Lessons from Neutrinos in the IceCube Deep Core Array

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Neutrino Telescopes

- AMANDA/ICECUBE : Cerenkov light in ice (South Pole)
- ANTARES, NEMO, NESTOR, etc. : Cerenkov light in water (Mediterranean)
- RICE: radio Cerenkov in ice (South Pole)
- ANITA: radio Cerenkov from ice (balloon at South Pole)
- PIERRE AUGER: air showers (Argentina,...)
- ...

What to look for?

- Point sources
- Diffuse fluxes
  - from astrophysical objects
  - from cosmic ray interactions
  - from dark matter annihilation
  - ...
- Correlations with other observations:

  cosmic rays, gamma rays...

Lessons for Particle Astrophysics

Weak interactions

- access to dense, violent envirenoments
- test mechanism powering astrophysical sources
- cosmic ray acceleration processes
- cosmic ray propagation and intergalactic backgrounds
- ...

Lessons for Particle Physics

high energies, beyond those accessible in colliders, etc.
weak interactions

- neutrino interaction cross-sections (in Standard Model!)
- neutrino properties
- new interactions/particles
- dark matter
- ...

How to do it?

- measure all you can!
- take into account everything you know/can think about!
- identify the right observables!

- energy distributions
- angular distributtions
- flavour composition
- better detector techniques
- smart tricks, unique signatures, etc.
- very good simulations
- correlations with other observables: photons, protons, etc.

- can distinguish particle physics from astrophysics effects
- learn about both!

Deep Core Array

- motivation: galactic sources, dark matter annihilation

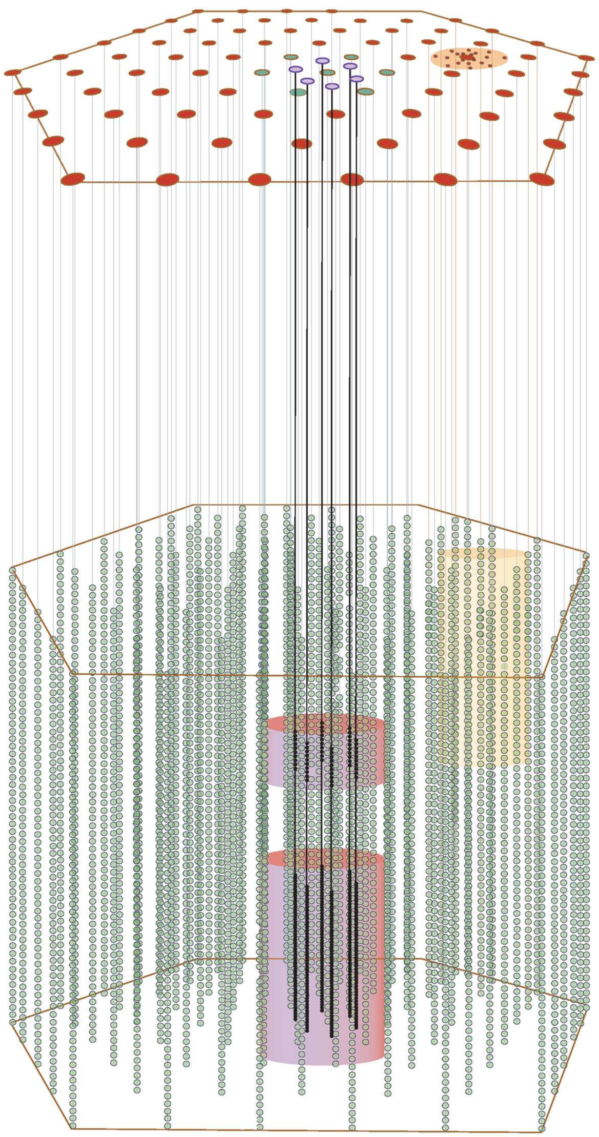
  galactic center above horizon at South Pole

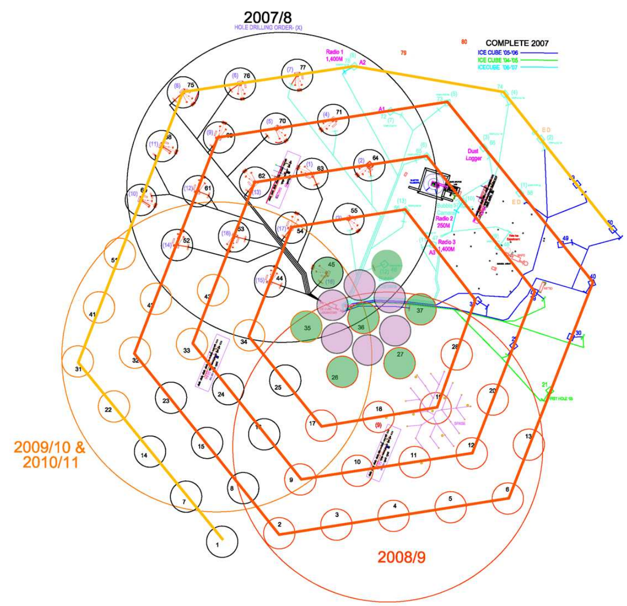
- need to reduce large cosmic muon background

- dense phototube coverage region

- in the deep ceter region of IceCube

Deep Core Array





Doug Cowen, Nu2008

Deep Core Array

- greatly reduce large cosmic muon background

- 4π coverage

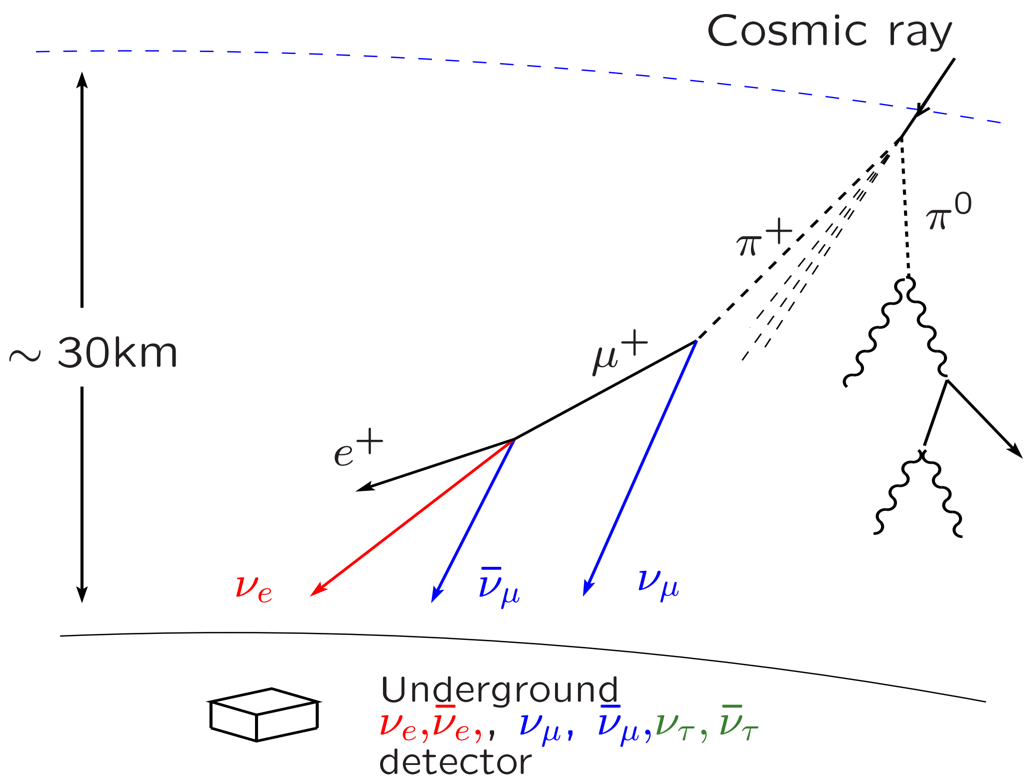
  look at downgoing events, galactic sources, galactic center

- low energy threshold

  open up the neutrino energy range from 10 Gev to 100 Gev

- overlap with Super-Kamiokande at low energy and IceCube at high energy

Atmospheric Neutinos



- background to many searches
- Lots of them!

Atmospheric Neutinos

Super-Kamiokande:

- Expect: $\frac{N(\nu_\mu+\bar{\nu}_\mu)}{N(\nu_e+\bar{\nu}_e)} \sim 2$ at low energy

  $\sim$isotropic

- used zenith angle distributin to prove neutrino oscillations

IceCube Deep Core

- $\frac{N(\nu_\mu+\bar{\nu}_\mu)}{N(\nu_e+\bar{\nu}_e)} \sim 10$

- steep energy spectrum (E_ν^{-3})

- ν_e flux not measured at high energies

Neutrino oscillations:

- massive and mixed neutrinos

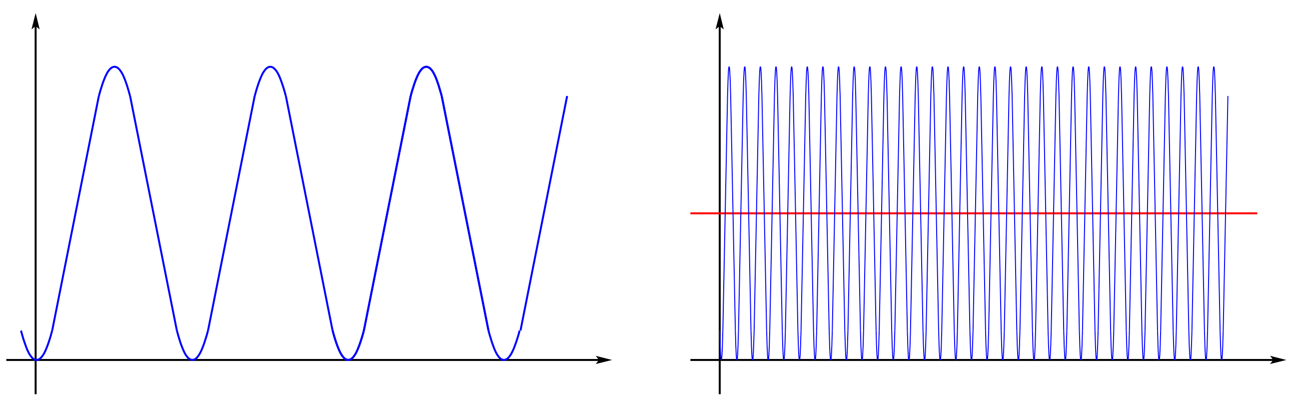
ν_e produced together with the electron in weak interactions does not have to be one of the definite mass particles ν_1 or ν_2

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

$$\Delta m^2_{ji} = m^2_j - m^2_i$$

$$[\Delta m^2] : eV, \quad [L] : km, \quad [E] : GeV$$



Summary of Experimental Results

- Solar Neutrinos: $\nu_e \to \nu_x$, $x = \mu, \tau$

+ reactor antineutrinos

$$\begin{aligned} \Delta m^2_{sol} &\simeq 7.6 \times 10^{-5} \mathrm{eV}^2 \\ \tan^2\theta_{sol} &\simeq 0.45 \end{aligned}$$

- Atmospheric Neutrinos: $\nu_\mu \to \nu_x$, $x = \tau$

+ accelerator neutrinos

$$\begin{aligned} \Delta m^2_{atm} &\simeq 2.5 \times 10^{-3} \mathrm{eV}^2 \\ \sin^2 2\theta_{atm} &\simeq 1 \end{aligned}$$

- Reactor antineutrinos: $\bar{\nu}_e \not\to \bar{\nu}_e$

$$\sin^2 2\theta_{reactor} \lesssim 0.1 \text{ for } \Delta m^2 \sim 10^{-3} eV^2$$

Three flavors neutrino oscillations

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\Delta m^2_{21} = \Delta m^2_{sol}, \quad \Delta m^2_{32} = \Delta m^2_{atm}$$

$$\theta_{12} = \theta_{sol}, \theta_{13} = \theta_{reactor}, \theta_{23} = \theta_{atm}, \delta$$

We want to measure:

- θ_{13}
- hierarchy (sign of Δm^2_{atm})
- CP violation (δ)

large effort to build new accelerator experiments for this purpose

use matter effetcs

Neutrino Oscillations in the IceCube Deep Core

tracks: μ like fully contained events

Angular distribution:

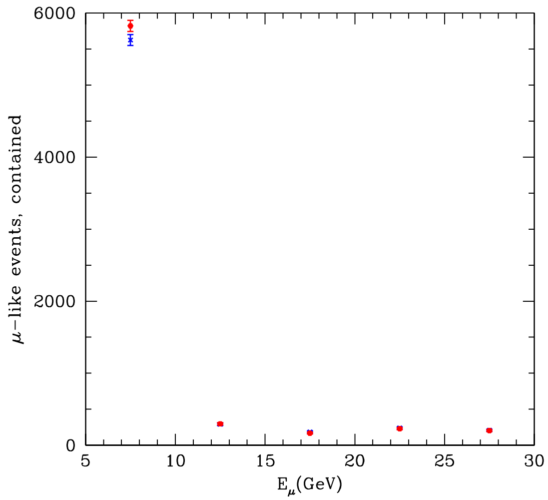
- $\cos\theta \in (0, 1)$ atmosperic flux normalization
- $\cos\theta \in (-0.9, 0)$ + main oscillation signal (Δm^2_{32}, θ_{23})
- $\cos\theta \in (-1, -0.9)$ + matter effects (θ_{13}, hierarchy, CP)

Energy distribution:

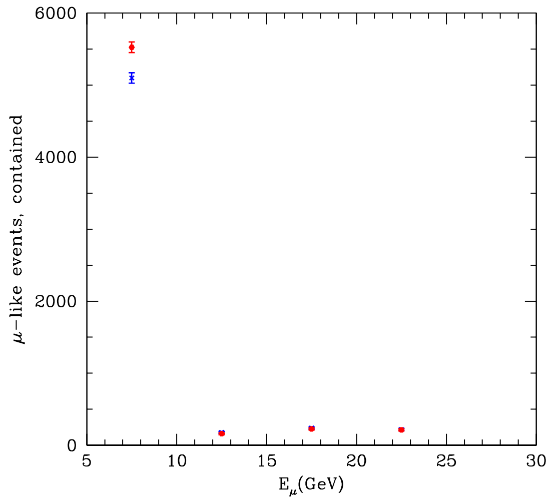
- $E \leq$ 40GeV: neutrino oscillations
- 50 GeV $\leq E \leq$ 5 TeV atmospheric neutrino flux
- $E \geq$ 10 TeV: Earth density profile

Normal versus inverted mass hierarchy

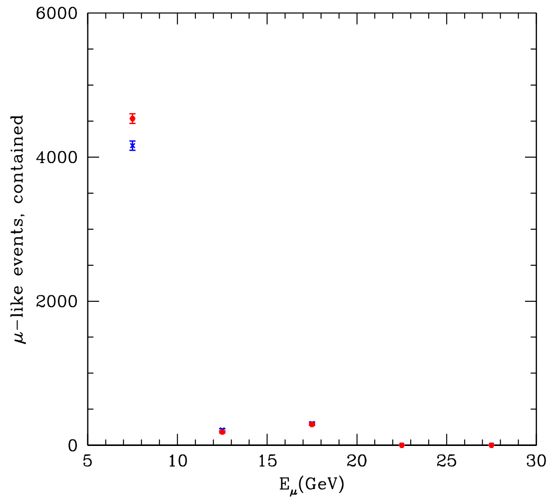
O. Mena, I. M., S. Razzaque, Phys.Rev.D78,093003 (2008)



$\cos_\theta \in (-1, -0.9)$



$\cos_\theta \in (-0.9, -0.8)$

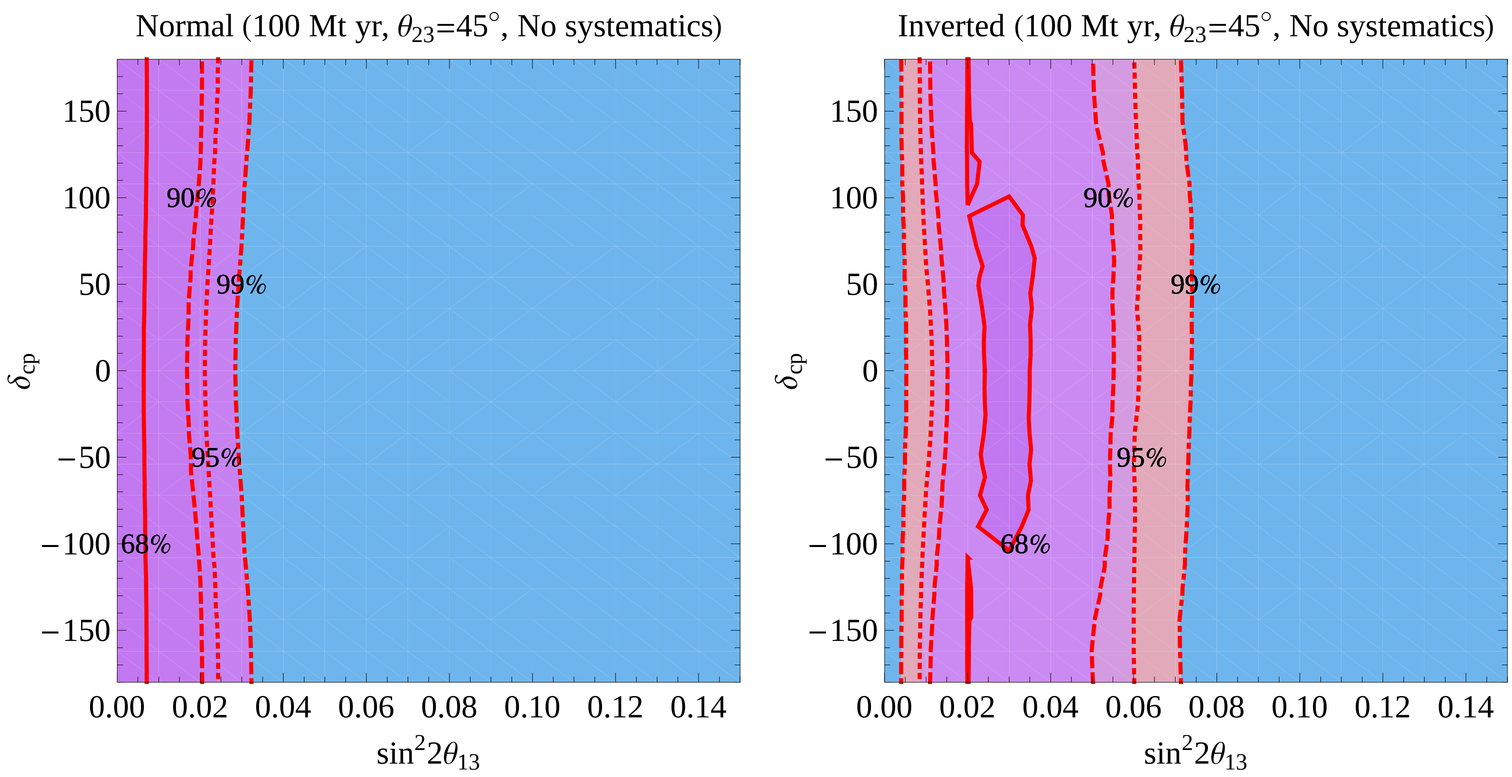


$\cos_\theta \in (-0.8, -0.7)$

Note $E_\mu \simeq 0.5 E_\nu$

Normal versus inverted mass hierarchy

- χ^2 fit to discriminate between normal and inverted hierarchy



Normal versus inverted mass hierarchy

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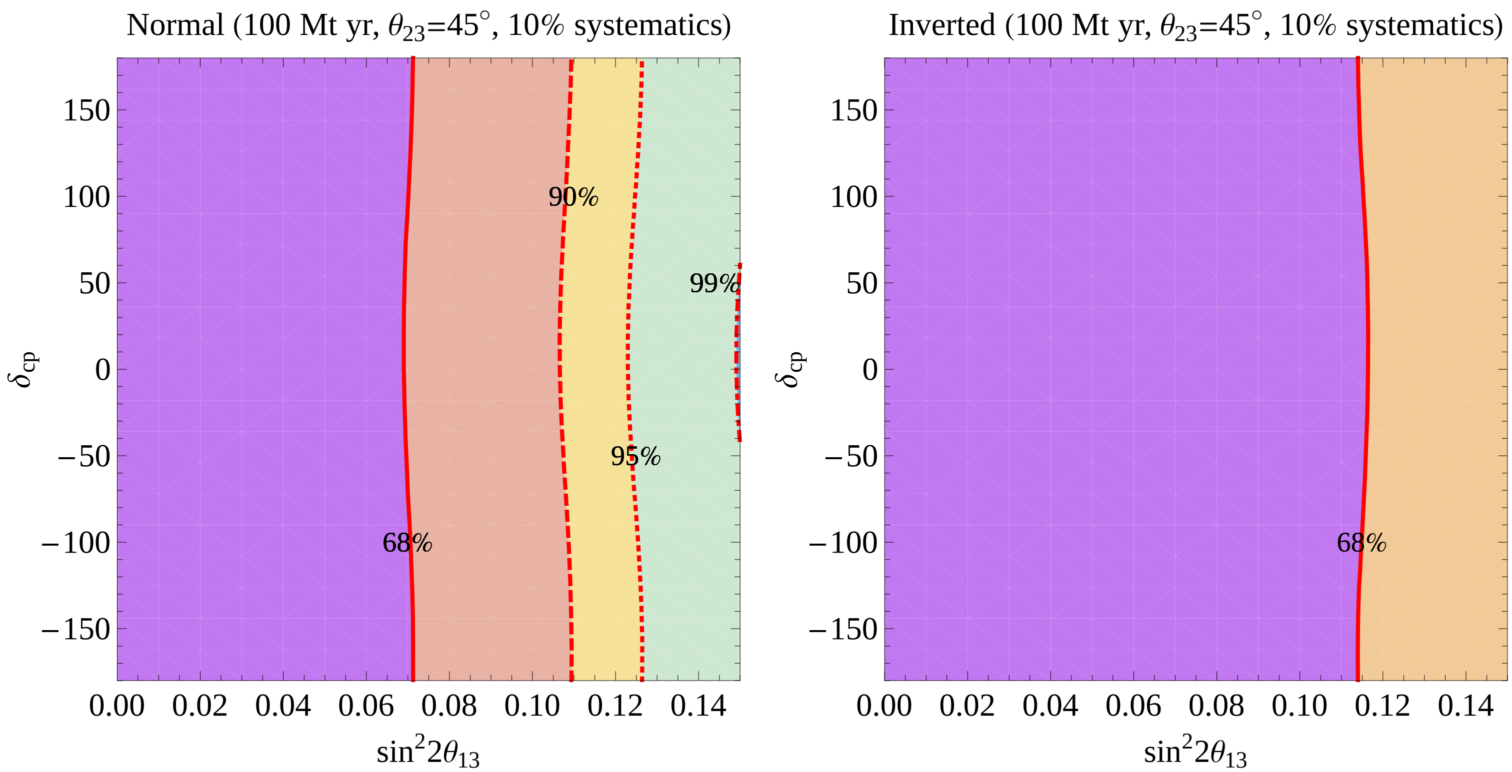


How about cascades?

- Electromagnetic cascades:

Tau decay: $\tau \rightarrow e + \bar{\nu}_e + \nu_\tau$

ν_e CC interactions: $\nu_e + N \rightarrow e + X$

- Hadronic cascades

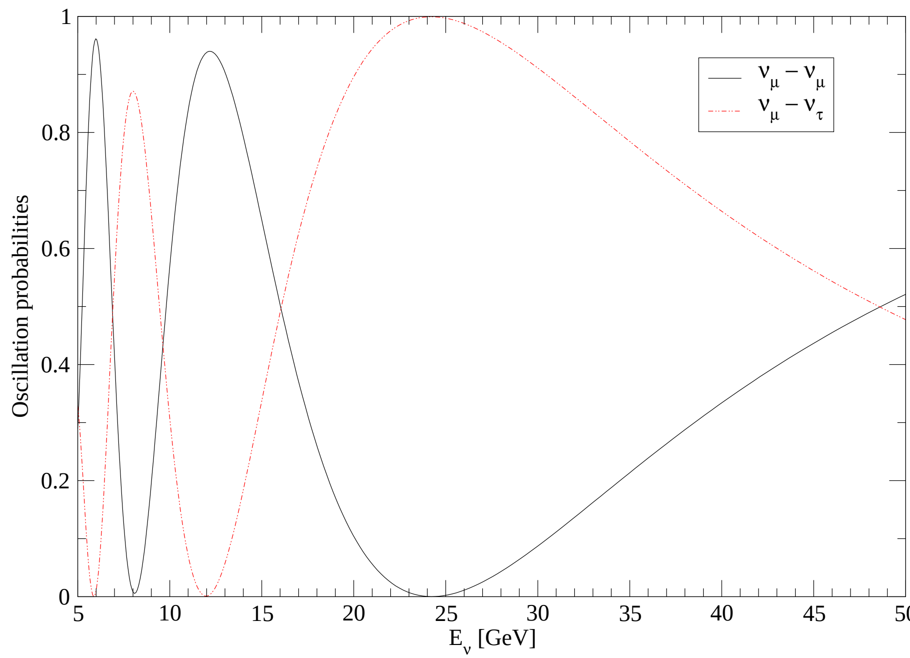
Tau decay: $\tau \rightarrow \nu_\tau + X$

ν_τ NC interactions: $\nu_\tau + N \rightarrow \nu_\tau + X$

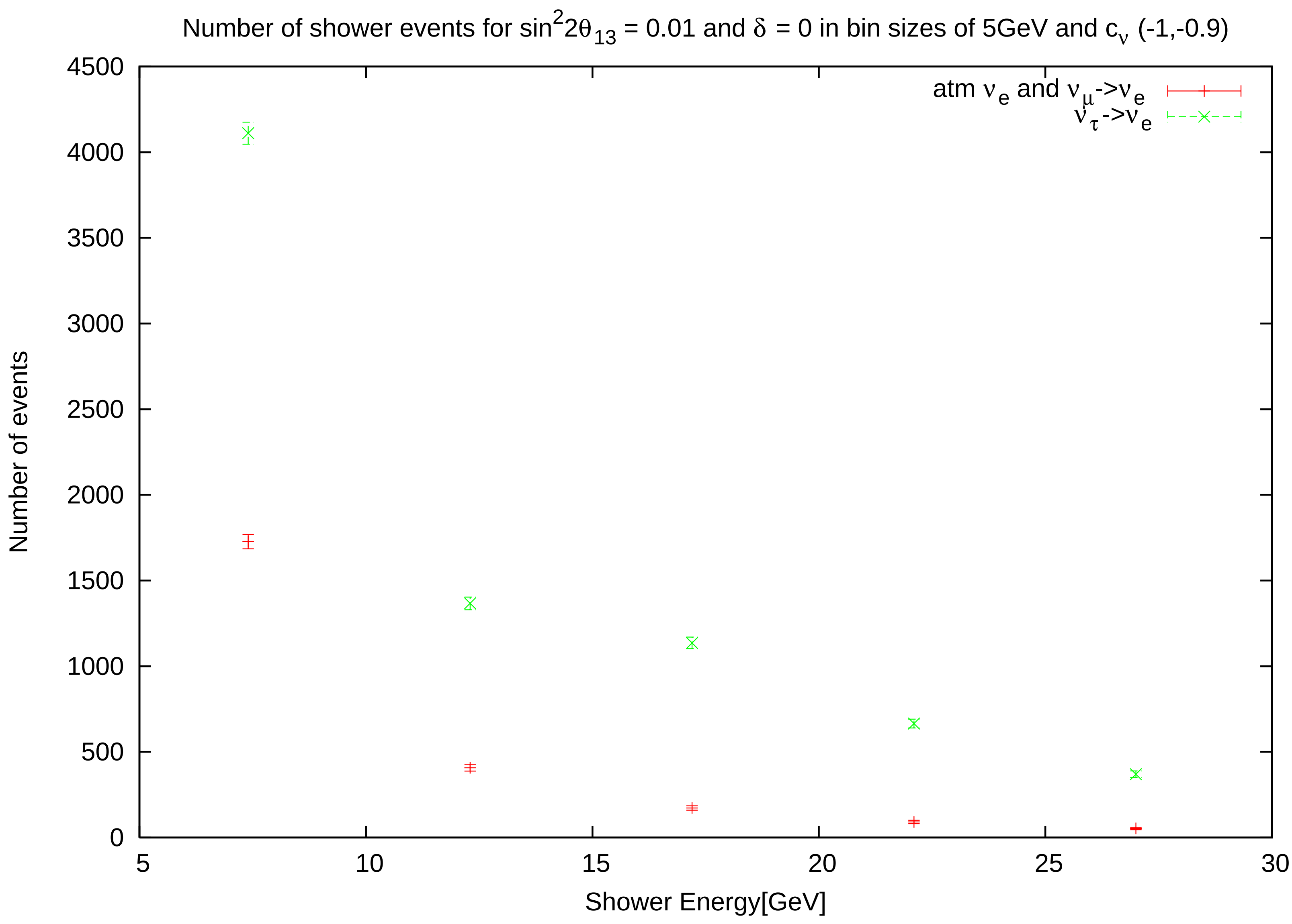
ν_τ CC interactions: $\nu_\tau + N \rightarrow \tau + X$

$\nu_{e,\mu}$ NC and CC interactions

ν_τ



large number of ν_τ



Number of shower events for $\sin^2 2\theta_{13}$ = 0.01 and δ = 0 in bin sizes of 5GeV and c_ν (-1,-0.9)
atm ν_e and ν_μ->ν_e
ν_τ->ν_e
Number of events
Shower Energy[GeV]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5
10
15
20
25
30

ν_τ cascades

with G. Giordano and O. Mena

- $\nu_\mu \longrightarrow \nu_\tau \longrightarrow \tau \longrightarrow$ e or hadrons dominates
- present world sample of ν_τ events: 9 (DONUT)
- high statistics ν_τ interactions
- first direct evidence for $\nu_\mu \longrightarrow \nu_\tau$ appearance
- ν_τ interaction cross-section
- non-standard interactions of ν_τ
- experience with cascade detection

Outlook

IceCube Deep Core

• galactic sources, dark matter annihilation

• atmospheric neutrinos
high statistics, large energy range
better understanding of background for other searches

• neutrino oscillations
mass hierarchy
ν_τ: oscillations, ν_τ interactions, cascade detection