Combining LSND and Atmospheric Anomalies

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Les Houches, 20 June 2001

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hep-ph/0106002

Study ways to obtain an excess of electron events for atmospheric neutrinos in a three neutrino analysis.

- Fit with additional SOLAR mass square difference.
- Fit with additional LSND mass square difference.

Study **three-active-neutrino** oscillation

$\Rightarrow$ Only two anomalies can be solved.

Atmospheric neutrinos: dominant $\nu_\mu \to \nu_\tau$ osc.

Conventional Scheme: ATM. + SOLAR

LSND Scheme: ATM. + LSND

For atmospheric neutrinos:
Can we see any difference between the two schemes when studying the **small corrections** to two-neutrino $\nu_\mu \to \nu_\tau$ oscillation?

Long baseline experiments:
K2K, MINOS, CNGS - is it possible to differentiate between the schemes?

Exotic solar solutions

- Sterile neutrino oscillation (SMA).
  '2+2' four-neutrino scheme.
- FCNC, e.g. ν_e + quark $\rightarrow$ ν_α + quark.
- Violation of equivalence principle.
- Large extra dimensions (sterile).
- Magnetic moment (requires $\Delta m^2 \simeq 10^{-8}\text{eV}^2$)
- Neutrino decay (bad fit).

Exotic LSND solutions

- (some amount of) sterile neutrino osc.
  '3+1' four-neutrino scheme (very bad fit).
- Lepton number violating muon decay.
  Almost ruled out in a model-independent way.

If the LSND anomaly is real it most likely should be solved by mainly active neutrino oscillation

Motivation from atm. electron ratios

Both LSND and Solar Anomalies concerns ν_e

The electron neutrino ratios R_e test the $\nu_e \rightarrow \nu_\mu$ oscillation

$$R_e = P_{ee} + r P_{e\mu}$$

$r \simeq 2$ in sub-GeV range and $r \simeq 3$ in Multi-GeV range.

Data indicates an excess of electron events for atmospheric neutrinos.

Need to consider a three neutrino analysis.

Additonal $\Delta m^2 < \Delta m^2_{\text{atm}}$ (SOLAR).

Addiional $\Delta m^2 > \Delta m^2_{\text{atm}}$ (LSND).

For atmospheric neutrinos we fit to Sub-GeV and Multi-GeV data only.

Stopping and through going ν_μ data sets are not expected to affect the comparision much.

Fit to the ratio of the measured number of events to the number of events expected from no-oscillation.

$$R = \frac{N^{\mathrm{exp}}}{N^0}$$

The atmospheric neutrino flux calculation does have large error, but mainly in the overall normalization.

For both schemes we use 4 fitting parameters.

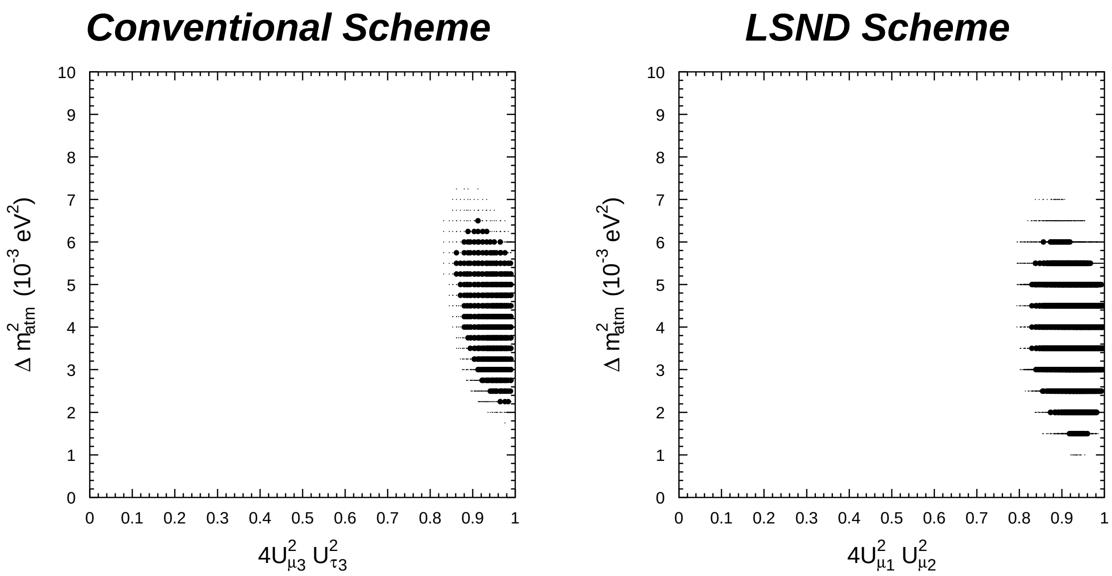
Conventional: solar angle is fixed near best fit to LMA

LSND: Choose $\Delta m^2_{\mathrm{LSND}}$ to fit LSND.

Only for large $\Delta m^2_\odot$ (LMA) and large $\sin^2(2\theta_{\mathrm{LSND}})$ do we get sizeable difference from the two neutrino osc.

Atmospheric and CHOOZ

Allowed region in $\Delta m^2_{\rm atm}$ and $\sin^2(2\theta_{\rm atm})$



Best fit points (55 data)

LSND scheme: $\sin^2(2\theta_{\rm LSND}) = 0.08$

$$\chi^2_{\rm min} = 44.9$$

Conventional scheme: $\Delta m^2_\odot = 2 \times 10^{-4}$ eV^2

$$\chi^2_{\rm min} = 45.3$$

The atmospheric data prefers large solar mass squared difference: $\chi^2_{\rm min} = 49.1$ for $\Delta m^2_\odot = 2 \times 10^{-5}$ eV^2.

Combining solar, atmospheric and CHOOZ

$$\chi^2/\text{dof} = 0.93$$

Best fit at $\Delta m^2_\odot = 8 \times 10^{-5}$ eV^2.

Gonzalez-Garcia *et. al.*: $\chi^2/\text{dof} = 0.97$
(Taking $\Delta m^2_\odot = 0$ for atm. analysis)

[Gonzalez-Garcia *et. al.*, hep-ph/0009350]

Combining LSND, atmospheric and CHOOZ

$$\chi^2/\text{dof} = 0.88$$

Best fit at $\sin^2(2\theta_{\text{LSND}}) = 0.08$

Including Bugey: $\chi^2/\text{dof} = 0.87$
Best fit $\sin^2(2\theta_{\text{LSND}}) = 0.06$

Electron excess

For the conventional scheme (solar+atm.) we have two important parameters.

$s_{13} \neq 0$

- Large excess for up-going Multi-GeV only.
- Proportional to $(rs_{23}^2 - 1)$.
- Excess on **dark** and deficit on **light** side.

[Akhmedov *et. al.*, hep-ph/9808270]

$\Delta m_\odot^2 \neq 0$

- Large excess for Sub-GeV only.
- Proportional to $(rc_{23}^2 - 1)$.
- Excess on **light** and deficit on **dark** side.

[Peres,Smirnov, hep-ph/9902312]

LIGHT DARK

0.5 s_{23}^2

$$r = \frac{\Phi_\mu^0}{\Phi_e^0}$$

Cannot produce excess in both Sub- and Multi-GeV.

Ratios for Multi-GeV down-going ν's are 1.

Electron excess

For the LSND scheme in the favored region ($\sin^2(2\theta_{LSND}) > 0.02$)

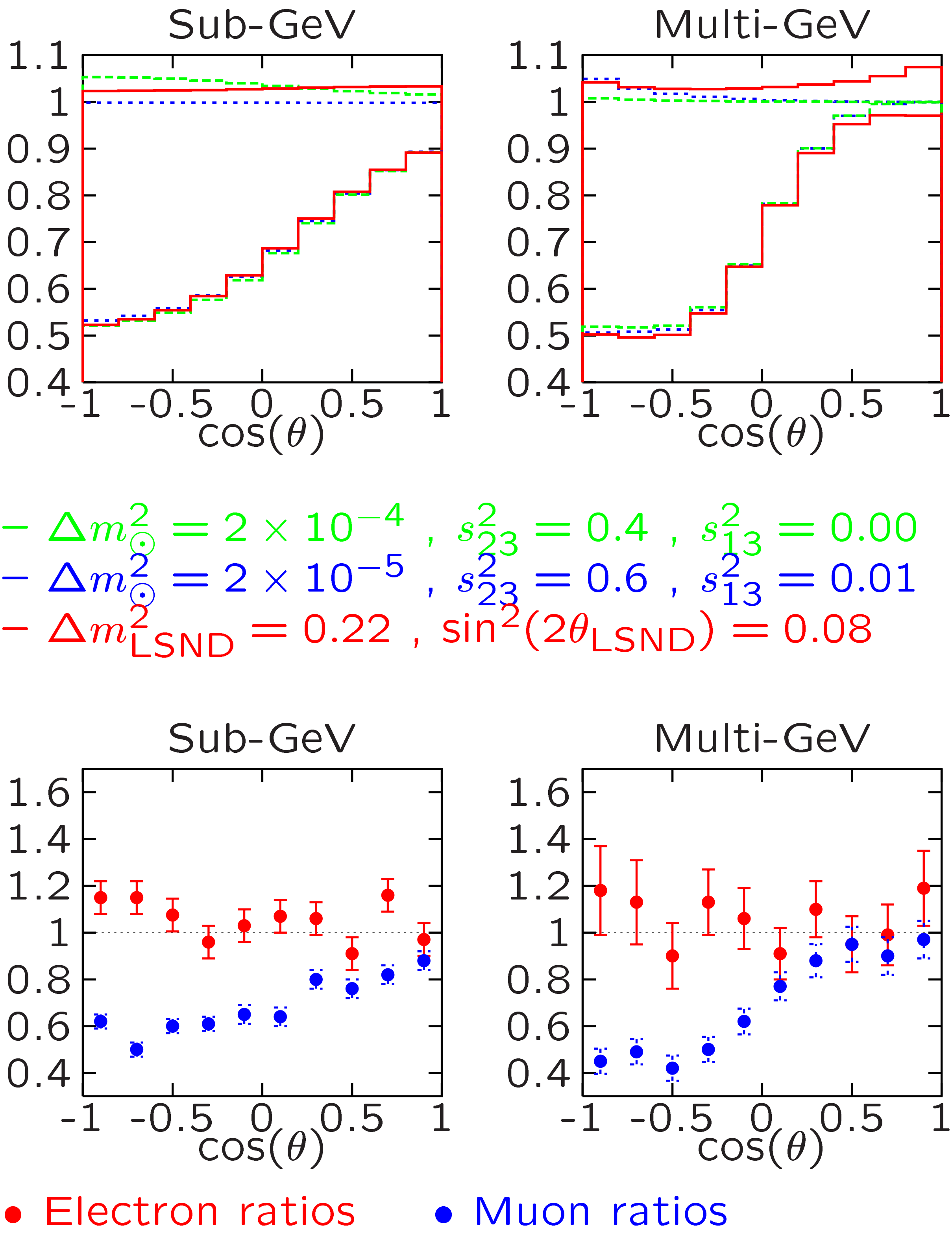
- Excess for both Multi-GeV and Sub-GeV.
- The Multi-GeV excess is slightly larger.
- Largest excess for down-going Multi-GeV.
- Up/down asymmetry is negative.

"Predictions where the effect is large"

For smaller value of the LSND angle the picture can be different.

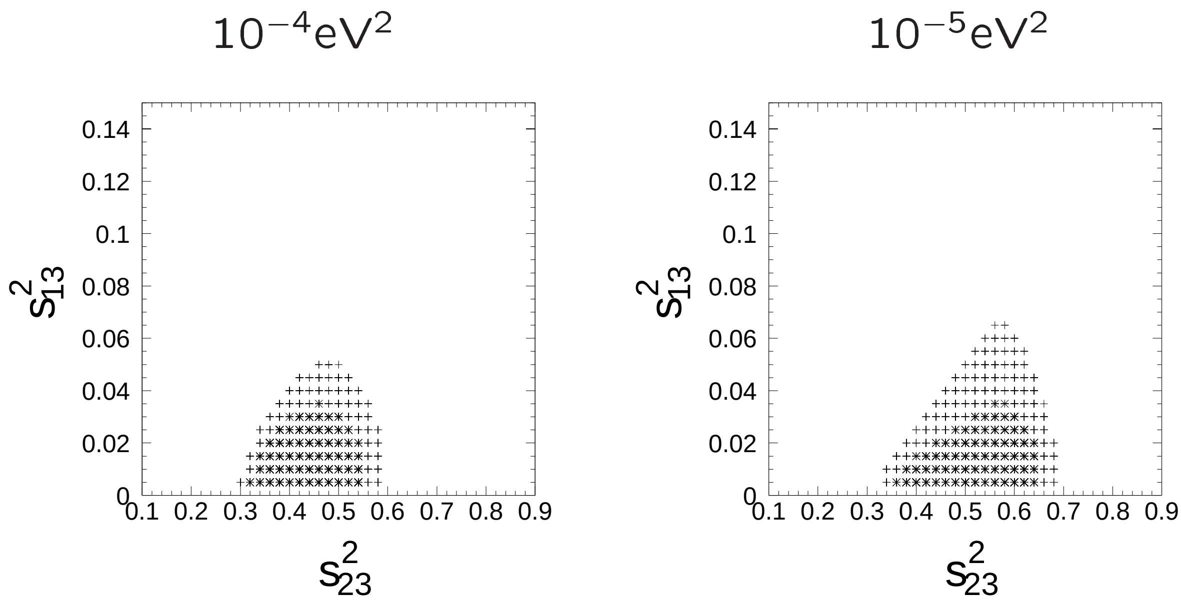
$$\xi_e \approx 2s_{13}^2 c_{13}^2 (r s_{23}^2 - 1)$$

$$+2r c_{13}^2 s_{12} c_{12} \sin(2\theta_{\text{atm}}) \sin^2\left(\frac{\Delta m_{\text{atm}}^2 L}{4E}\right)$$



Sub-GeV
Multi-GeV
cos(θ)
cos(θ)
– Δm²⊙ = 2 × 10⁻⁴ , s²23 = 0.4 , s²13 = 0.00
– Δm²⊙ = 2 × 10⁻⁵ , s²23 = 0.6 , s²13 = 0.01
– Δm²LSND = 0.22 , sin²(2θLSND) = 0.08
Sub-GeV
Multi-GeV
cos(θ)
cos(θ)
• Electron ratios
• Muon ratios

Allowed region for the conventional scheme constraining $\Delta m^2_\odot$.



For large $\Delta m^2_\odot$ nearly all the dark side is disallowed.

For small $\Delta m^2_\odot$ the dark side allows large values of s_{13}.

Long baseline experiments

The capability of differentiating between the two schemes, depends on the value of L/E. If the atmospheric Δm^2 dominates the oscillation you cannot see the difference

- K2K will not be able to see difference, unless the LSND angle is very large.

  $\sin^2(\Delta m^2_{\text{atm}} L/4E)$ is large.

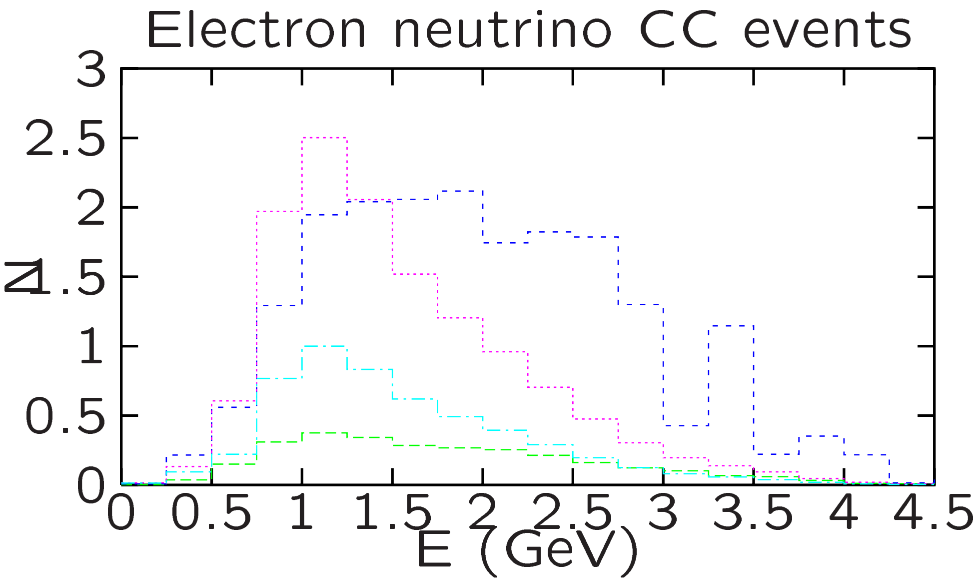
- Minos cannot see the difference either if they run only with the low energy beam option.

  $\sin^2(\Delta m^2_{\text{atm}} L/4E)$ is large.

- CNGS will give us the answer (hopefully).

  $\sin^2(\Delta m^2_{\text{atm}} L/4E)$ is small.

K2K electron events spectrum



- LSND

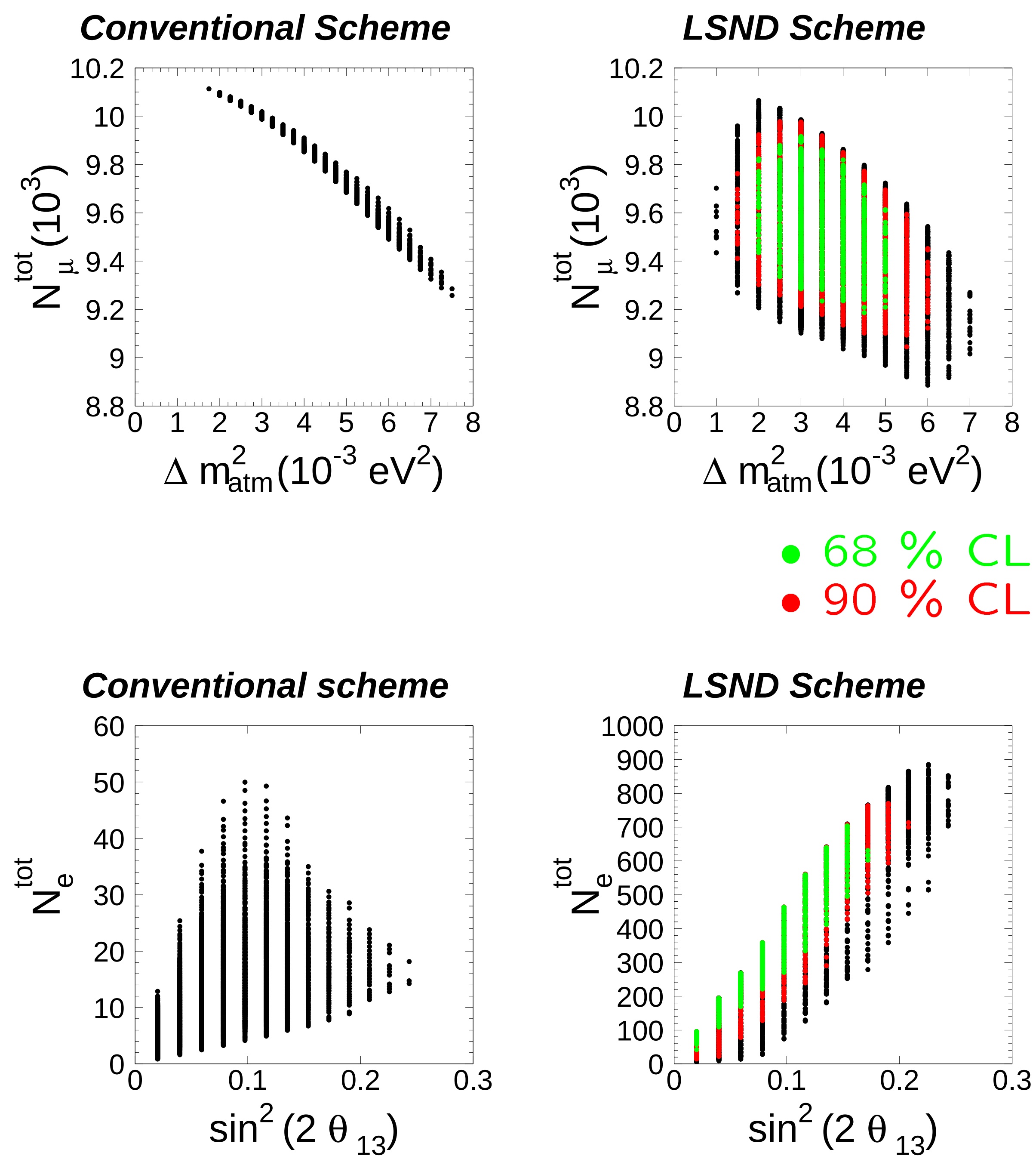
- LSND

- Conventional

- Conventional

Possible a small excess for high energies in the LSND scheme.

CERN to Gran Sasso (5 years and per kton)



Total number of events for all points within 99% CL

New atmospheric fluxes

Several new calculations of atmospheric neutrino fluxes. [T.Montaruli this session]

All predicts that the neutrinos fluxes should be lowered compared to the standard ones (Bartol, Honda).

Smaller neutrino fluxes are mainly due to new meusuments of the amospheric μ fluxes.

$\Rightarrow$ Larger excess of ν_e.

Also new energy dependence:
- Sub-GeV 5% lower
- Multi-GeV 15% lower

[G.Battistoni et. al, hep-ph/9907408]

SK two neutrino fit to $\nu_\mu \to \nu_\tau$; Best fit upscale the normalization of the new predicted fluxes by 20%. [Totsuka this session]

Indicates that a three neutrino fit with $\Delta m^2_{\mathrm{LSND}}$ could be desirable.

Conclusions

- LSND and Atmospheric anomalies gives a good fit in the three-neutrino scheme. (improves the two-neutrino fit)

- Large LSND angles are favored and $\sin^2(2\theta_{\mathrm{LSND}})$ can be as large as 0.1.

- $\Delta m^2_{\mathrm{LSND}}$ migth be desirable for the electron ratios for atmospheric neutrinos. (especially with new neutrino fluxes)

- CNGS should tell us what scheme and therefore what mass pattern is realized.