Neutrino mass hierarchy study with PINGU

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on behalf of
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Outline

- Introduction
  - Neutrino oscillations, MSW effect, neutrino mass hierarchy
- PINGU detector
  - Possible design, expected performance
- Study of PINGU's sensitivity to neutrino mass hierarchy

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:

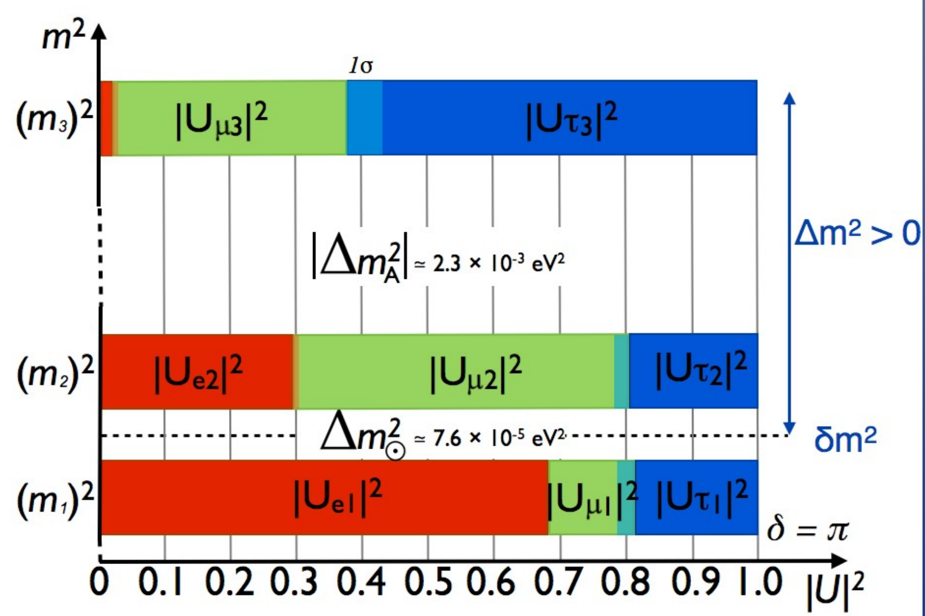
$$P_{\alpha\rightarrow\beta}(E,L) = \Sigma_{j=1,2,3}\ \Sigma_{k=1,2,3}\ U_{\alpha j}\ U^*_{\beta j}\ U^*_{\alpha k}\ U_{\beta k} \exp(\ i\ \Delta m_{kj}^2 L / 2E\ )$$

- Parametrization of U: 3 mixing angles θ_{ij}, complex phase δ

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

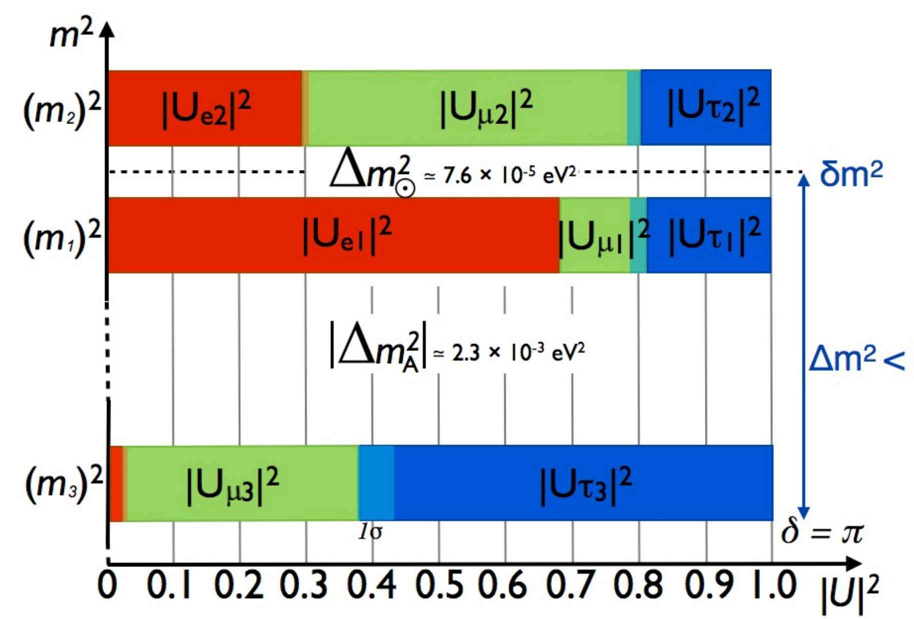
Status of neutrino oscillation physics

- 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?



Fogli et al. convention, $\delta m^2 = \Delta m^2 = m^2 - m^2$

$\Delta m^2 = m_3^2 - (m_1^2 - m_2^2)/2$ parameters: Fogli et al, Phys. Rev. D 86, 013012 (2012)



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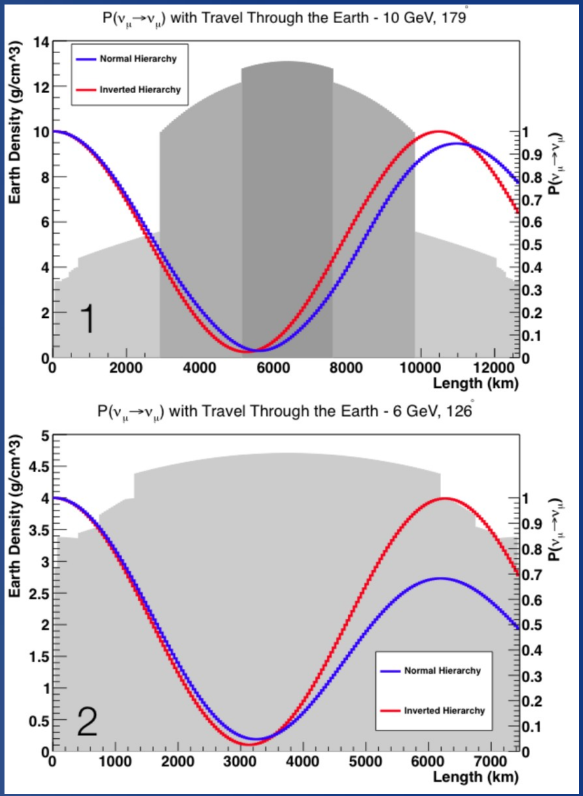
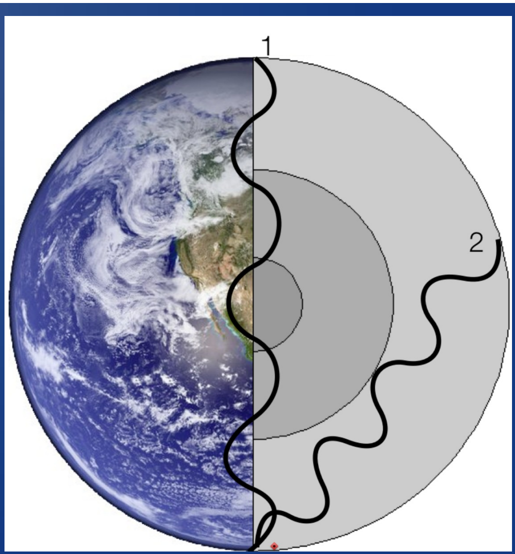
How we want to measure it?

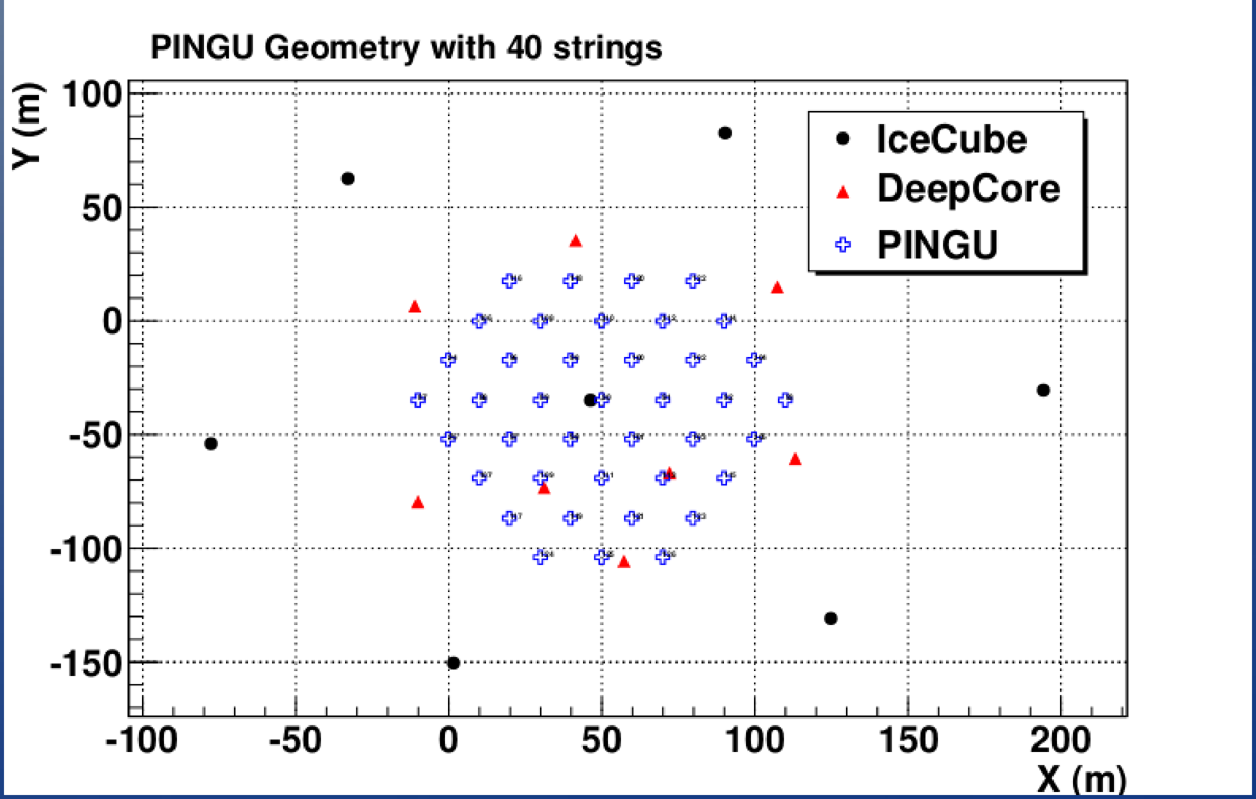
- MSW effect: neutrino oscillations in matter differ from vaccuum
  - strongest effects for E<10 GeV
- MSW effect depends on hierarchy
- Atmospheric neutrinos: CR interaction in the atmosphere, pion, kaon decay
- Need high statistics of events below 10 GeV
  - This is achievable for ice Cherenkov detectors
    - 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

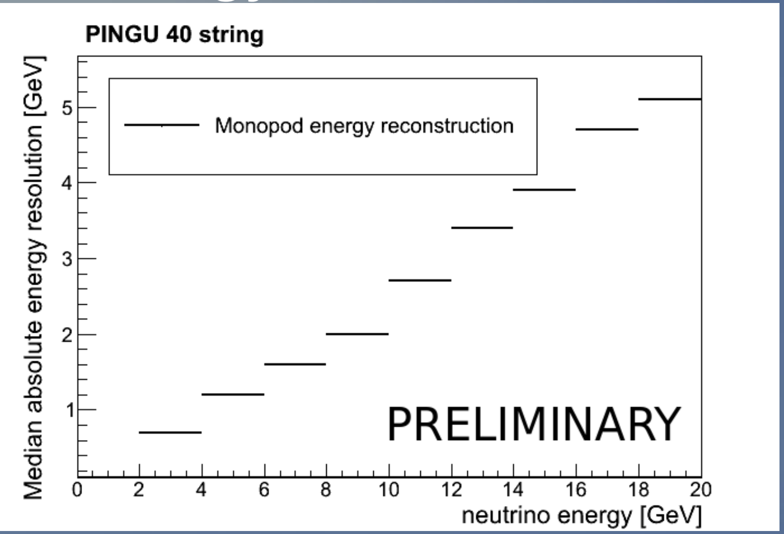


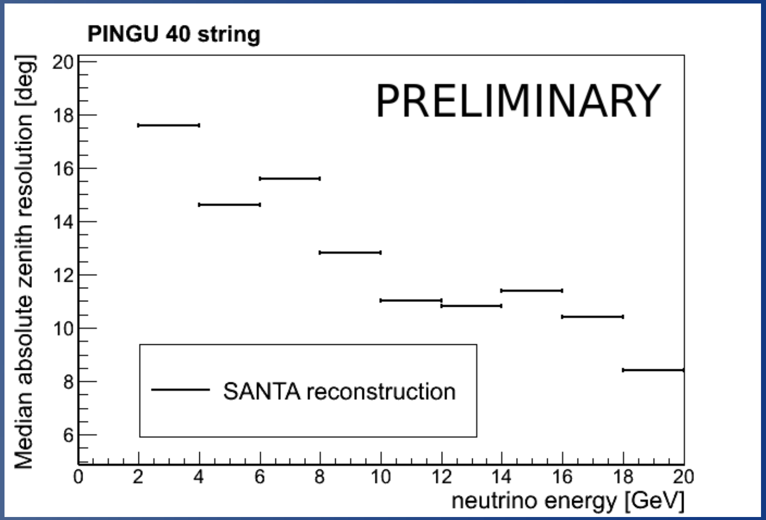
Some more technical info

- 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 recent 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

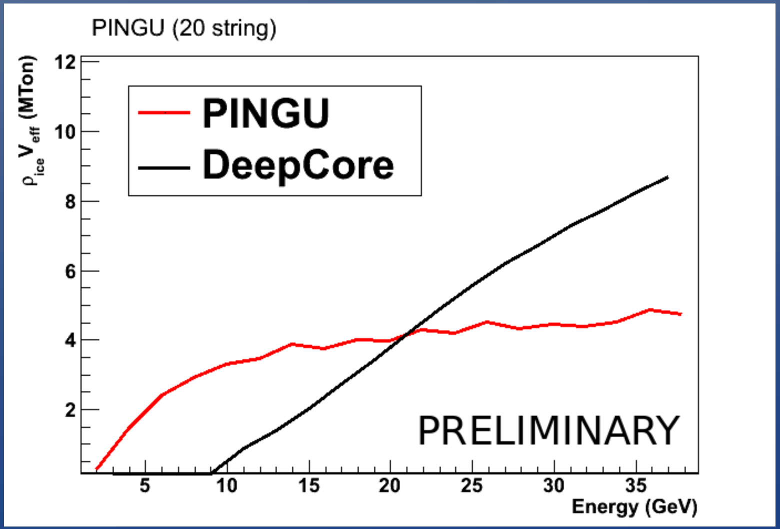
PINGU performance

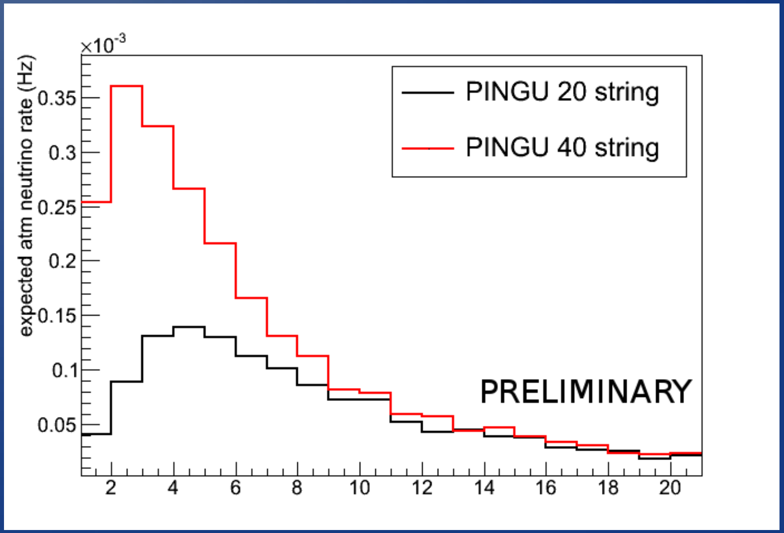
- Energy and direction reconstruction





Event rate/effective volume





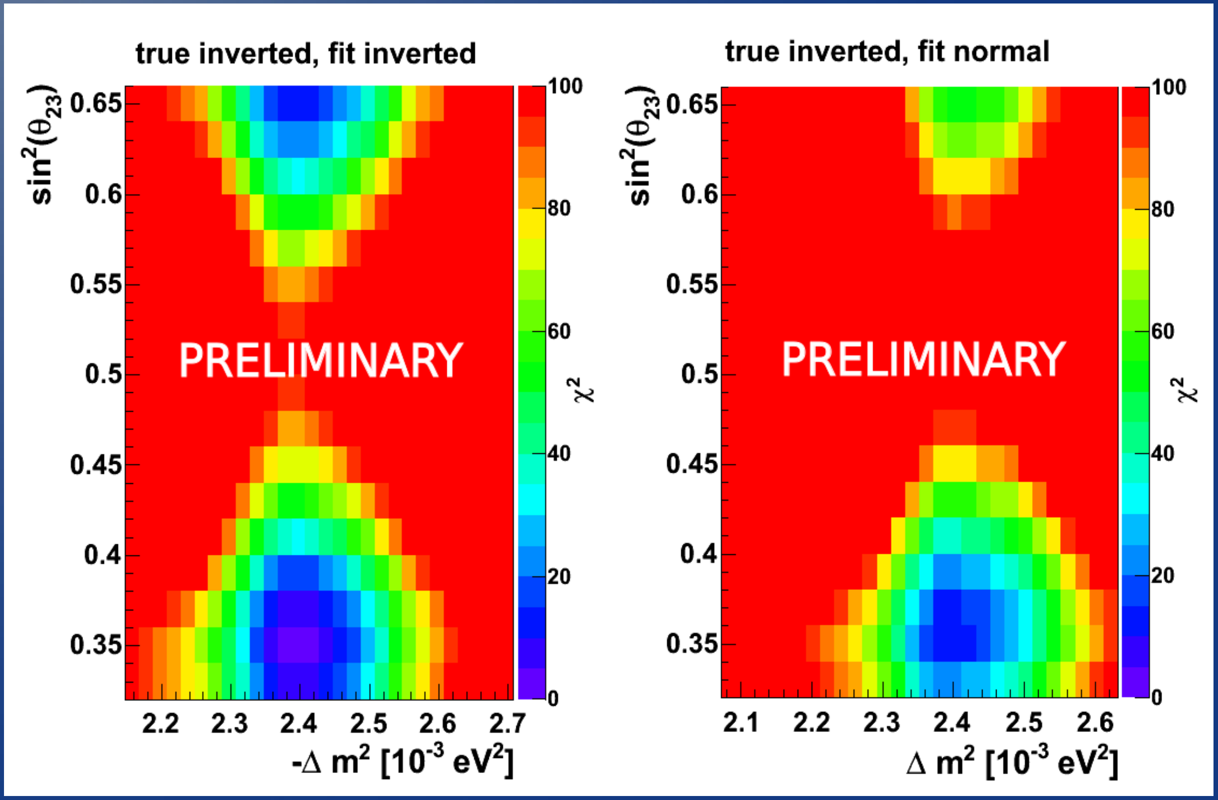
40 strings: enlarged effective volume, in particular for E < 5 GeV

A study to determine PINGU's sensitivity to neutrino mass hierarchy

- Perform an analysis of oscillation parameters
  - Define χ^2 as a function of the oscillation parameters
  - Take into account systematic uncertainties via the pull method
  - Treat Δm^2 as a signed quantity
  - Define $\Delta\chi^2 = \min\ \chi^2(NH) - \min\ \chi^2(IH)$ as test statistics for the neutrino mass hierarchy
  - Apply the analysis to a representative ('Asimov') dataset
  - The significance for this data set is an approximation for the median significance

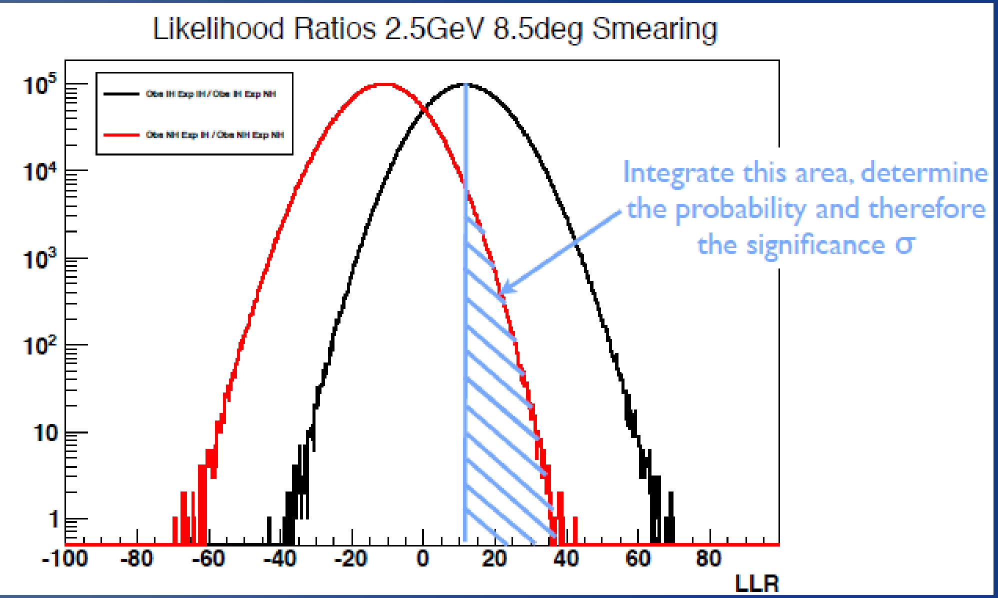
How is it done?

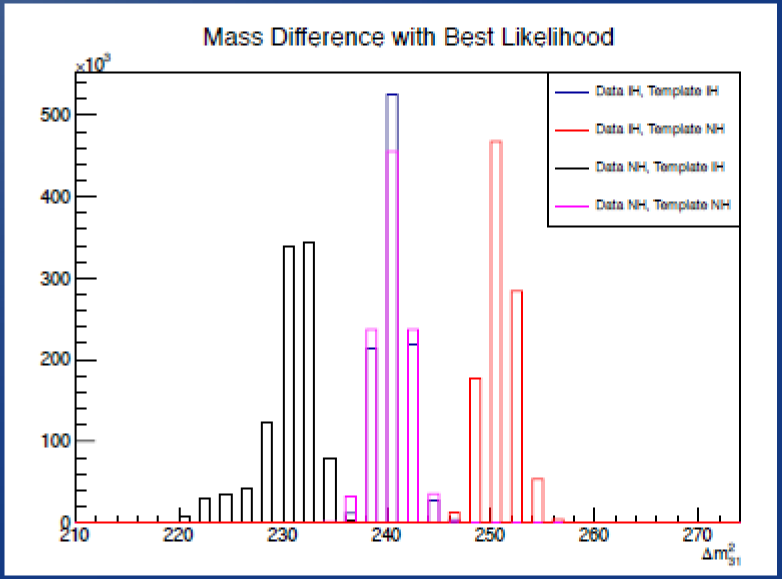
- Assume true oscillation parameters (here: Δm^2=-2.4x10^{-3} eV^2, $\sin^2(\theta_{23})$=0.35, 1 year 40 string PINGU)
- Calculate the expected number of events in each bin (energy, zenith) for these parameters
- 'Asimov' pseudo-data: perform the analysis to these data
- Obtain χ^2 as a function of oscillation parameters
- Find minimum χ^2 for $\Delta m^2>0$ and for $\Delta m^2<0$
- Here: difference between these minima $\Delta\chi^2$=12.1 (~3.4 σ)
- Assumed signal efficiency 50% for rejection of bg



LLH ratio method

- Define patterns (expectation values in energy/zenith bins) for normal and inverted hierarchy
- Define LLH
- Test statistics: LLH ratio normal hierarchy vs inverted hierarchy
- Scan various values for Δm^2
- Asumptions: low signal efficiency is assumed, 20 strings config, resolutions from parametrization



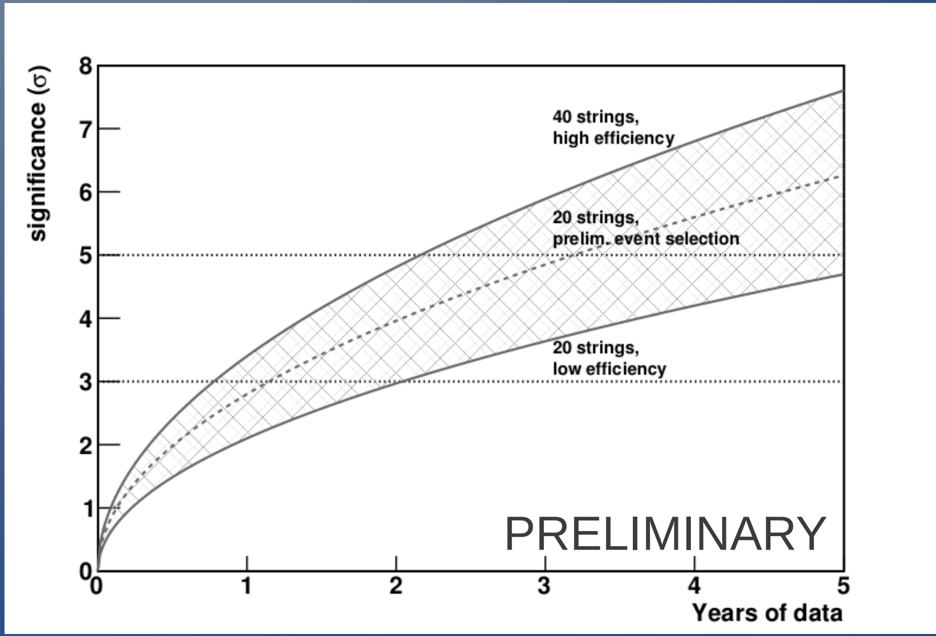


Summary

- 3 studies performed:
  - Asimov study (discussed above)
  - LLH ratio study (discussed above)
  - LLH analysis
    - Based on oscillation analysis (as χ^2 study)
    - Use event selection similar as IceCube
    - Most backgrounds implemented

The sensitivity of PINGU

- Scan of different true oscillation parameters
- Comparison of results obtained by different methods (e.g. similar to D. Franco et al., JHEP 1304 (2013) 008)
- This results in a range of expectations (significance vs time)



- Caveats: small impact of CP violating phase δ and θ_{13} not included here

Backup

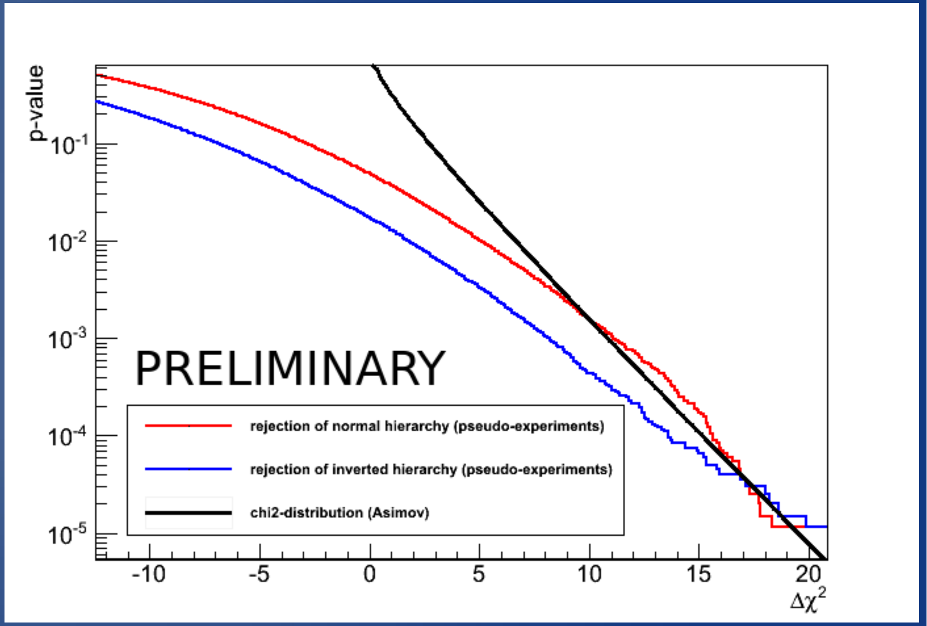
Crosscheck of the test statistics

Question: is the Asimov approximation using sqrt($\Delta\chi^2$) a good approximation?

Check by the following procedure:

- Run pseudo-experiments (Poisson fluctuations) for different true oscillation parameters
- Compare median $\Delta\chi^2$ of pseudo-exp to Asimov dataset
- Define test statistics for the rejection of the wrong hierarchy: What is the fraction of pseudo-experiments in the wrong hierarchy which gives a larger χ^2 difference?
- Choose the most conservative distribution for any oscillation parameters
- Compare this distribution to the χ^2 distribution assumed for the Asimov approach

See also Qian et al. and Evslin et al.



Not shown here: Asimov dataset agrees with median from pseudo-exp within 1-2%

Conclusion: the Asimov approximation is a good approximation