PINGU and the Neutrino Mass Hierarchy

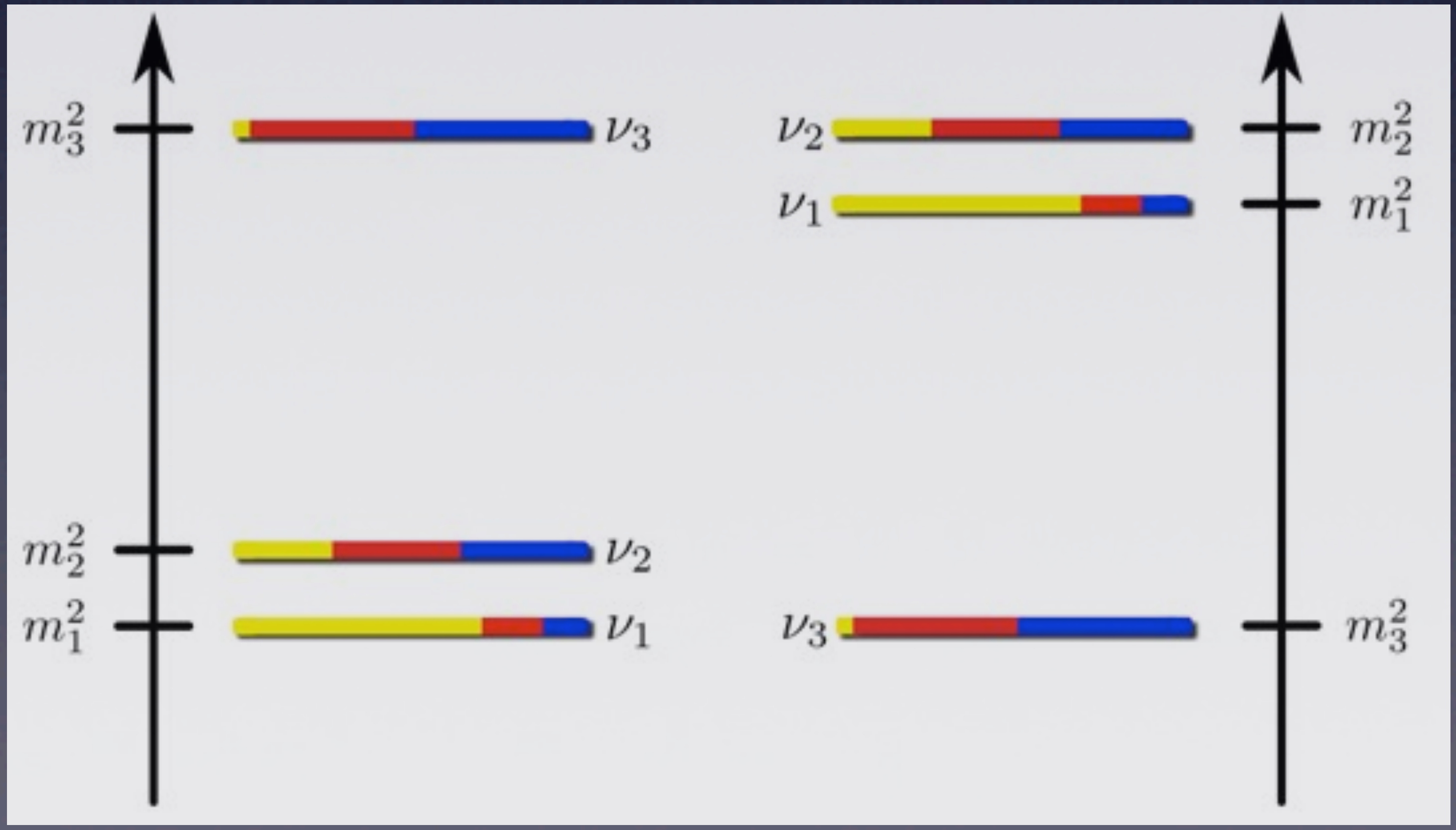
Ken Clark, Penn State University
Neutrinos at the Forefront - Lyon, Oct 2012

Neutrino Oscillations

- Neutrino oscillations parametrized by
  - mass squared differences Δm^2_{ij}
  - mixing angles θ_{ij}
  - CP phase δ_{CP}
- Several questions remain
  - What is the mass hierarchy ($m_3 > m_1$?)

Neutrino Mass Hierarchy

- Focus on the mass hierarchy in this talk
- We know Δm^2_{13} but not the sign



Experiments

- Several experiments targeting the mass hierarchy
- NOvA to start data collection soon
- R&D ongoing on Daya Bay II, LBNE, GLACIER, LENA, ORCA, PINGU

Theory - Atmospheric Neutrinos

- Why use atmospheric neutrinos?
  - Not usually considered for use in precision parameter determination
- Broad range of baselines (~50 - 12500 km)
- Broad range of energies (~GeV - PeV)

Theory

- Case for atmospheric neutrinos has been studied previously (Phys. Rev. D 78, 093003 (2008) in particular although there are others)
- In essence this requires distinction between normal and inverted hierarchy in counts
- Hierarchy effects seen as neutrinos pass through matter
  - ν oscillation probability is enhanced if hierarchy is <u>normal</u>
  - $\bar{\nu}$ oscillation probability is enhanced if hierarchy is <u>inverted</u>
  - and: $\nu, \bar{\nu}$ have different cross sections
- Matter effects depend on size of θ_{13} which is now better defined

Starting Point Math

- Interested primarily the ν_μ survival probability
- Note in particular the dependence on Δm^2_{31}

$$P_{\nu_\mu \to \nu_\mu} = 1 -$$

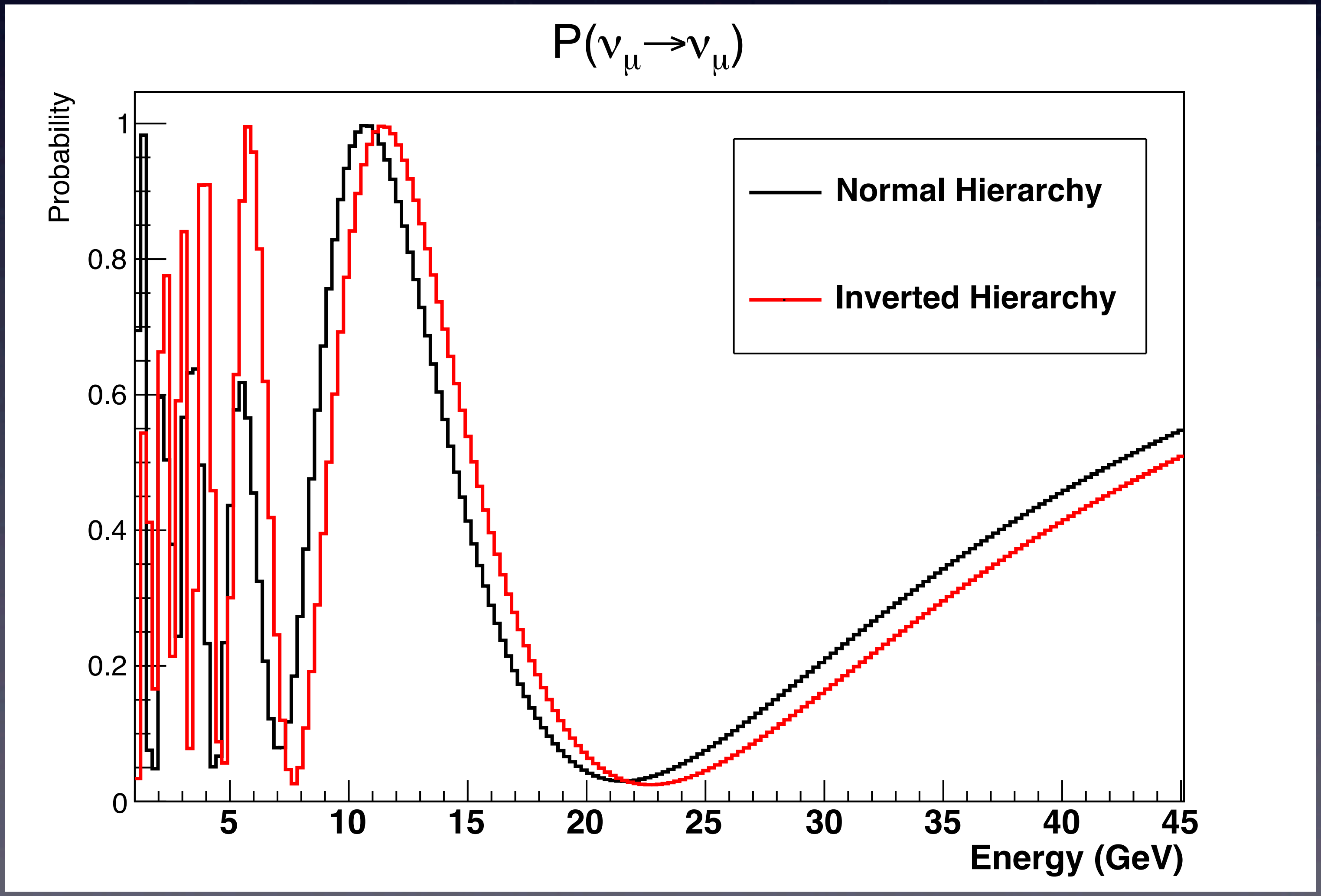
$$cos^2\theta^m_{13} sin^2 2\theta_{23} \times sin^2\left[1.27\left(\frac{\Delta m^2_{31} + A + (\Delta m^2_{31})^m}{2}\right)\frac{L}{E}\right]$$

$$-sin^2\theta^m_{13} sin^2 2\theta_{23} \times sin^2\left[1.27\left(\frac{\Delta m^2_{31} + A - (\Delta m^2_{31})^m}{2}\right)\frac{L}{E}\right]$$

$$-sin^4\theta_{23} sin^2 2\theta^m_{13} sin^2\left[1.27(\Delta m^2_{31})^m\frac{L}{E}\right]$$

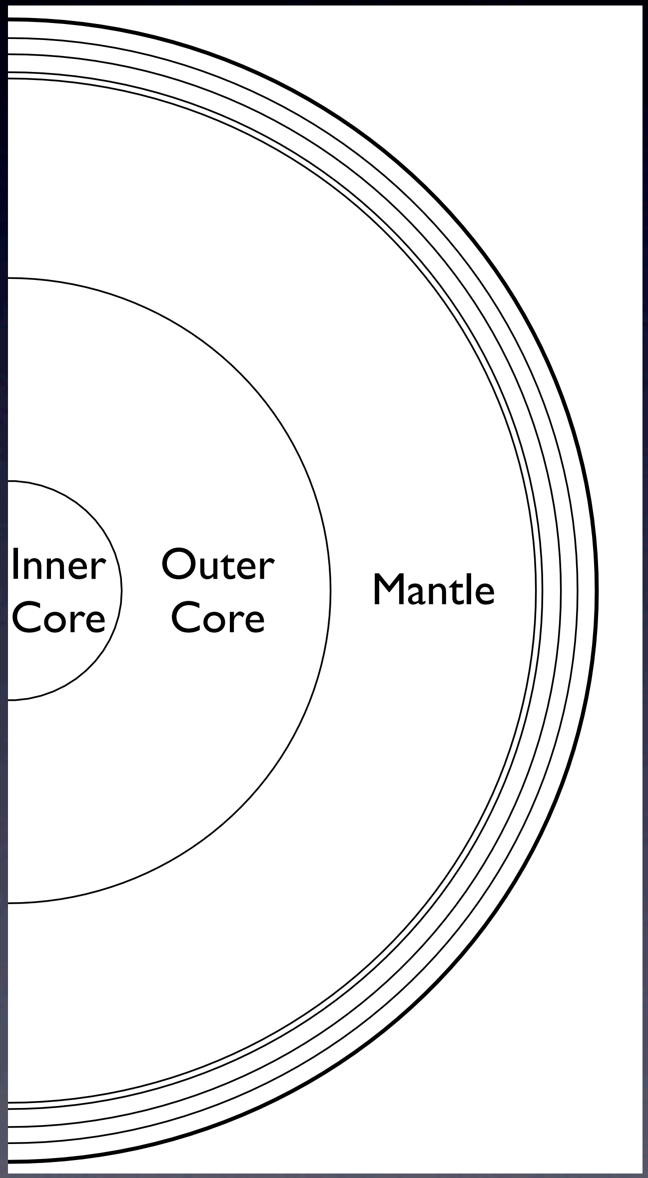
Starting Point Plots

- Clear differences emerge between the hierarchies
- This is at a fixed zenith angle, ~150 degrees



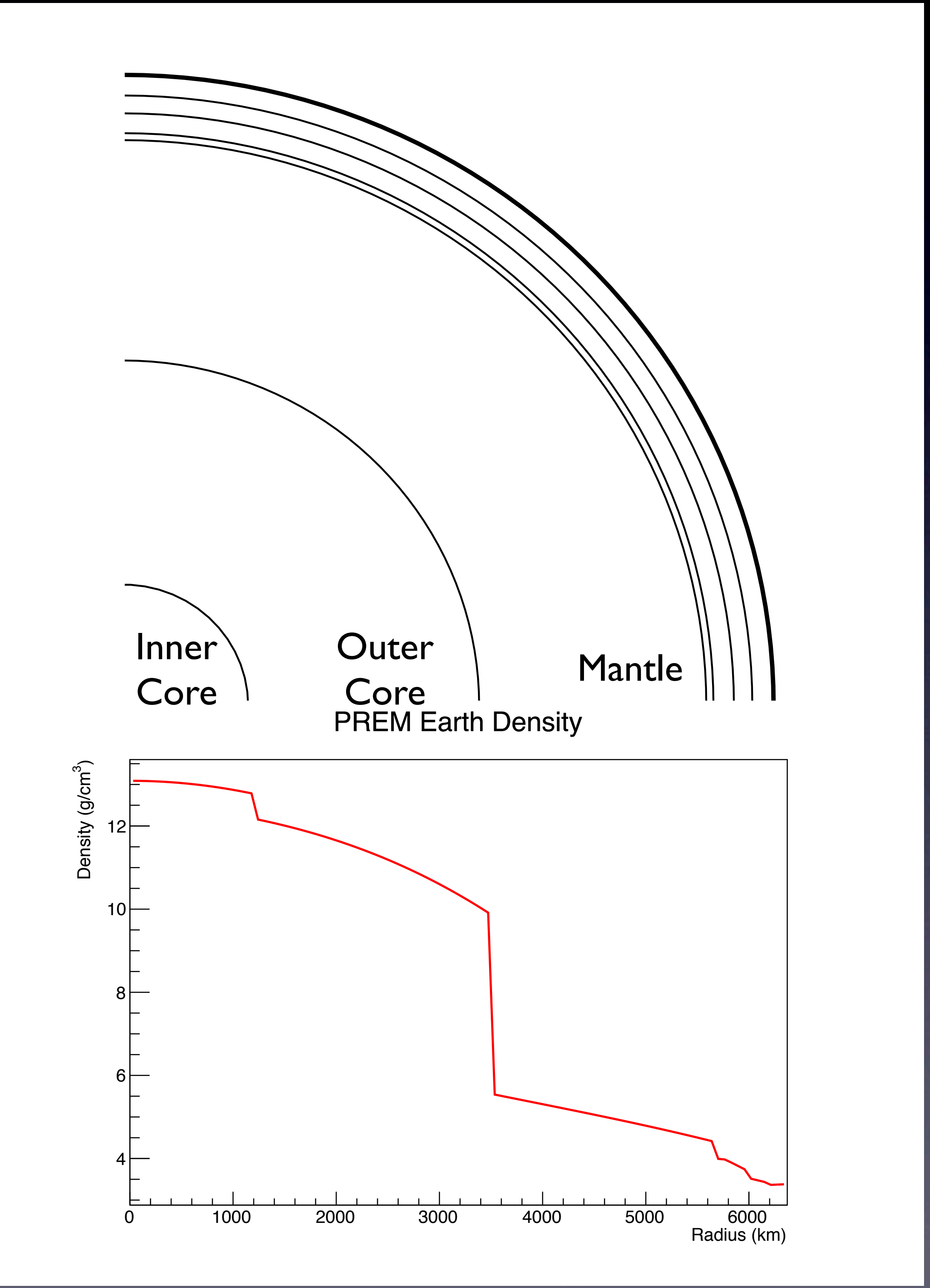
Preliminary Reference Earth Model (PREM)

- Current "best guess" as to the variation of density in the Earth
- Been around a long time, still retains the preliminary name



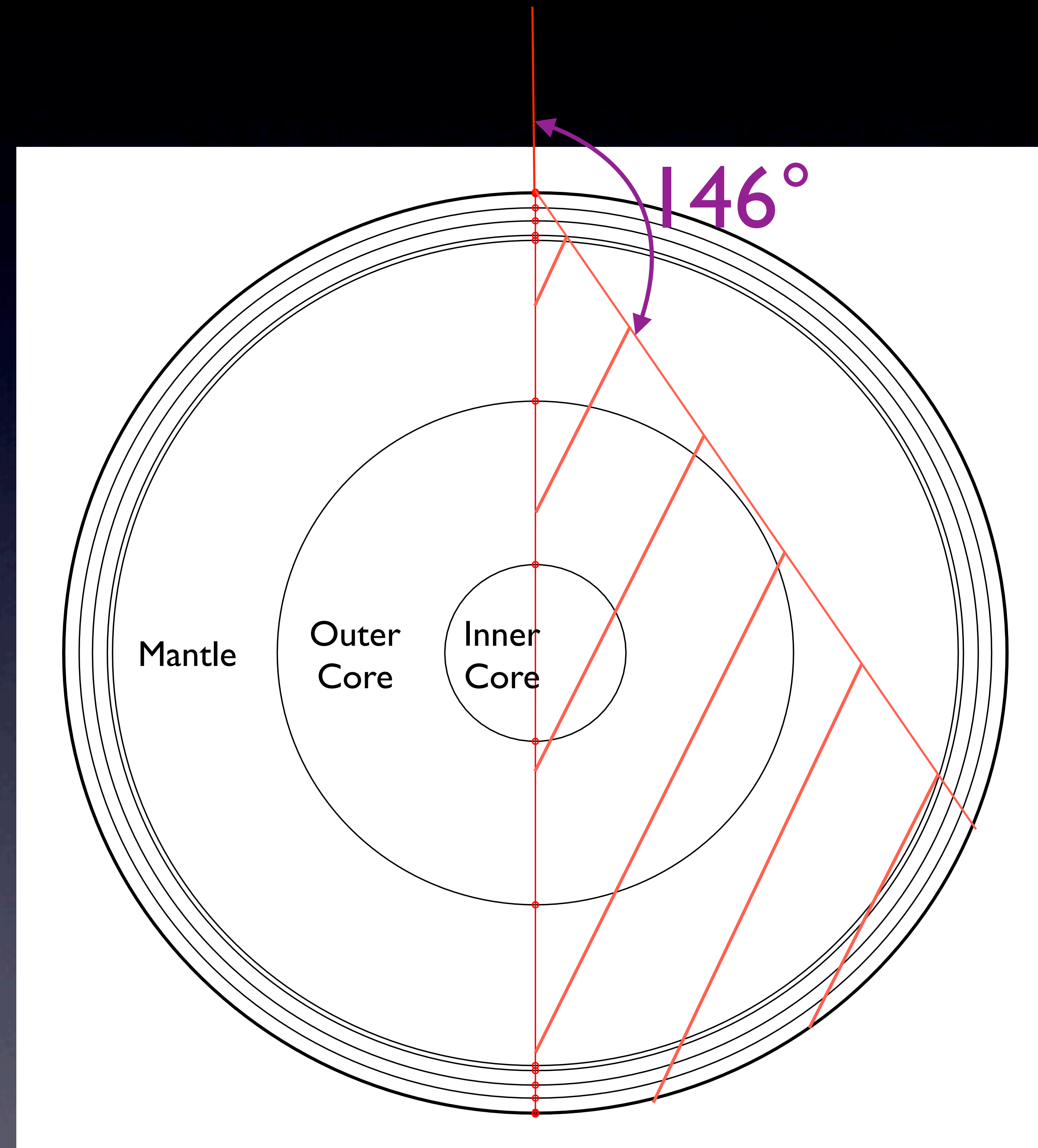
Matter effects

- Previous probabilities were just for one path length
  - upgoing neutrinos experience effect of traveling through the Earth (or a fraction of it)



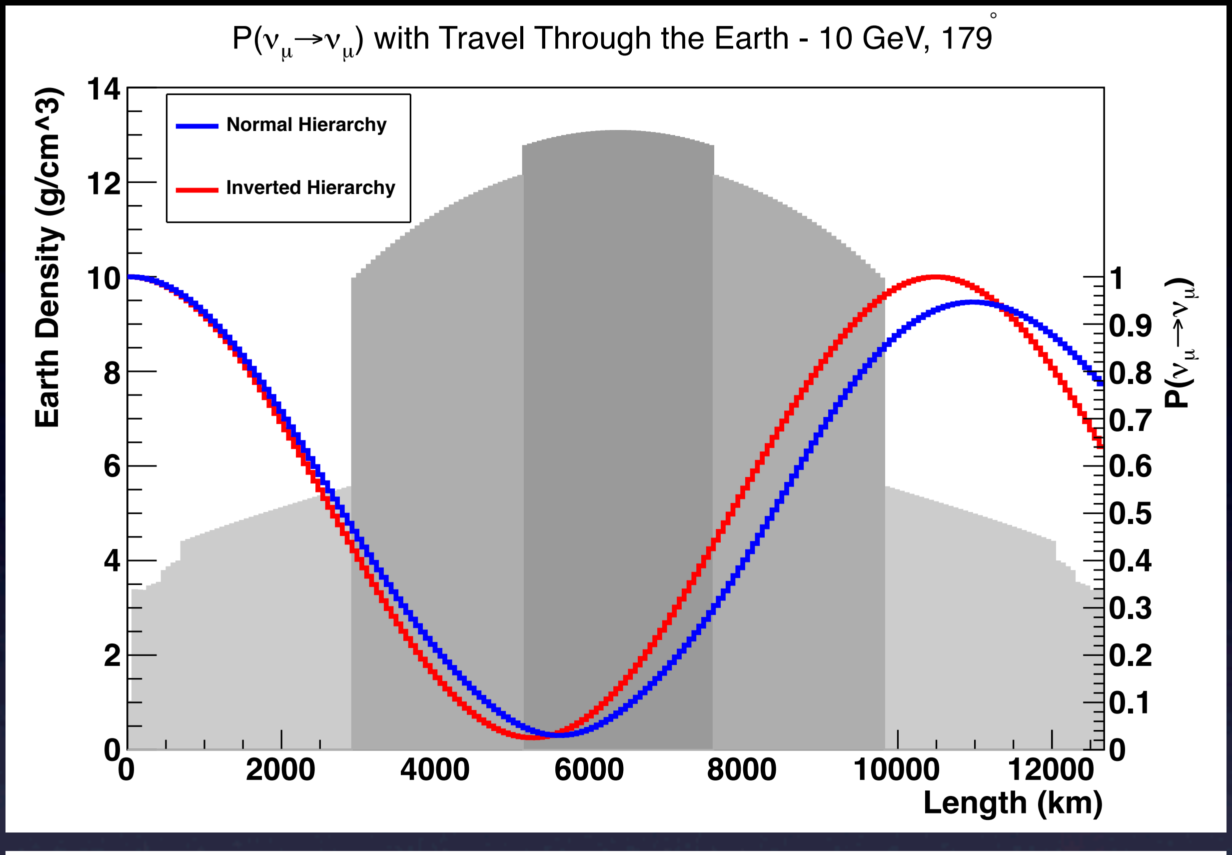
Matter Effects - I

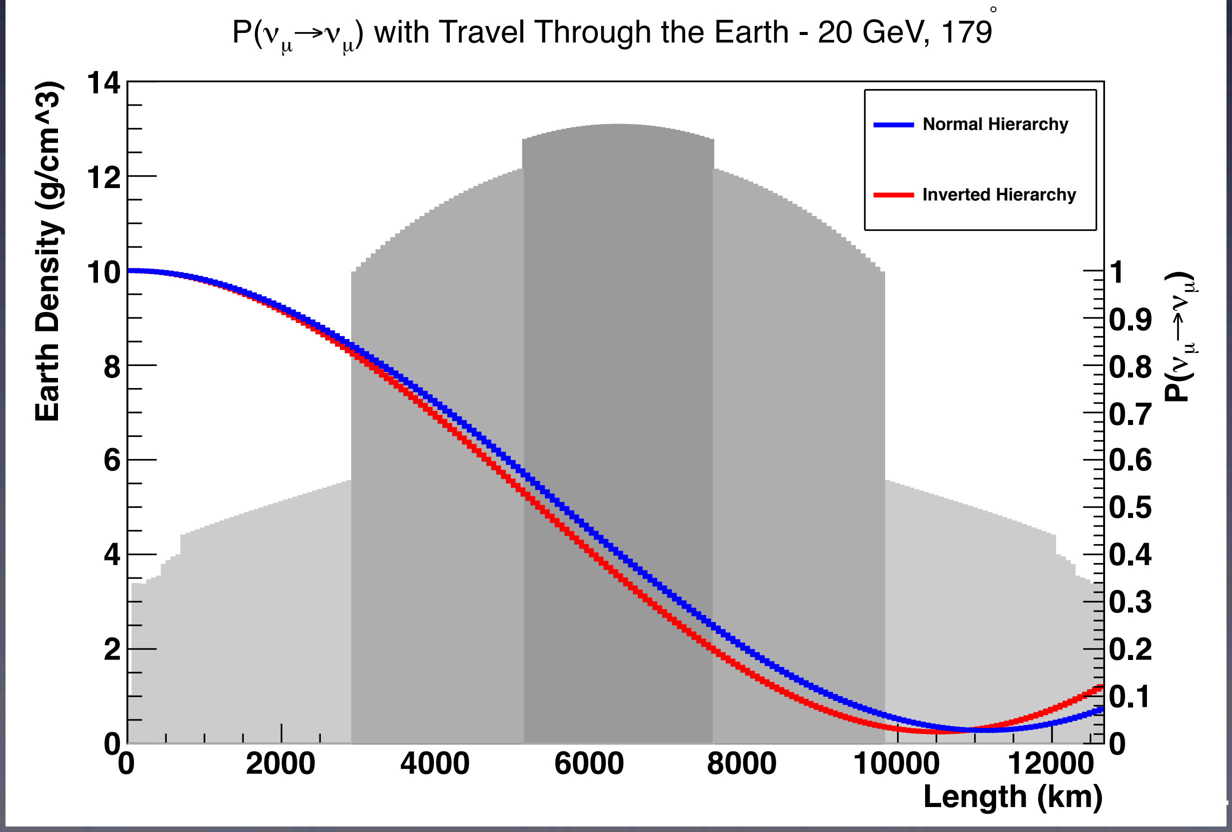
- At angles >146°
  - ν pass through mantle and core
  - parametric enhancement of oscillations take place



Matter Effects

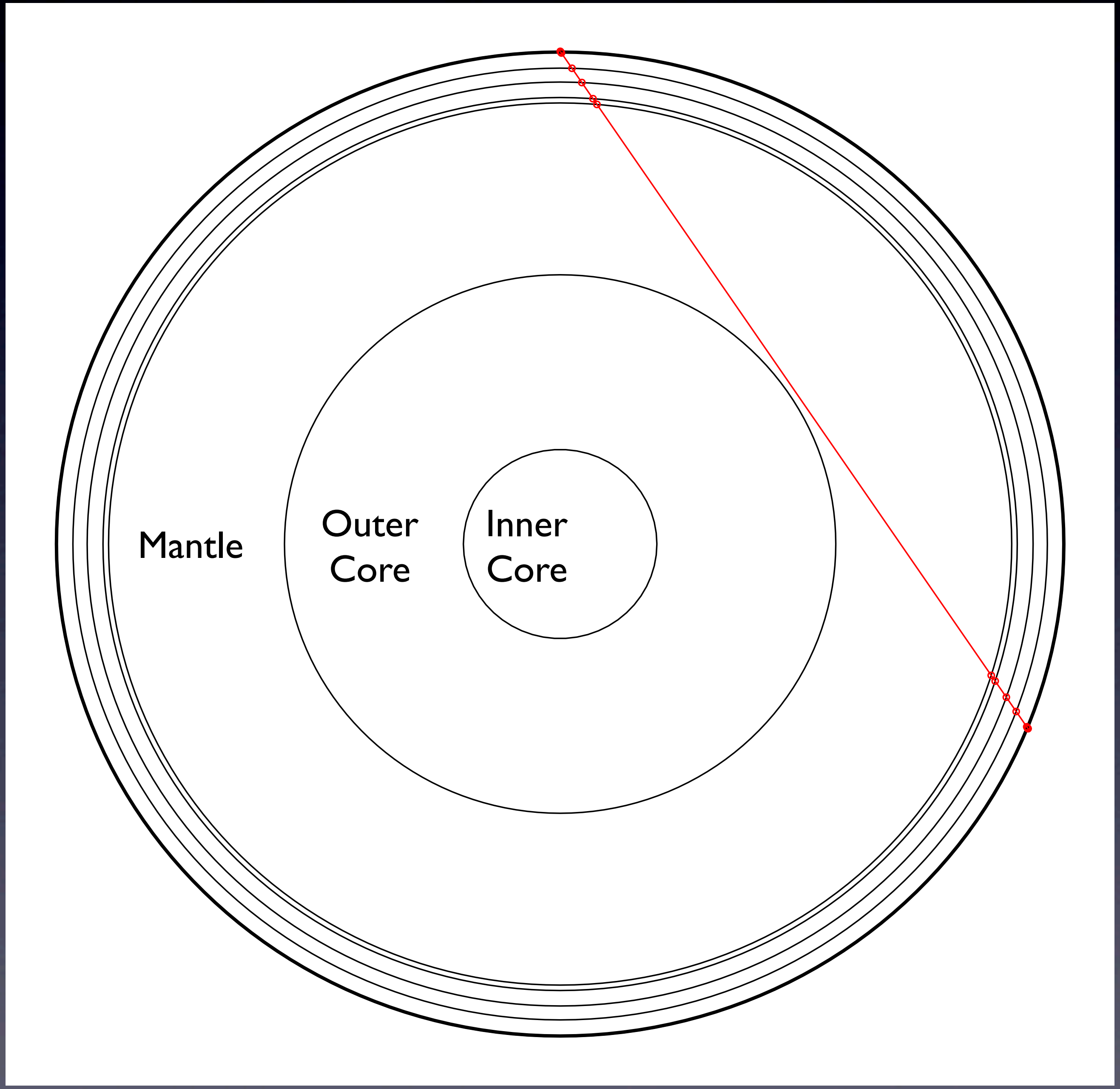
- These are almost directly upgoing
- Two different energies show magnitude of final effect
- This zenith dominated by parameteric resonance





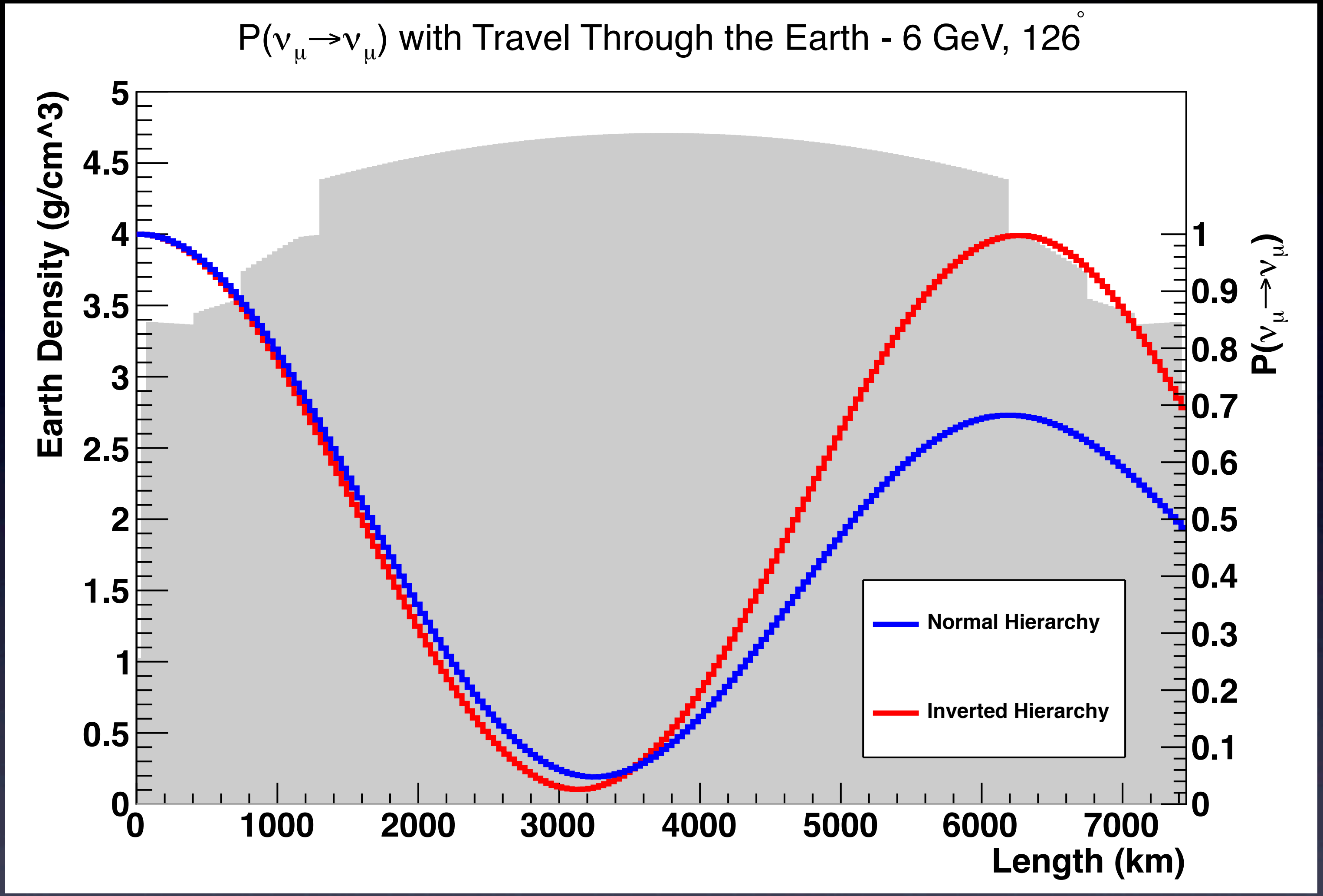
Matter Effects - II

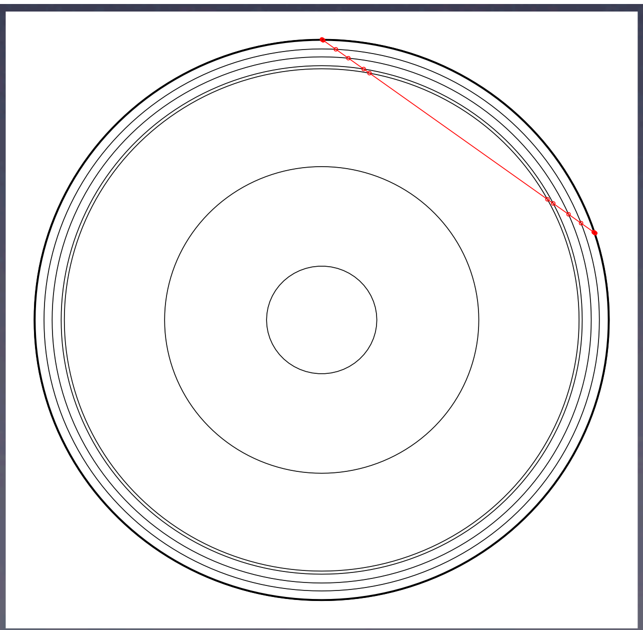
- At angles <146°
  - ν pass through mantle only
  - MSW enhances ν_μ to ν_e



Matter Effects

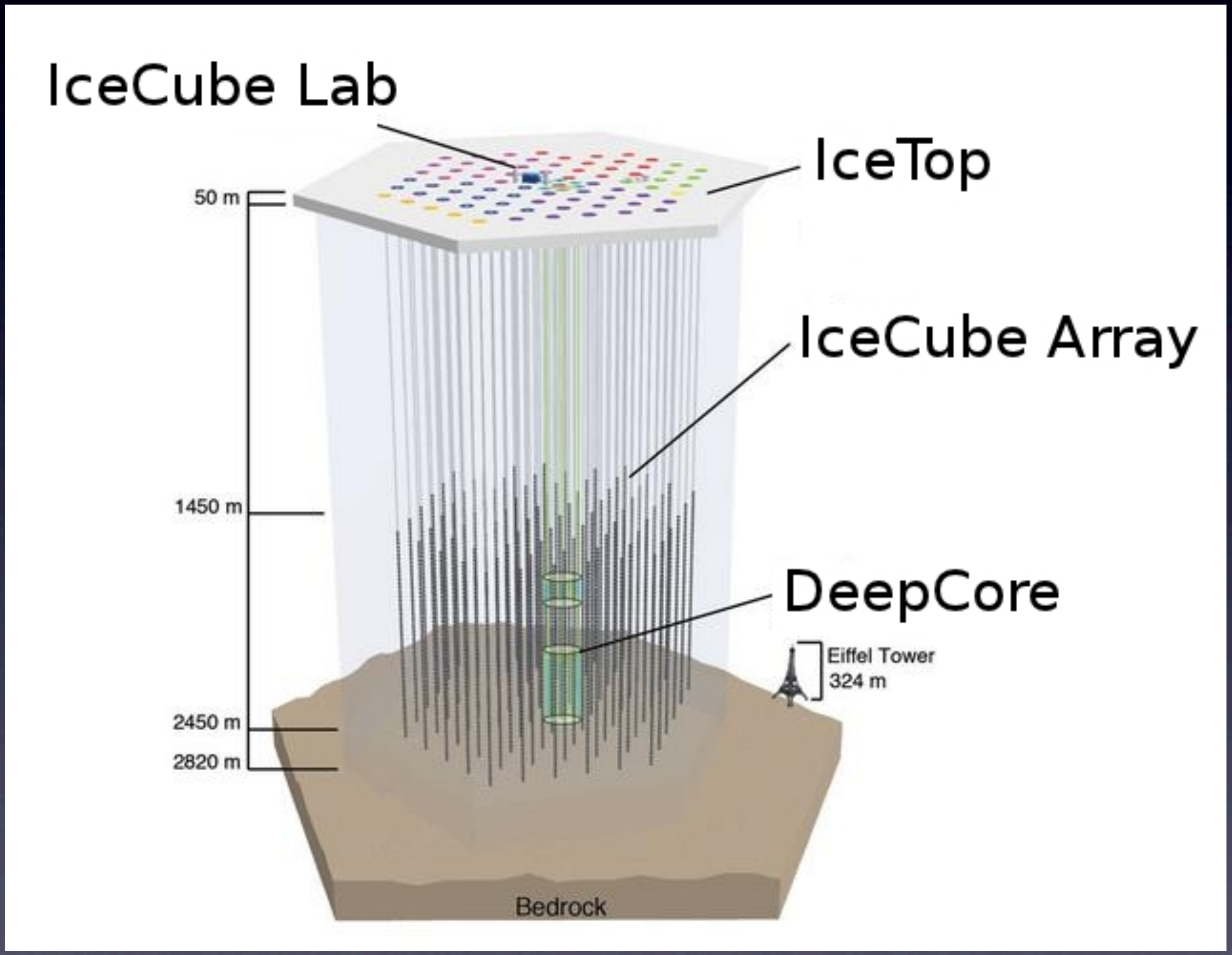
- Much less upgoing angles show MSW effects
- Note change in Earth density plot





Detection Method

- IceCube and DeepCore successfully detecting neutrinos for years
- IceCube: ~5160 PMTs in $1km^3$
- DeepCore: denser string and DOM spacing
- High efficiency PMTs



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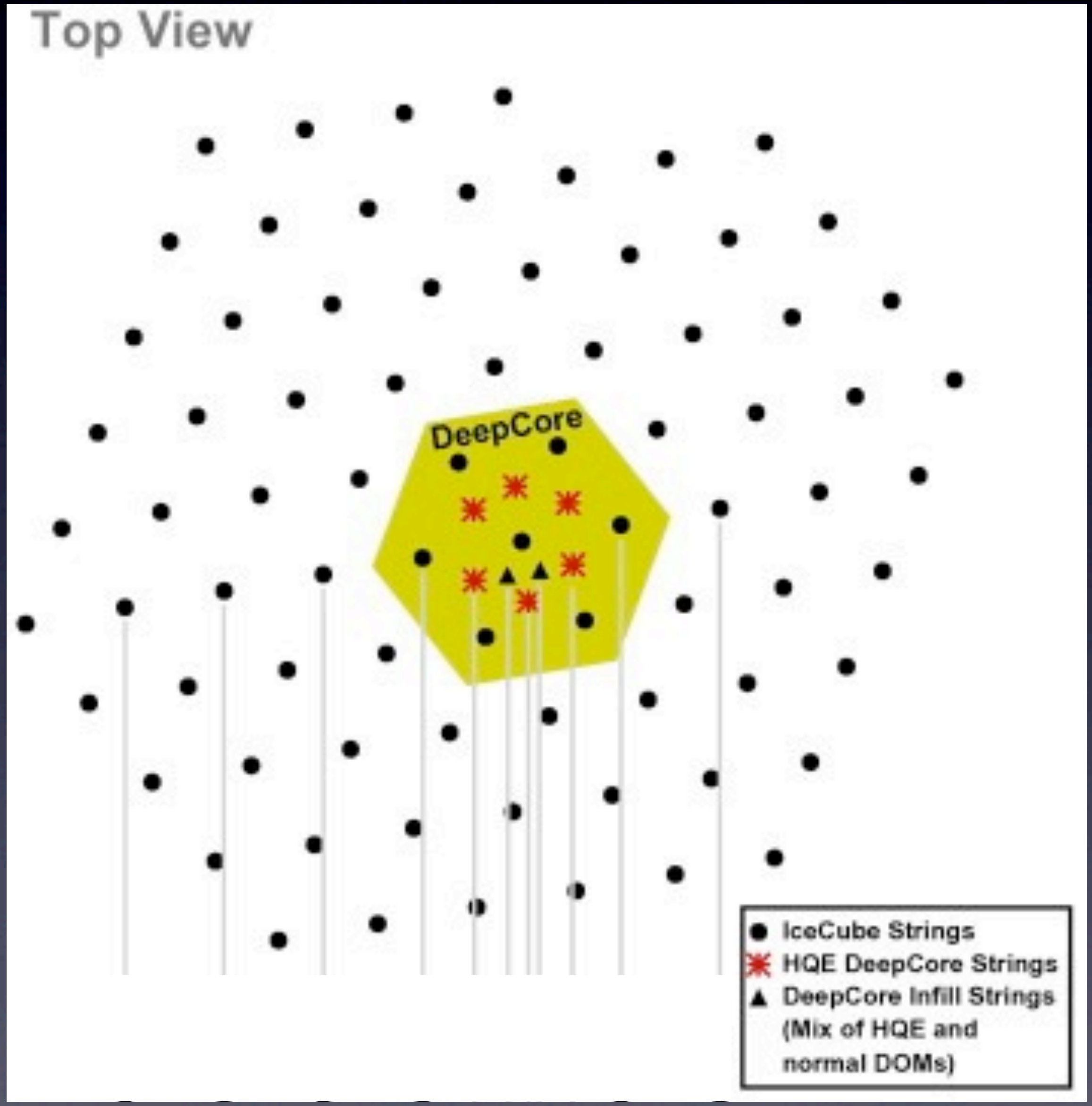
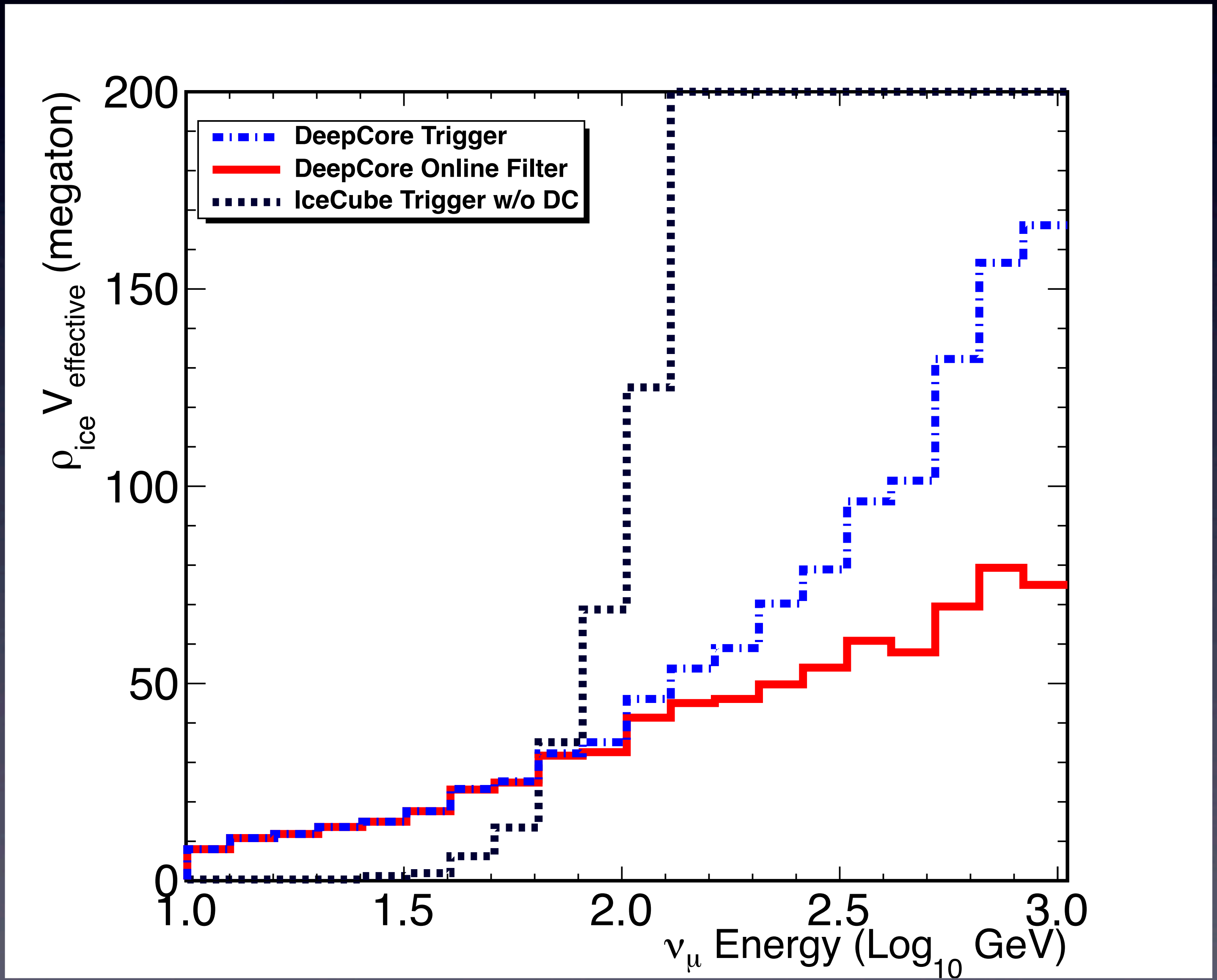


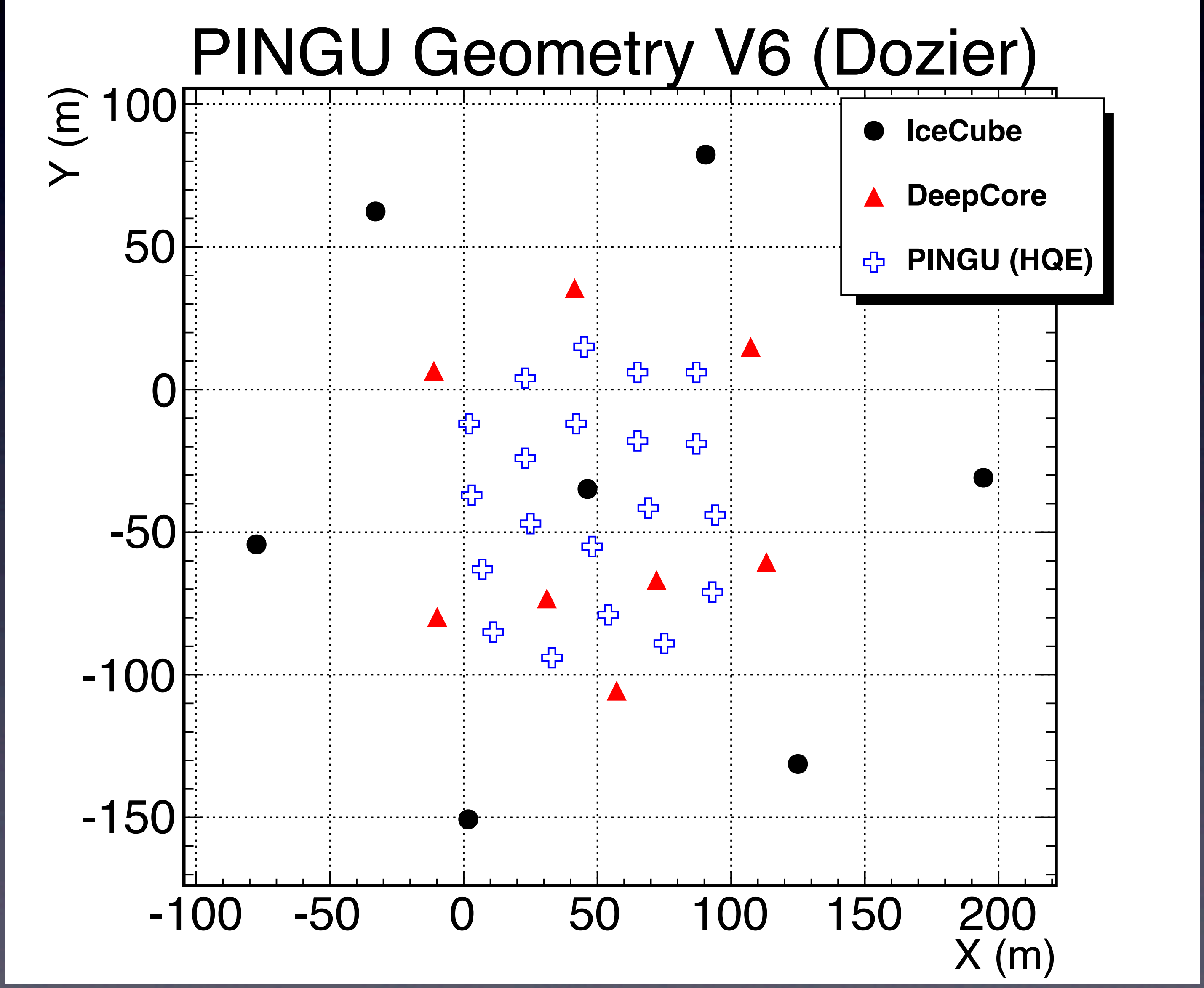
DeepCore Energy Range

- Detection threshold lowered to ~10 GeV in DeepCore
- Effective volume at trigger level increased below 100 GeV



Step up to PINGU

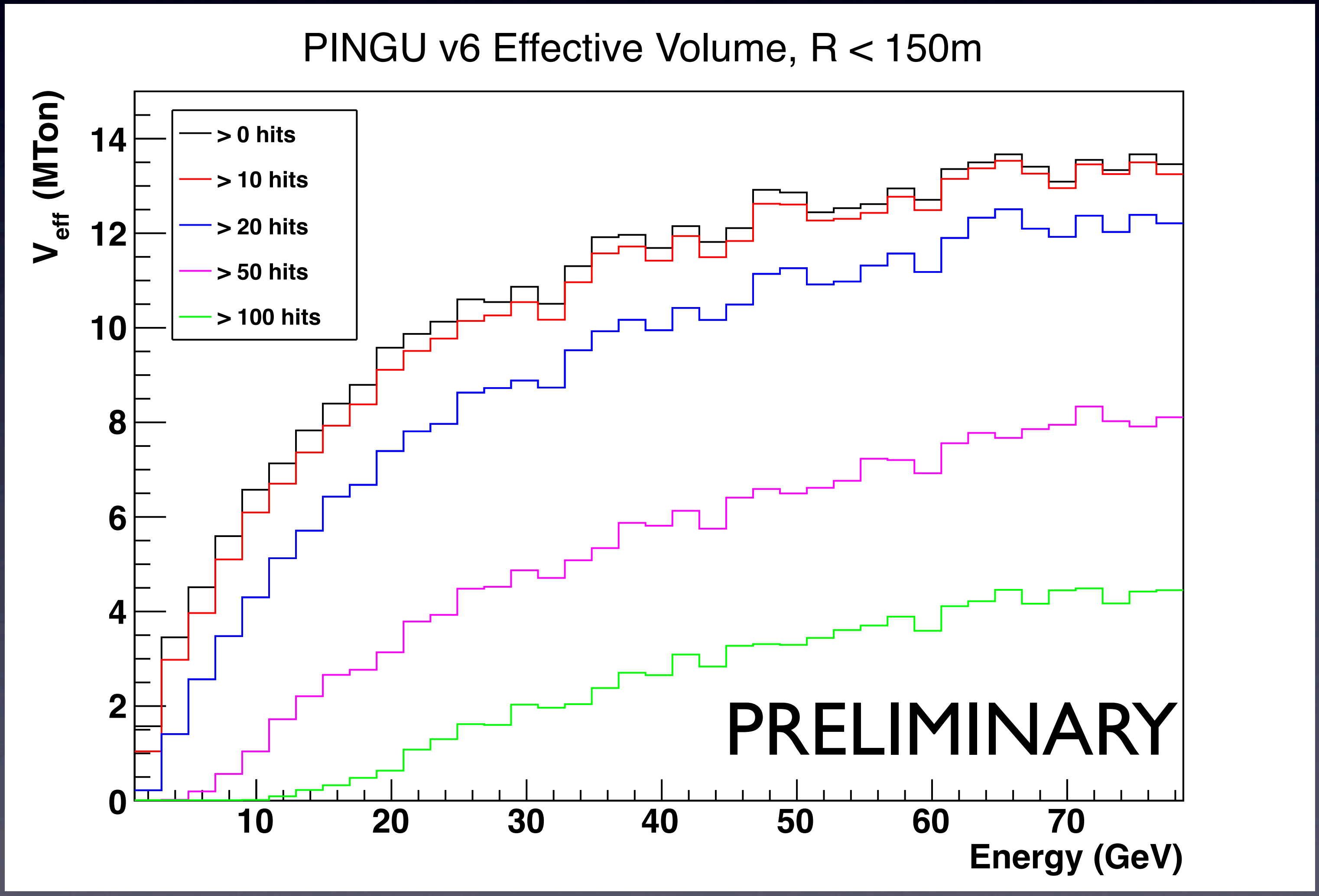
- Add another 20 strings
- Denser string and DOM spacing
- Energy threshold lowers again



Step up to PINGU

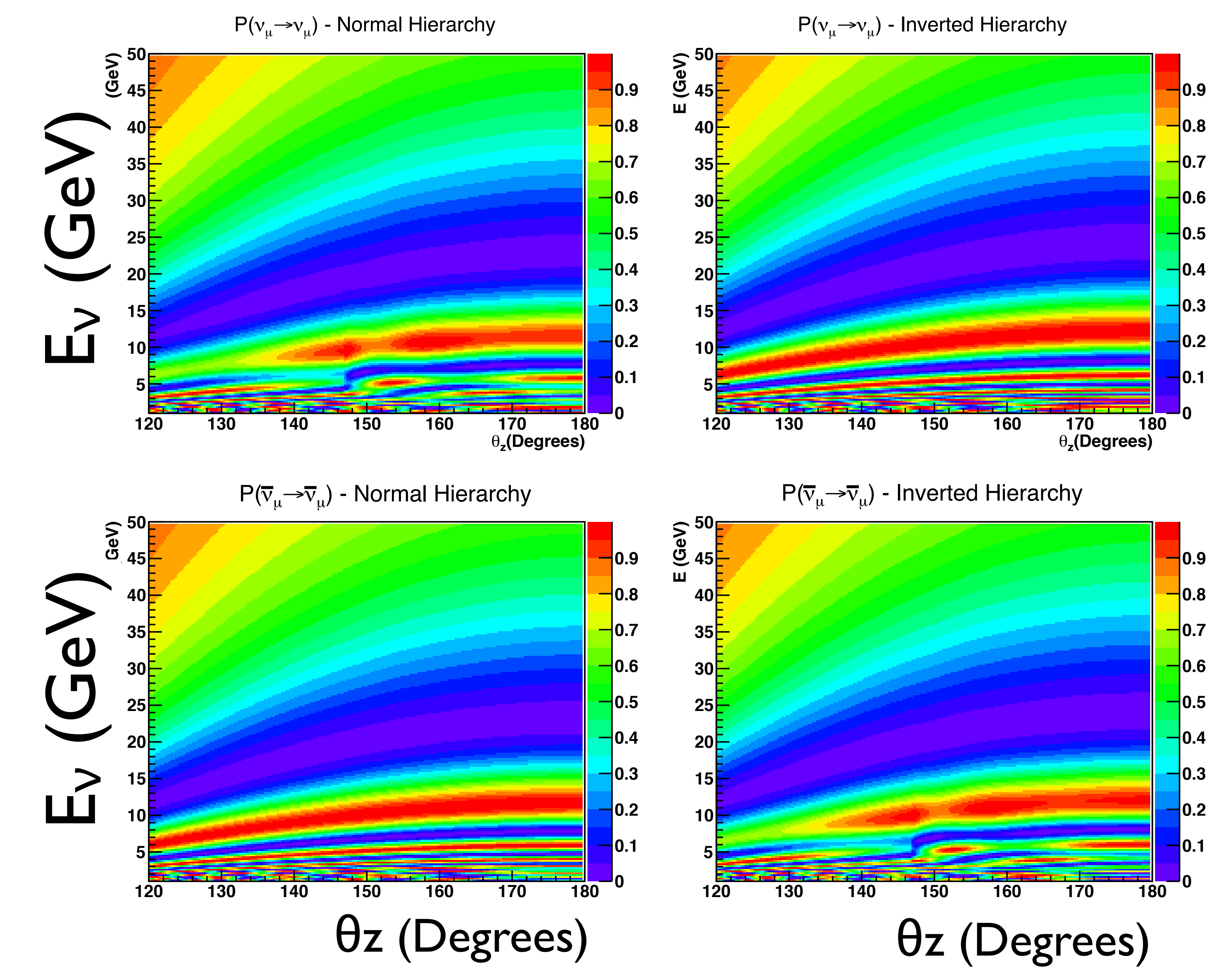
PRELIMINARY

- Add another 20 strings
- Denser string and DOM spacing
- Energy threshold lowers again



2 Dimensional Plotting

- Now we need to extend this to two dimensions to show the probability vs energy and zenith angle



Distinguishability

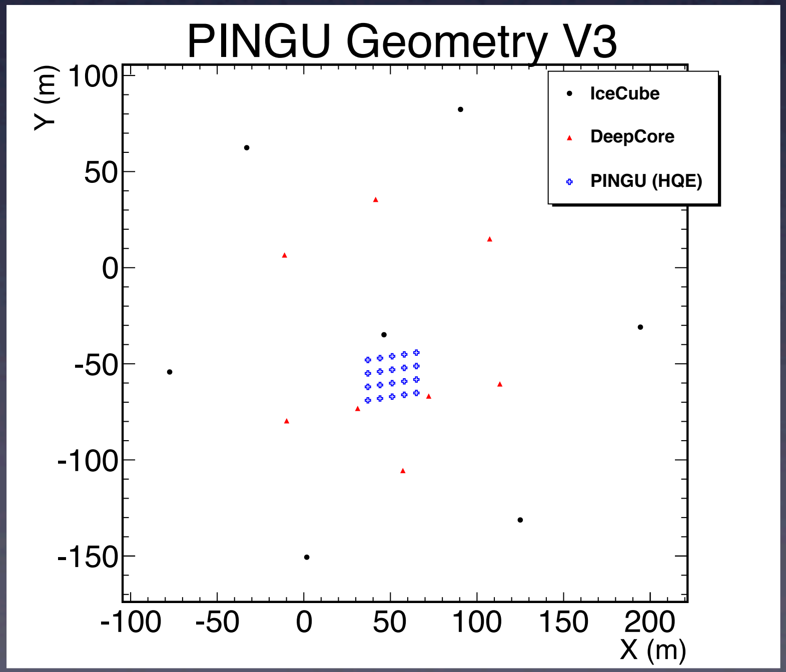
- Use method outlined in arXiv:1205.7071 (Akhmedov, Razzaque and Smirnov)

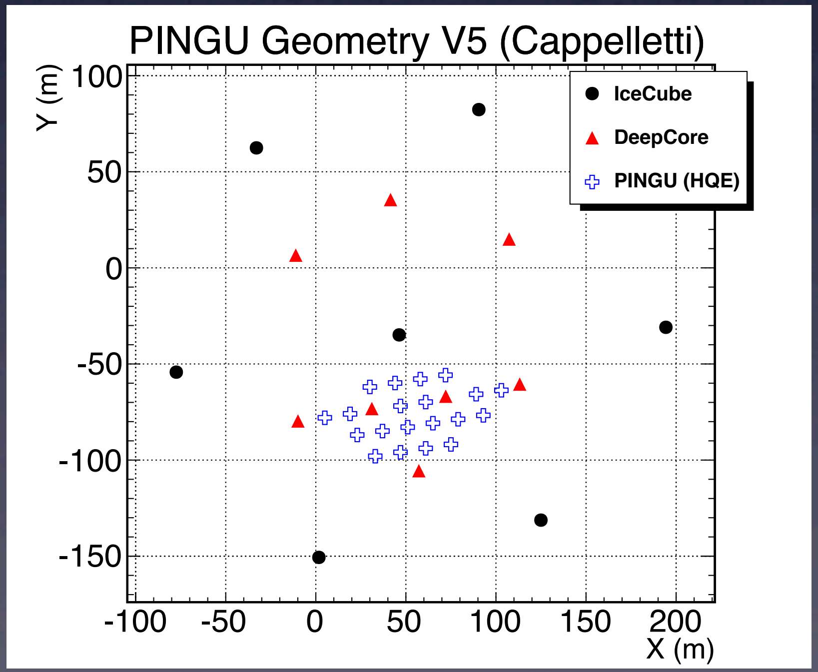
$$S^{tot} = \sqrt{\Sigma_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{N_{ij}^{NH}}}$$

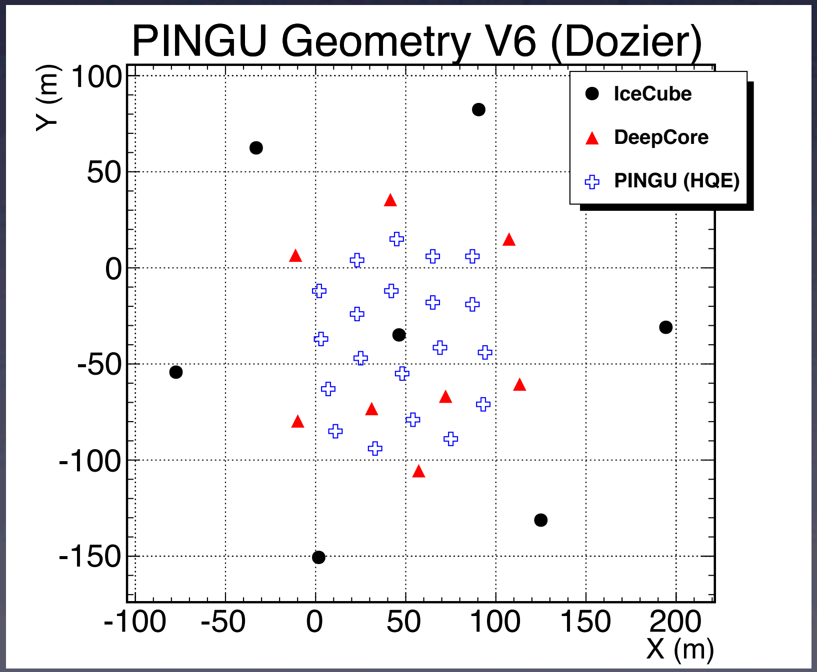
- Essentially bin everything up and subtract the two hierarchies, scaled by the number of events in the Normal hierarchy bin

Simulations

- Simulations now carried out using IceCube MC structure
- Currently studying different PINGU geometries with different spacings







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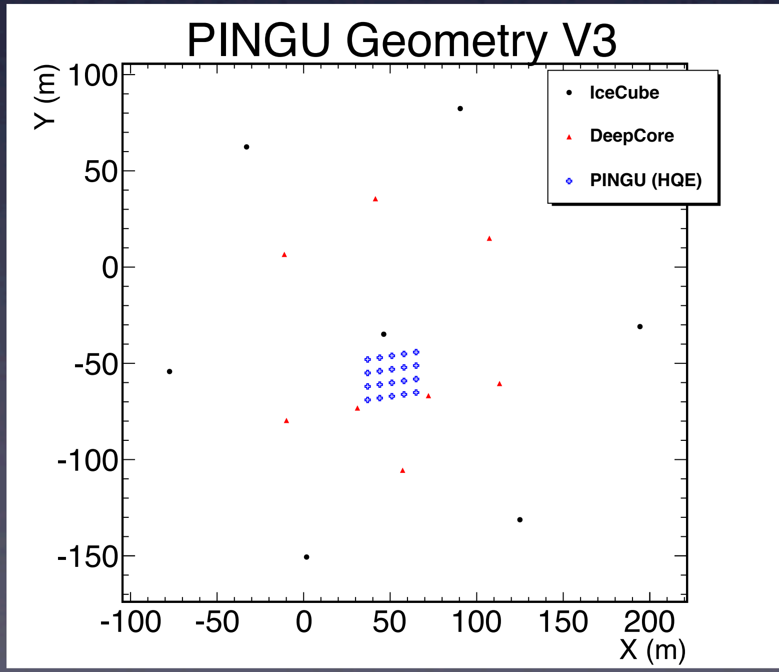
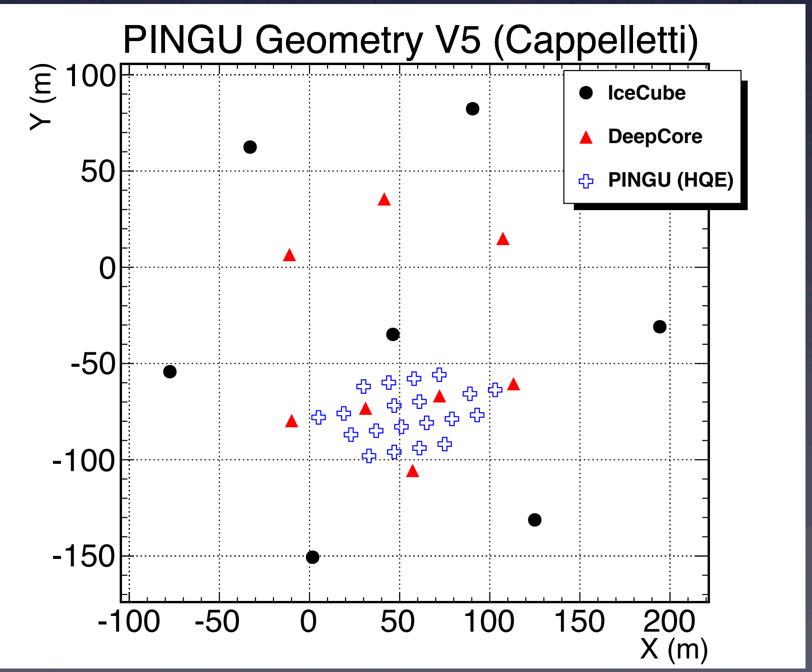
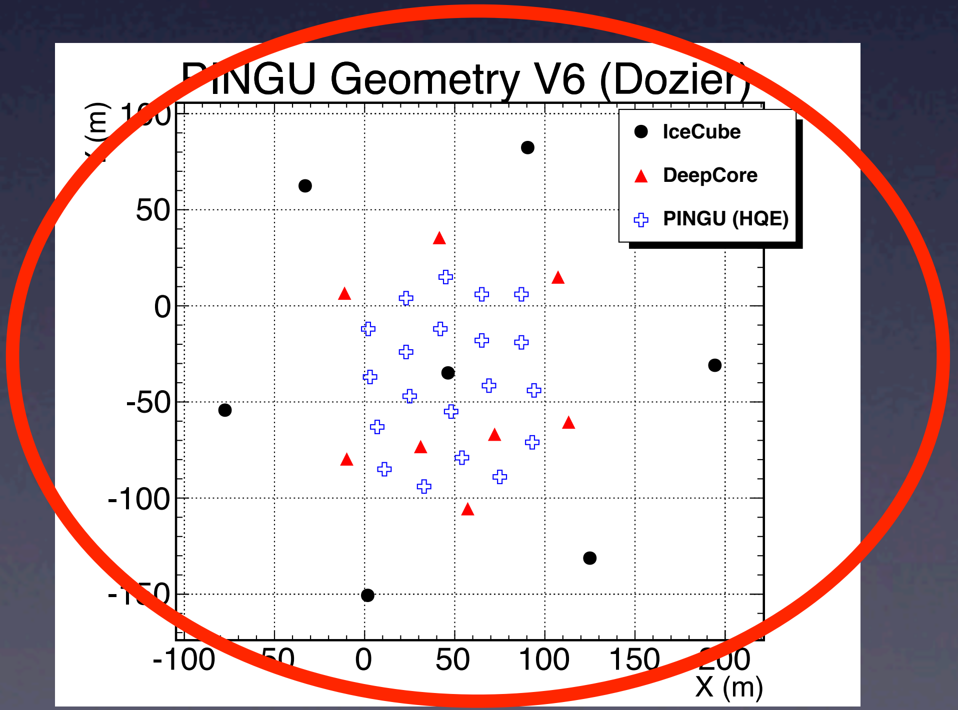
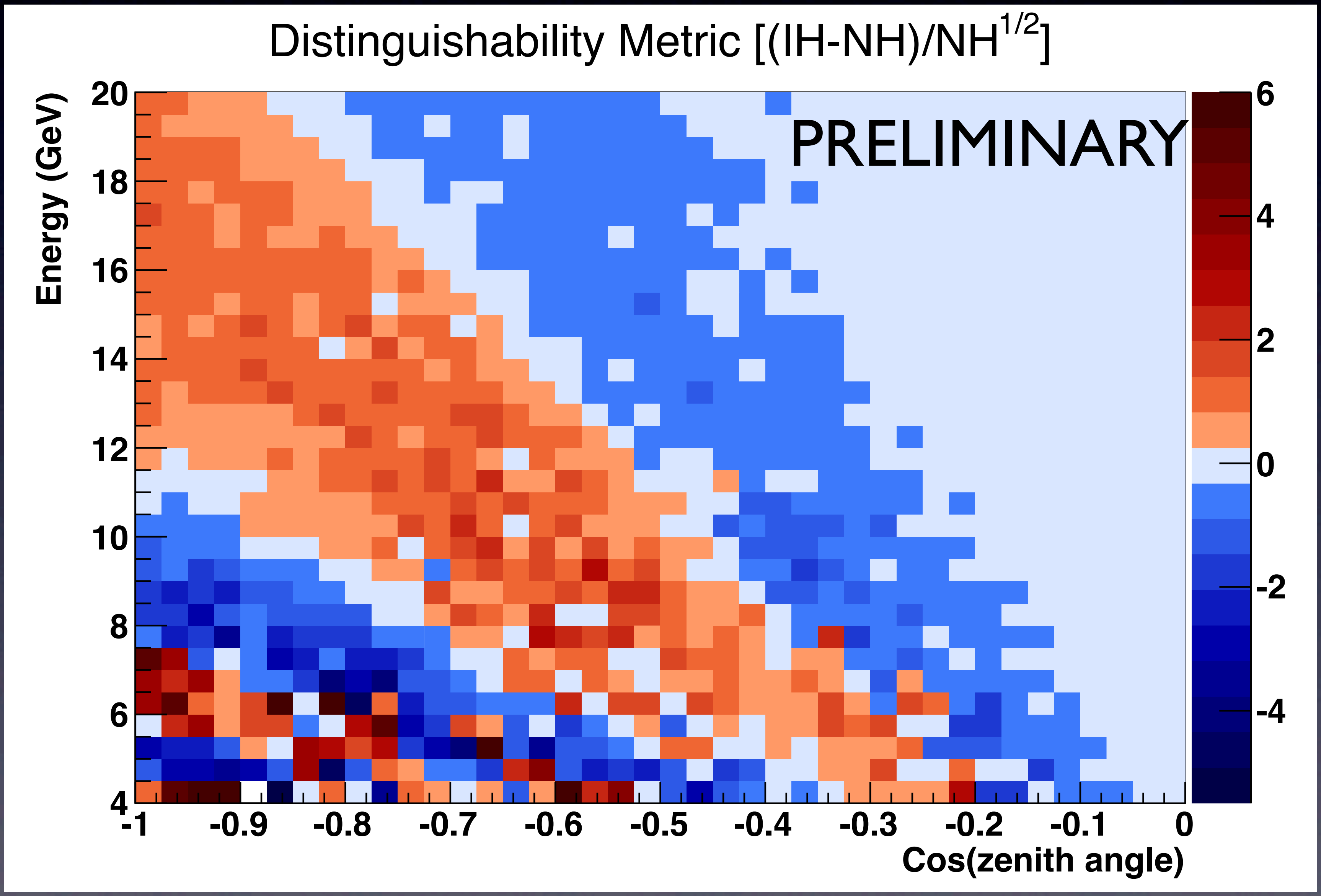






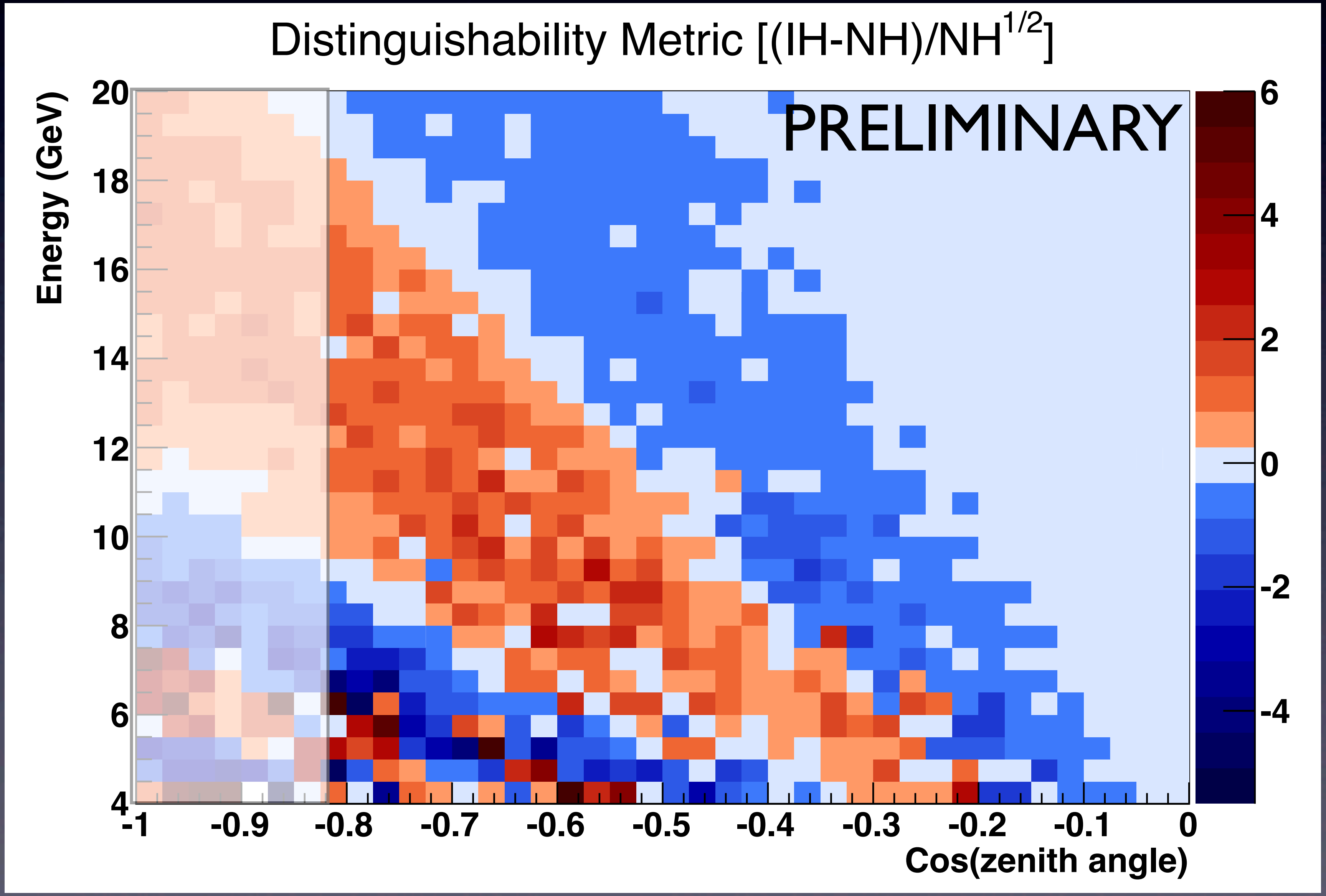
Distinguishability Plots

- Use our simulations
- First use neutrino zenith angle and energy
- Shown without square root to illustrate pattern



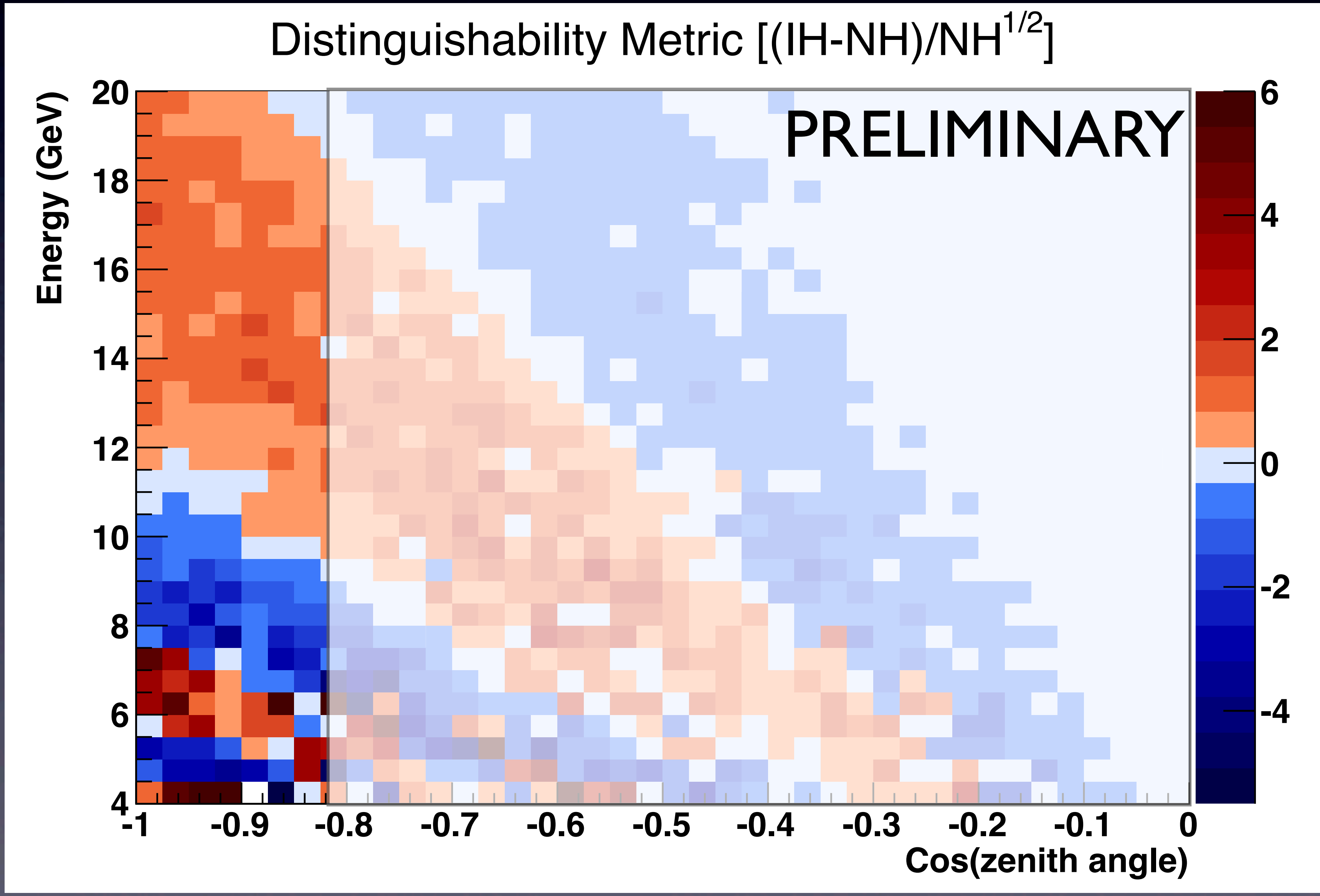
Distinguishability Plots

- Matter effects due to MSW



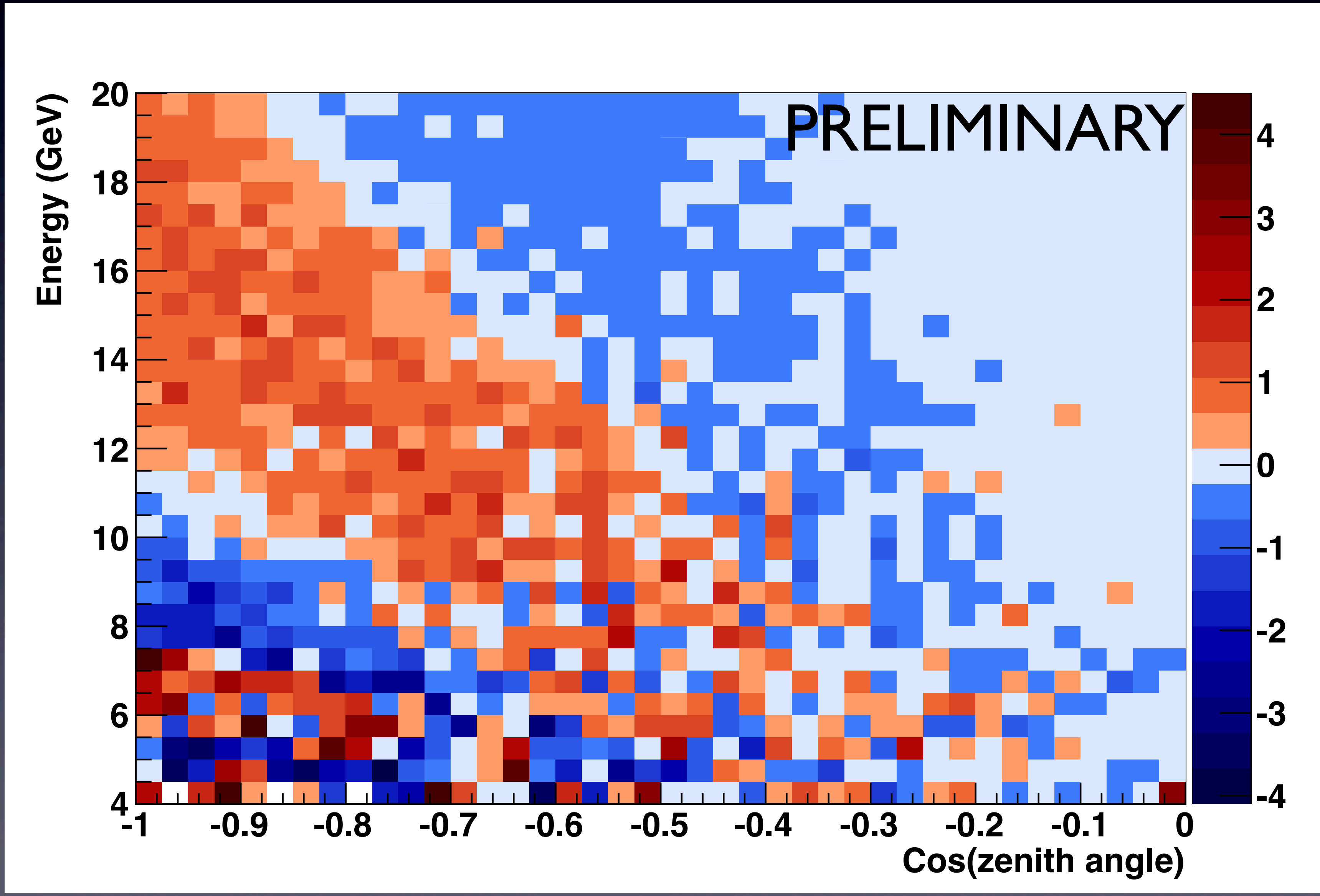
Distinguishability Plots

- Primarily parametric oscillation effects in this region



Distinguishability Plots

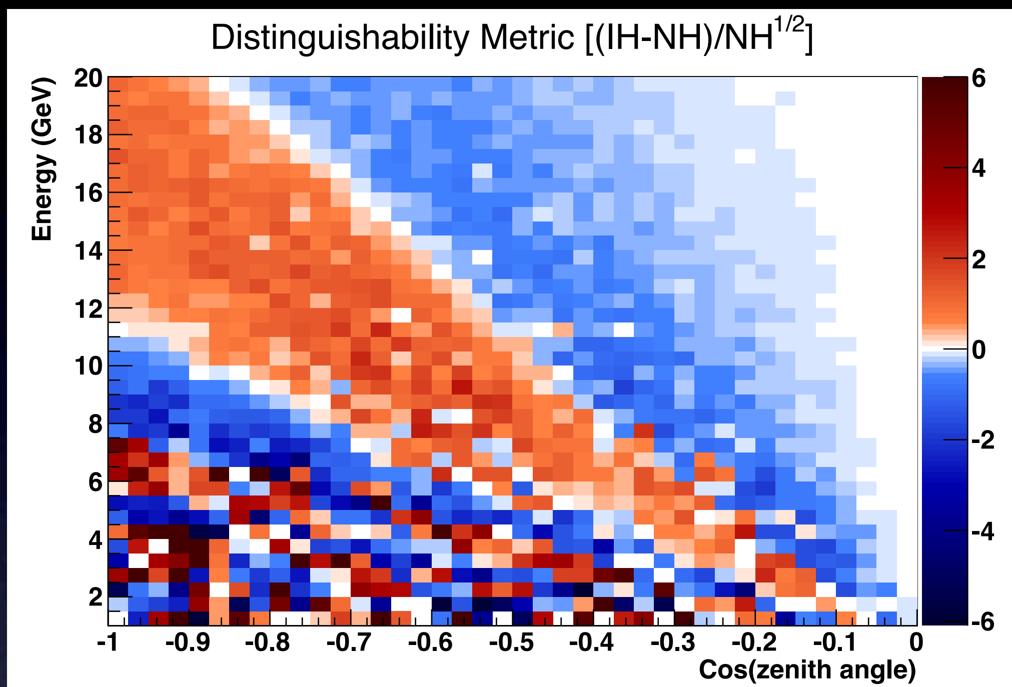
- Then use muon zenith angle and neutrino energy
- Shown without square root to illustrate pattern



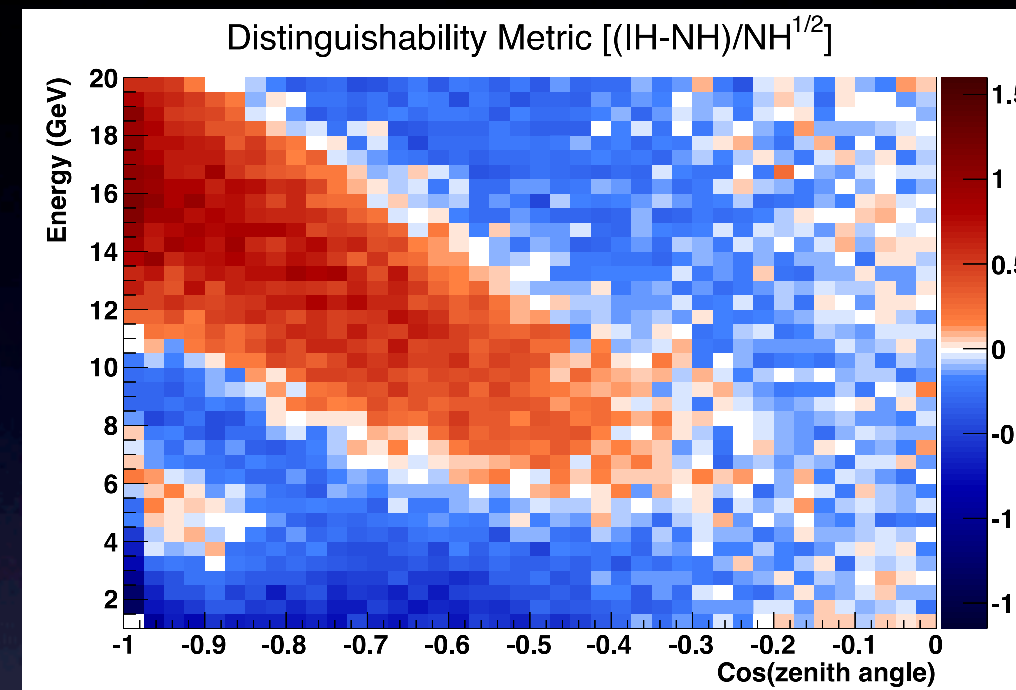
Reconstruction

- Previous plots showed perfect detector resolution
- This (probably) won't be the case
- Need to account for the reconstruction effects
- Add a gaussian "smearing" to the angles and energies

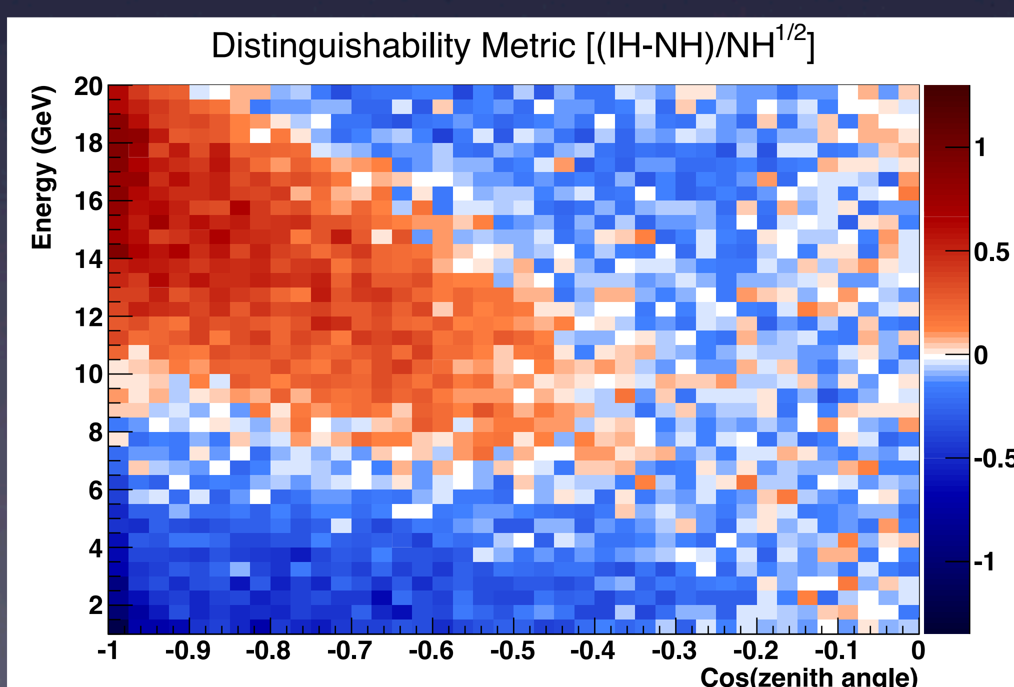
Detector Resolution



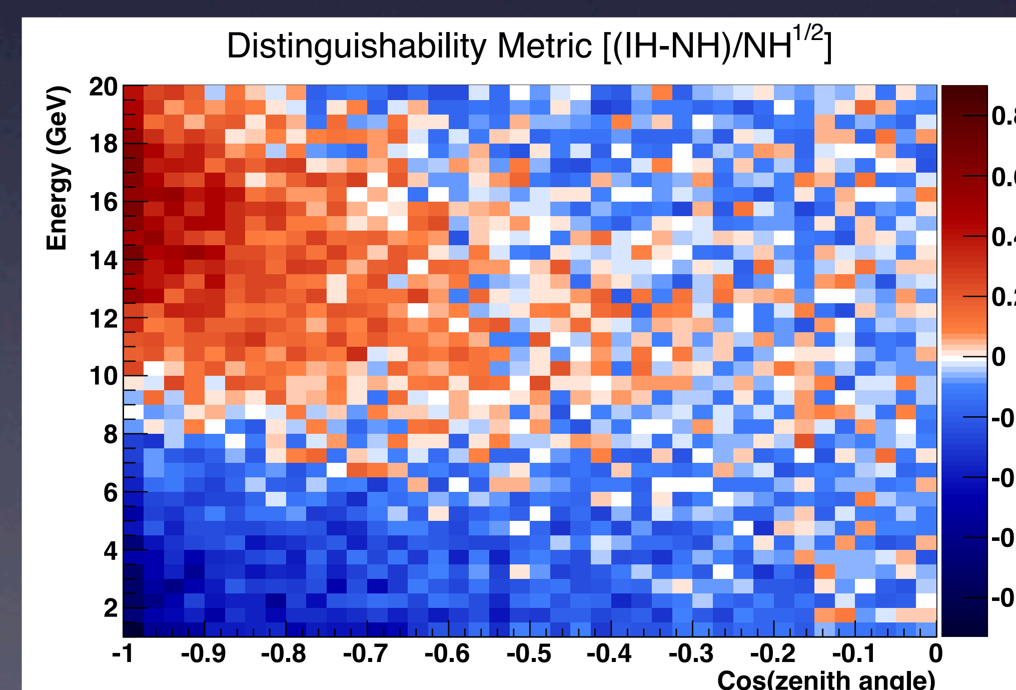
0 GeV, 0°



2 GeV, 11.25°

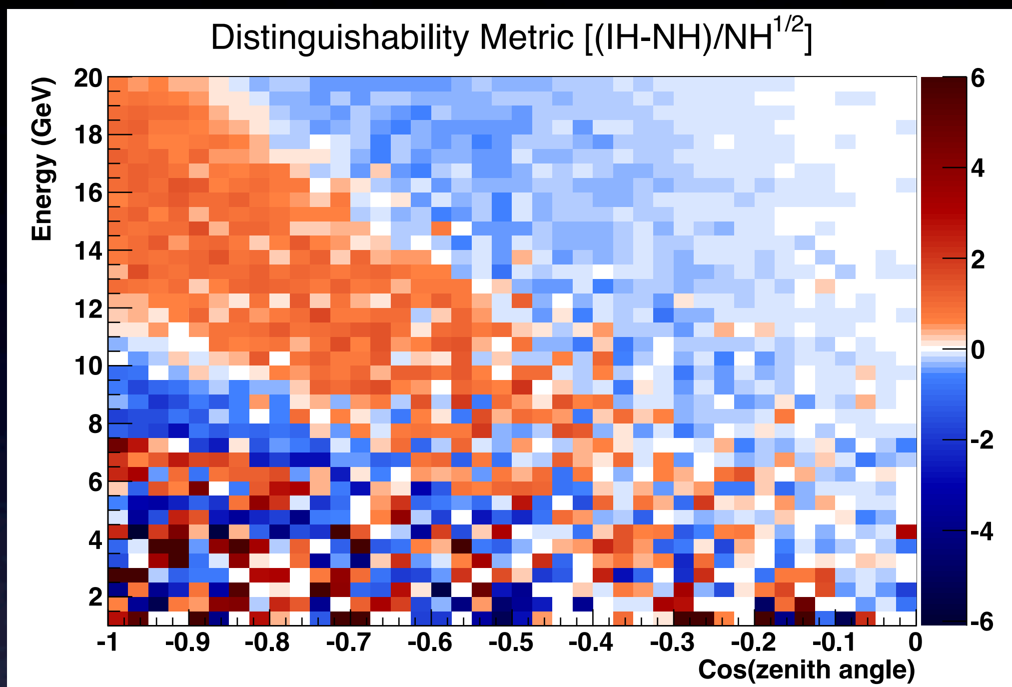


3 GeV, 15°

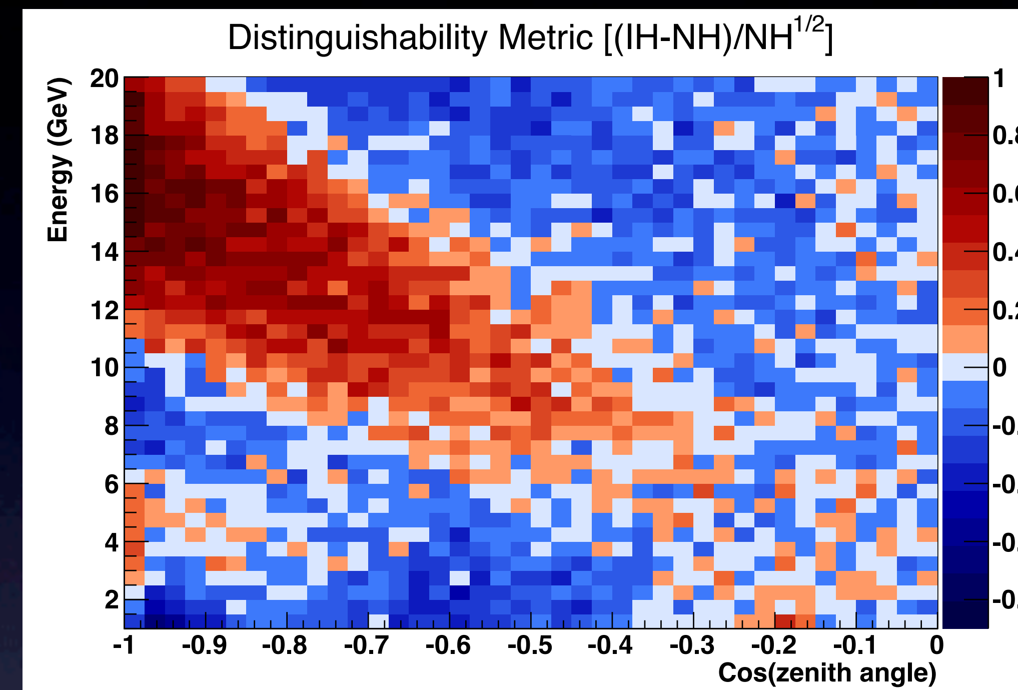


4 GeV, 22.5°

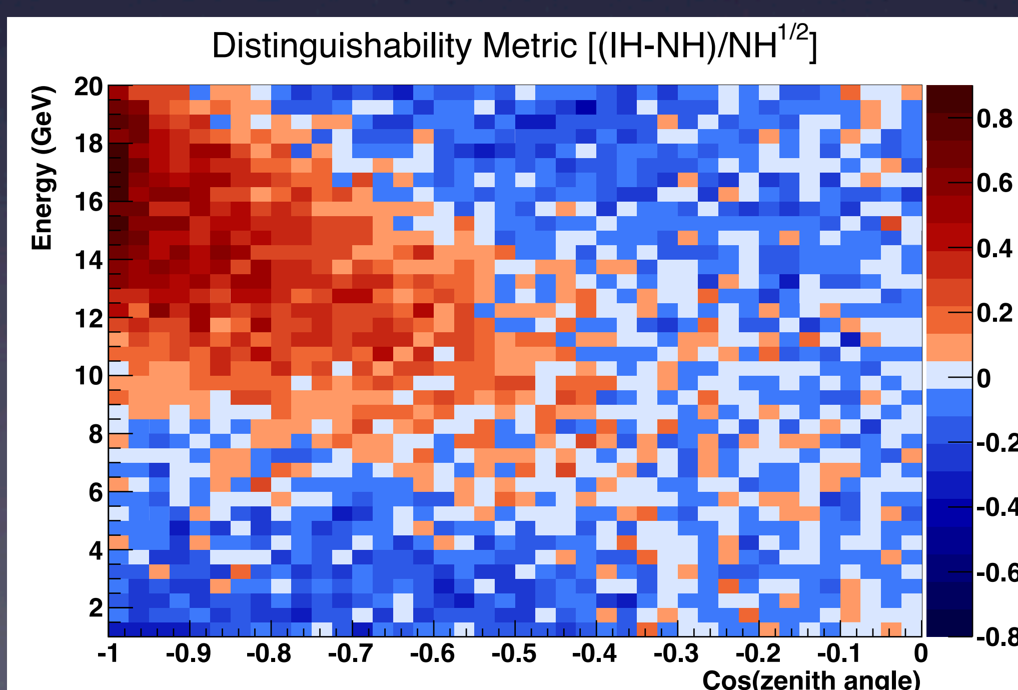
Detector Resolution



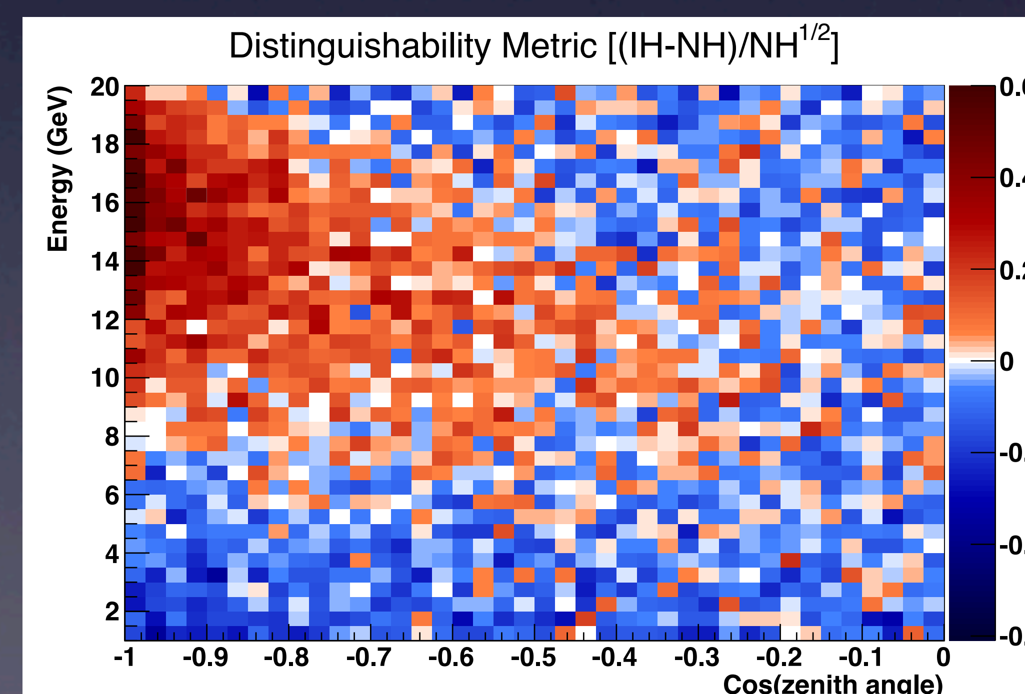
0 GeV, 0°



2 GeV, 11.25°



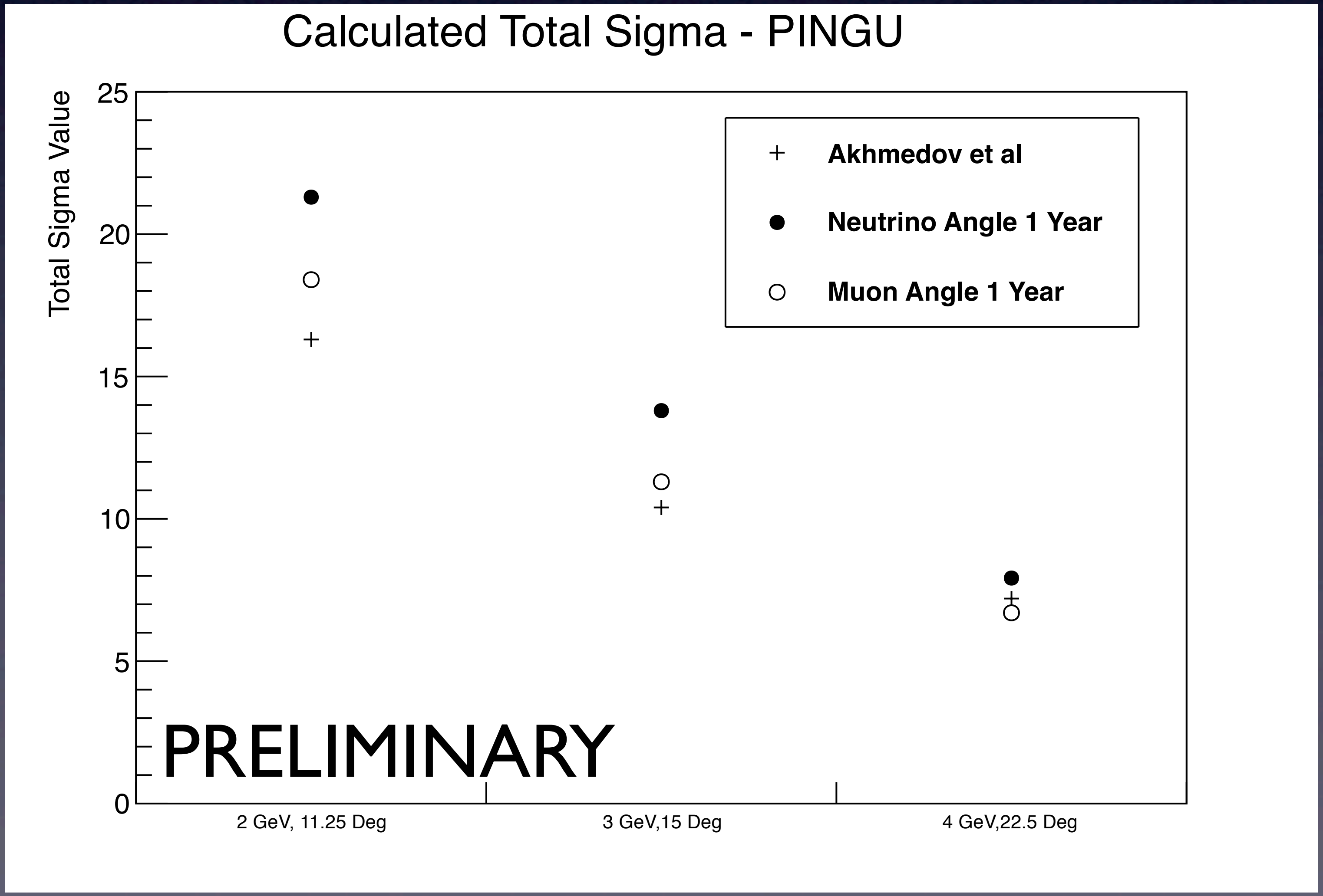
3 GeV, 15°



4 GeV, 22.5°

Comparisons

- Following model in publication, used three different resolution pairs
  - (2GeV,11.25°),(3GeV,15°),(4GeV,22.5°)

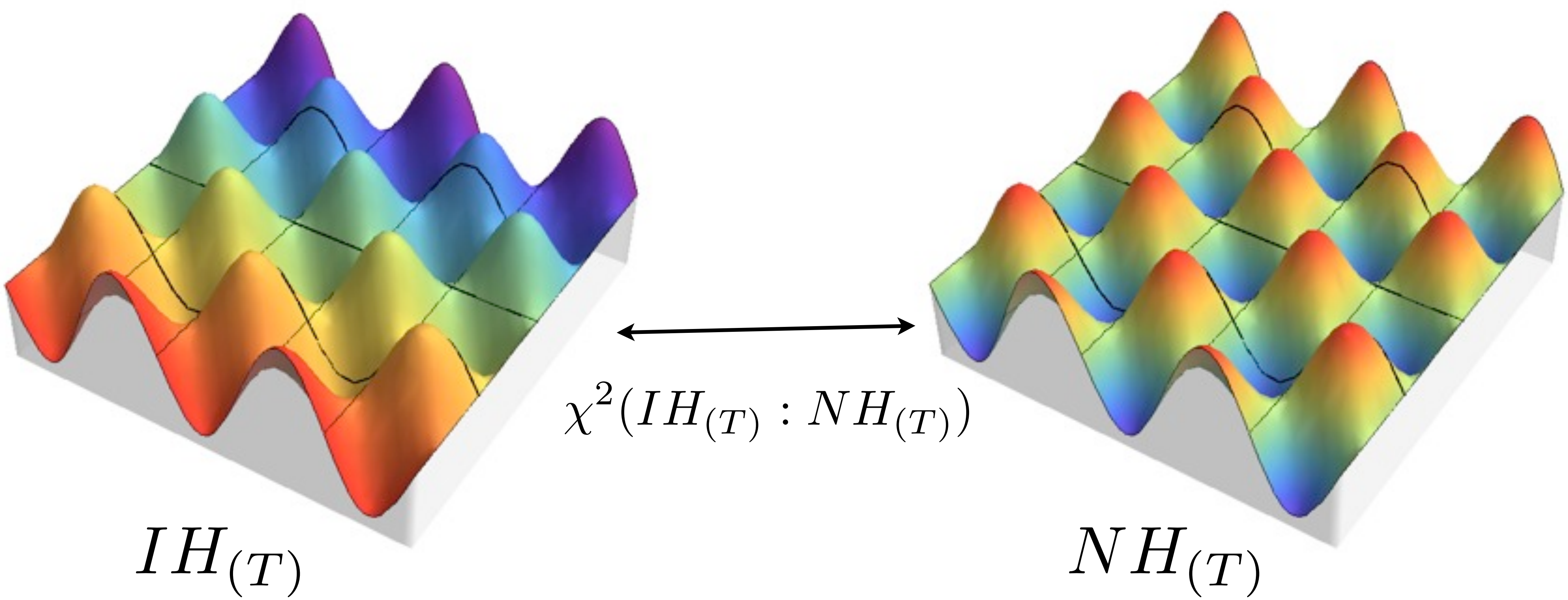


Systematics

- Studied several effects

1. Systematic energy shift +/-5%, +/-10%
2. Systematic angle broadening +/-5%, +/-10%
3. PREM quantities incorrect
    - Core radii +/-5%, +/-10%
    - Core densities +/-5%, +/-10%

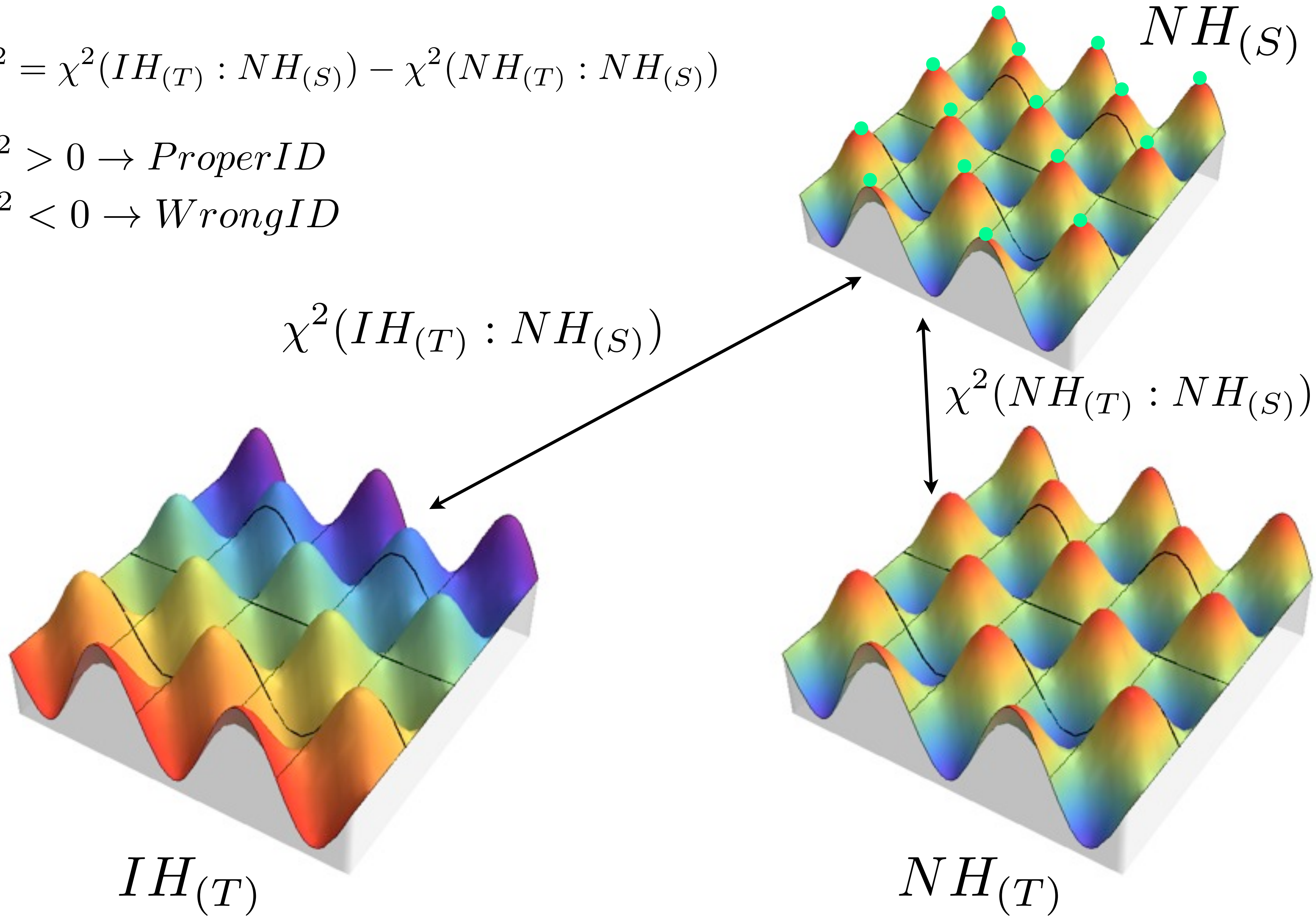
Systematics - Illustrated



Systematics - Illustrated

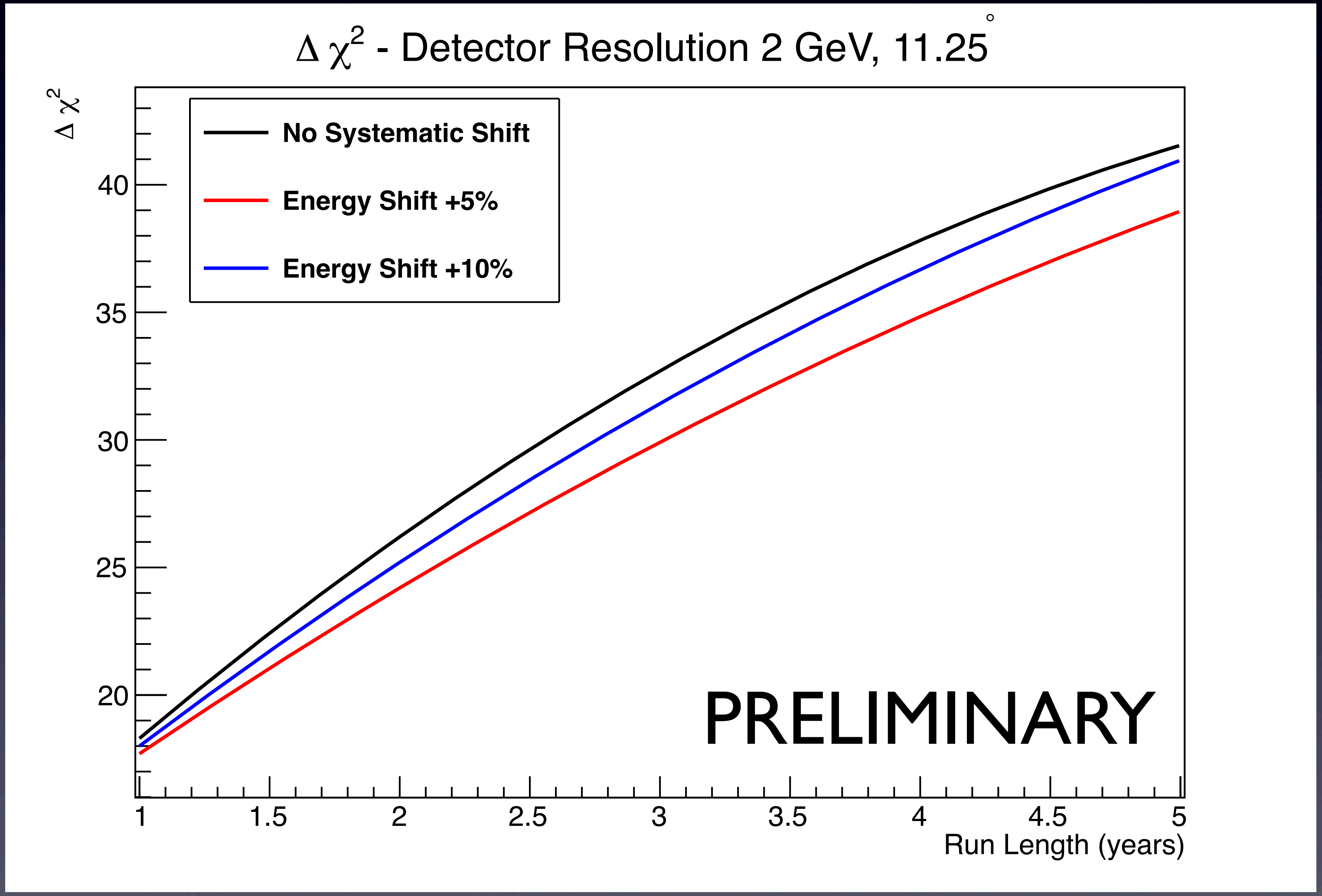
$$\Delta\chi^2 = \chi^2(IH_{(T)} : NH_{(S)}) - \chi^2(NH_{(T)} : NH_{(S)})$$

$$\Delta\chi^2 > 0 \rightarrow ProperID$$
$$\Delta\chi^2 < 0 \rightarrow WrongID$$



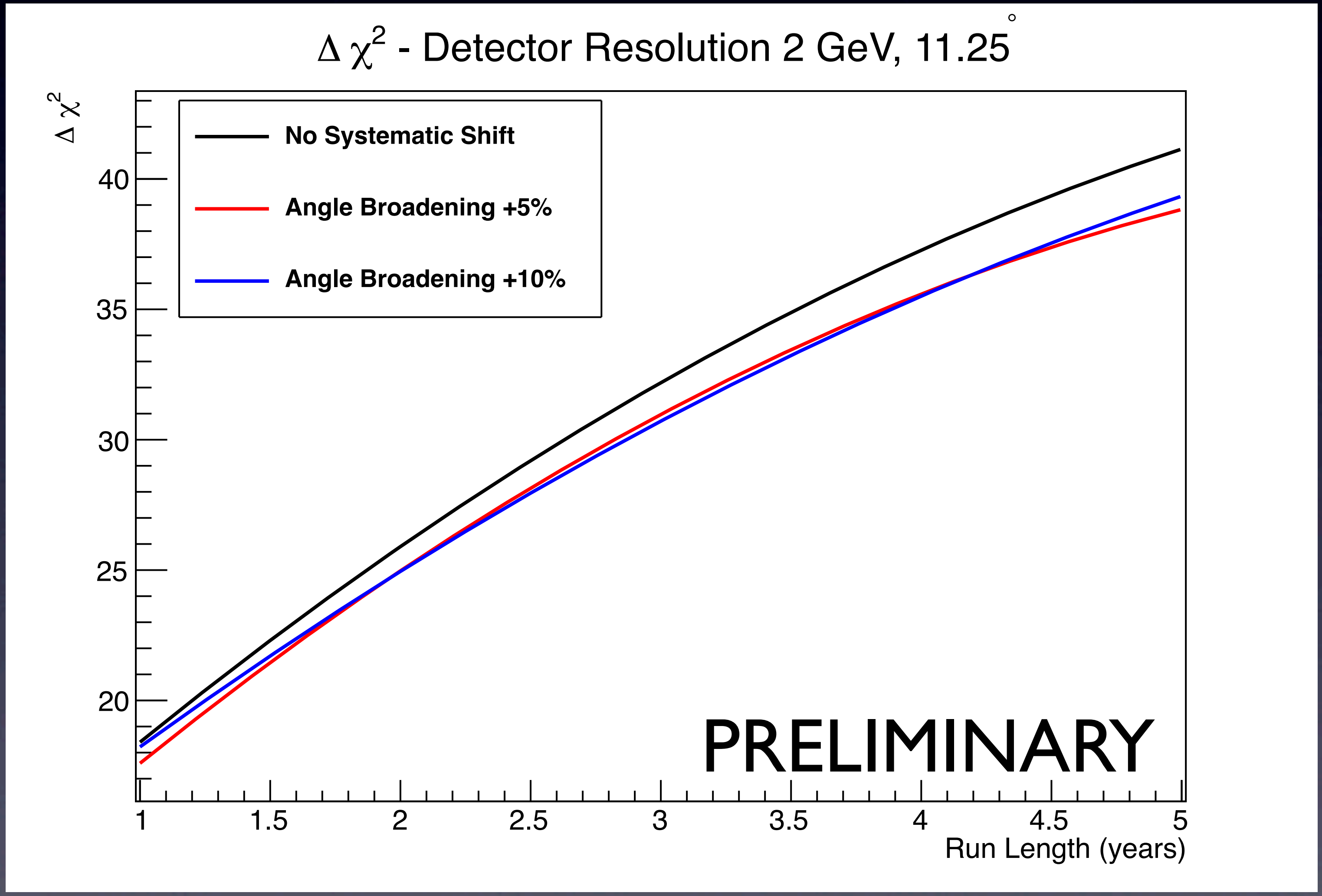
Energy Shift

- Systematic shift in energy has little effect



Angle Broadening

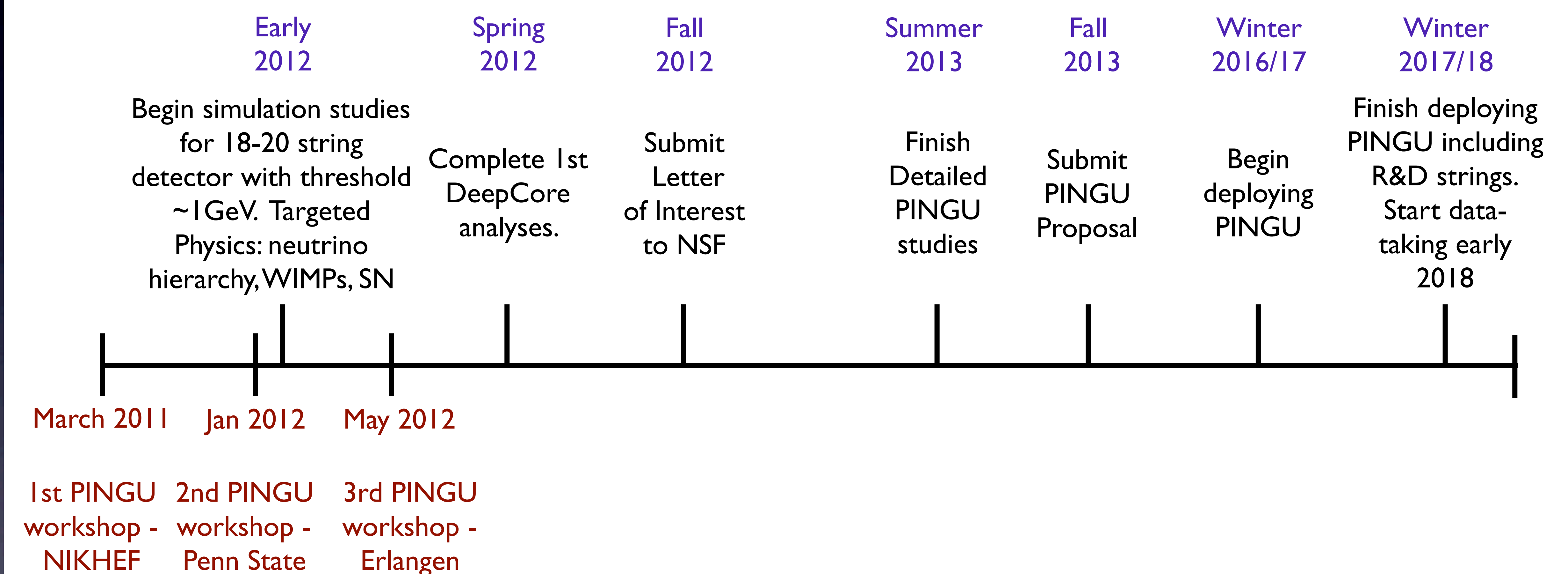
- Not a systematic shift in zenith
- Misunderstanding of the detector resolution



Next Steps

- Next objective is to include detector resolution effects properly using reconstructions
- Need to perform detailed analysis of systematics
- Start with quantification of best geometry

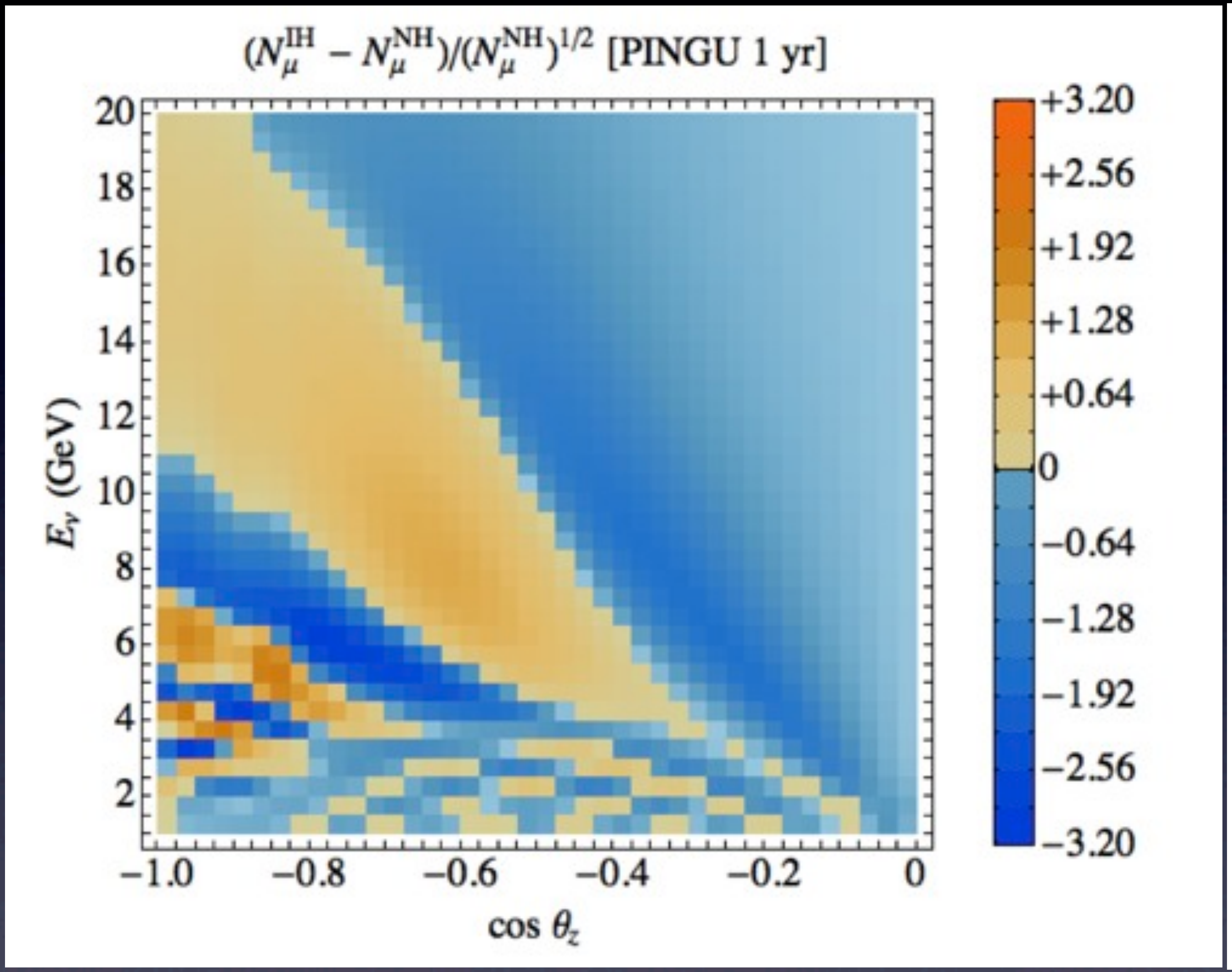
Timescale

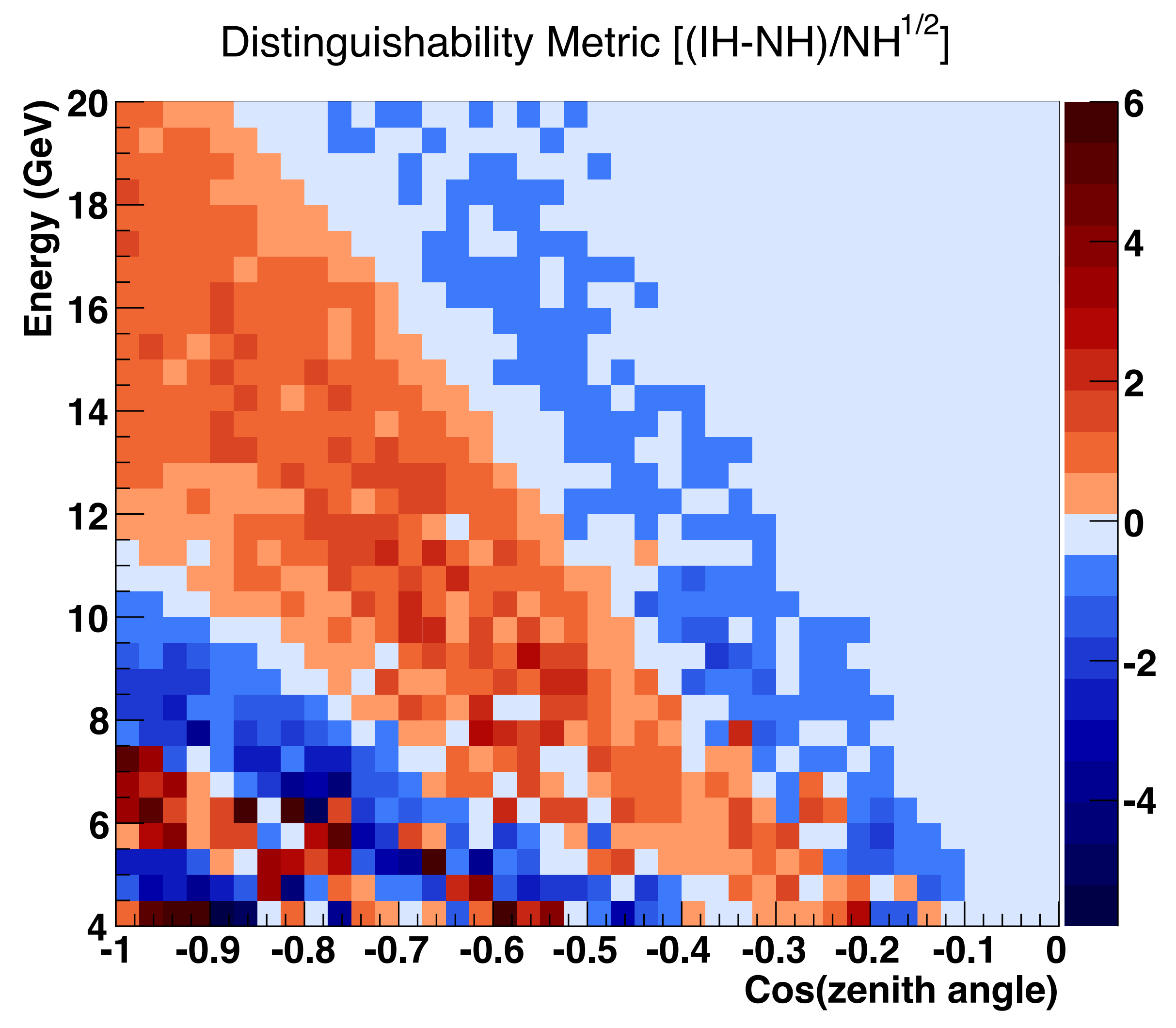

Early 2012
Begin simulation studies for 18-20 string detector with threshold ~1GeV. Targeted Physics: neutrino hierarchy, WIMPs, SN
Spring 2012
Complete 1st DeepCore analyses.
Fall 2012
Submit Letter of Interest to NSF
Summer 2013
Finish Detailed PINGU studies
Fall 2013
Submit PINGU Proposal
Winter 2016/17
Begin deploying PINGU
Winter 2017/18
Finish deploying PINGU including R&D strings. Start data-taking early 2018
March 2011
1st PINGU workshop - NIKHEF
Jan 2012
2nd PINGU workshop - Penn State
May 2012
3rd PINGU workshop - Erlangen

Conclusion

- Determination of the neutrino mass hierarchy with atmospheric neutrinos appears feasible
- PINGU allows for this determination quickly in a cost effective implementation

Comparison

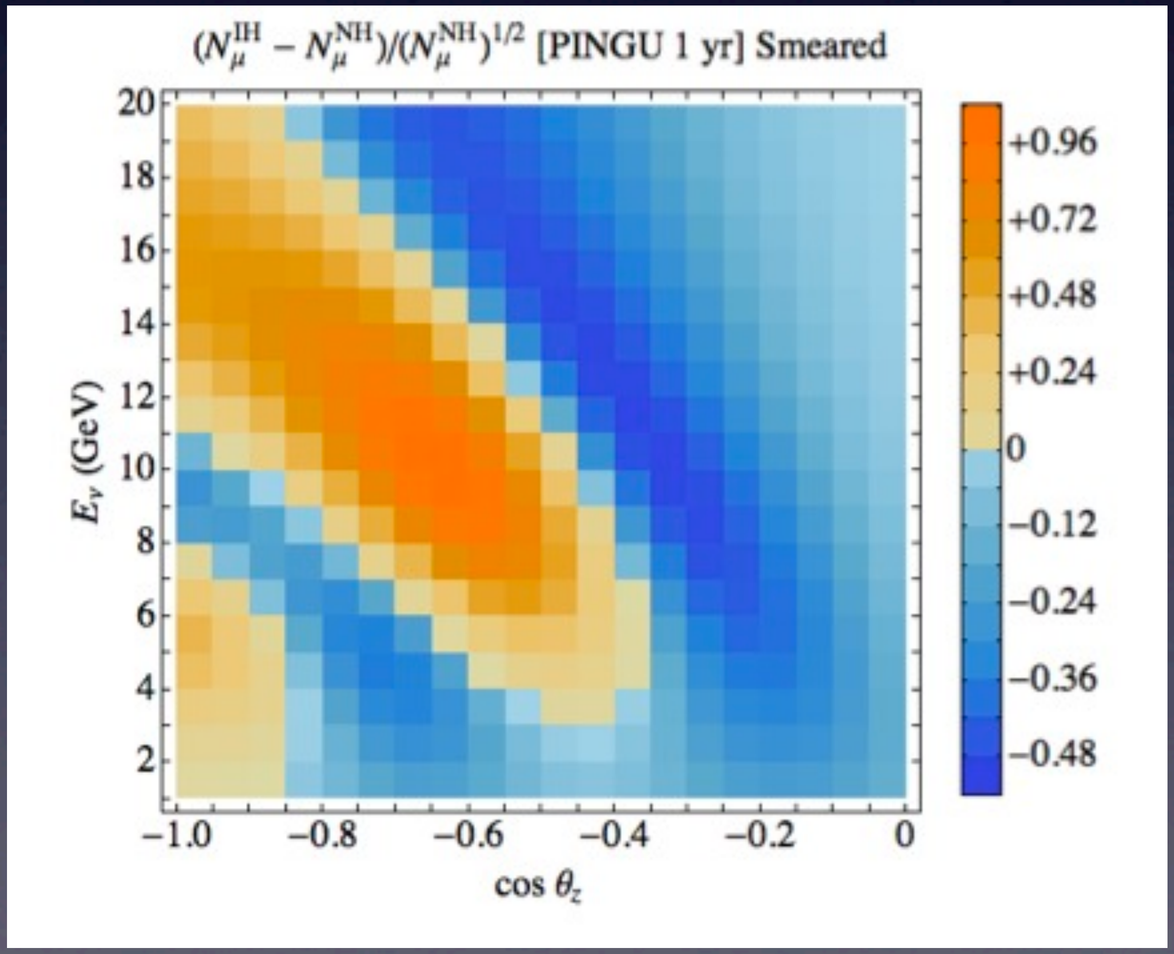


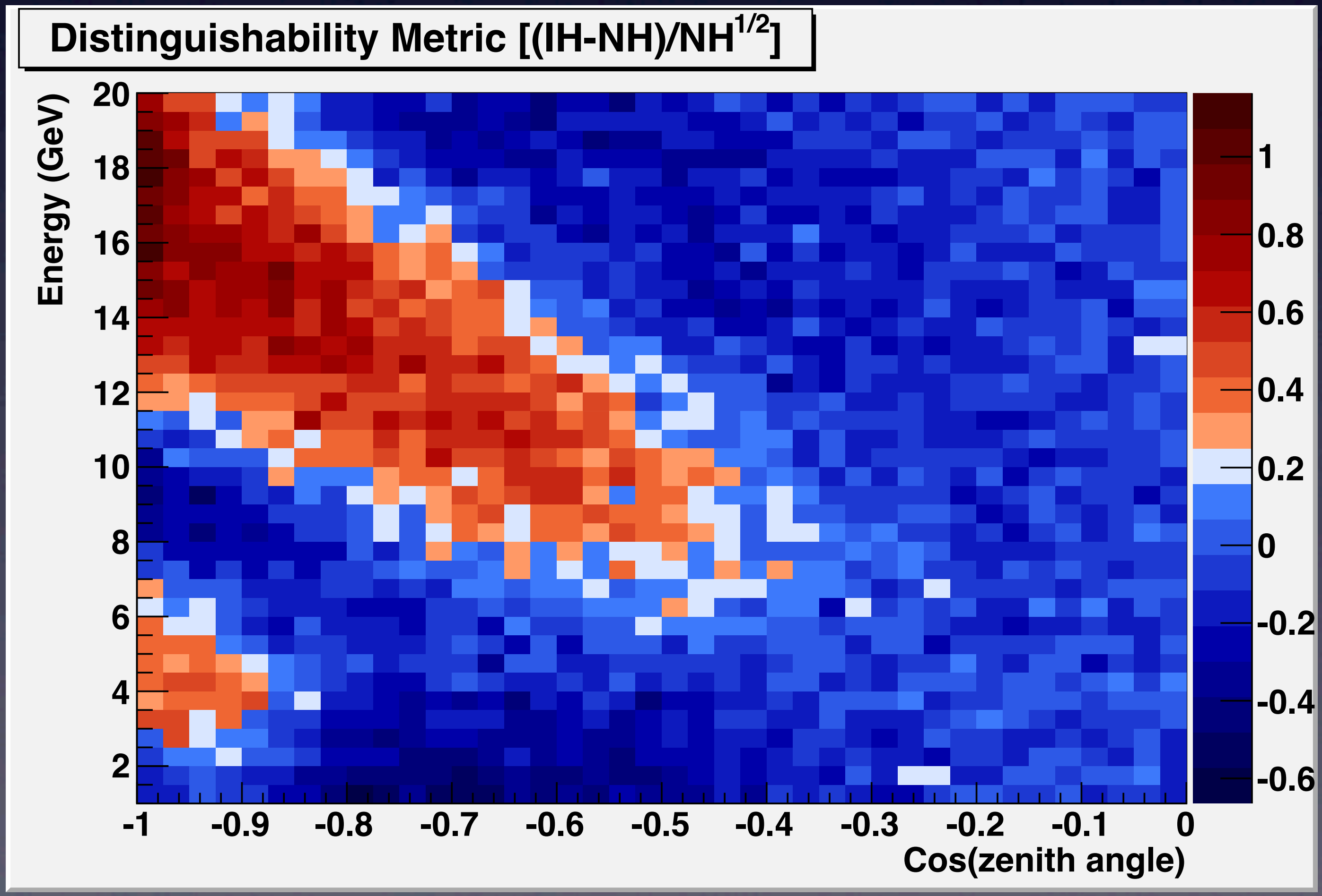


Things seem to compare reasonably well

Detector Resolution Plots

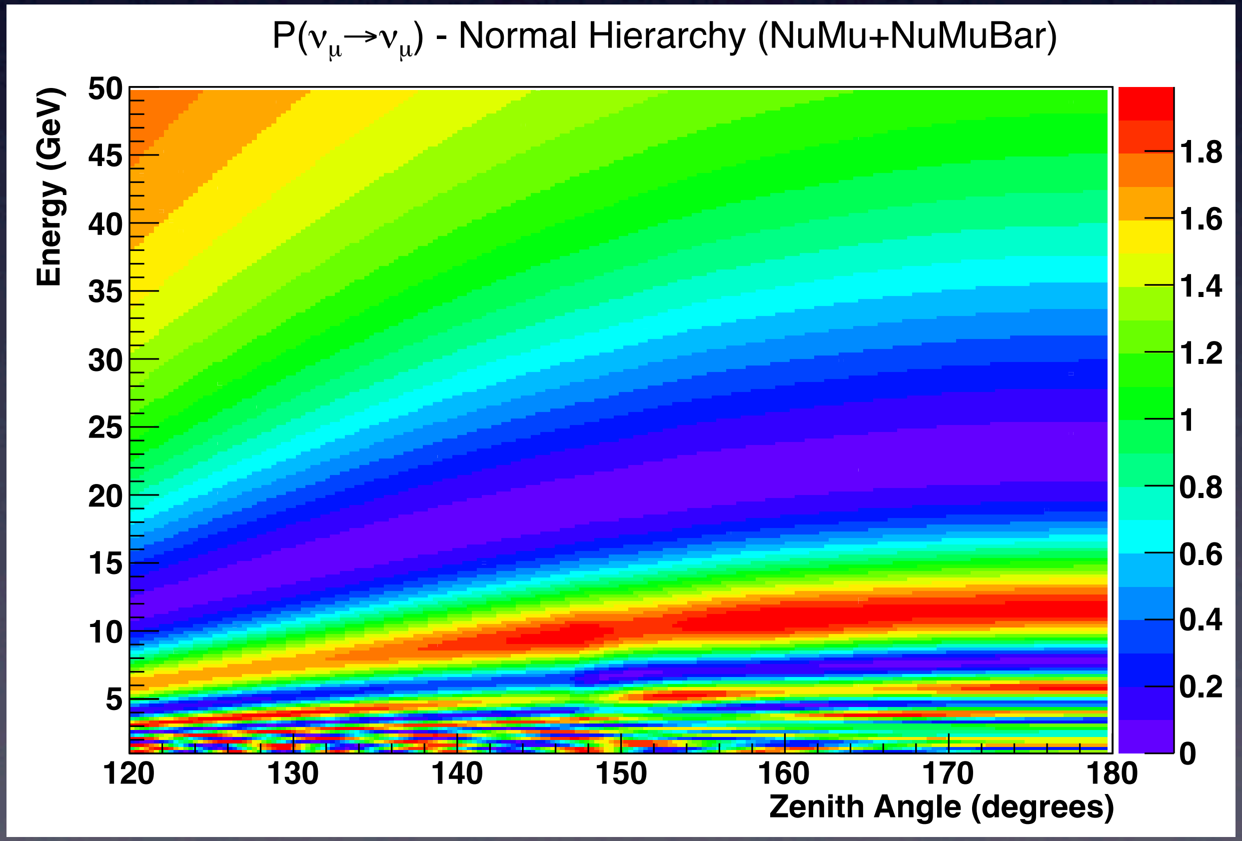
- Shown with detector resolution 2 GeV, 11.25°

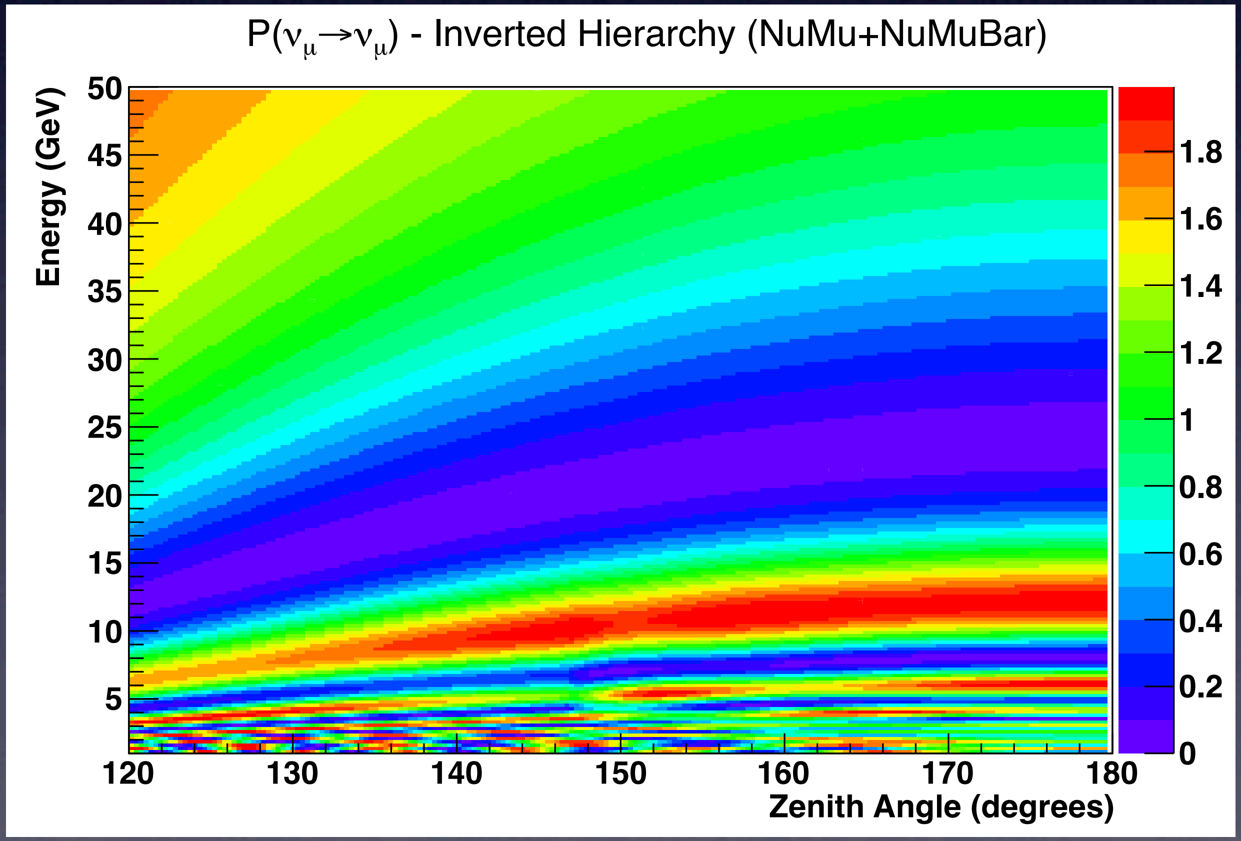




Reality(-ish)

- For ν_μ-like events we really get a mixture of ν_μ and $\bar{\nu}_\mu$





Systematics

- Can also add systematics on the simulated data:

1. Apply detector resolution to both hierarchies (IH and NH)
2. Copy both hierarchies
3. Apply systematic shift to one copy for each
4. For each copy, calculate the significance of the opposite unshifted hierarchy and the same unshifted hierarchy
5. Subtract the same from the opposite value