The sensitivity of PINGU to Neutrino Mass Hierarchy

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Outline

- Neutrino Oscillations, Mass Hierarchy
- PINGU detector
- Reconstruction of low energy neutrinos
- Selection of low energy neutrinos, rejection of backgrounds
- The calculation of the sensitivity

Neutrino oscillations

- Mass eigenstates ν_i != flavor eigenstates ν_α
  - $|\nu_j\rangle = \Sigma_{\alpha=e,\mu,\tau} U^*_{\alpha j} |\nu_\alpha\rangle$
  - $|\nu_\alpha\rangle = \Sigma_{j=1,2,3} U_{\alpha j} |\nu_j\rangle$

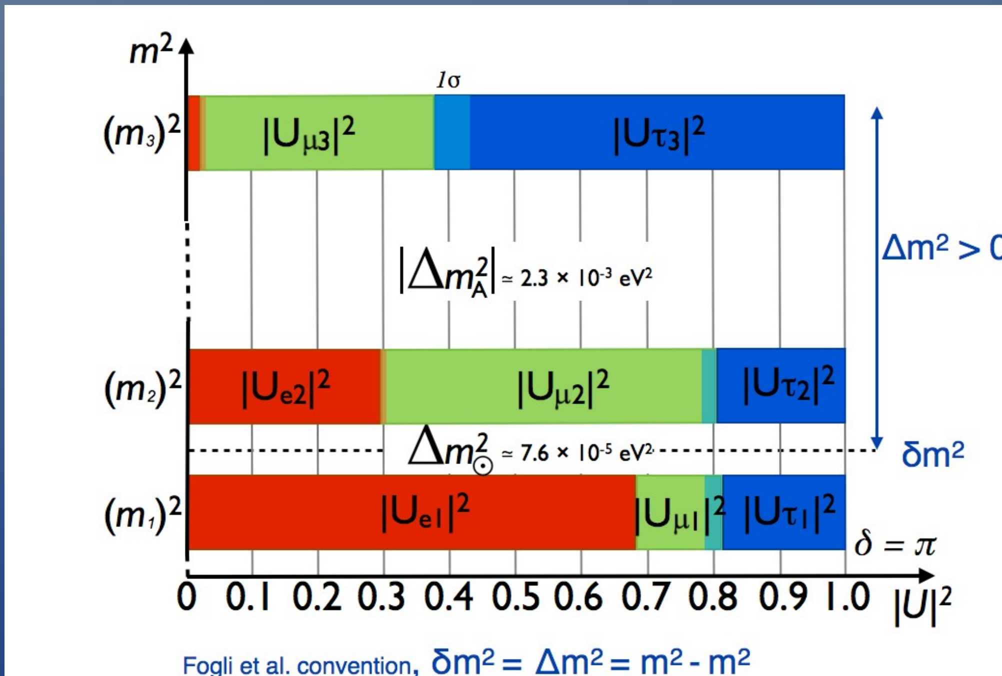
  with transition matrix $U_{\alpha j}$ (PMNS*-Matrix)
- Propagation:
  - $|\nu_j(t)\rangle = e^{-iE_j t} |\nu_j\rangle$
- Resulting transition probability:

  $P_{\alpha\rightarrow\beta}(E,L) = \Sigma_{j=1,2,3} \Sigma_{k=1,2,3} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \exp(i \Delta m_{kj}{}^2 L / 2E)$
- Parametrization of U: 3 mixing angles θ_{ij}, complex phase δ

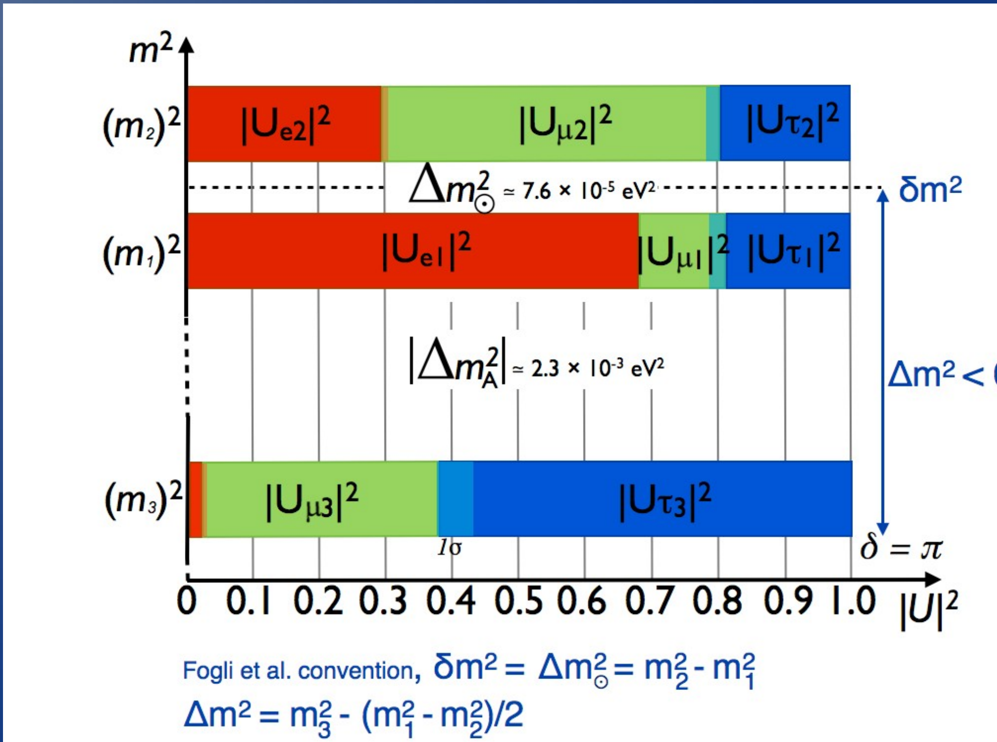
*PMNS-Matrix: Pontecorvo-Maki-Nakagawa-Sakata-Matrix

Status of neutrino oscillation physics

- Known parameters:
  - mixing angles
  - absolute mass differences, mass ordering of ν_1 and ν_2
- Unknown parameters:
  - Complex phase δ
  - Mass ordering: is ν_3 the lightest or the heaviest neutrino?

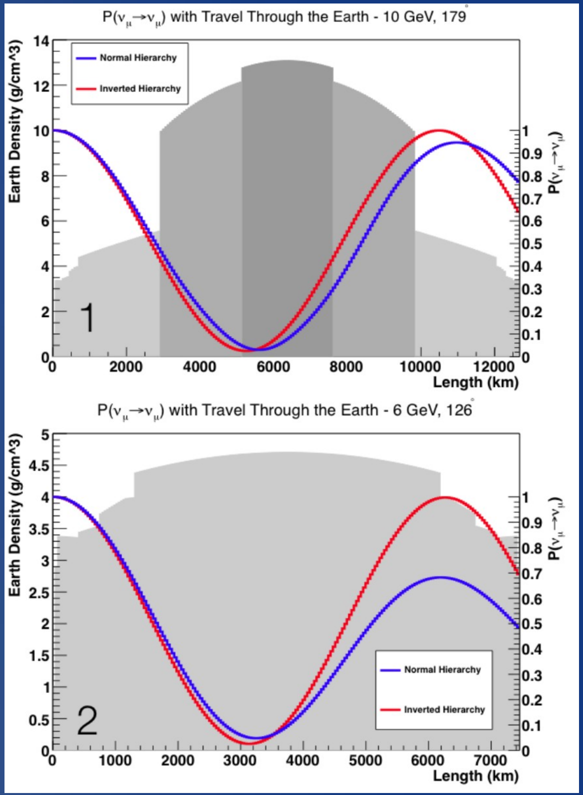


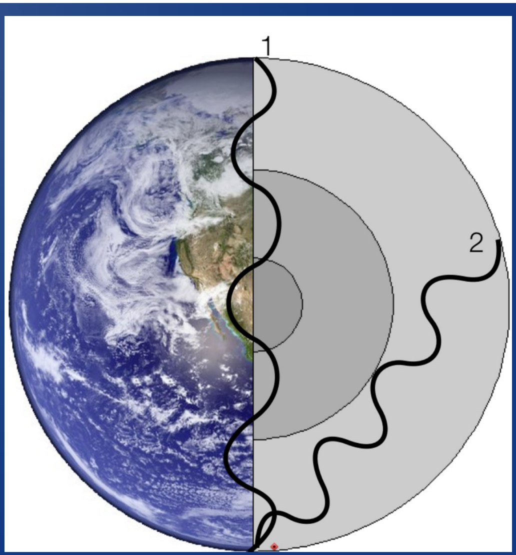
parameters: Fogli et al,
Phys. Rev. D 86, 013012 (2012)



How we want to measure it?

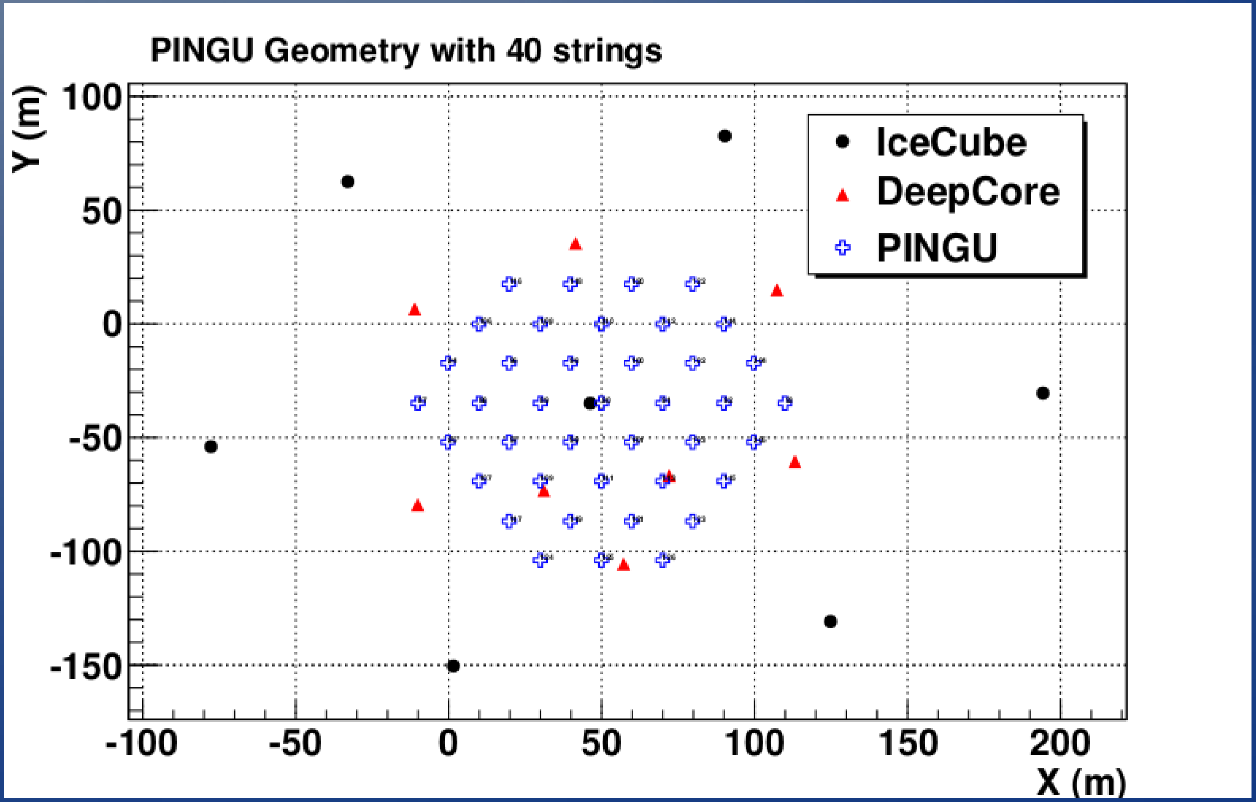
- MSW effect: neutrino oscillations in matter differ from vaccuum
  - strongest effects for E<10 GeV
- MSW effect depends on hierarchy
- Atmospheric neutrinos: CR interaction in the atmosphere, pion, kaon decay
- Need high statistics of events below 10 GeV
  - This is achievable for ice Cherenkov detectors
    - Use denser instrumentation than for IceCube/DeepCore, ANTARES
    - Instrument a larger volume than for Super-K





Potential design of PINGU

- PINGU (Preciscion IceCube Next Generation Upgrade) is designed to measure the **neutrino mass hierarchy** with atm neutrinos by reaching a threshold below 10 GeV



Some more technical info

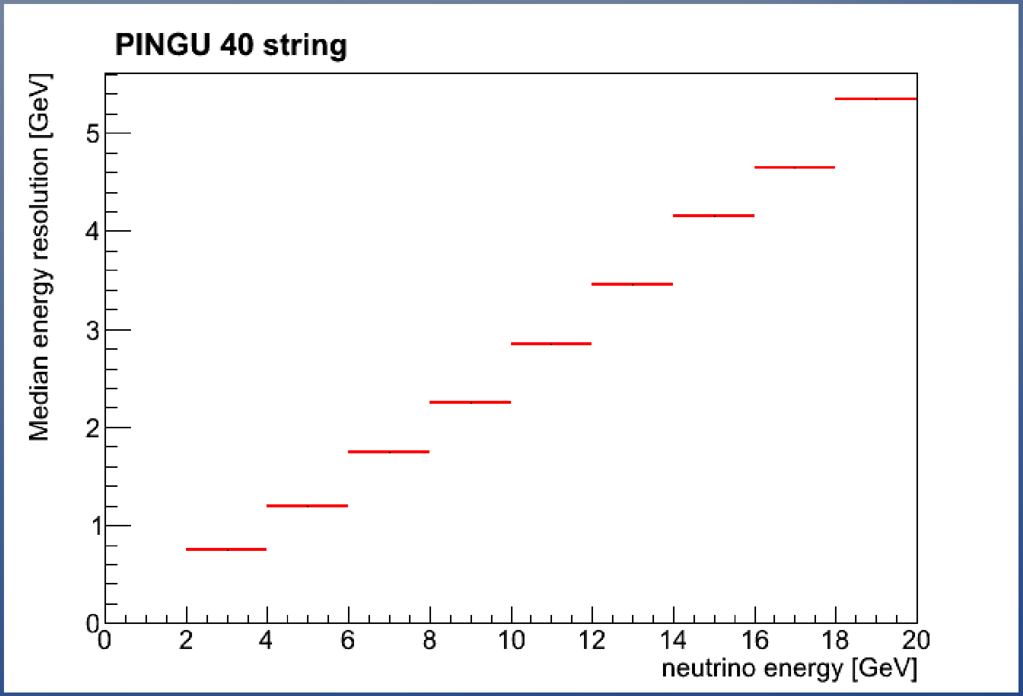
- Wide use of IceCube experience
- Refrozen hole ice has shorter scattering length then bulk ice
  - De-gas water column in the hole before refreezing
- Use more modern in-ice electronics
  - Remove local coincidence condition for data transmission
  - Use only one sampling device
- Deployment of 40 strings realistic in 3 subsequent polar seasons

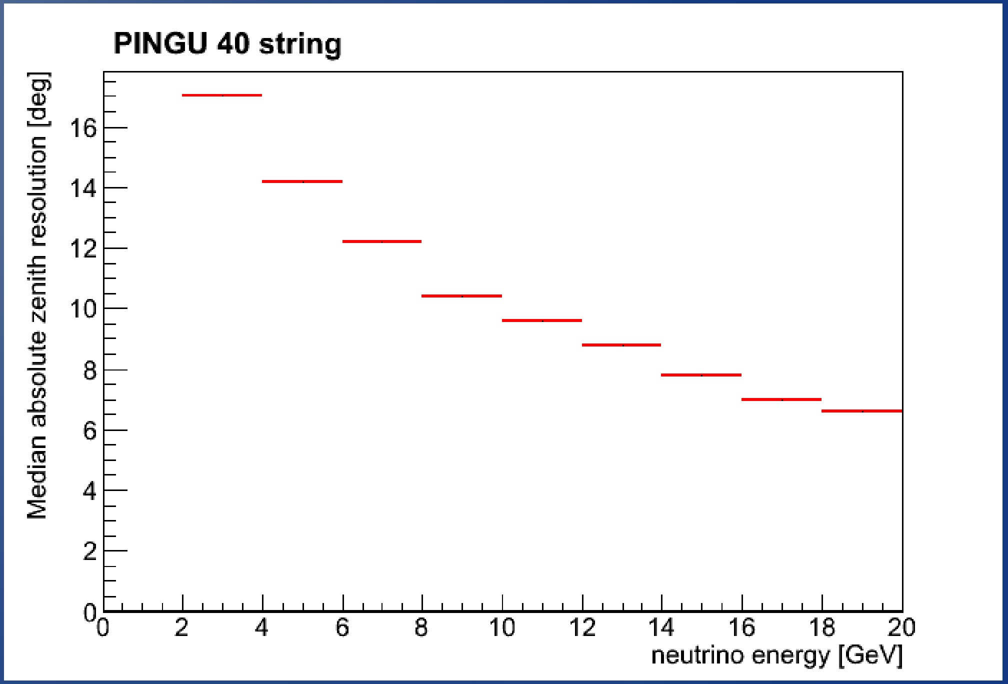
Event reconstruction in PINGU

- „first generation“
  - Use existing IceCube/DeepCore reconstructions
  - Reconstruct cascade and track separately
  - Use pure cascade reconstruction for energy reco (output is well correlated)
  - Use pure muon reconstruction (based on direct hits – Antares-like) for track reconstruction
- „second generation“
  - Developed dedicatedly for PINGU
  - Reconstruct cascade and track together
  - Use Multinest algorithm for minimum search

Performance of the reconstruction - first generation-

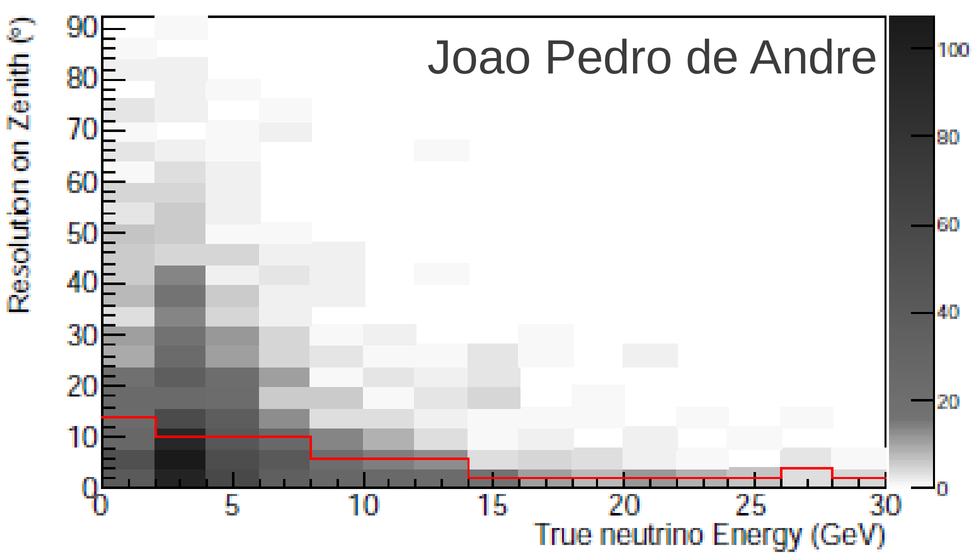
- This is the performance we have shown in ICRC, VLVnT etc



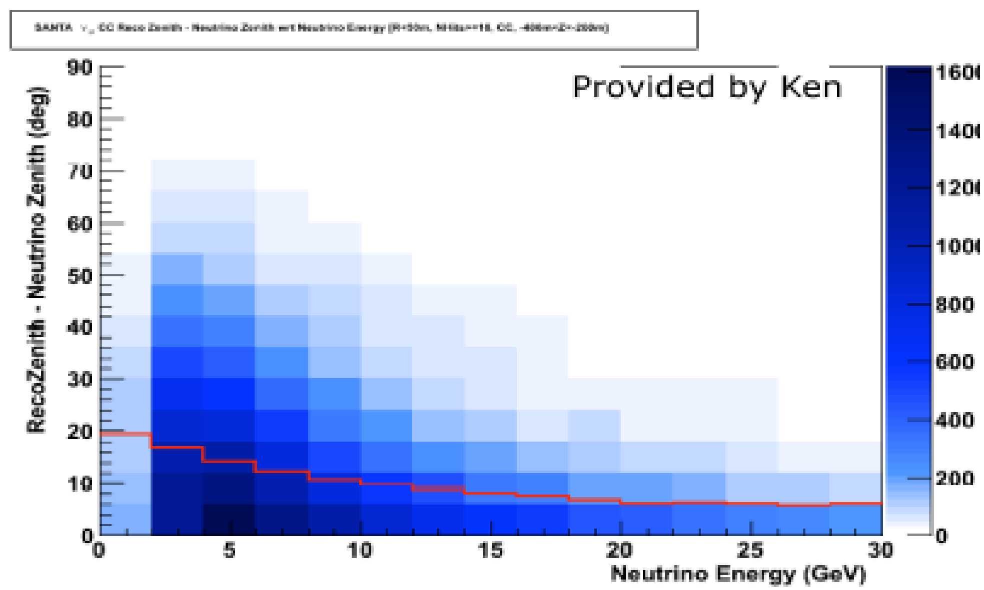


But we can do much better...
- angular reconstruction -

- Performance of the new HybridReco Multinest reconstruction much better



Red line shows median value of the resolution

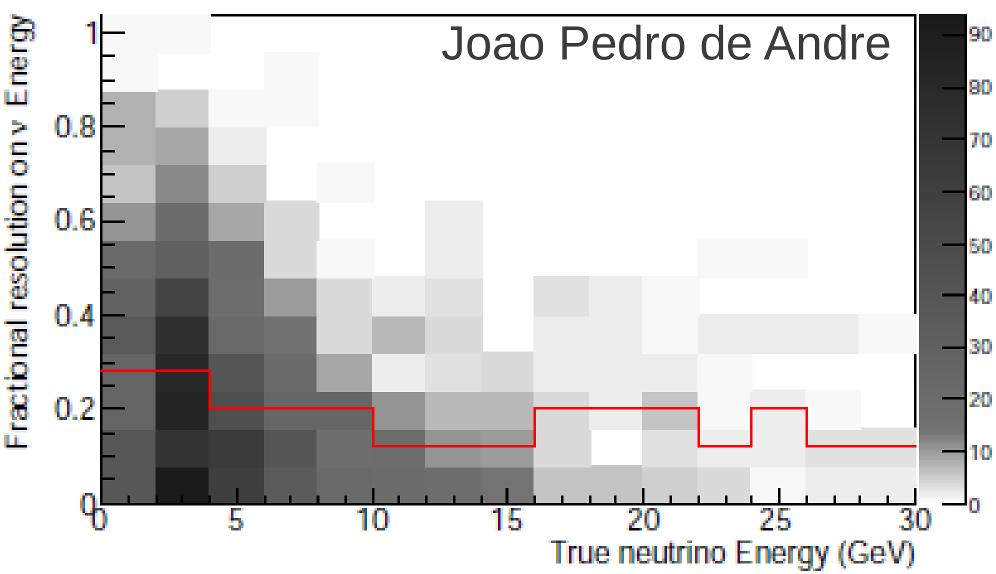


10 deg zenith resolution (median) can be reached above 2 GeV

Multinest: arxiv.org:0809:3437

But we can do much better...
- energy reconstruction -

- Performance of the new HybridReco NultiNest reconstruction much better



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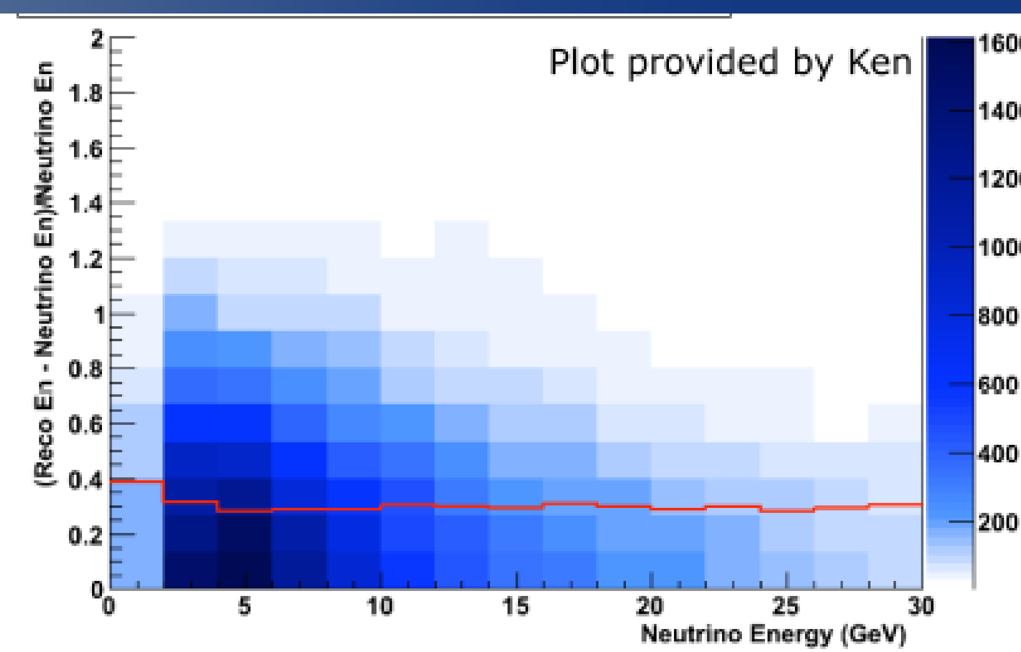
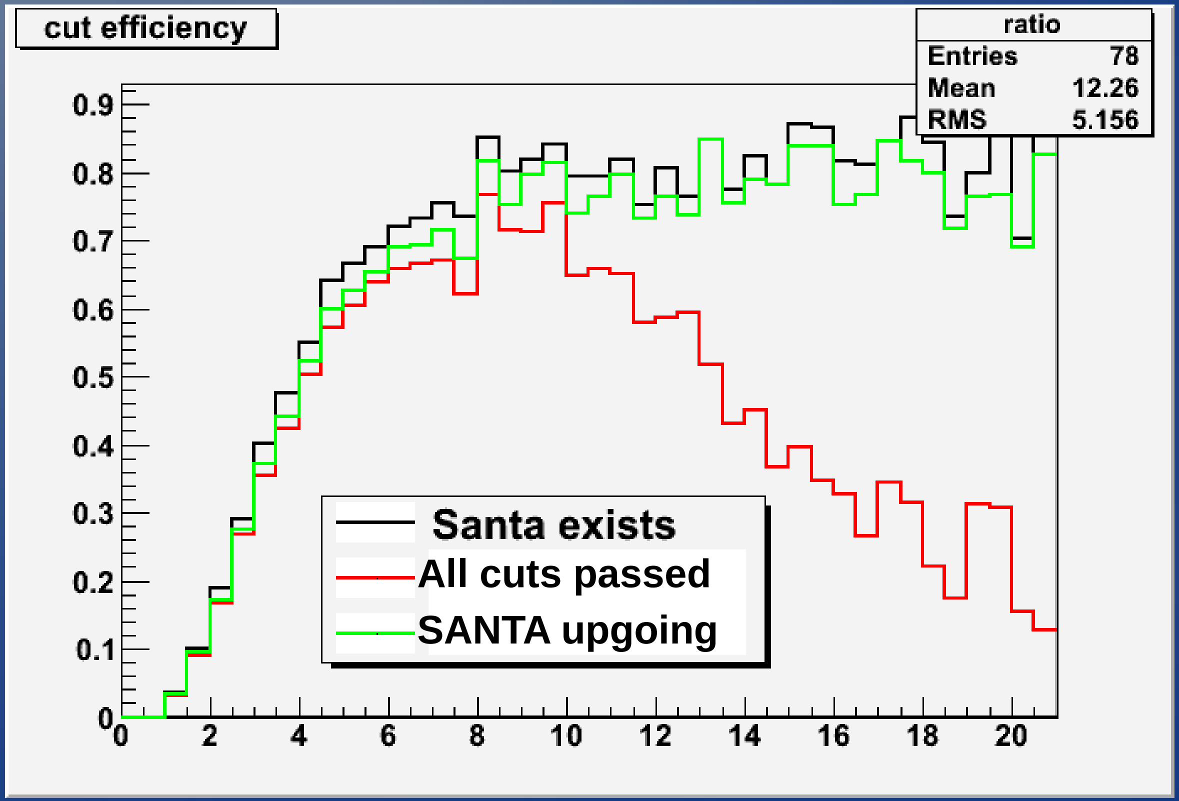


20% energy resolution (median) can be reached above 4-5 GeV

Event selection

- We can reject the background while keeping a large fraction of the signal
- Here: use track direction, vertex containment, energy reco and hit topology for air shower rejection
- Limiting factor: convergence of 1st generation zenith reco



Evaluation of the sensitivity to neutrino mass hierarchy

- We have 3 approaches evaluating PINGU's sensitivity to NMH
  - Fisher Matrix study with parametric resolutions
  - χ^2 study with full MC propagation, Asimov dataset
  - LLH ratio study based on MC pseudo-experiments
- All do include the uncertainty of θ_{23} and Δm^2_{13} as nuisance parameters
- Number of detector systematics included varies for each approach
- We are currently in the process to update these studies for the second generation reconstruction and the new (more efficient) event selection

Strength of different methods

- Fisher: fastest iteration over systematics
- Asimov/χ^2: still relatively fast to include many systematics, but includes tails of resolution as well as correlations
- LLH ratio method: Avoids using Wilk's theorem, but slowest to implement systematics
- Common settings for these:
  - 10 bins in cos(zenith) from -1 to 0
  - 20 bins in logE from 0 (1 GeV) to 2 (100 GeV)
  - Same event selection, systematics

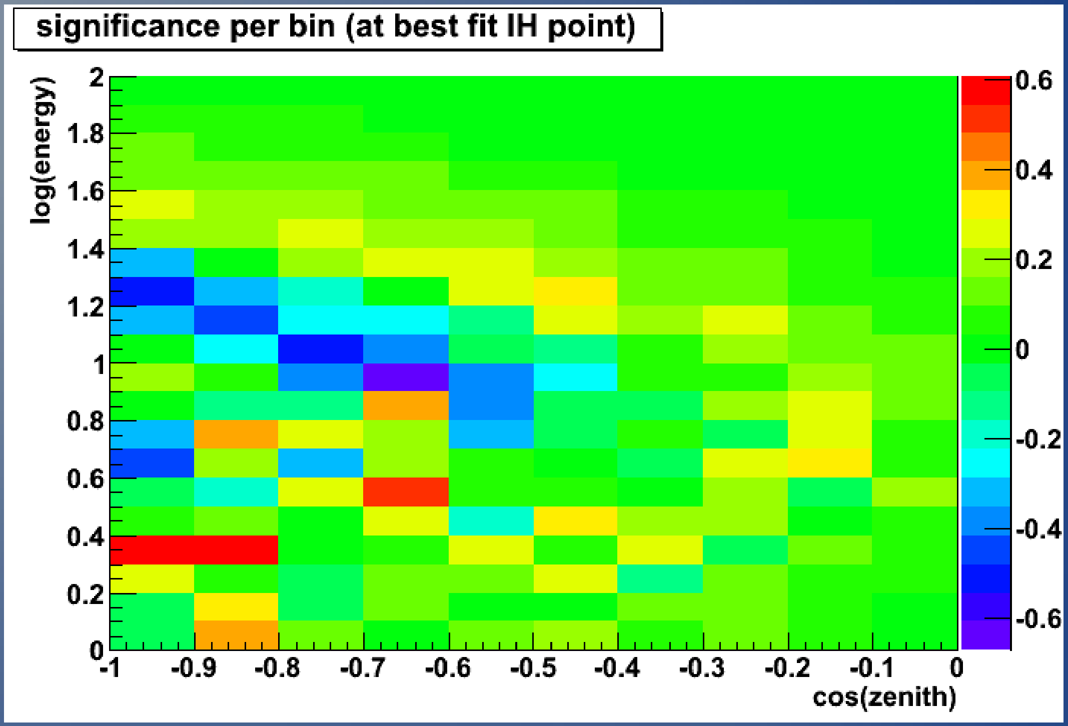
Systematics studied so far

- Uncertainty of the absolute energy scale (design goal for PINGU: 5%)
- Uncertainty of the ice parameters and reconstruction performance: parametrized by a 10% bias of counts in vertical vs horizontal bins
- Uncertainty of the atmospheric neutrino flux normalization (30%)
- Uncertainty of the atmospheric neutrino flux spectrum (+-0.05 in the spectral index)

Status

- Unfortunately, we did not process sufficient MC with these new parameters by now
- We extrapolated a statistical sensitivity of 3.0 sigma/year assuming
  - Updated effective area
  - Gaussian resolution of 12 deg in zenith, 30% in energy
  - Only phyiscs nuisance parameters included
- Experience from previous studies
  - Detector systematics reduce by ~0.1-0.2 sigma/year
  - Cascade backgrounds reduce by ~0.5-0.7 sigma/year (assuming no particle-ID – we can do better)

Status



- Resolutions are slightly better than these assumptions
- We will have some particle ID
- Hence, design goal of >=2 sigma/year appears feasable
- Final sensitivity expected in a short time scale