Oscillation of very low energy atmospheric neutrinos

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Seminar's plan

1. 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

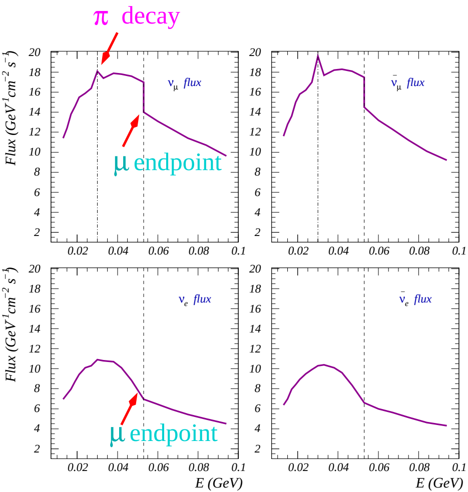
$$p + p(p + n) \rightarrow X + \pi^+/K^+$$

$$\lfloor\!\longrightarrow \mu^+ \nu_\mu$$

$$\lfloor\!\longrightarrow e^+ \nu_e \bar{\nu}_\mu$$

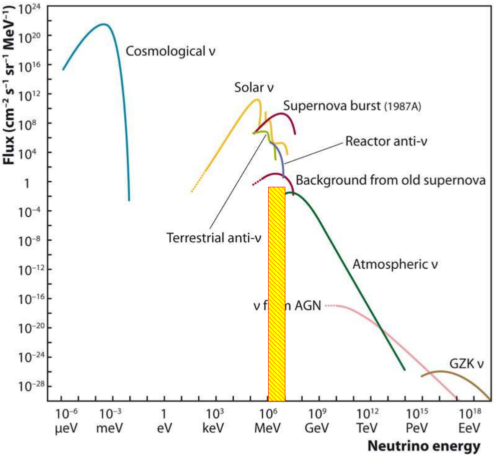
But also we have contribution from π and μ decays at rest. For very low energies, below 0.1 GeV we can have neutrinos from both processes (decays in flight and at rest) . In this work we study to look for oscillation effects for these very low atmospheric neutrinos: sub-subGeV sample.

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.

Three generation oscillations for lower energies, $\Delta m^2_{21} \neq 0$

- The full probabilities are

$$\begin{aligned} P(\nu_e \to \nu_e) &= c_{13}^4 |A'_{ee}|^2 + s_{13}^4, \\ P(\nu_\mu \to \nu_e) &= c_{13}^2 \left| -s_{13} s_{23} e^{-i\delta} A'_{ee} + c_{23} A'_{e\mu} \right|^2 + s_{13}^2 c_{13}^2 s_{23}^2, \end{aligned}$$

and for the inverse channel:

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

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

where $A'_{\alpha\beta}$ are the amplitudes for 1-2 sector: θ_{12} and Δm^2_{21}; $s_{13}^2 \equiv \sin^2\theta_{13}$;$c_{23}^2 \equiv \cos^2\theta_{23}$

Three generation oscillations for lower energies, $\Delta m^2_{21} \neq 0$

- The typical for oscillations in matter, is due transition between the 1-2 and 1-3 families (for neutrinos only)

$$\begin{aligned} E_R^{21} &= 0.96\ \mathrm{GeV} \left(\frac{\Delta m^2_{21}}{7.3\cdot 10^{-5}\mathrm{eV}^2}\right)\left(\frac{2.0\mathrm{g/cm}^3}{Y_e\rho}\right)\left(\frac{\cos 2\theta_{12}}{0.424}\right) \\ E_R^{31} &= 9.64\ \mathrm{GeV} \left(\frac{\Delta m^2_{31}}{2.1\cdot 10^{-3}\mathrm{eV}^2}\right)\left(\frac{2.0\mathrm{g/cm}^3}{Y_e\rho}\right)\left(\frac{\cos 2\theta_{31}}{1.}\right) . \end{aligned}$$

This implies that for very low neutrino energy, E$<<$ 0.1 GeV we have

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

Neutrino fluxes

- The electron neutrino flux at the detector

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

Neutrino fluxes

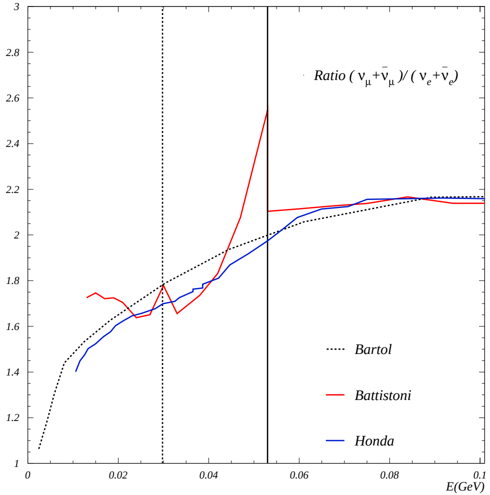
- The electron neutrino flux at the detector

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

where $R_{e\mu} \equiv \mathrm{Re}(\tilde{A}^*_{e\mu}\tilde{A}_{ee})$, $I_{e\mu} \equiv \mathrm{Im}(\tilde{A}^*_{e\mu}\tilde{A}_{ee})$,
$\tilde{P} \equiv |\tilde{A}_{e\mu}|^2$, $r = r\,(E,\Theta_\nu) \equiv \frac{F_\mu^0(E,\Theta_\nu)}{F_e^0(E,\Theta_\nu)}$.
$s_{13} \equiv \sin(\theta_{13})$, $s_{23} \equiv \sin(\theta_{23})$, $\delta =$ 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, $(rc_{23}^2 - 1) \to 0$,

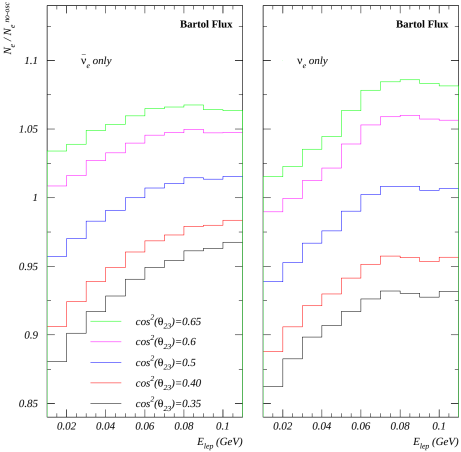
$$\frac{F_e}{F_e^0} = \boxed{1 + (rc_{23}^2 - 1)\tilde{P}} \sim 1$$

But for lower energies, r deviate from 2 and we can 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 apropppriate nuclear effects. The following plots are for Super-Kamiokande experiment.

Oscillation for null θ_{13}

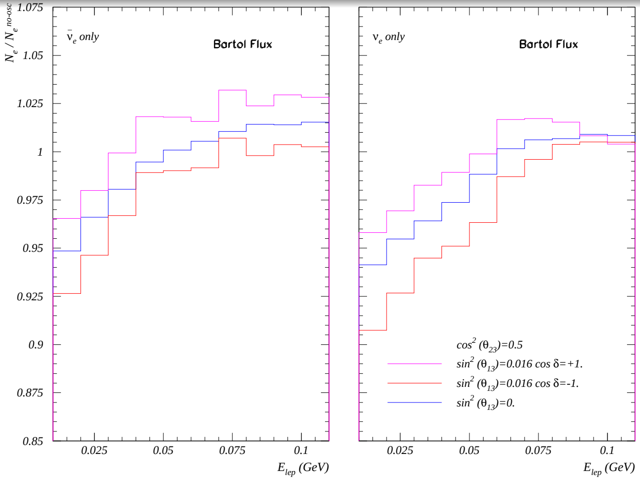


Oscillation for $\theta_{13} \neq 0$

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

The functions $R_{e\mu}, I_{e\mu}, \tilde{P}$ can be computed numerically or via Magnus expansion . We use $\sin^2 2\theta_{12} = 0.82$, and $\Delta m^2_{21} = 7.3 \times 10^{-5}$ 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

$$\nu_\mu + X \rightarrow X' + \mu^-$$

Invisible muons in water detectors

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

$$\begin{tikzcd}[column sep=small] \nu_\mu + X \rightarrow X' + & \boxed{} \arrow[d, dash] & \\ & {} \arrow[r] & e^- \bar{\nu}_e \nu_\mu \end{tikzcd}$$

But produce electrons.

Invisible muons in water detectors

The rate of invisible muons depend of muon survival probability.

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

where

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

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

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

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

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

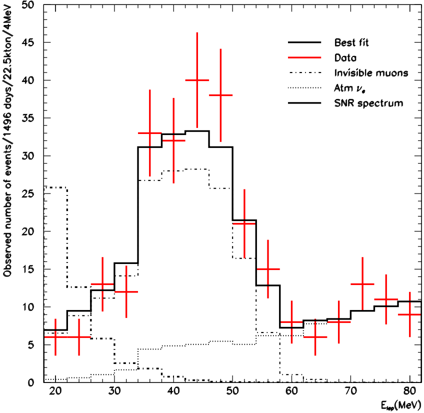
We folded this distribution with an resolution function.

The sub-sub GeV atmospheric neutrinos in SK.

- At the present, LSD put only an upper bound on the $\bar{\nu}_e-$flux: $F_{\bar{e}} < 5 \cdot 10^4 \mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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.

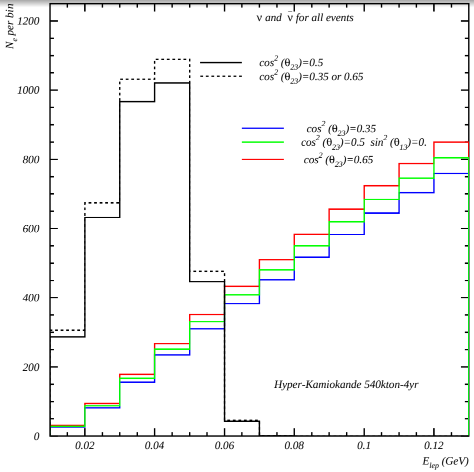
- From Super-Kamiokande Collaboration, M. Malek *et. al.*, Phys. Rev. Lett. **90** (2003) 061101.



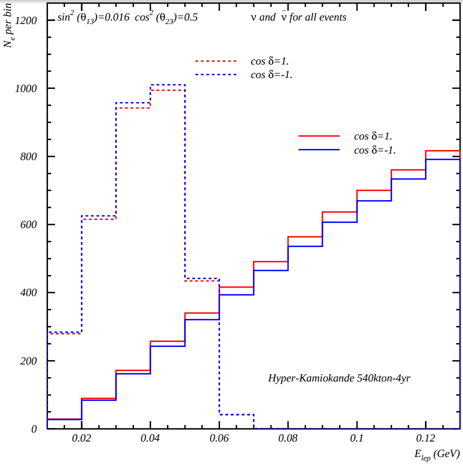
Future Megaton detectors for null θ_{13}

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 $\theta_{13} \neq 0$



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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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Comparation between different computations