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The ORCA option for KM3NeT

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The plan for the next 20 minutes:

- Introduction
- KM3NeT and ORCA
- Some first performance figures for ORCA
- Towards a measurement of the neutrino mass hierarchy?
- Summary

Sincere thanks to all colleagues who provided advice and material for preparing this presentation

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Introduction

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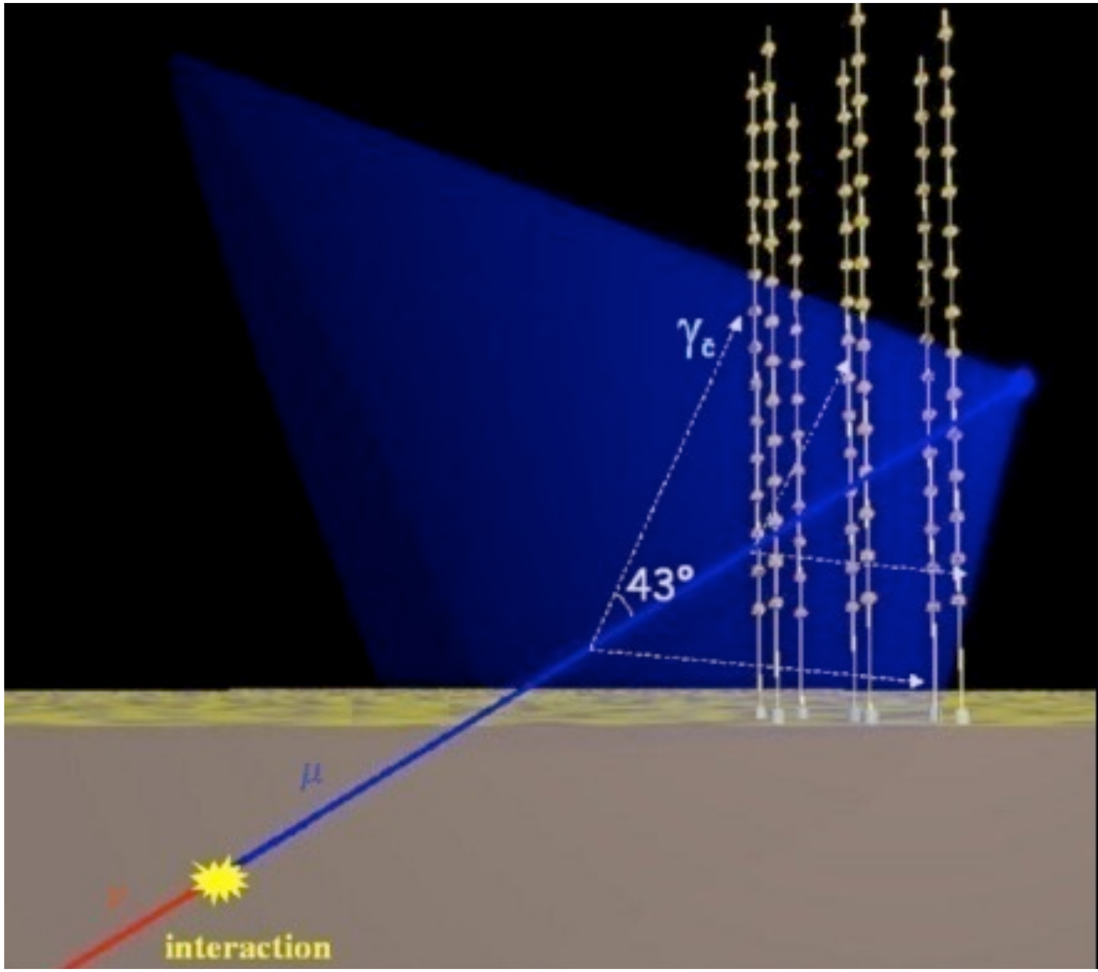
How does a neutrino telescope work?

- Neutrino interacts in the (vicinity of the) telescope
- Charged secondaries cross the detector volume (water or ice) and stimulate Cherenkov emission
- Recorded by a 3D-array of photo-sensors
- Most important channel: $\nu_\mu + N \rightarrow \mu + X$
- Typical energy range : 10(0) GeV – some PeV
- Angular resolution: <1° for E>1 TeV
- Δ[log(E)] ~ 0.3



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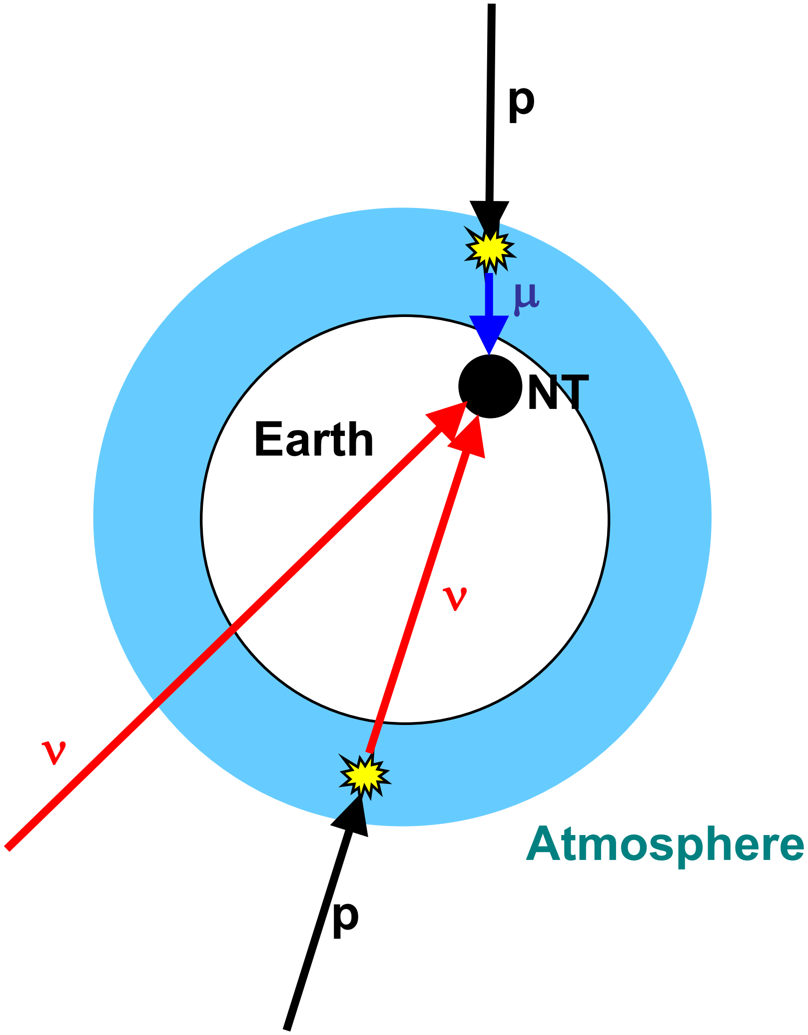
Backgrounds, or maybe not

- Atmospheric neutrinos from cosmic-ray interactions in atmosphere
  - irreducible
  - important calibration source
  - allow for oscillation studies
- Atmospheric muons from cosmic-ray interactions in atmosphere above NT
  - penetrate to NT
  - exceed neutrino event rate by several orders of magnitude
- Sea water: light from K40 decays and bioluminescence



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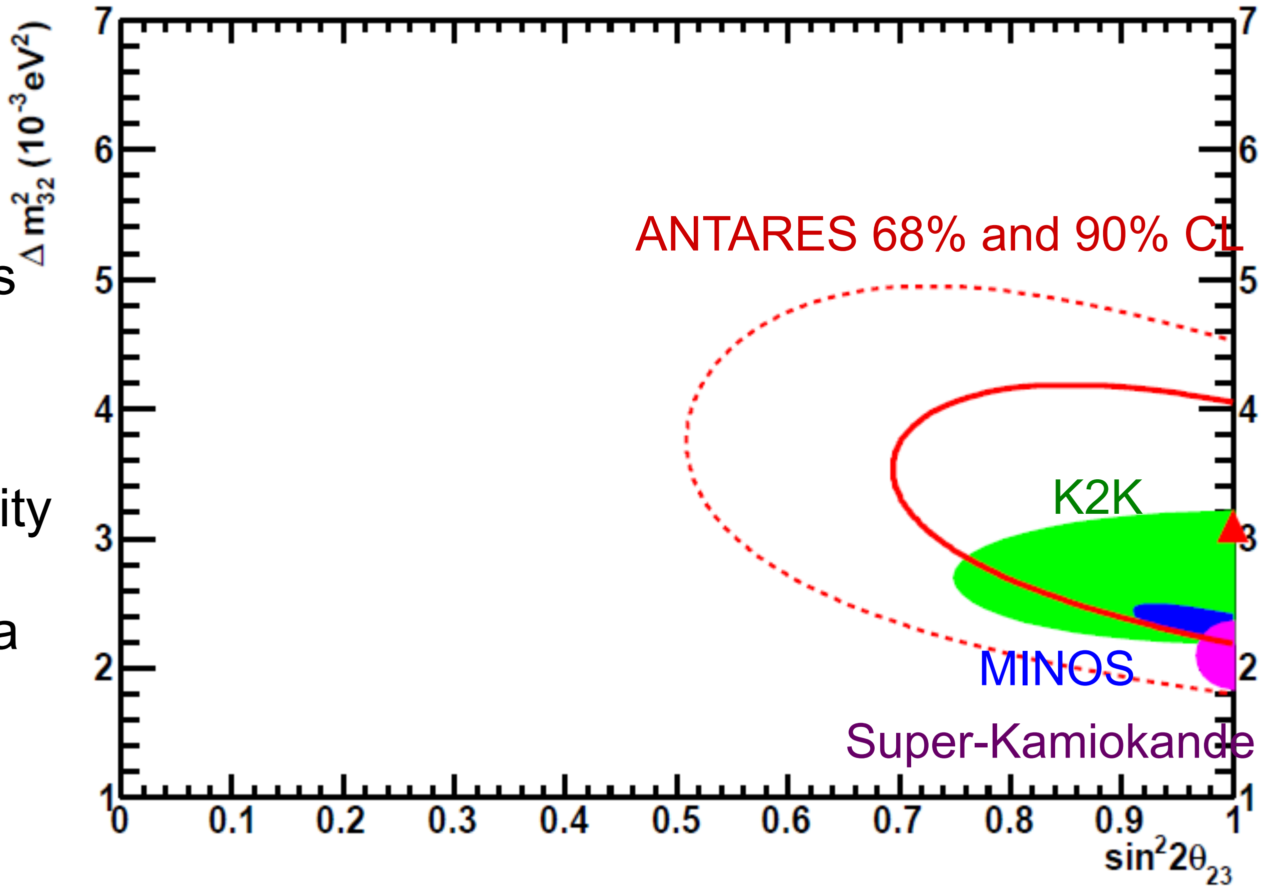
ANTARES: Neutrino oscillations

- Measure distribution of reconstructed
  $E/\cos\theta \propto E/L$
- Expected oscillation signal at lowest values
- Significant signal observed
- Demonstrates capability to reconstruct events down to 20 GeV with a detector optimised for the TeV range
- Results agree nicely with other experiments

Phys.Lett.B714(2012)224



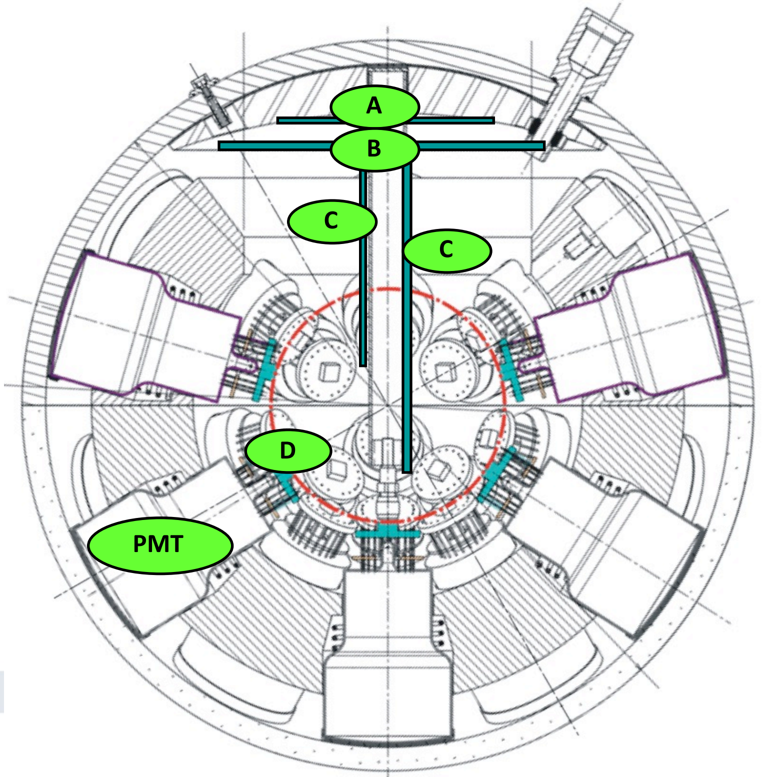
KM3NeT and ORCA

KM3NeT and ORCA in their strategic context

- KM3NeT:
  - Focus on neutrino astronomy (1-100 TeV)
  - Funding for first construction phase available (40 M€), must be spent by early 2015
- ORCA: Oscillation Research with Cosmics in the Abyss
  - Alternative plan for first KM3NeT installation
  - Could be a DeepCore-like part of the full KM3NeT neutrino telescope
  - Would imply a major change of paradigm in KM3NeT
  - Will not be pursued if mass hierarchy measurement is not possible
- ORCA: Currently a feasibility study using “typical” detector configurations – no concrete proposal yet

OM with many small PMTs

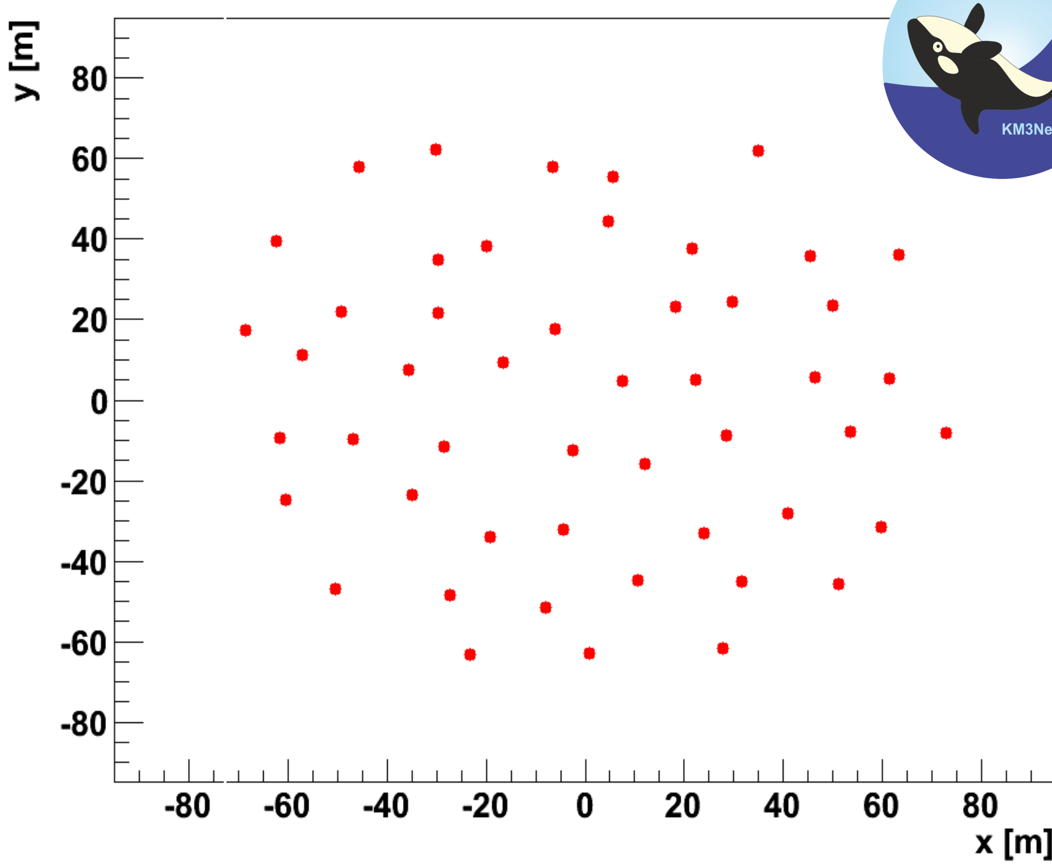
- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10" PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by compressible foam core
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- 2mm optical gel
- Advantages:
  - increased photocathode area
  - 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - directionality



ORCA: A case study for KM3NeT

- Investigated: 50 strings, 20 OMs each
- KM3NeT design: 31 3-inch PMTs / OM
- 20 m horizontal distance
- 6 m vertical distance
- Instrumented volume: 1.75 Mton water

Note; This is just a (scalable) example configuration



ORCA: Hardware and construction issues

- Use agreed KM3NeT technology;
  no major modifications required,
  but cable lengths etc. to be adapted
- String length restricted to avoid entanglement
  due to deep-sea currents
- Deployment requires care and studies
  (operation of deep-sea submersibles (ROVs) between deployed strings is impossible)
- New deployment scheme proposed
  (several strings in one sea operation)
- Very tight time constraints due to funding situation

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ORCA Studies

The major experimental questions

- What are the trigger/event selection efficiencies?
- How and how efficiently can we separ… ferent event classes?
- How can we reconstruct the … d what resolutions can we reach on E_ν and …
- How can we cont… grounds?
- What are t… systematic effects and how can we control them…
- What precision of calibration is needed and how can it be achieved?

Questions under investigation,
no firm conclusions yet

A proposal requires knowing the answers!

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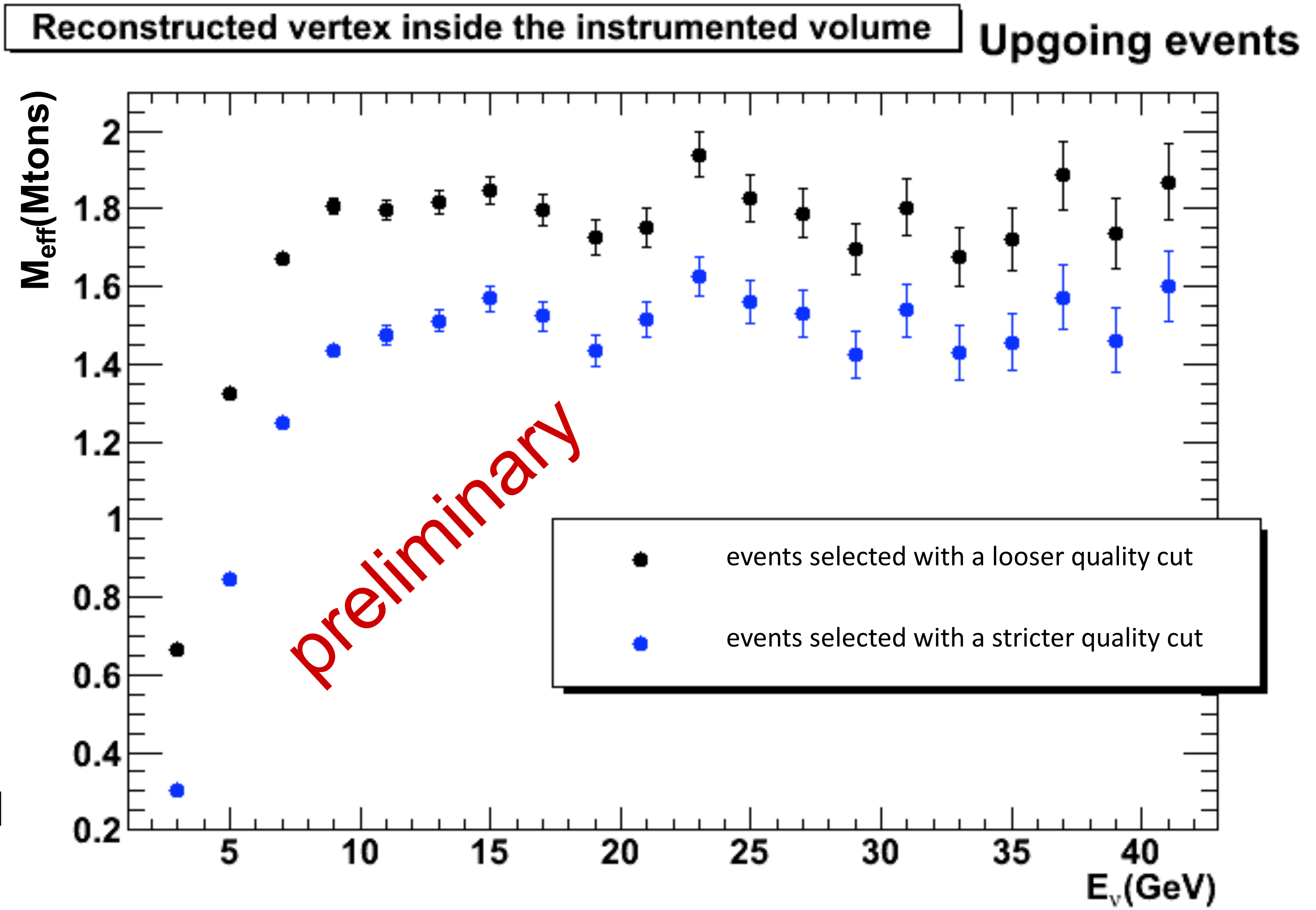
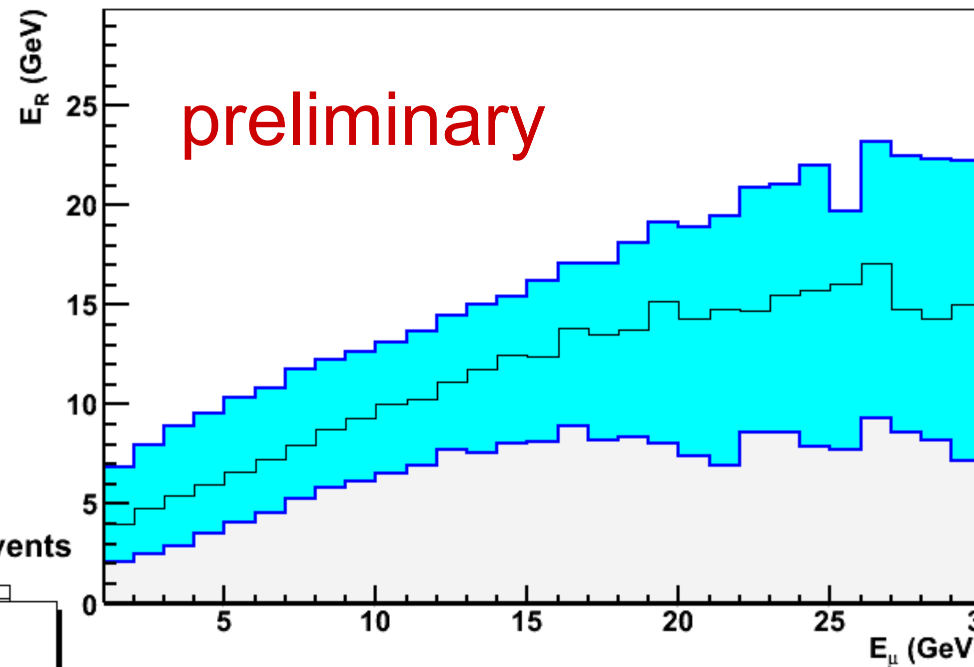
ORCA reconstruction efficiency

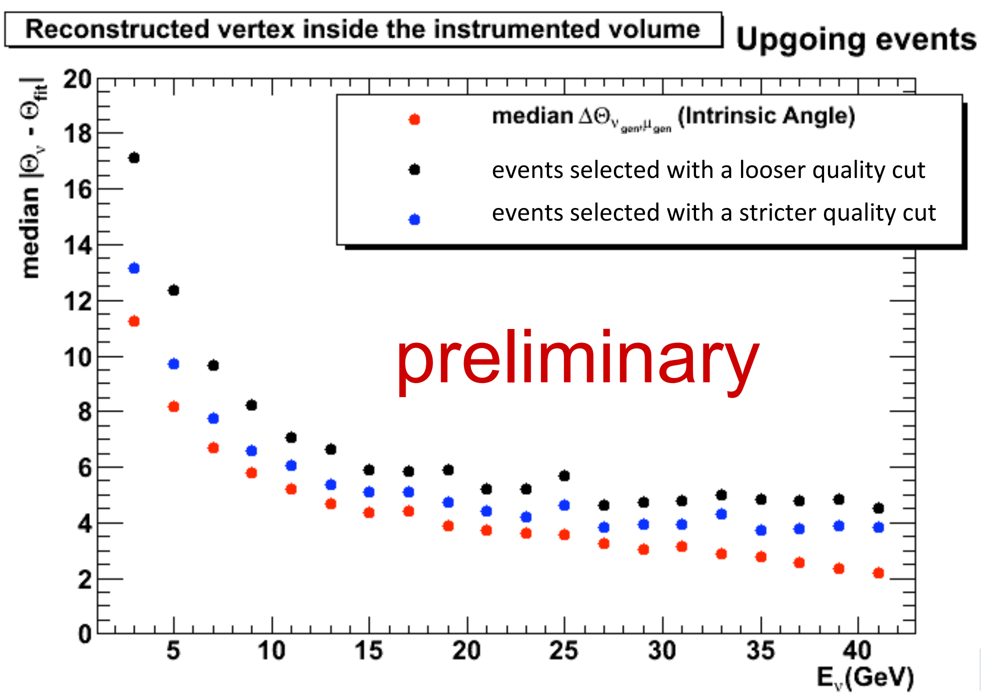
- Isotropic ν_μ CC events generated
- Event must be reconstructed as up-going with vertex in instrumented volume
- Efficiencies determined for two levels of quality cuts
- No background rejection



ORCA energy and zenith resolutions

- E_μ reconstructed from μ track length
- Shaded region: 16% and 84% quantiles as function of E_μ^{true}
- $\Delta E_\nu \overset{?}{\approx} 1\,\text{GeV}|_\mu + 0.2 E_{\text{shower}}$





- Median of zenith angle difference ν – rec. μ

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ORCA and PINGU detector systematics

ORCA (water):

- optical background from K40 and bioluminescence
- missing veto detector
- temporal variations of data taking conditions

PINGU (ice):

- inhomogeneity of ice
- light scattering in ice
- missing segmentation of photocathode

Systematics are complementary –
it may be wise to pursue both experiments

Towards a mass hierarchy measurement

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Mass hierarchy and atmospheric neutrinos

- Determining the sign of Δm^2_{23} requires matter effect. Oscillation of ν_e and/or $\overline{\nu}_e$ must be involved.
- 3-flavour oscillations of $\nu_e \leftrightarrow \nu_\mu$ in matter:

$$P_{e\to\mu} \approx P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2(2\theta_{13}^{\text{eff}})\sin^2\left(\frac{\Delta_{13}^{\text{eff}}L}{2}\right)$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E_\nu} \qquad \sin^2(2\theta_{13}^{\text{eff}}) = \frac{\Delta_{13}^2\sin^2(2\theta_{13})}{\Delta_{13}^{\text{eff}}L}$$

$$\Delta_{13}^{\text{eff}} = \sqrt{[\Delta_{13}\cos(2\theta_{13}) - A]^2 + \Delta_{13}^2\sin^2(2\theta_{13})}$$

$$A = \sqrt{2}G_F N_e \text{ for } \nu \text{ and } A = -\sqrt{2}G_F N_e \text{ for } \overline{\nu}$$

- "Matter resonance" for $A = \Delta_{13}\cos(2\theta_{23})$ (maximal mixing, minimal oscillation frequency). This is the case for $E_\nu \approx 30\,\text{GeV}/\rho[\text{g cm}^{-3}]$

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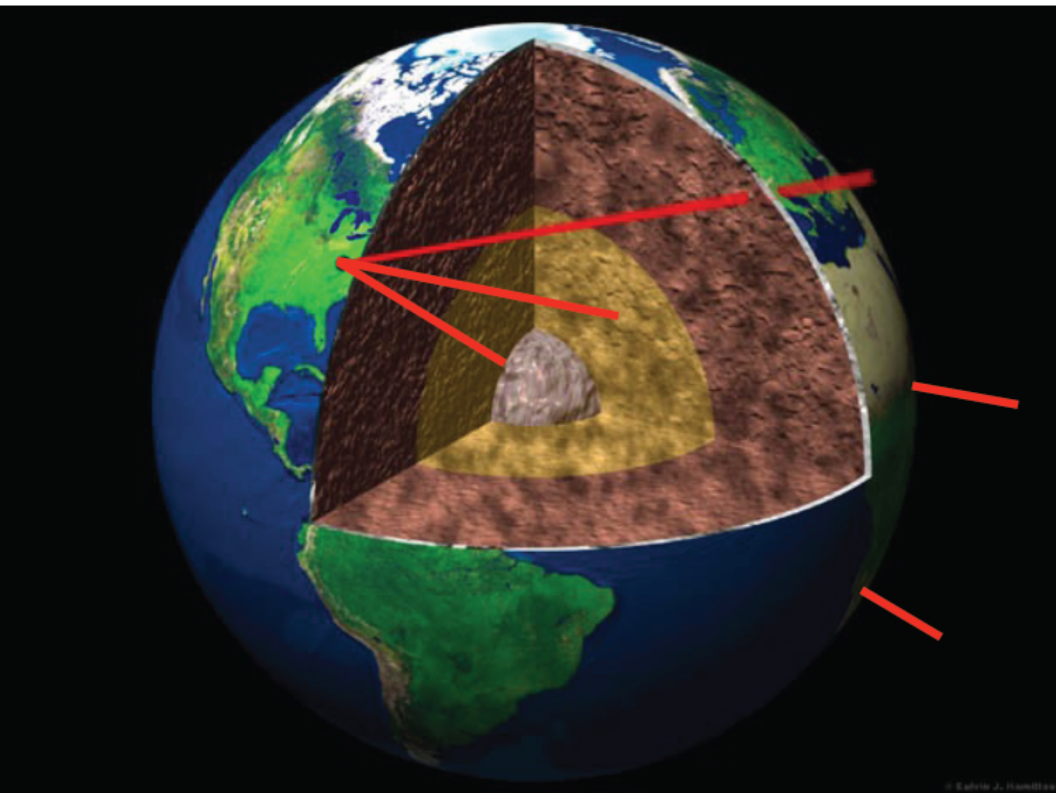
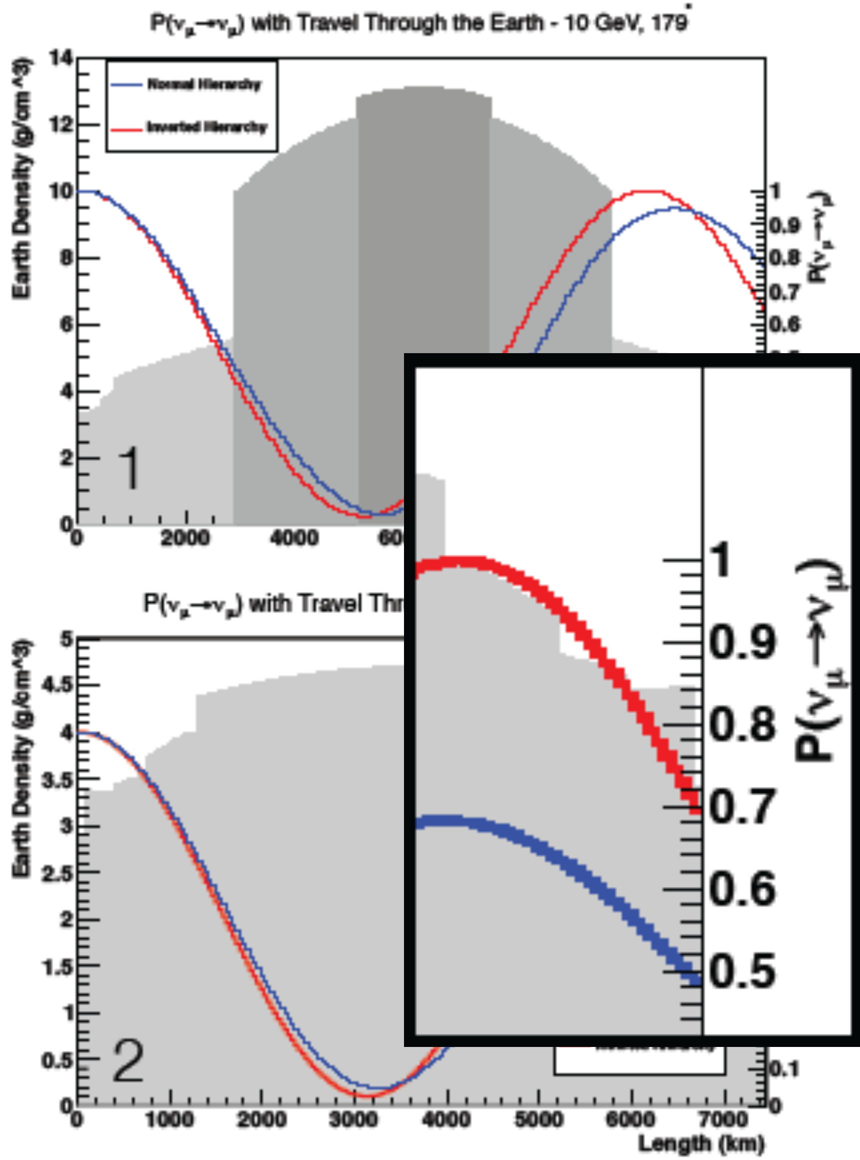
Neutrino oscillations in Earth

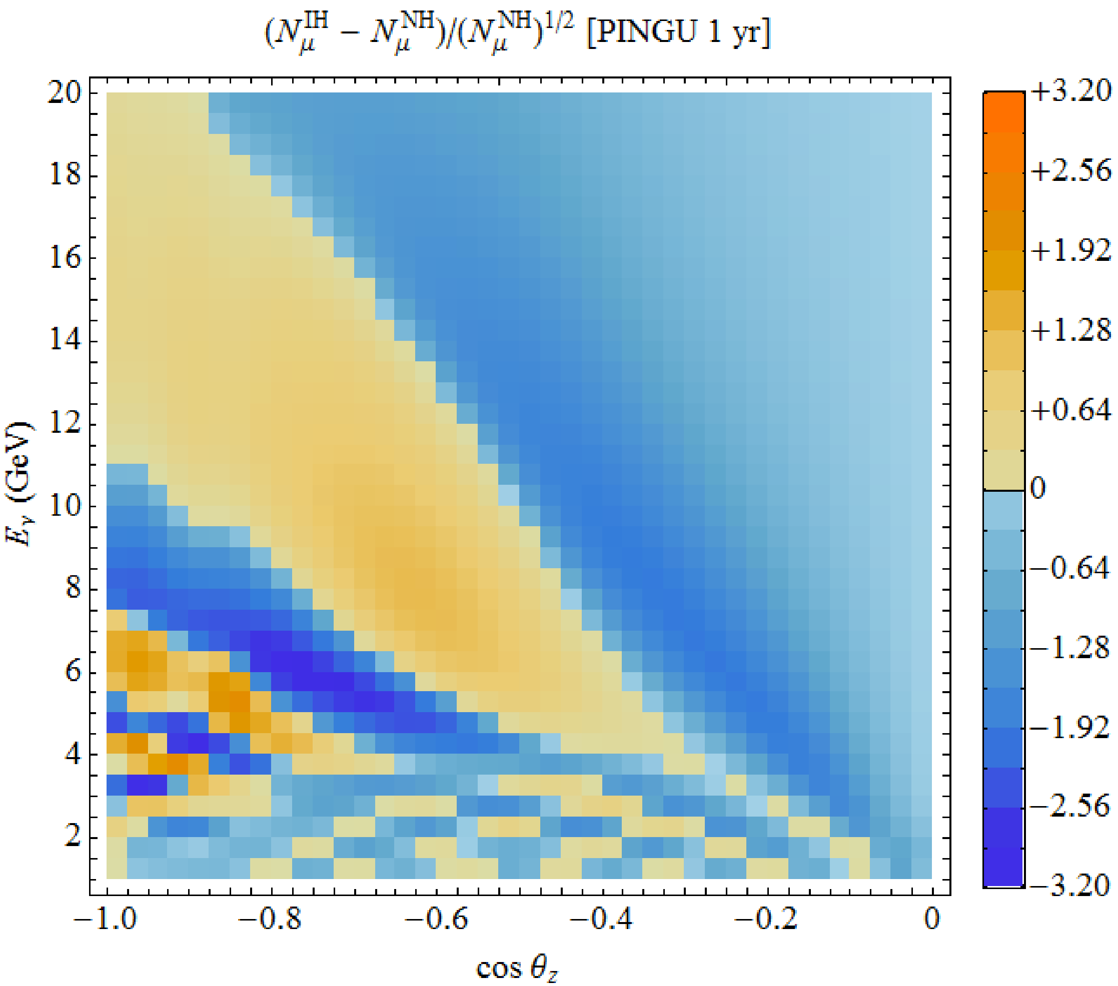
- Earth density 4-13 g/cm^3
- Relevant: $E_\nu \sim 3\text{–}10\,\mathrm{GeV}$





FOR ASTROPARTICLE PHYSICS

The Akhmedov/Razzaque/Smirnov paper (1)



JHEP 1302 (2013) 082; arXiv 1205.7071

- Significance for perfect resolution:

$$S_{\rm tot} = \sqrt{\sum_{\rm bins} \frac{(N_i^{\rm NH} - N_i^{\rm IH})^2}{\sigma_i}}$$

with $\sigma_i = N_i^{\rm NH} + f(N_i^{\rm NH})^2$

- Uncorrelated system. errors assumed (f)
- Result (5 years):

$f = 0.00$: $S_{\rm tot} = 45.5\sigma$

$f = 0.05$: $S_{\rm tot} = 28.9\sigma$

$f = 0.10$: $S_{\rm tot} = 18.8\sigma$

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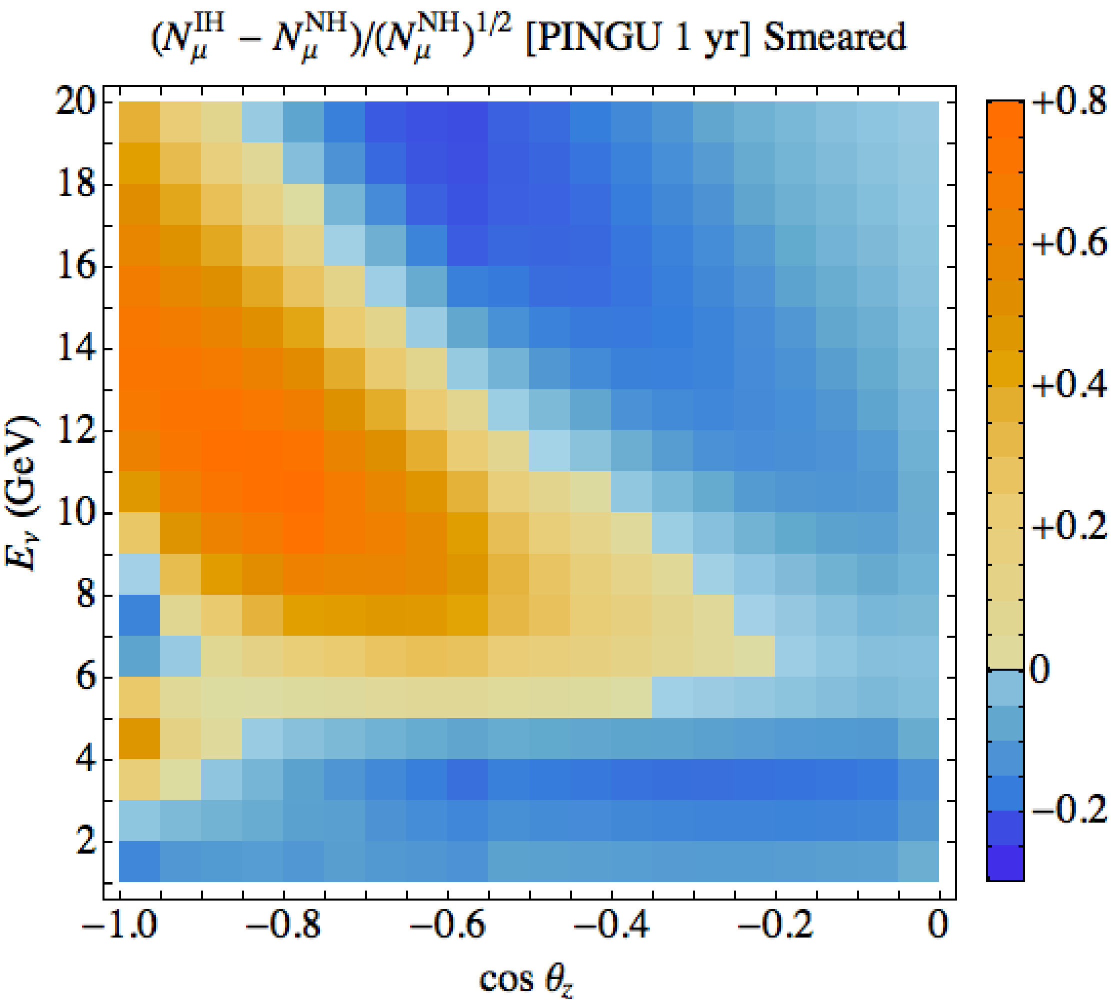
The Akhmedov/Razzaque/Smirnov paper (2)



- Taking into account experimental resolutions

  $\sigma_E = 0.2 E_\nu; \sigma_\theta = \sqrt{m_p/E_\nu}$

  (just an example) deteriorates result

- Remaining significances as low as 3σ

- Not yet included:
  - Non-Gaussian tails
  - Inefficiencies
  - Flavour separation
  - Backgrounds
  - …

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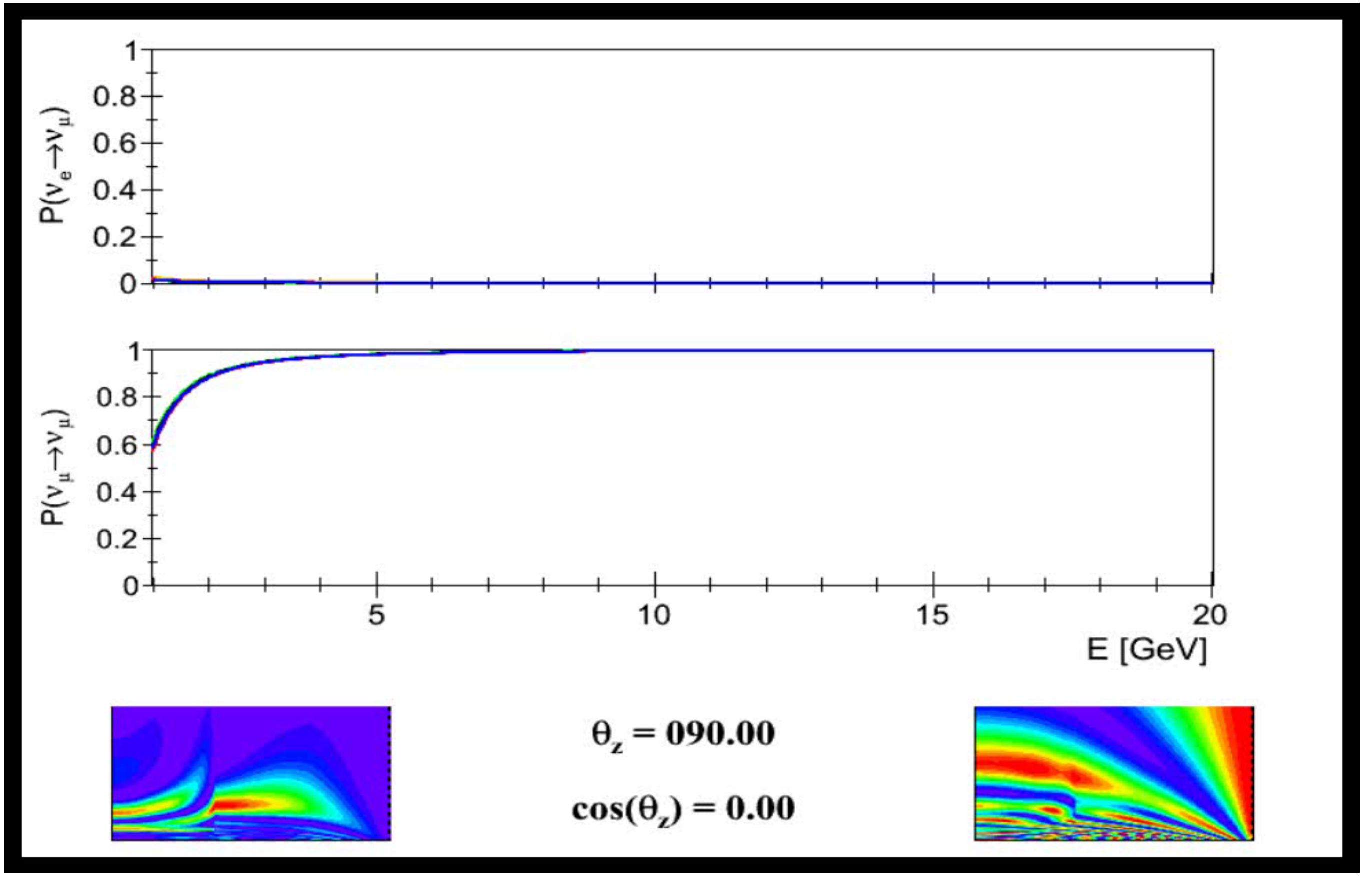
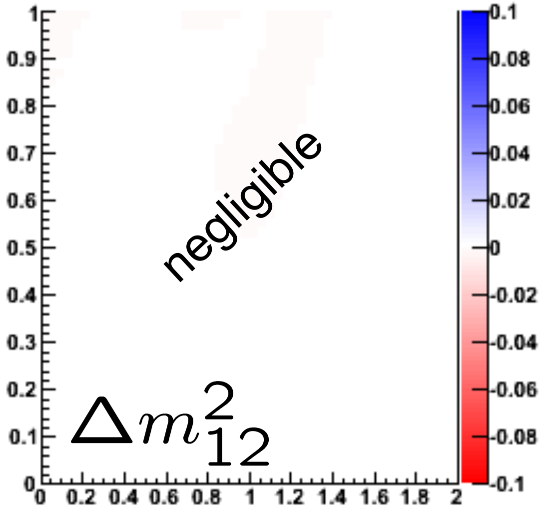
Impact of oscillation uncertainties (1)

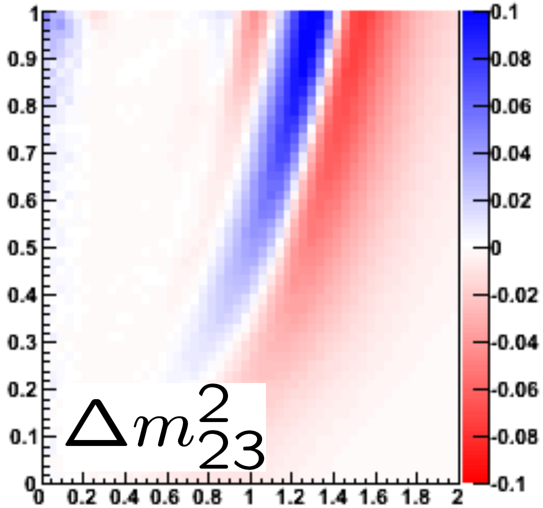
$$P = \theta_{23}$$

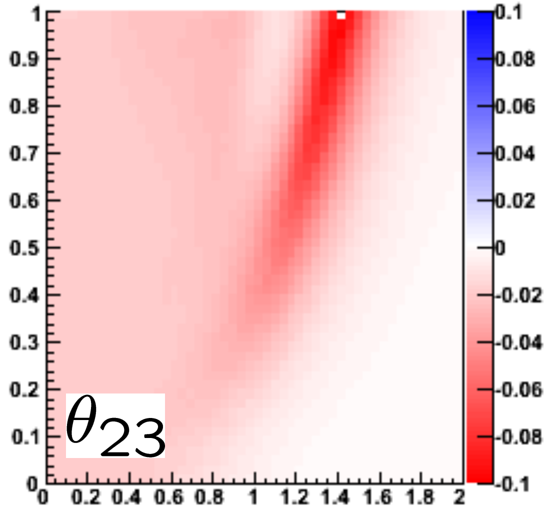
- P(+3σ,NH)
- P(+1σ,NH)
- P(0σ,NH)
- P(-1σ,NH)
- P(-3σ,NH)
- P(+0σ,IH)

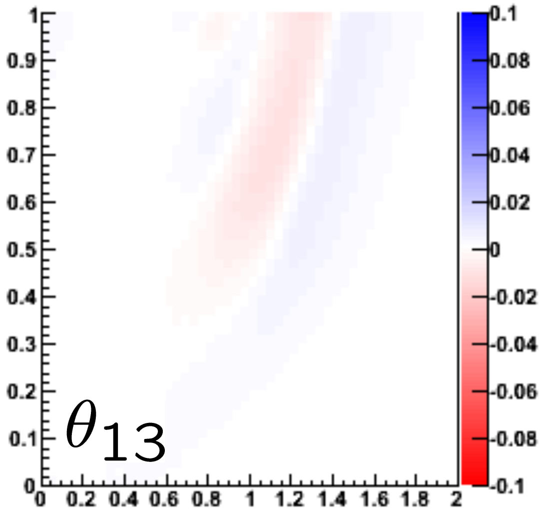


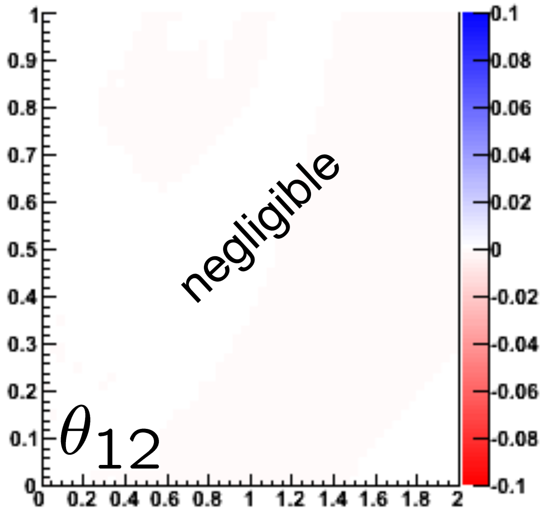
Impact of oscillation uncertainties (2)

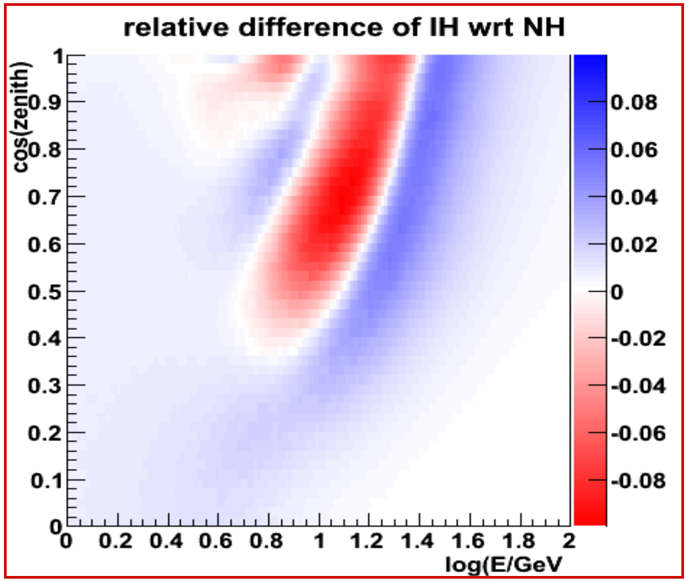












An optimistic toy analysis

- Neutrino inte
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- Assume 20%
- No backgrou
- Assume hiera
  within experi
- Perform log-l
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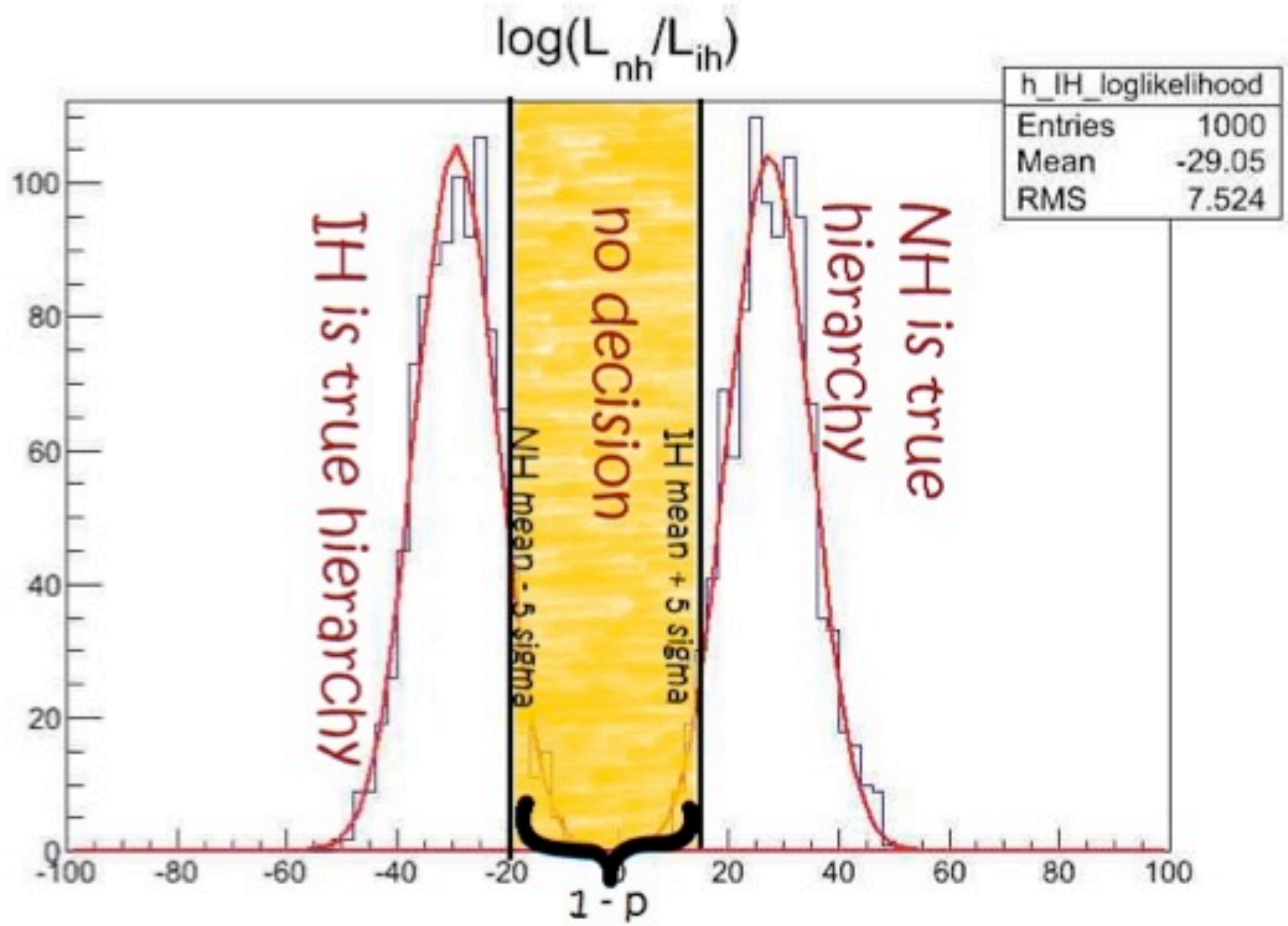
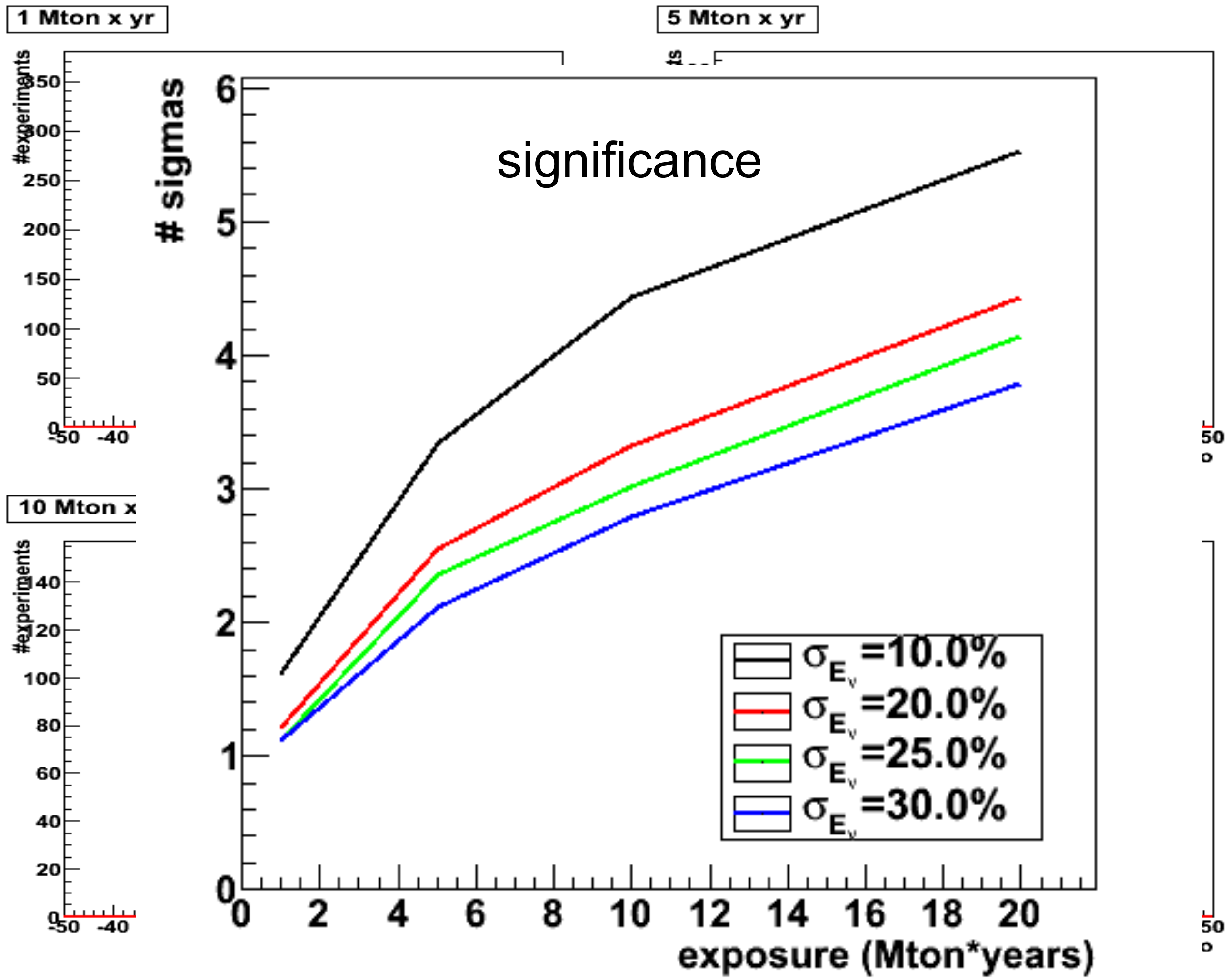
- Investigate lo



Results of toy analysis:

- Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years
- Improved determination of Δm^2_{23} and θ_{23} seems possible



Summary

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- Neutrino telescopes in deep water have demonstrated that low-energy measurements are possible (some 10 GeV).
- Even lower energies could be studied with densely instrumented configurations.
- A determination of the neutrino mass hierarchy with atmospheric neutrinos may be in reach but is experimentally difficult. Energy resolution is a key issue.
- If possible, this approach will be significantly faster and cheaper than alternative approaches.
- We will know more in a year – stay tuned.