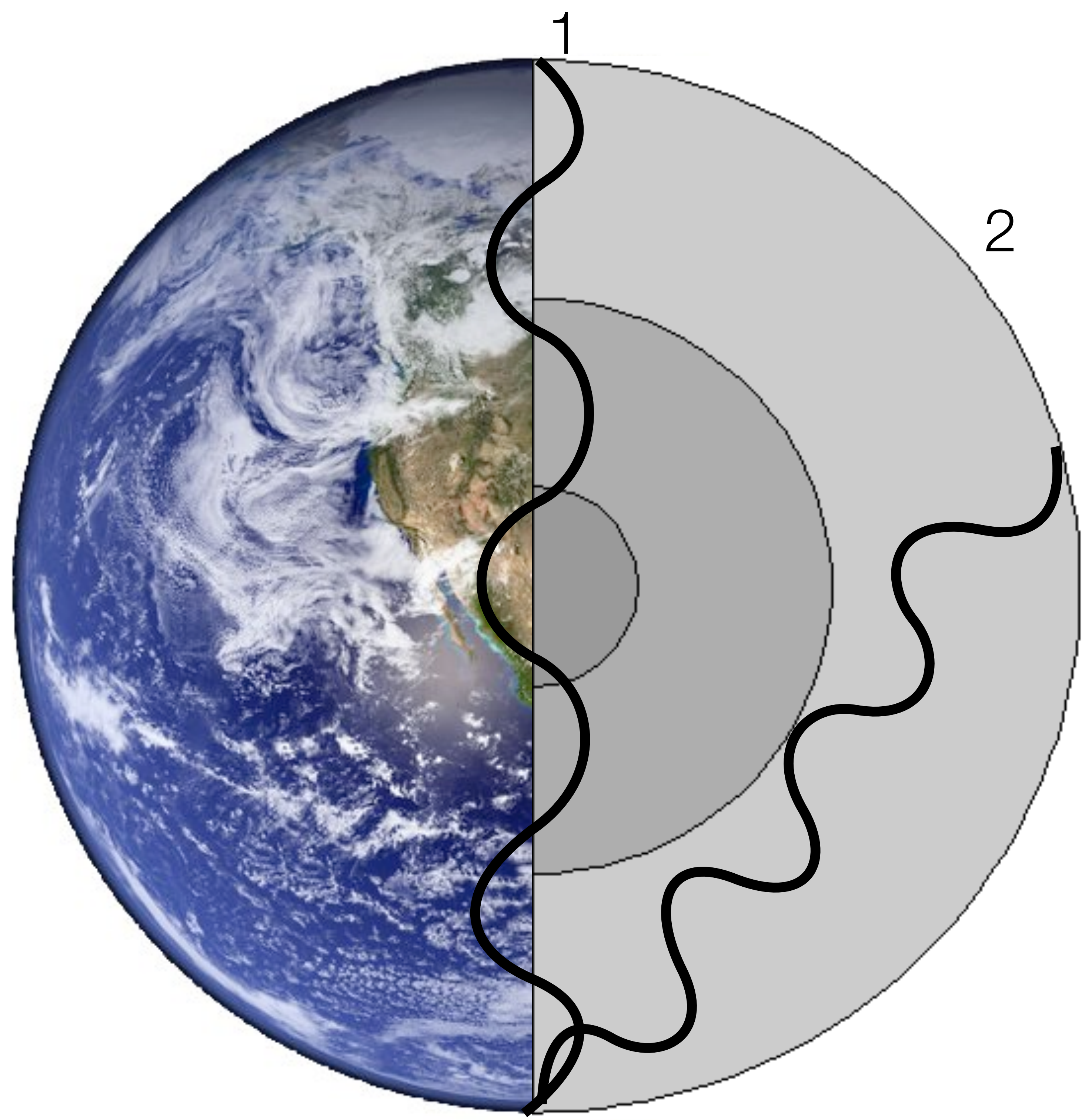
- Possible to use many "beam" paths of atmospheric neutrinos: PINGU, ORCA, INO
- Reactor experiments: JUNO, RENO-50
- Accelerator beam: T2K, NOνA, DUNE (formerly LBNE/F)

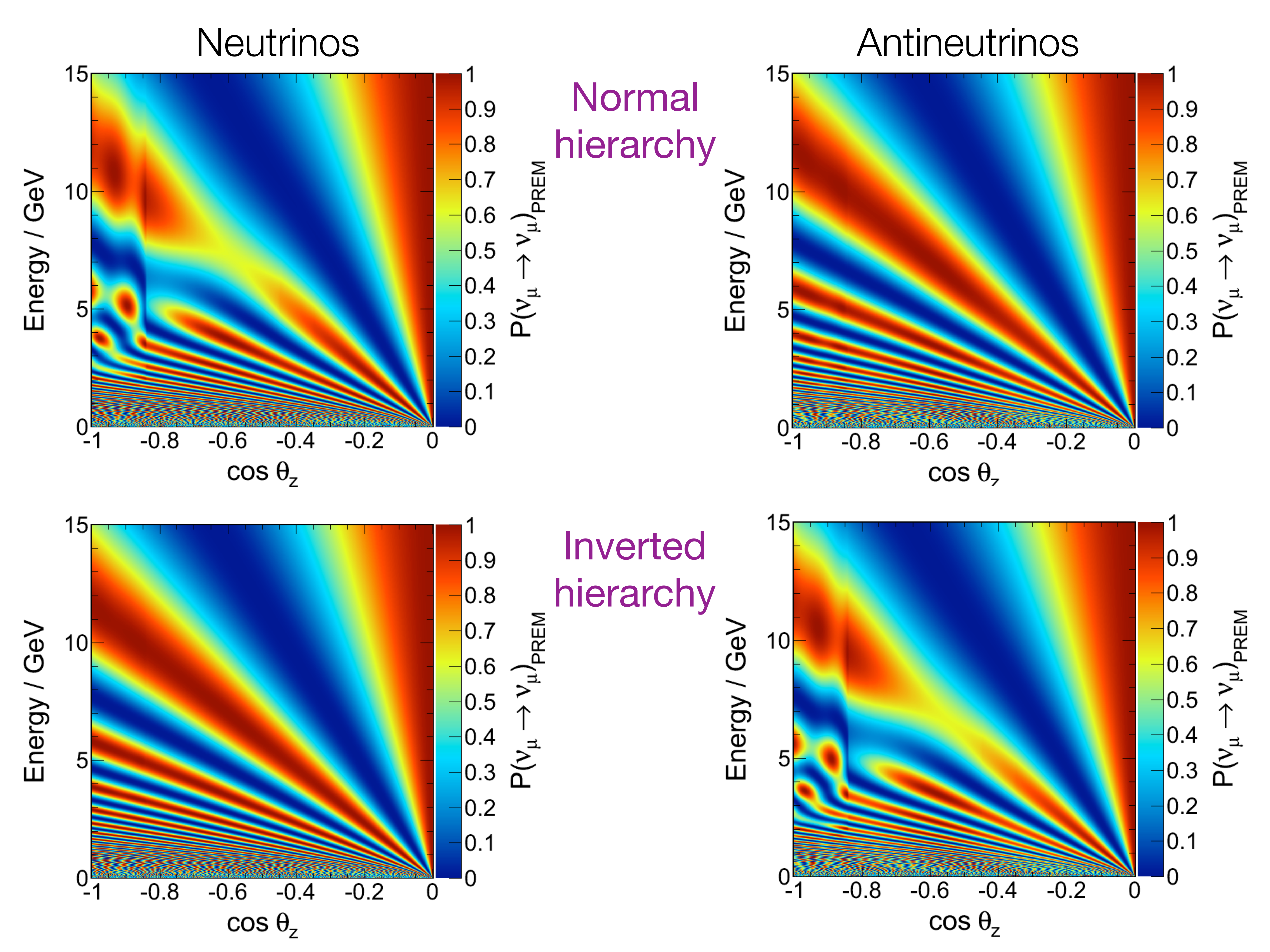
Atmospheric neutrinos and the NMH

- Up to 20% differences in ν survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy





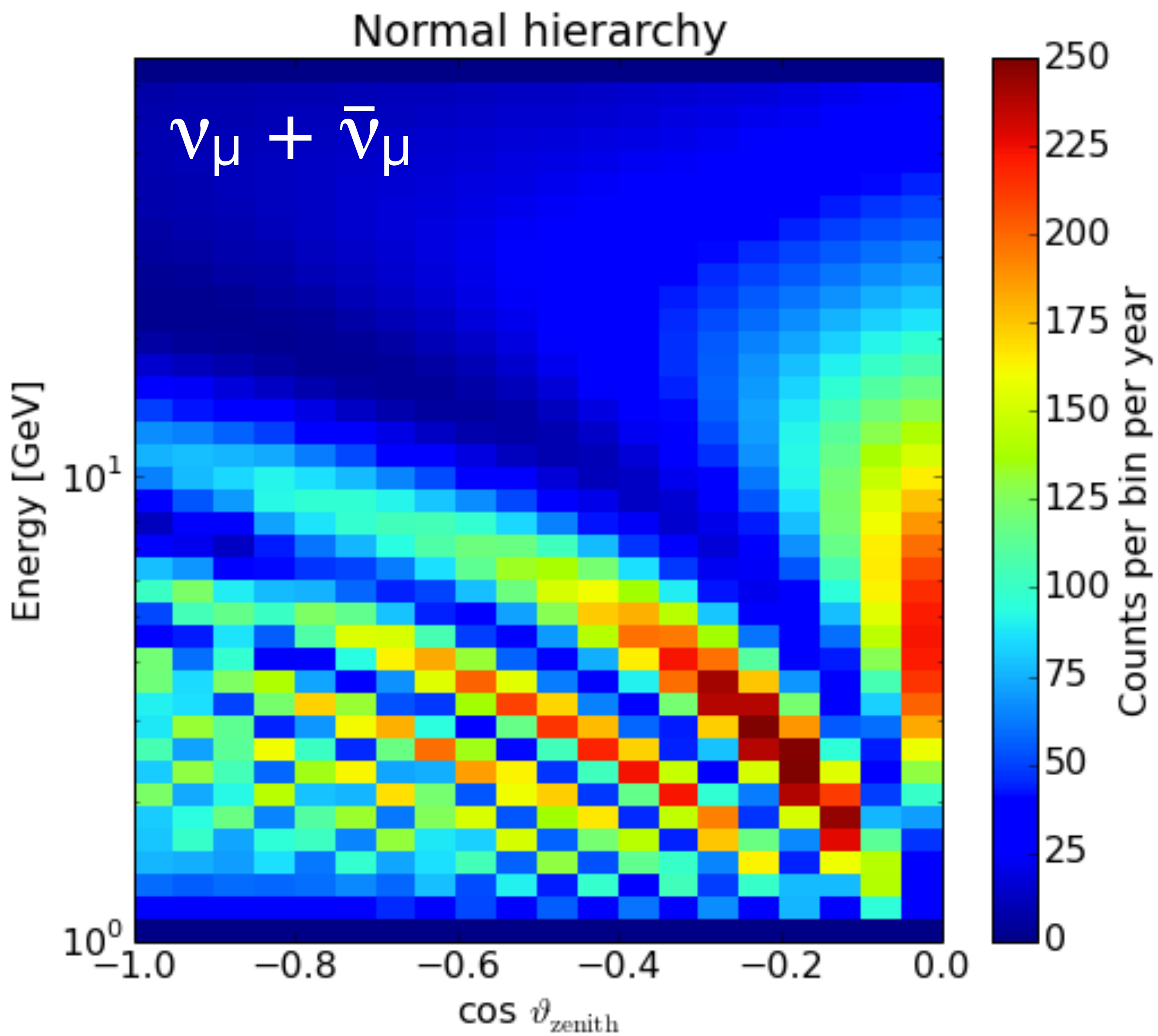




Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Energy / GeV
cos θz
P(νμ → νμ)PREM

PINGU Perfect Detector: NMH Signature

- No ν/anti-ν discrimination
- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
  - ✦ Rates of all flavors are affected
- Small but distinct signatures observable in both tracks (ν_μ CC) & cascades (ν_e and ν_τ CC, v_x NC)
- Detected rates (after cuts)
  - ✦ ~ 50k ν_μ + anti-ν_μ per year
  - ✦ ~ 38k ν_e + anti-ν_e per year



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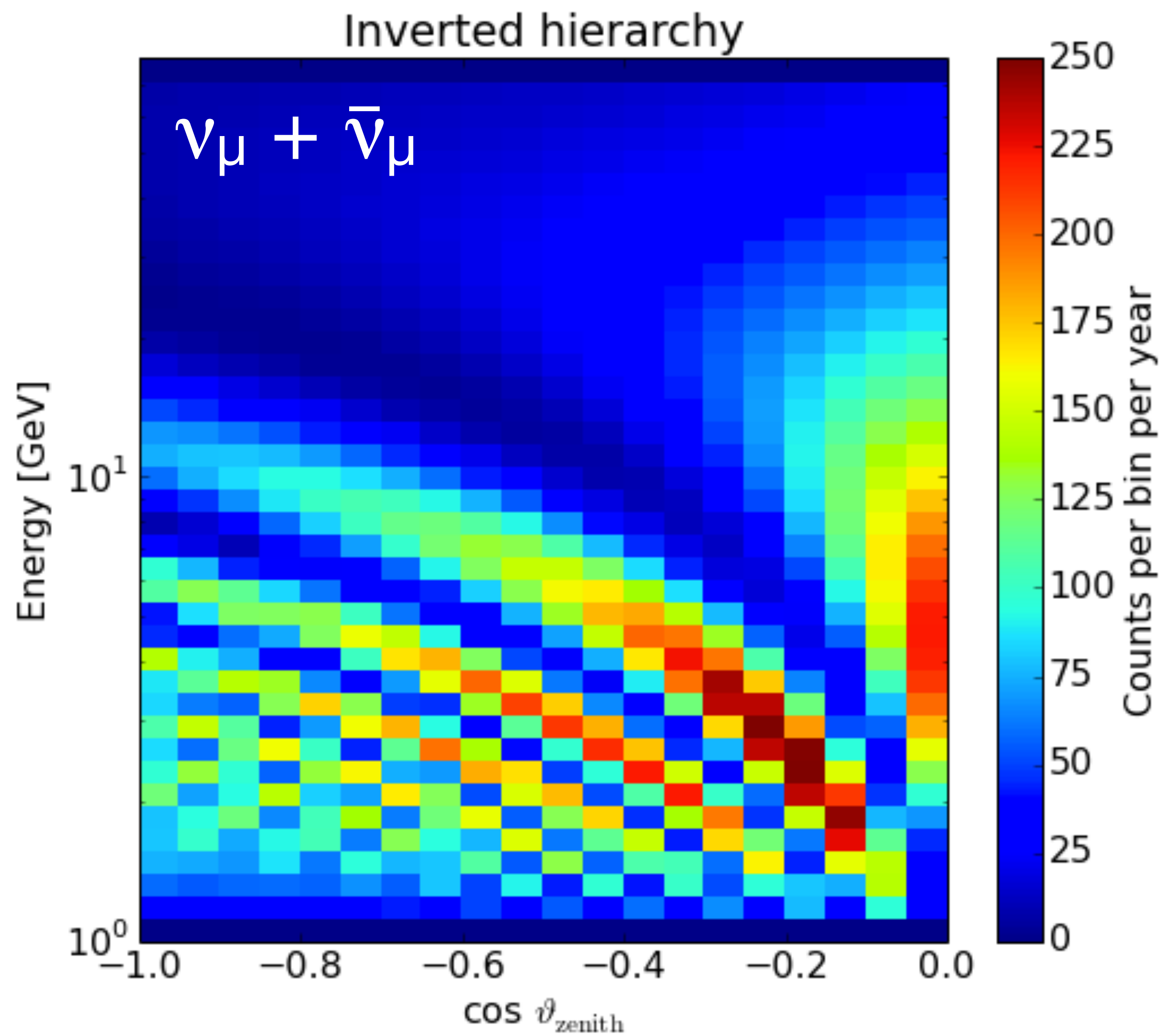
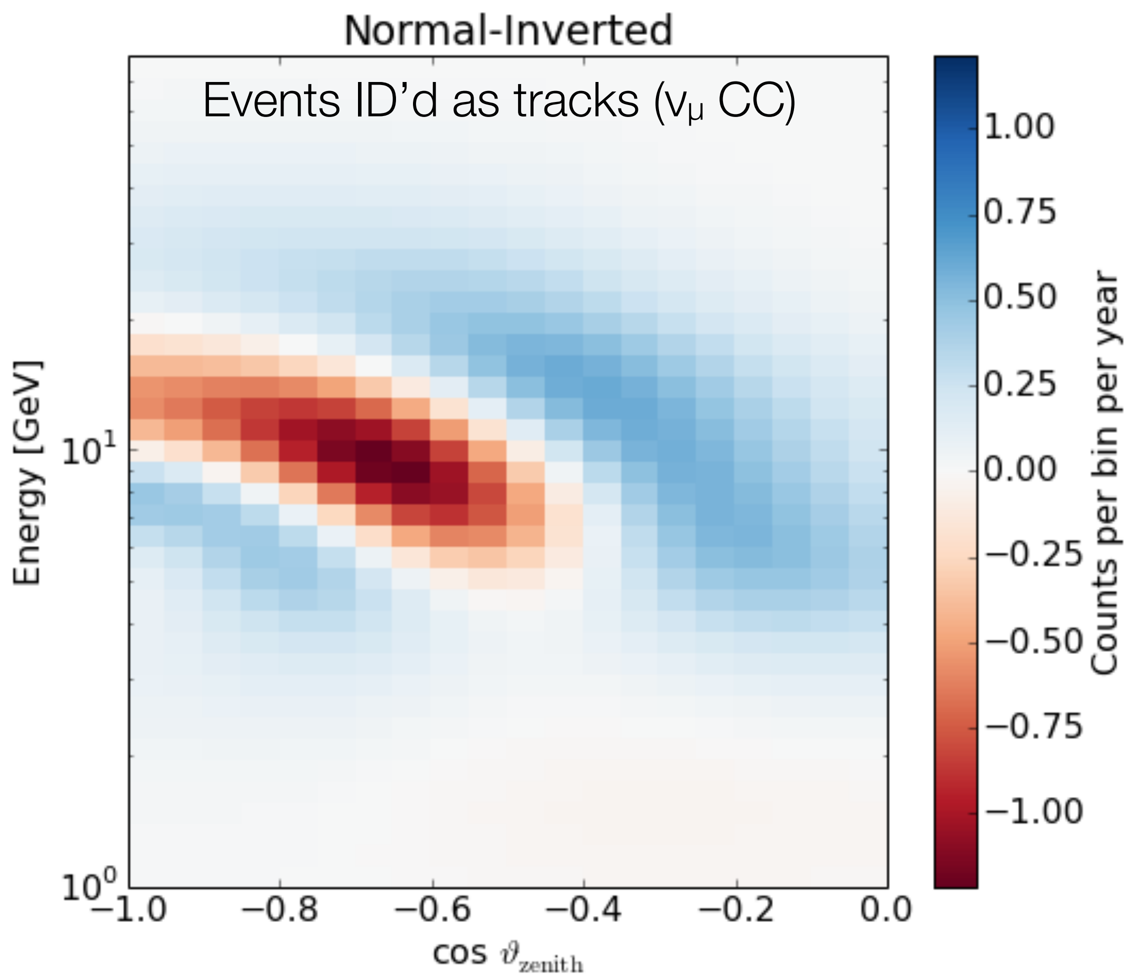
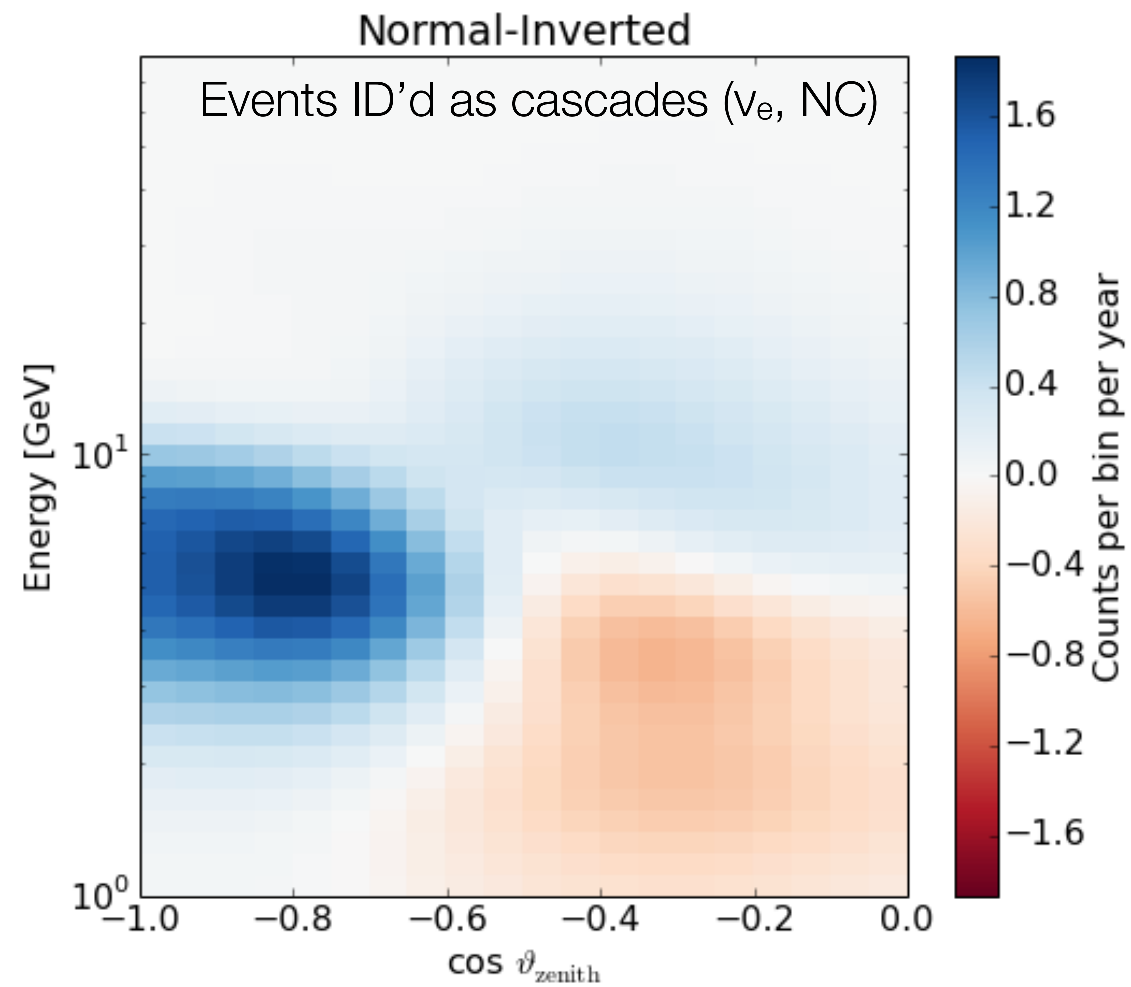


NMH in PINGU-with Resolutions, PID

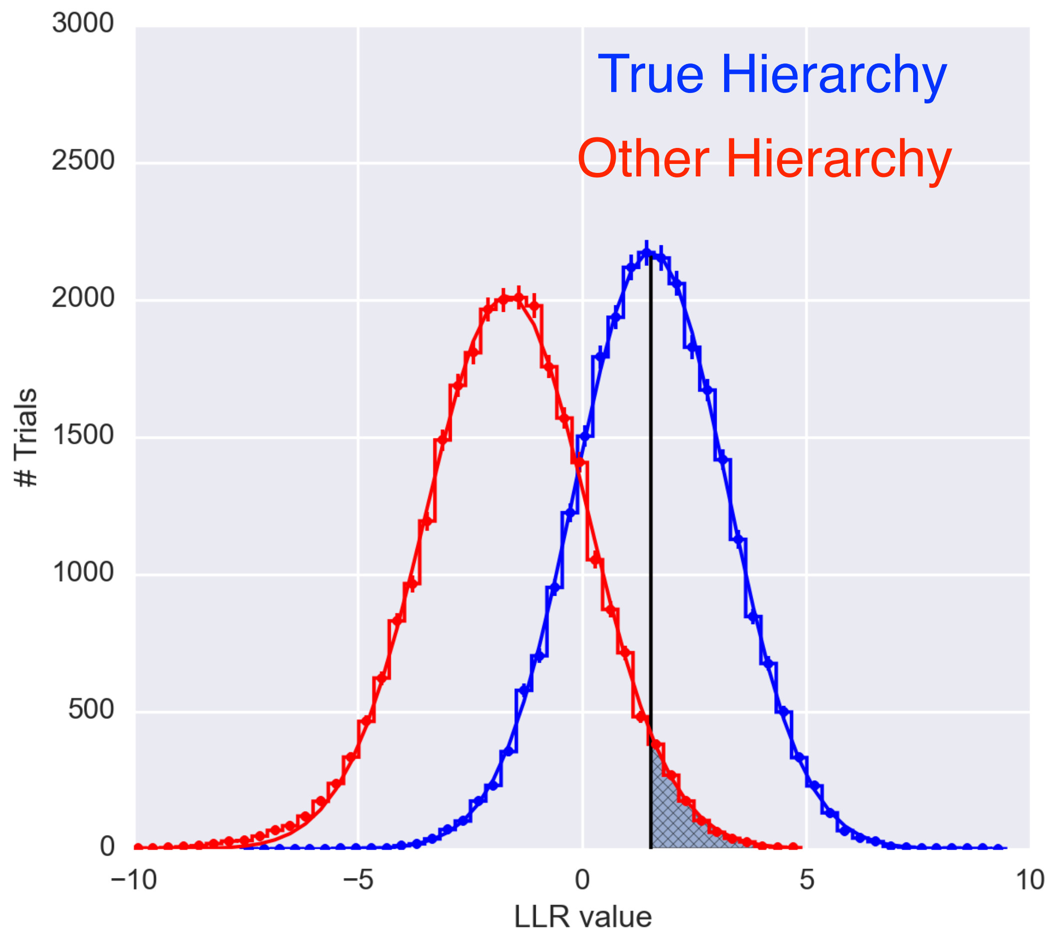




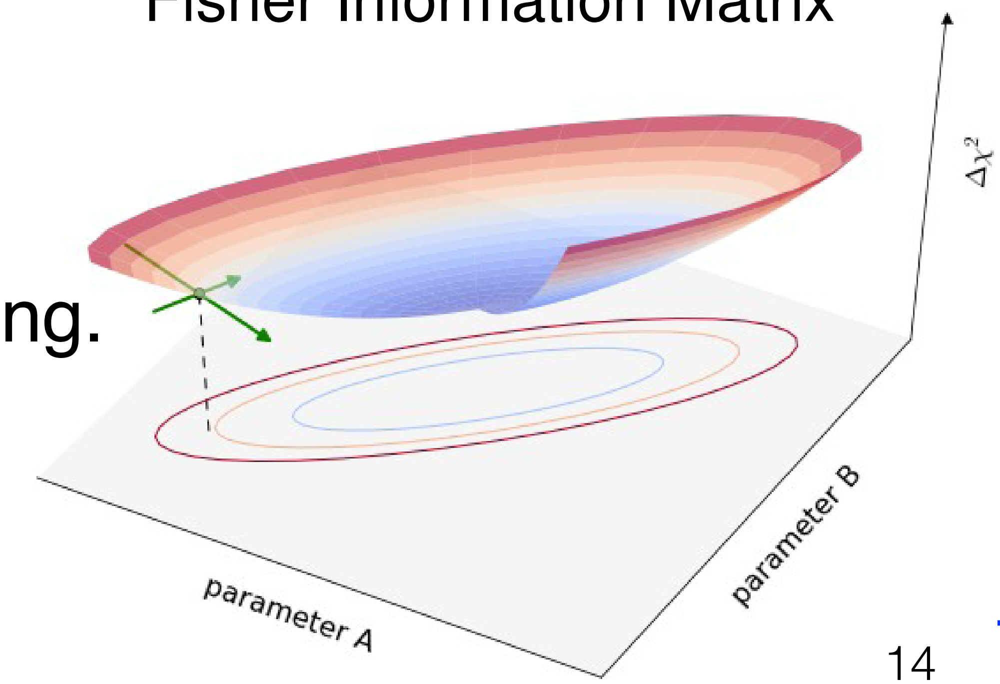
- Include all detector effects: resolutions and particle identification
  - Distinct and hierarchy-dependent signatures are visible in both track-like and cascade-like channels

Calculating the Sensitivity to NMH

- Method 1: LogLikelihood Ratio
  - Generate ensemble of pseudo data sets.
  - LLR provides degree of agreement between pseudo data set and the true hierarchy vs the other hierarchy.
  - Shaded region corresponds to probability of mis-identifying the hierarchy
- Method 2: Fisher information matrix
  - Uses gradients in parameter space to determine covariance matrix
  - Much faster, but uses simplified statistics, only applicable if model is well-behaved
  - Not well-behaved if θ_{23} close to maximal mixing.
- Methods agree in safe regime ✔



Fisher Information Matrix



Systematic Parameters

- Oscillation parameters (from nu-fit.org [1]):
  - **Δm^2_{31}** (NH/IH) = 0.00246 / -0.00237 eV [2] (no prior)
  - **θ_{23}** (NH/IH) = 42.3° / 49.5° (no prior)
  - **θ_{13}** = 8.5° ± 0.2°
- Detector/flux/cross sections:
  - **event rate** (effective area, flux normalization) = nominal (no prior)
  - **energy scale** = nominal ± 0.10 (from current calibration data)
  - **ν_e/ν_μ ratio** = nominal ± 0.03 (ref [2])
  - **ν/anti-ν ratio** = nominal ± 0.10 (ref [2] and [3])
  - **atmospheric spectral index**: nominal ± 0.05 (ref [2])
  - Also studied separately:
    - detailed cross section systematics based on GENIE [3] parameters
    - detailed atmospheric flux uncertainties from [2]

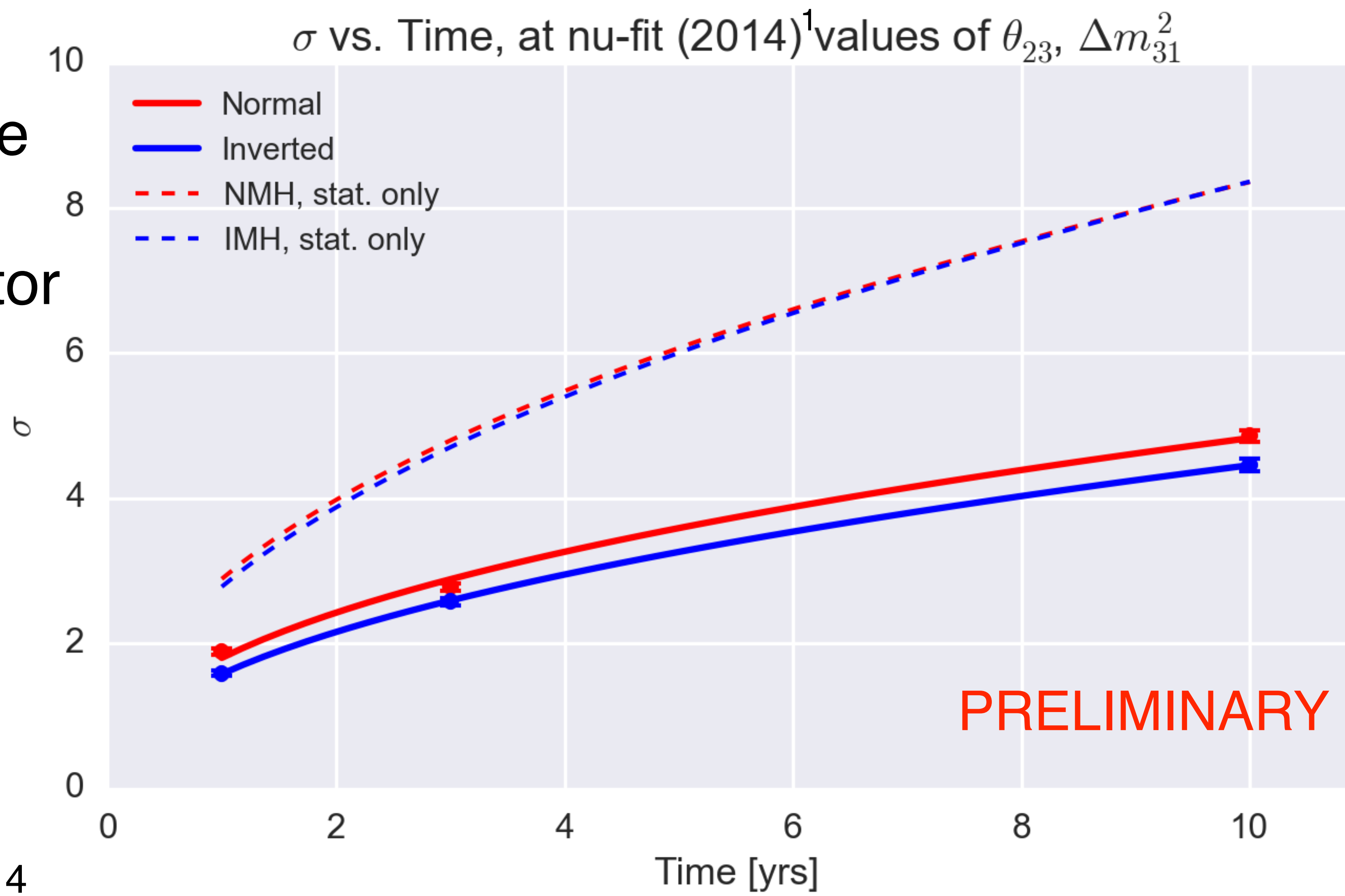
[1] M.C. Gonzalez-Garcia, et al. *JHEP* **11** 052, 2014

[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)

Results: Sensitivity to NMH

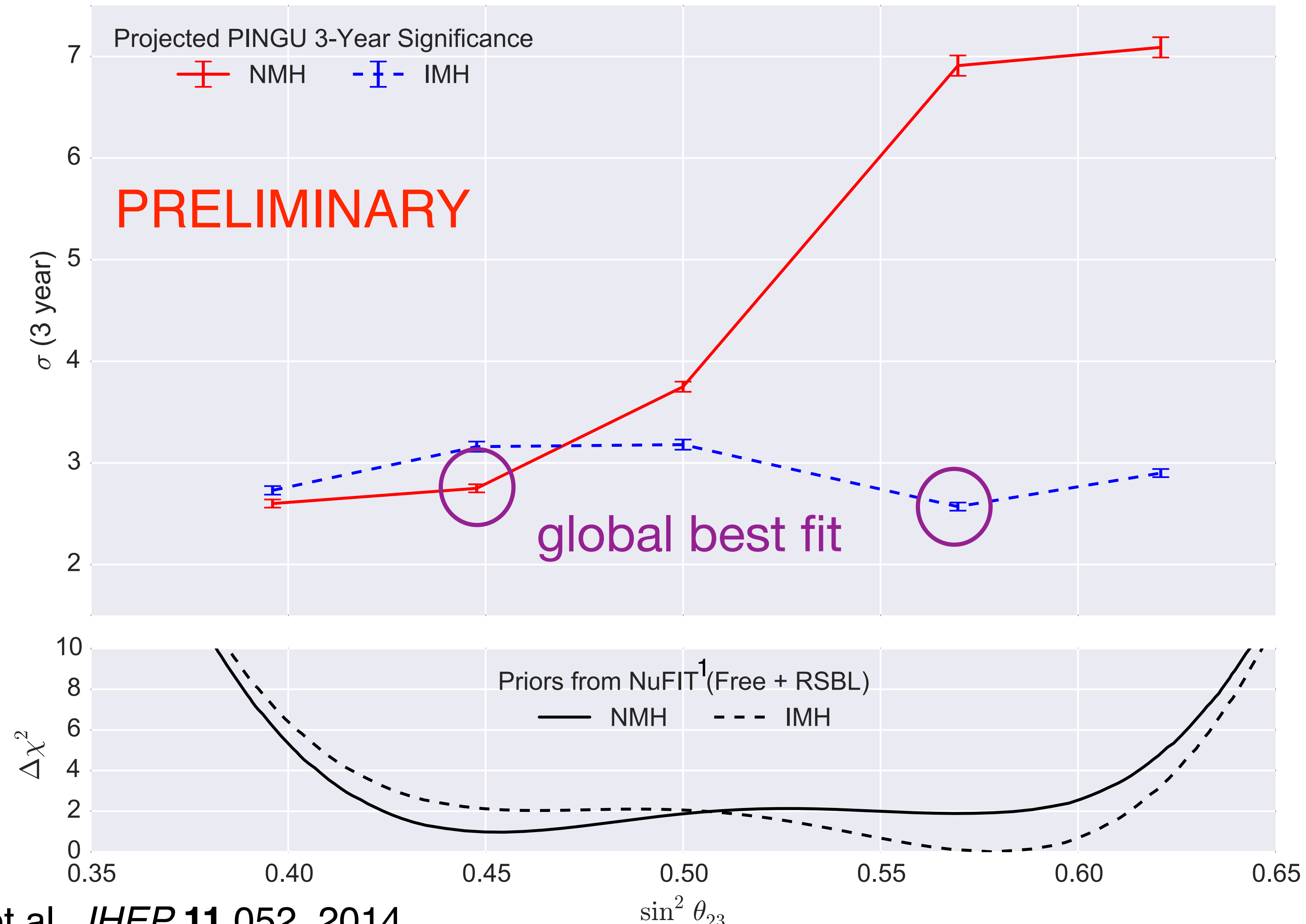
- Includes detector resolutions and PID as well as systematics shown on previous slide
- At current global best fits for oscillations parameters[1], reach 3 sigma in ~ 3-4 years.
  - Would be shortened by using existing DeepCore data and partially deployed PINGU detector
- Systematics dominated by θ_{23} then Δm^2_{31}



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

Significance vs. Mixing Angle

- Current best fit values of θ_{23} yields nearly the lowest possible significance, making our estimate conservative
- For +/- 2σ current allowed values of θ_{23}/NMH we find after 3 years, sensitivity = 2.6σ - 7σ.



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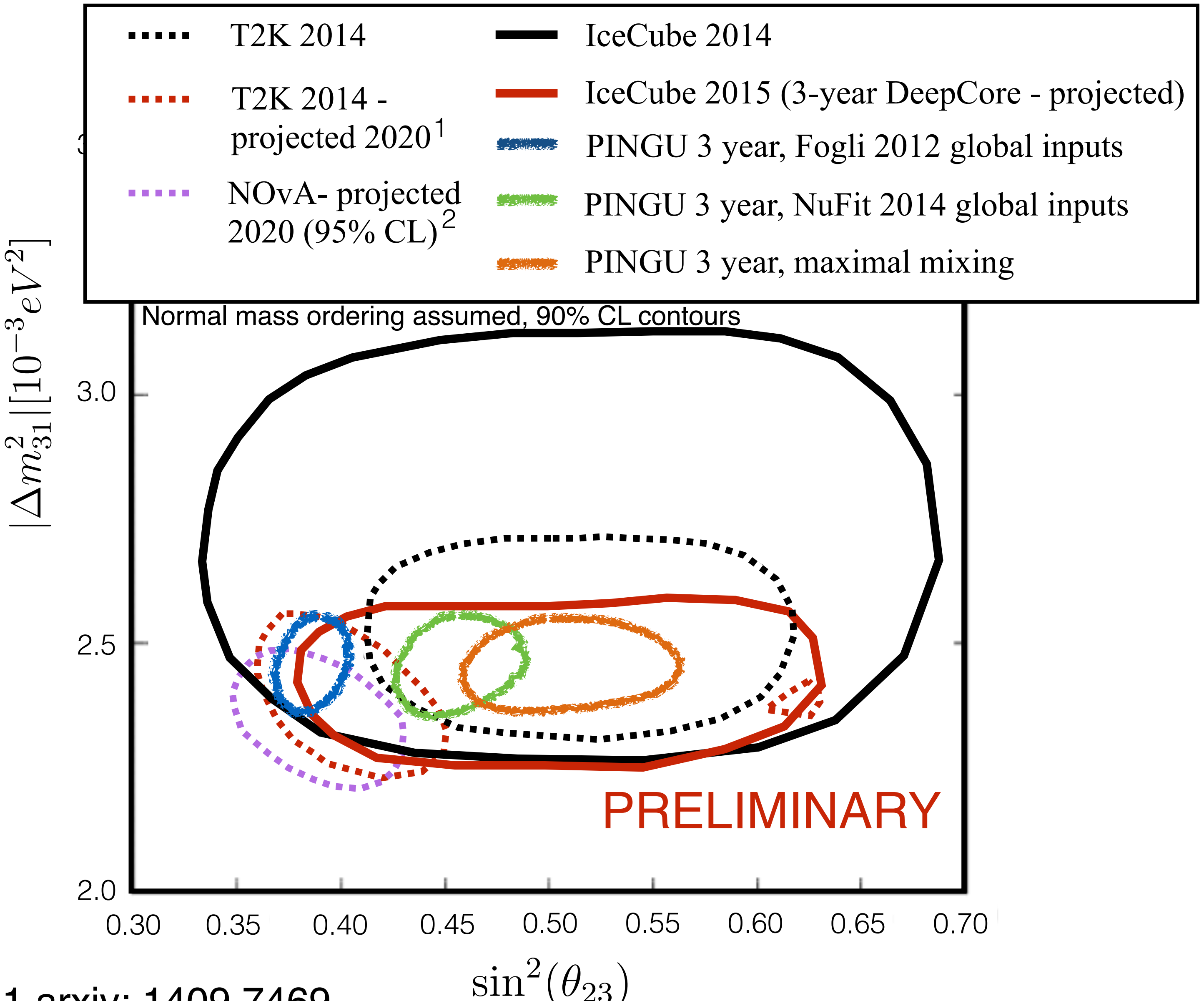
More Oscillation Physics with PINGU

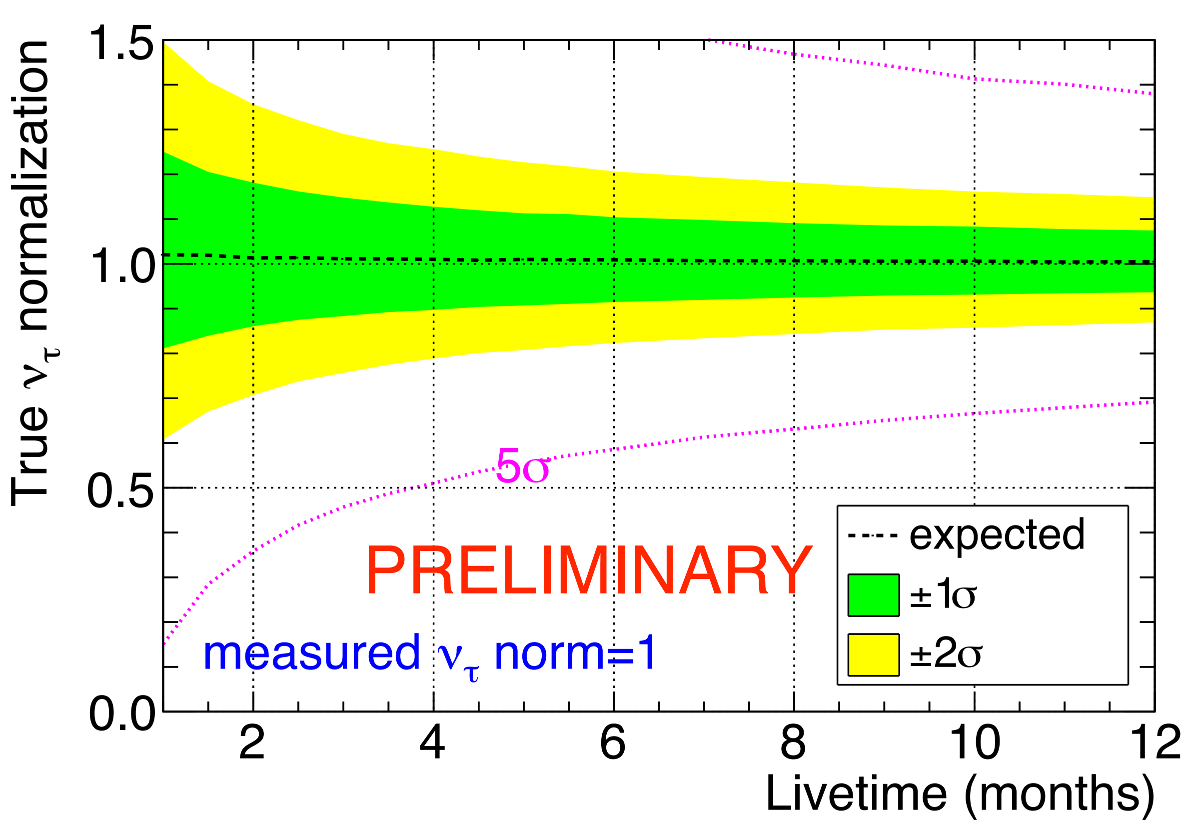
- Expected: very competitive atmospheric mixing parameter constraints



1 arxiv: 1409.7469

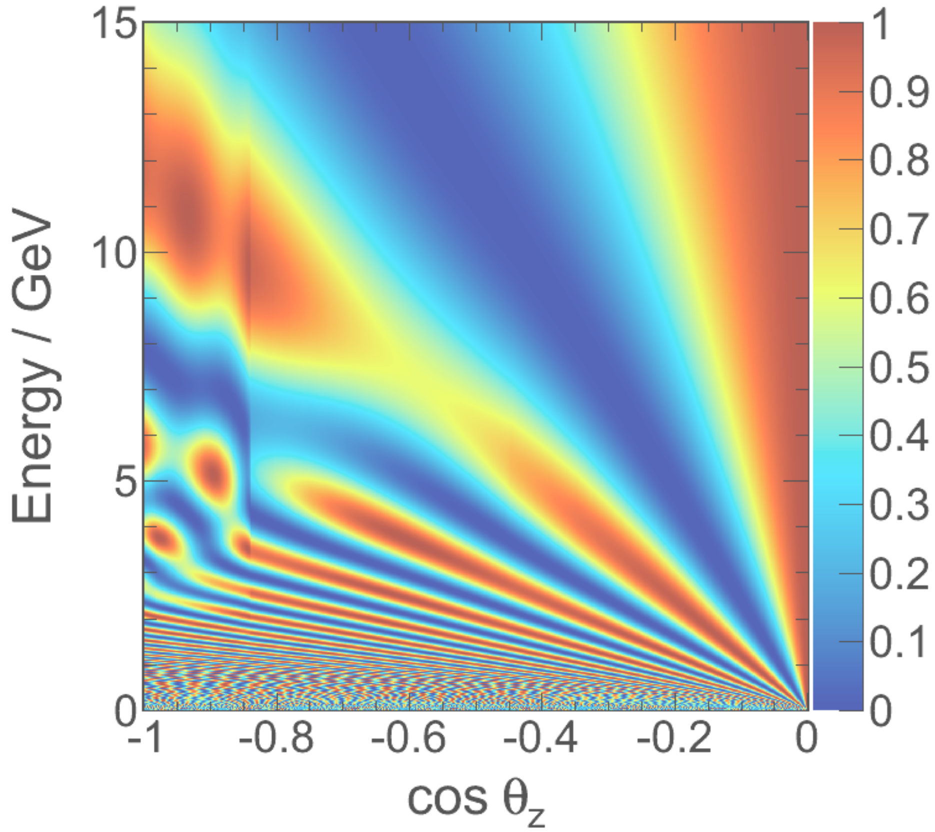
2 http://www-nova.fnal.gov/plots_and_figures/plot_and_figures.html

- ν_τ appearance predicted ~5 σ within one month
  - will detect around ~3k ν_τ/yr
  - Tests of unitarity of 3x3 ν mixing



Outlook

- IceCube and DeepCore have paved the way towards a robust atmospheric oscillation physics program in the South Pole ice.
- PINGU will be an integral part of the IceCube-Gen2 observatory[1]
- Construction and Cost
  - (time of proposal approval) + 4-5 years
  - Deployment: relies on well-understood engineering from previous IceCube experience
  - cost effective
- Improved LoI available shortly
  - Improved statistical analysis method
  - Increased number of systematics studied
  - Optimized detector geometry



[1] white paper: arXiv:1412.5106

Thank You

The IceCube–PINGU Collaboration

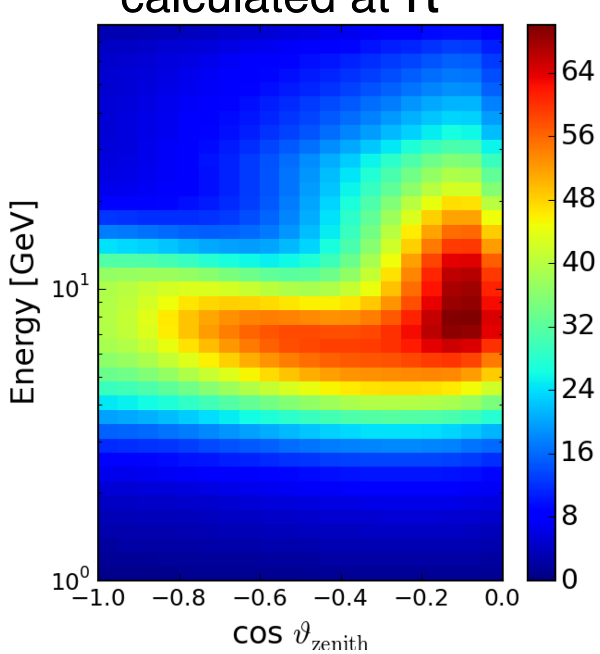
International Funding Agencies

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)

LLR Analysis Method

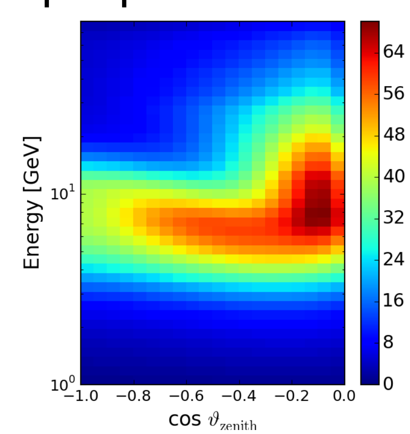
- Greatly improved statistical analysis method since LoI
  - ✦ Ability to include many more systematics (from 2 → ~10) by using a minimizer to find optimal LLH fit rather than grid scan
  - ✦ Run optimizer twice to search for solutions in both octants of θ_{23}.
- To test for significance of true hierarchy (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}



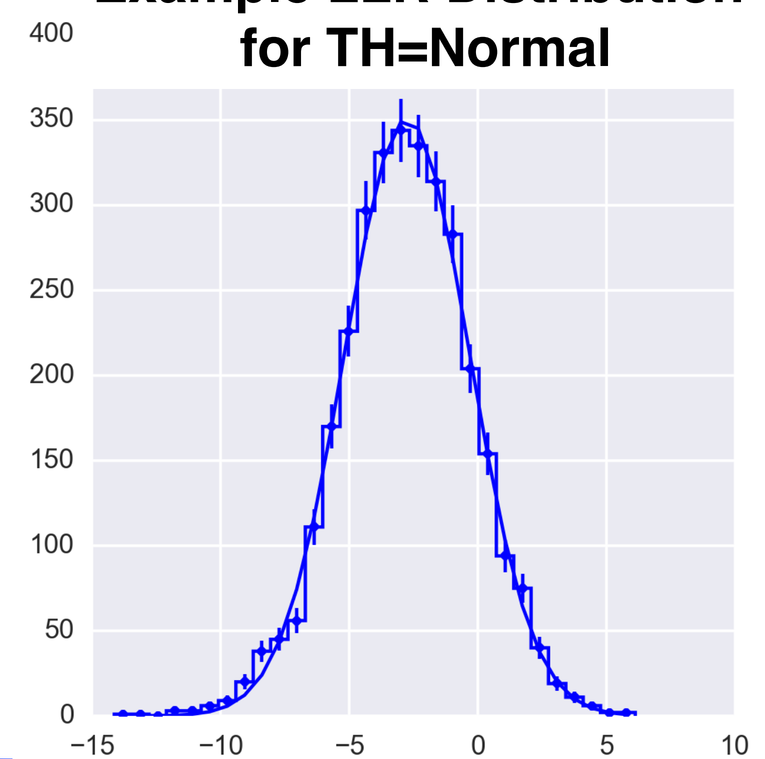
Poisson Fluctuations

Example pseudo data for TH:



Accumulate LLR distribution for TH

Example LLR Distribution for TH=Normal



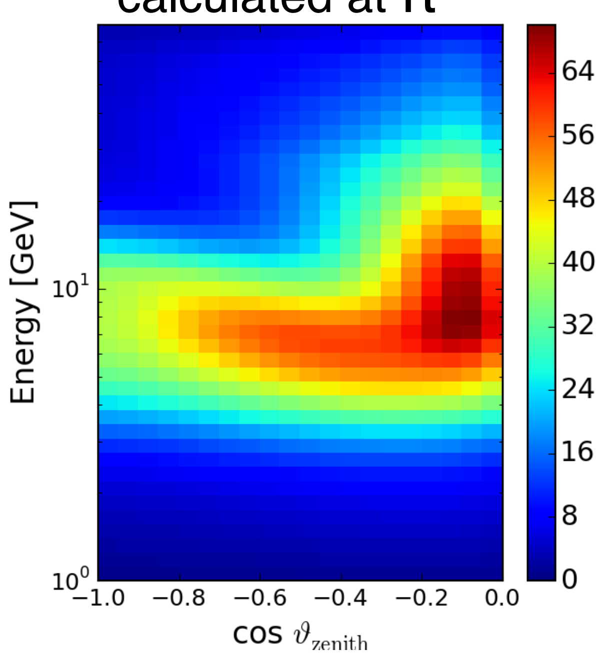
$$\text{Calculate LLR} = \frac{\text{max LLH(Inverted hypothesis, fit } \pi)}{\text{max LLH(Normal hypothesis, fit } \pi)}$$

Repeat Many Times

LLR Analysis Method

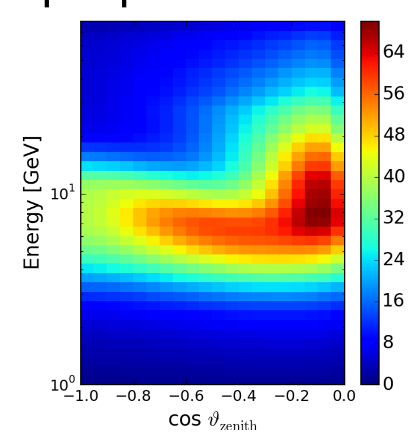
- Greatly improved statistical analysis method since LoI
  - Ability to include many more systematics (from 2 → ~10) by using a minimizer to find optimal LLH fit rather than grid scan
  - Run optimizer twice to search for solutions in both octants of θ_{23}.
- To test for significance of true hierarchy (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:

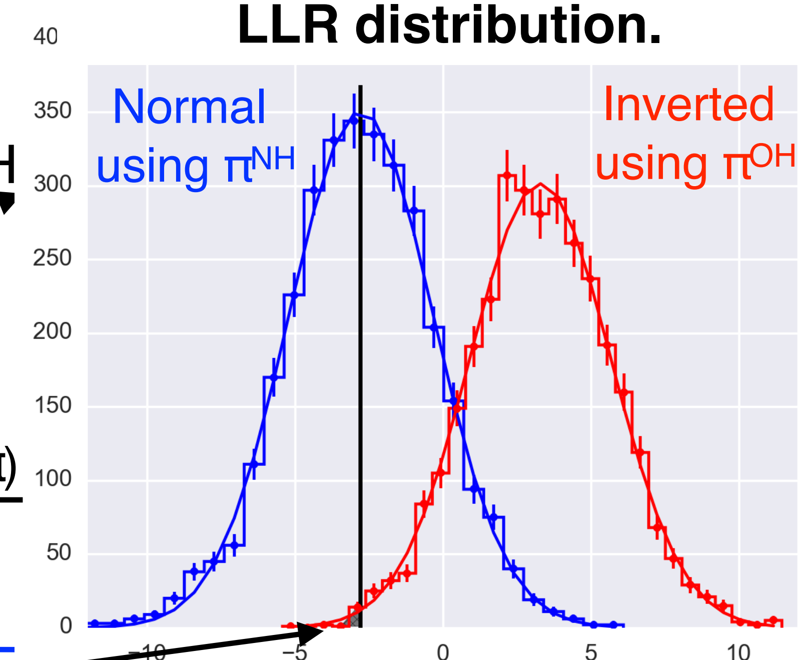


Accumulate LLR distribution for OH

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

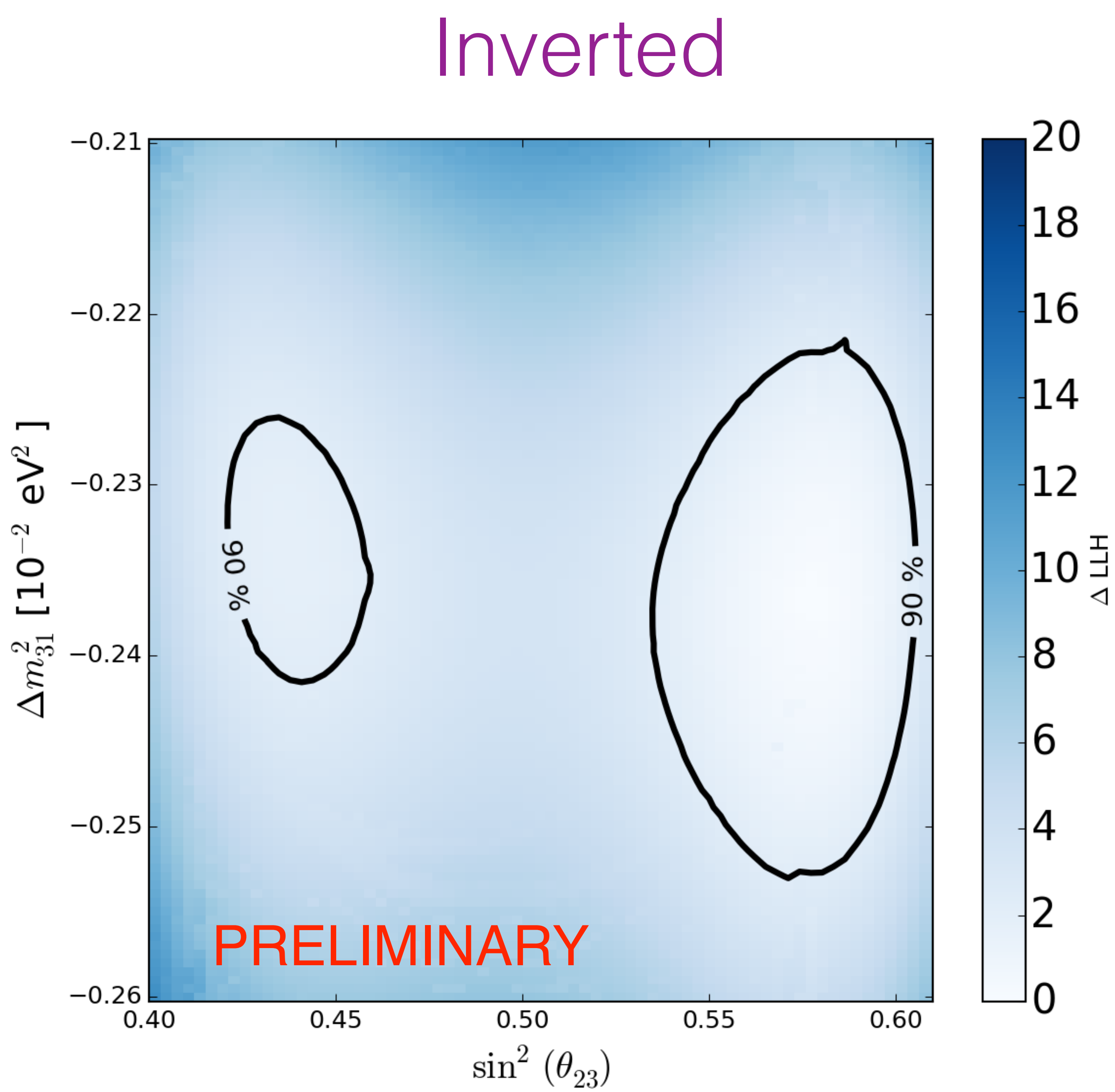
Repeat Many Times

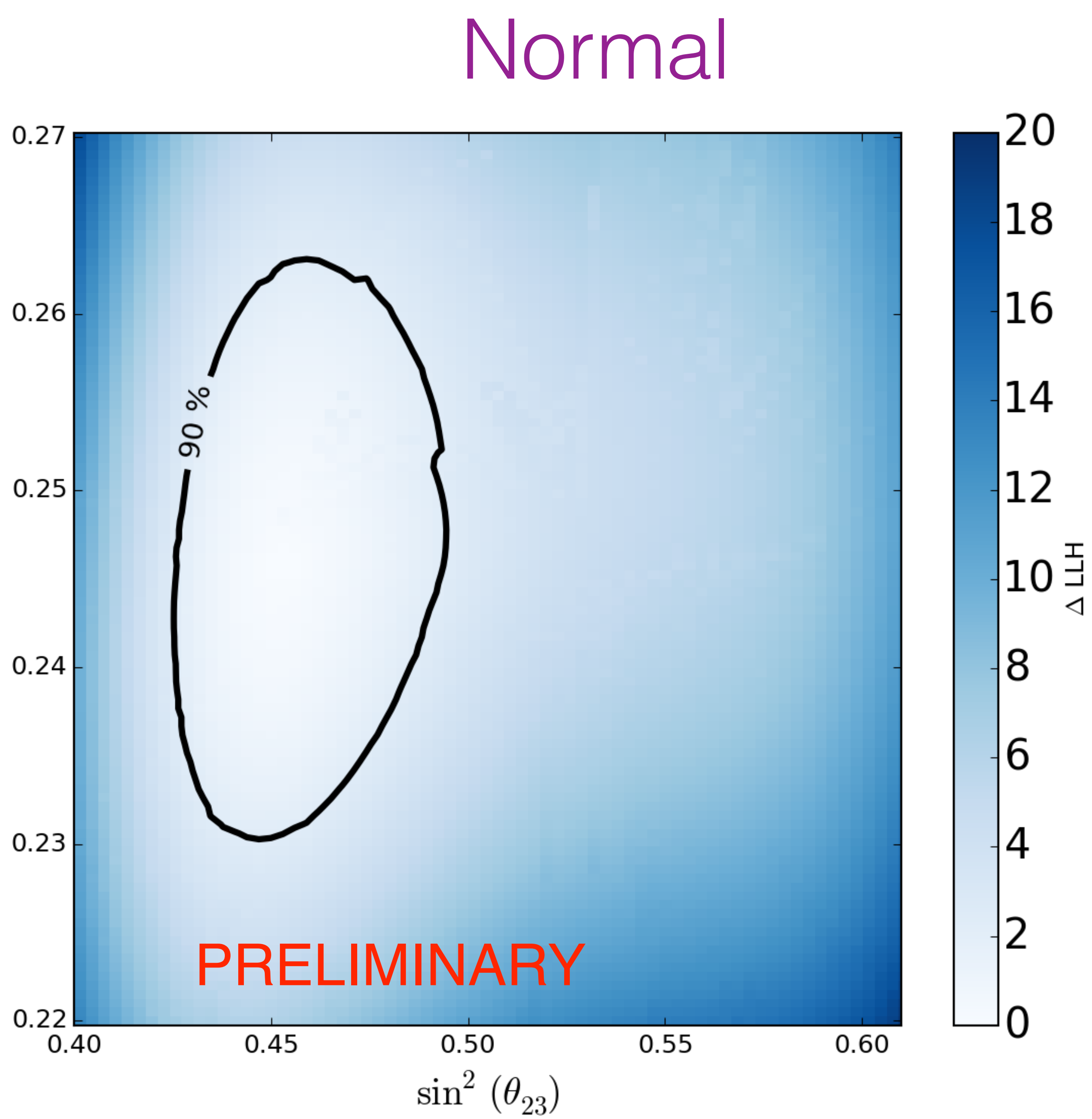
Example LLR Distribution for TH=Normal, and OH=Inverted LLR distribution.



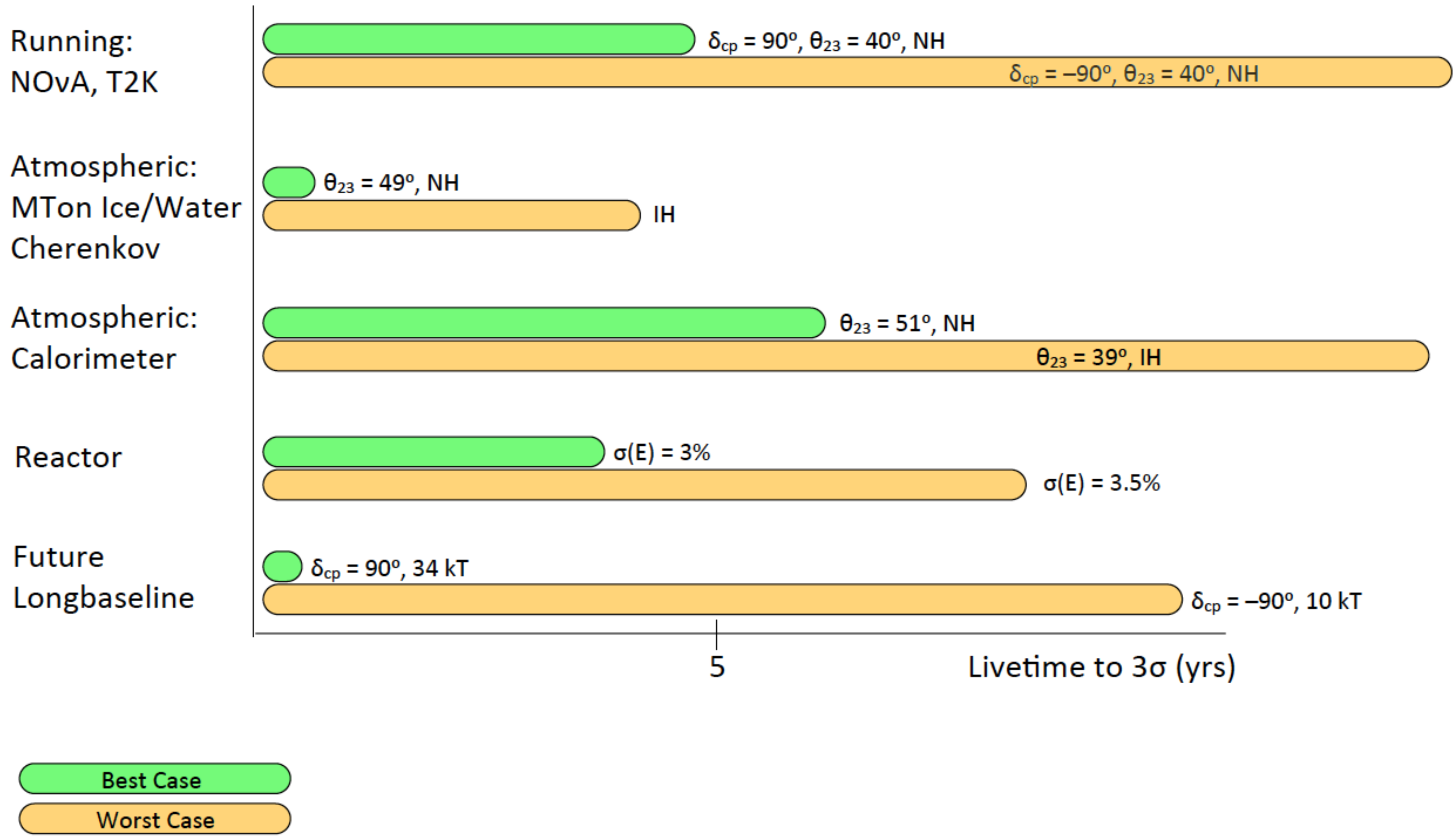
find p value=hierarchy mis-identification probability

Atmospheric Mixing Params





Sensitivity to the Neutrino Mass Hierarchy



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

Systematics impact

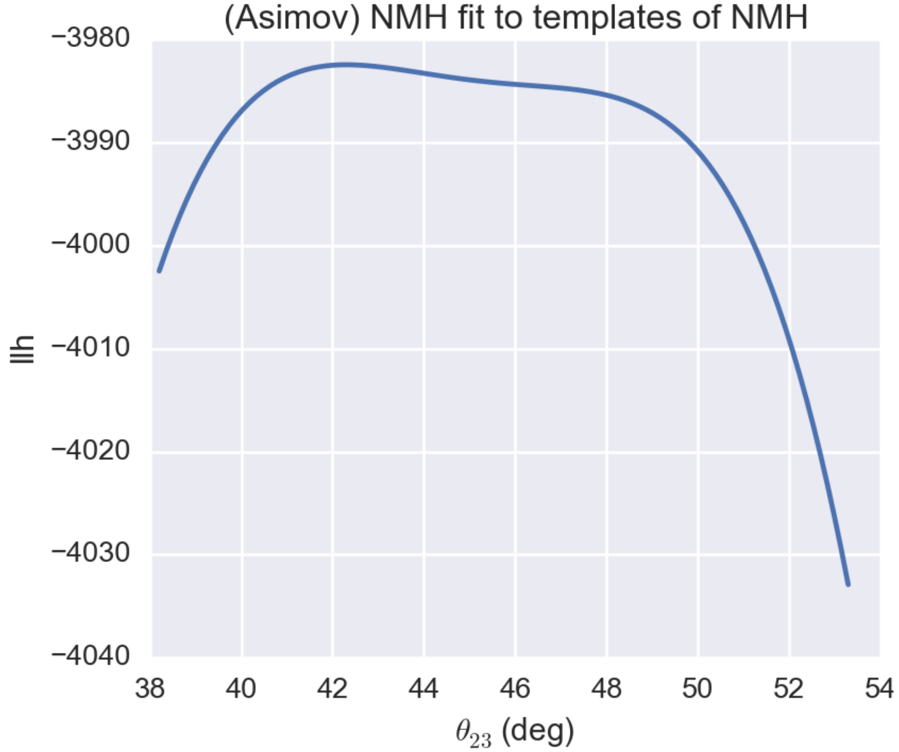
Type	3 yr σ (NMH)	3 yr σ (IMH)
stat only	4.84	4.82
osc only	2.96	2.53
θ_{23} only	3.52	3.26
flux only	4.55	4.56
detector only	4.06	3.99
All	2.90	2.51

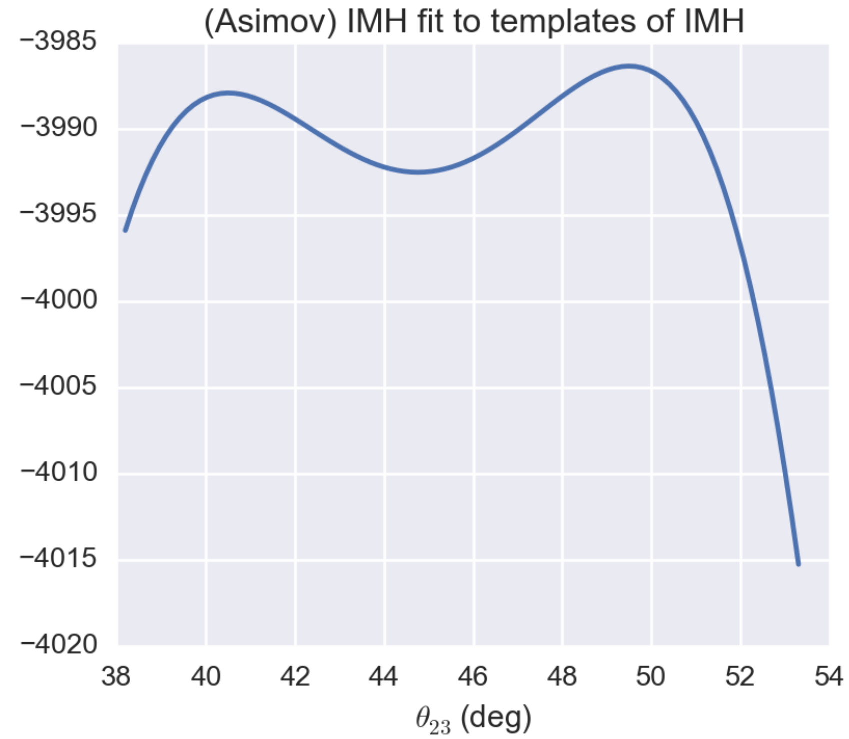
PRELIMINARY

- Dominated by atmospheric oscillation parameter systematics:
  - θ_{23} and also Δm^2_{31}.
- Next most important group:
  - detector: overall normalization (aeff_scale) and energy scale

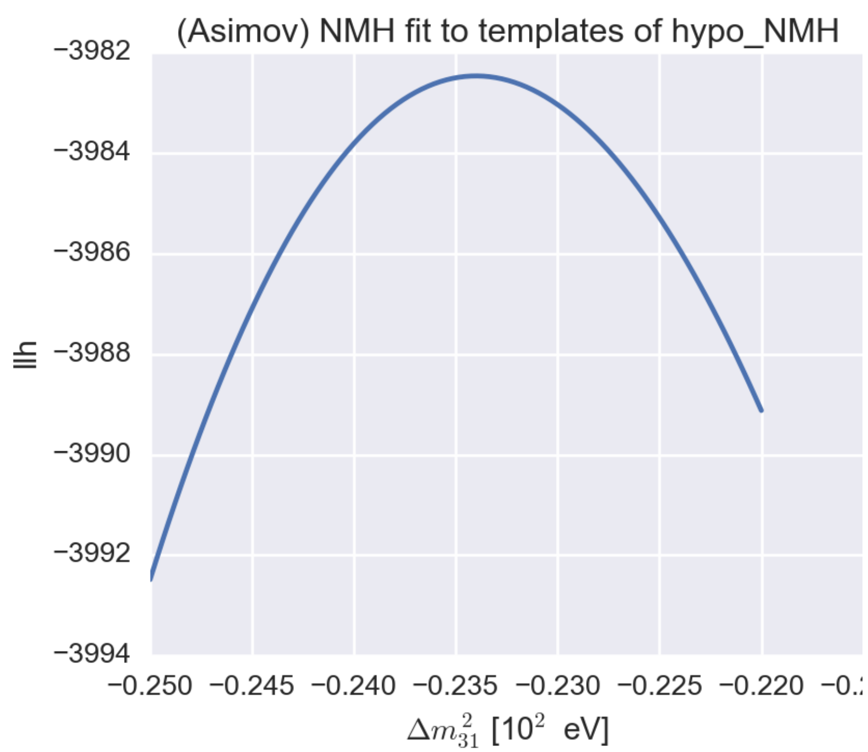
LLH Scan in θ_{23}

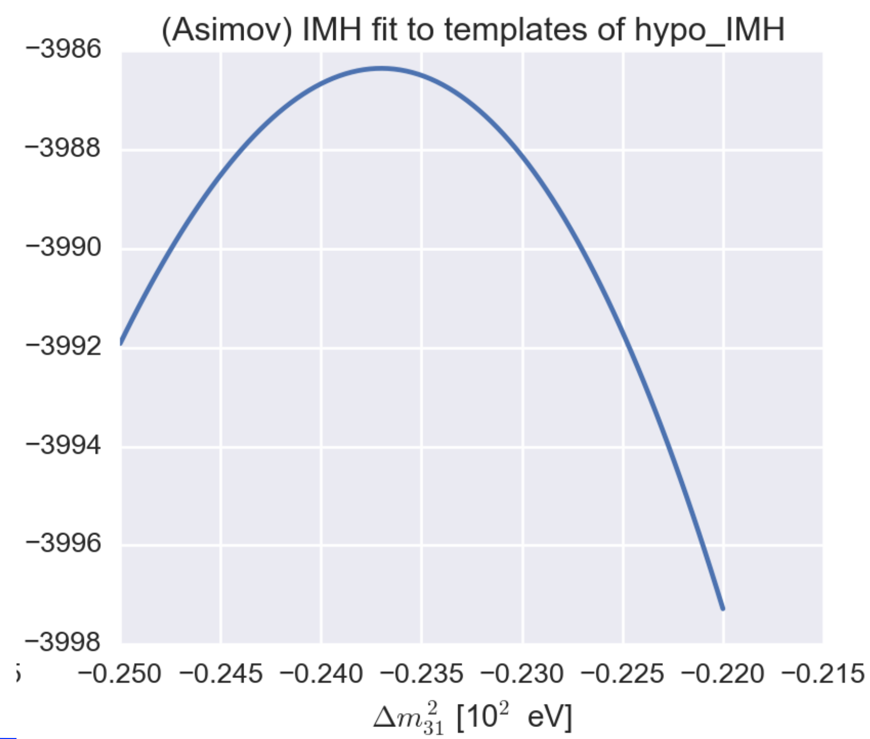
- θ_{23} is not well-behaved for minimization or linearization of gradient:



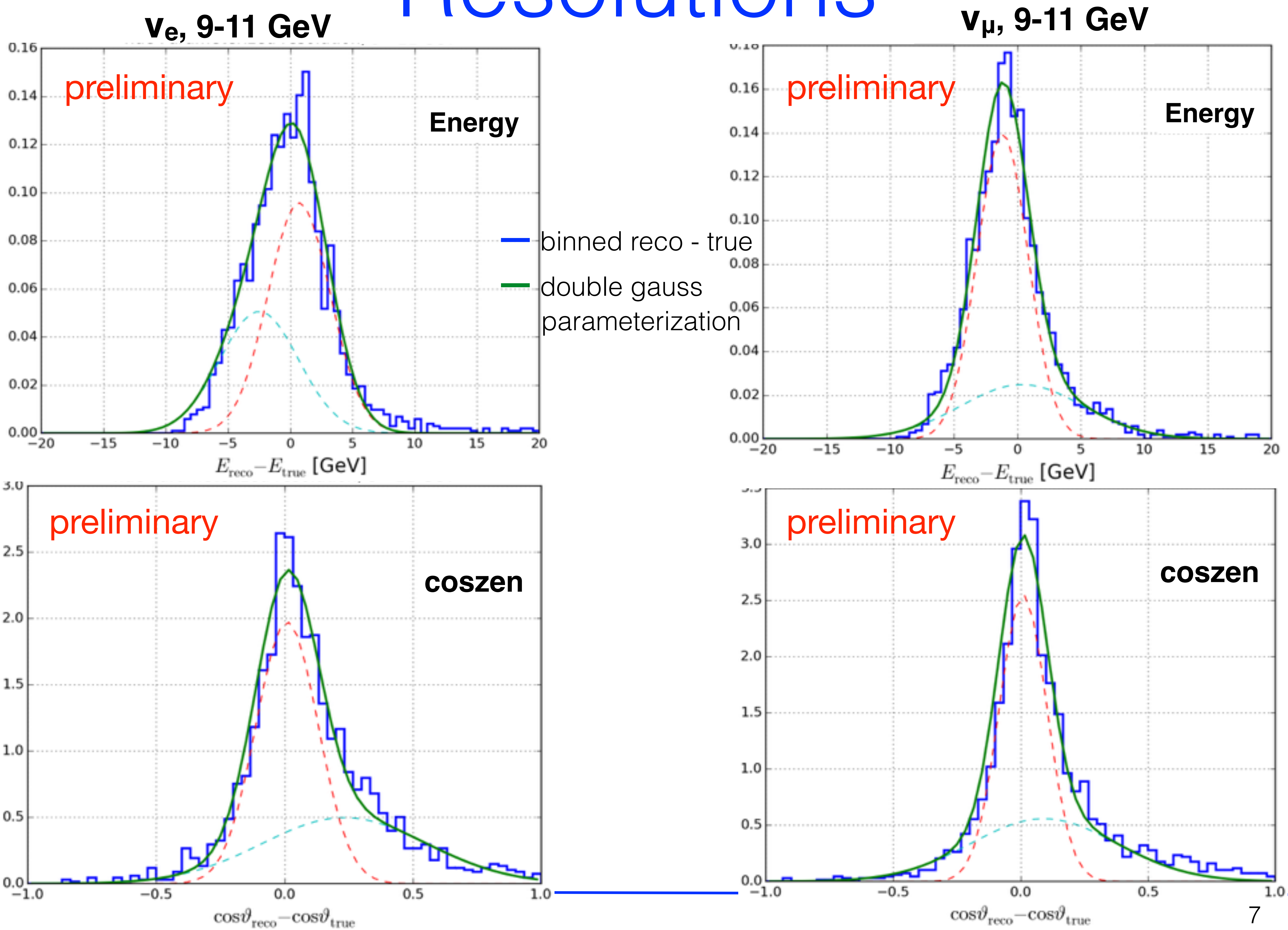


- But Δm^2_{31} (and the other parameters studied) are well-behaved:





Resolutions



Neutrino Interaction Uncertainties

- Biggest effects so far: uncertainties in Bodek-Yang higher twist parameters, axial mass term for hadron resonance production
  - ✦ Ad hoc scalings still included, and covariance not accounted for – likely over-counting…
- Small additional effect compared to existing systematics