

Oscillation of very low atmospheric neutrinos

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Seminar's plan

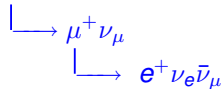
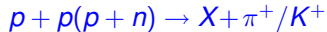
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Introduction

- Atmospheric Neutrinos in general
- Oscillations for very low energy
- Invisible muons in water detectors
- Present status of sub-sub GeV atmospheric ν
- Summary

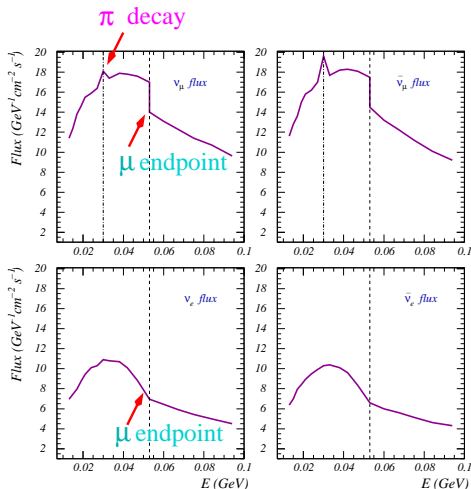
Atmospheric neutrinos

- Most of atmospheric neutrinos event sample are from pion/kaon decay in **flight**



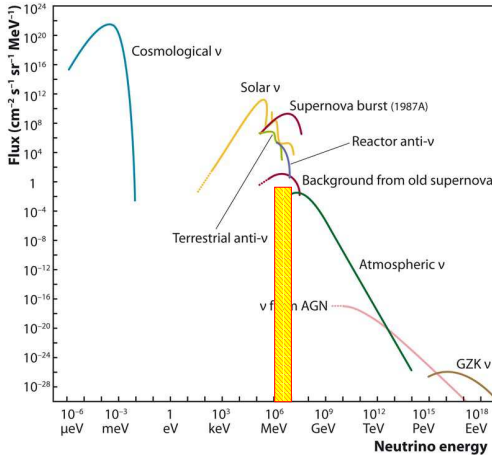
But also we have contribution from π and μ decays **at rest**. For very low energies, below 0.1 GeV we can have neutrinos from both processes (decays in flight and at rest) . **In this work we study to look for oscillation effects for these very low atmospheric neutrinos: sub-subGeV sample.**

Fluxes of atmospheric neutrinos



Adapted from Battistoni, Ferrari, Montaruli, Sala, *Astropart. Phys.* **23** (2005) 526.

General view of neutrinos fluxes



First discussed as background for searches of

diffuse neutrino relic supernova detection and future SN bursts by Fogli, Lisi, Mirizzi and Montanino.



Oscillations for lower energies

- The resonant energy for transition between the 1-2 and 1-3 families (for neutrinos only)

$$E_R^{21} = 0.96 \text{ GeV} \left(\frac{\Delta m_{21}^2}{7.3 \cdot 10^{-5} \text{ eV}^2} \right) \left(\frac{2.0 \text{ g/cm}^3}{Y_e \rho} \right) \left(\frac{\cos 2\theta_{12}}{0.424} \right)$$

$$E_R^{31} = 9.64 \text{ GeV} \left(\frac{\Delta m_{31}^2}{2.1 \cdot 10^{-3} \text{ eV}^2} \right) \left(\frac{2.0 \text{ g/cm}^3}{Y_e \rho} \right) \left(\frac{\cos 2\theta_{31}}{1} \right).$$

This implies that for very low neutrino energy, $E \ll 0.1 \text{ GeV}$ we have

$$E \lesssim E_R^{21} \quad E \ll E_R^{31}$$



Oscillations for lower energies

- The full probabilities are

$$P(\nu_e \rightarrow \nu_e) = c_{13}^4 |A'_{ee}|^2 + s_{13}^4,$$

$$P(\nu_\mu \rightarrow \nu_e) = c_{13}^2 \left| -s_{13} s_{23} e^{-i\delta} A'_{ee} + c_{23} A'_{e\mu} \right|^2 + s_{13}^2 c_{13}^2 s_{23}^2,$$

and for the inverse channel:

$$P(\nu_e \rightarrow \nu_\mu) = P(\nu_\mu \rightarrow \nu_e)(\delta \rightarrow -\delta).$$

$$P(\nu_\mu \rightarrow \nu_\mu) = \left| c_{23}^2 A'_{\mu\mu} - s_{13} \cos \delta \sin 2\theta_{23} A'_{e\mu} + s_{13}^2 s_{23}^2 A'_{ee} \right|^2 + c_{13}^4 s_{23}^4$$



Neutrino fluxes

- The electron neutrino flux at the detector

$$F_e = F_e^0 P(\nu_e \rightarrow \nu_e) + F_\mu^0 P(\nu_\mu \rightarrow \nu_e)$$



Neutrino fluxes

- The electron neutrino flux at the detector

$$\frac{F_e}{F_e^0} = \boxed{1 + (rc_{23}^2 - 1)\tilde{P}} - rs_{13}c_{13}^2 \sin 2\theta_{23}(\cos \delta R_{e\mu} + \sin \delta I_{e\mu}) \\ - 2s_{13}^2 \left[(1 - rs_{23}^2) + \tilde{P}(r - 2) \right] + s_{13}^4(1 - rs_{23}^2)(2 - \tilde{P}),$$

where $R_{e\mu} \equiv \text{Re}(\tilde{A}_{e\mu}^* \tilde{A}_{ee})$, $I_{e\mu} \equiv \text{Im}(\tilde{A}_{e\mu}^* \tilde{A}_{ee})$,

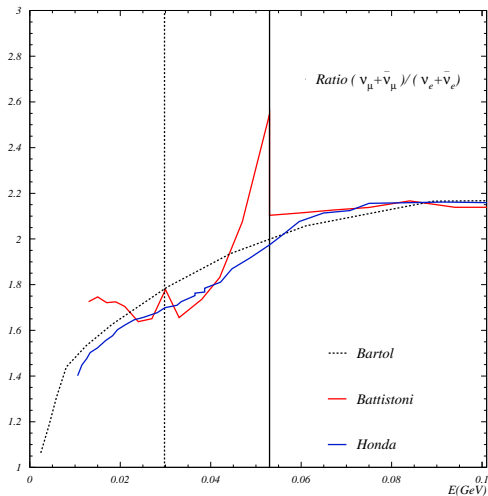
$$\tilde{P} \equiv |\tilde{A}_{e\mu}|^2, r = r(E, \Theta_\nu) \equiv \frac{F_\mu^0(E, \Theta_\nu)}{F_e^0(E, \Theta_\nu)}.$$

$s_{13} \equiv \sin(\theta_{13})$, $s_{23} \equiv \sin(\theta_{23})$, $\delta = \text{CP phase}$.

From O. L. G. Peres and A. Y. Smirnov, Phys. Lett. B **456**, 204 (1999); Nucl. Phys. B **680**, 479 (2004)



The flavor ratio for sub-sub GeV neutrinos



The flavor ratio for sub-sub GeV neutrinos

For larger energies $r \sim 2$ and for almost maximal mixing we have suppression of oscillation, $(rc_{23}^2 - 1) \rightarrow 0$,

$$\frac{F_e}{F_e^0} = \boxed{1 + (rc_{23}^2 - 1)\tilde{P}} \sim 1$$

But for lower energies, r deviate from 2 and we can see some effect

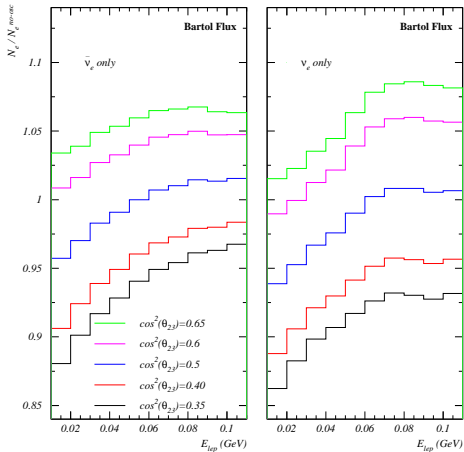


The flavor ratio for sub-sub GeV neutrinos

We use Bartol fluxes (we have plots for Honda and Battistoni fluxes as well) and cross sections $\bar{\nu}_e H$, $\bar{\nu}_e O$ and $\nu_e O$, using quasi-elastic formalism with appropriate nuclear effects. The following plots are for Super-Kamiokande experiment.



Oscillation for null θ_{13}



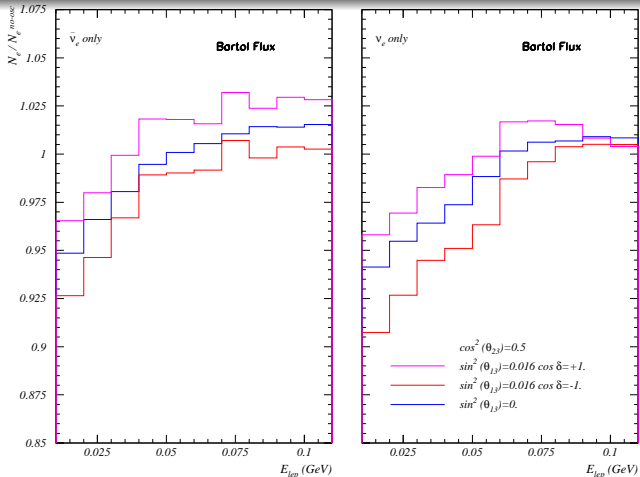
Oscillation for $\theta_{13} \neq 0$

$$\frac{F_e}{F_e^0} = 1 + (rc_{23}^2 - 1)\tilde{P} - \boxed{rs_{13}c_{13}^2 \sin 2\theta_{23}(\cos \delta R_{e\mu})} + \sin \delta I_{e\mu} \\ - 2s_{13}^2 \left[(1 - rs_{23}^2) + \tilde{P}(r - 2) \right] + s_{13}^4 (1 - rs_{23}^2)(2 - \tilde{P}),$$

The functions $R_{e\mu}$, $I_{e\mu}$, \tilde{P} can be computed numerically or via Magnus expansion (see talks by Ioannian and by Aguilar-Arevalo in this conference). We use $\sin^2 2\theta_{12} = 0.82$, and $\Delta m_{21}^2 = 7.3 \times 10^{-5} \text{ eV}^2$.



Oscillation for $\theta_{13} \neq 0$



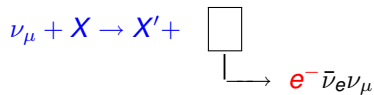
Invisible muons in water detectors

Atmospheric muon neutrinos (or muon anti-neutrinos) made muons (antimuons) **inside** the detector



Invisible muons in water detectors

Some of them did not produce Cerenkov radiation due to have momenta below the threshold. they are called invisible muons



But produce electrons.



Invisible muons in water detectors

The rate of invisible muons depend of muon survival probability.

$$\begin{aligned}
 \frac{F_{\mu}}{F_{\mu}^0} &= \boxed{1 - \frac{1}{2} \sin^2 2\theta_{23}} - c_{23}^2 \tilde{P} \left(c_{23}^2 - \frac{c_{13}^2}{r} \right) - \\
 &- s_{13} \sin 2\theta_{23} \left\{ \cos \delta \left[\frac{R_{\mu e}}{r} - c_{23}^2 (R_{e\mu} + R_{\mu e}) \right] \right. \\
 &- \left. \sin \delta \left[\frac{I_{\mu e}}{r} + c_{23}^2 (I_{e\mu} + I_{\mu e}) \right] \right\} + O(s_{13}^2).
 \end{aligned}$$

where

$$\begin{aligned}
 R_{e\mu} &\equiv \text{Re}(\tilde{A}_{e\mu}^* \tilde{A}_{ee}), \quad I_{e\mu} \equiv \text{Im}(\tilde{A}_{e\mu}^* \tilde{A}_{ee}), \quad R_{\mu e} \equiv \text{Re}(\tilde{A}_{\mu e}^* \tilde{A}_{ee}), \\
 I_{\mu e} &\equiv \text{Im}(\tilde{A}_{\mu e}^* \tilde{A}_{ee}), \quad \tilde{P} \equiv |\tilde{A}_{e\mu}|^2, \quad r = r(E, \Theta_{\nu}) \equiv \frac{F_{\mu}^0(E, \Theta_{\nu})}{F_{e}^0(E, \Theta_{\nu})}.
 \end{aligned}$$

$$s_{13} \equiv \sin(\theta_{13}), \quad s_{23} \equiv \sin(\theta_{23}), \quad \delta = \text{CP phase.}$$

Invisible muons in water detectors

In turn, these muons are generated by the ν_μ -flux with typical energies (150 - 250) MeV.

The spectrum of electrons from invisible muons is described by the Michel spectra. The normalization is equal of the number of muons that decay. The electron spectra is

$$\frac{dN_e}{dE_{lep}} = N_\mu E_{lep}^2 \left(\frac{3}{2} - \frac{E_{lep}}{(m_\mu/2)} \right)$$

We folded this distribution with an resolution function.



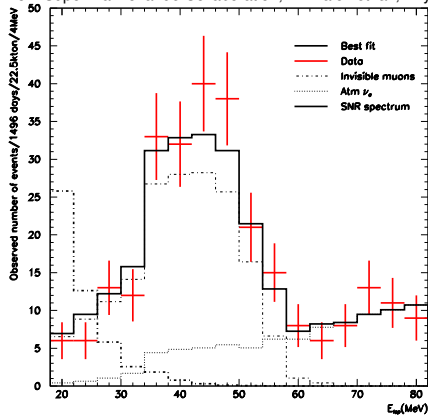
The sub-sub GeV atmospheric neutrinos in SK.

- At the present, LSD put only an upper bound on the $\bar{\nu}_e$ -flux:
 $F_{\bar{e}} < 5 \cdot 10^4 \text{cm}^{-2}\text{s}^{-1}$ for the energy range $12 < E < 26$ MeV.
Super-Kamiokande detected 88 ± 12 produced by interactions of the atmospheric ν_e and $\bar{\nu}_e$, and 174 ± 16 from decays of invisible muons for a **90kt-yr exposure time**.



The sub-sub GeV atmospheric neutrinos in SK.

- From Super-Kamiokande Collaboration, M. Malek *et. al.*, Phys. Rev. Lett. **90** (2003) 061101.

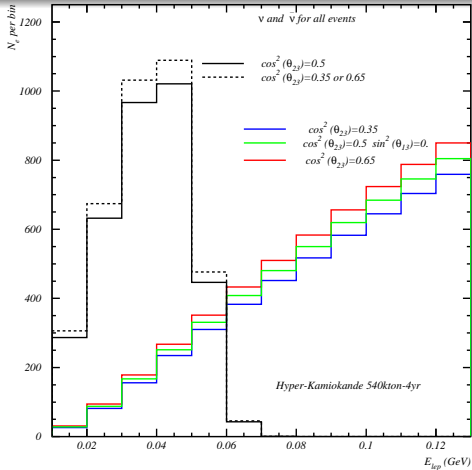


Future Megaton detectors for null θ_{13}

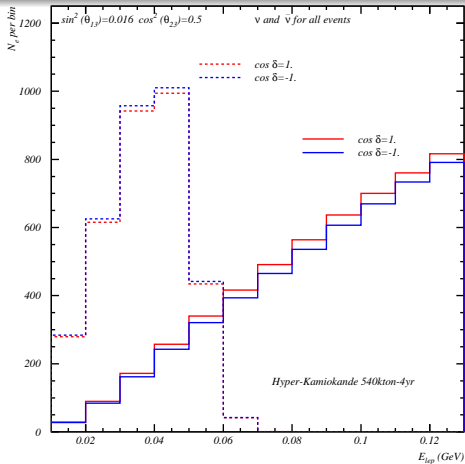
At the present time it not statistically important this effect but can be important for future Megaton detectors. We use here as a example a Hyper-Kamiokande with 540kton-4yr.



Future Megaton detectors for null θ_{13}



Future Megaton detectors for $\theta_{13} \neq 0$



Summary

- There are several new features which appear at low energies in production, oscillations and detection of the atmospheric ν .
- For the e -like events at $s_{13} = 0$ the effects due to the oscillations driven by the 1-2 mixing can be $10 - 15\%$. The 1-3 mixing can reach $\pm 4\%$ ($\pm 6\%$) at low (high) energies;
- To study oscillation effects discussed in this paper one needs much larger statistics which can be achieved with the Megaton-scale detector. The sub-sub GeV sample can be used to measure deviation of 2-3 mixing from maximal, the 1-3 mixing and the phase δ . We urge to have a full understanding of fluxes of these neutrinos that can have implication for detection of diffuse neutrinos from relic supernova.



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Comparison between different computations

