Atmospheric Neutrino

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NOON03

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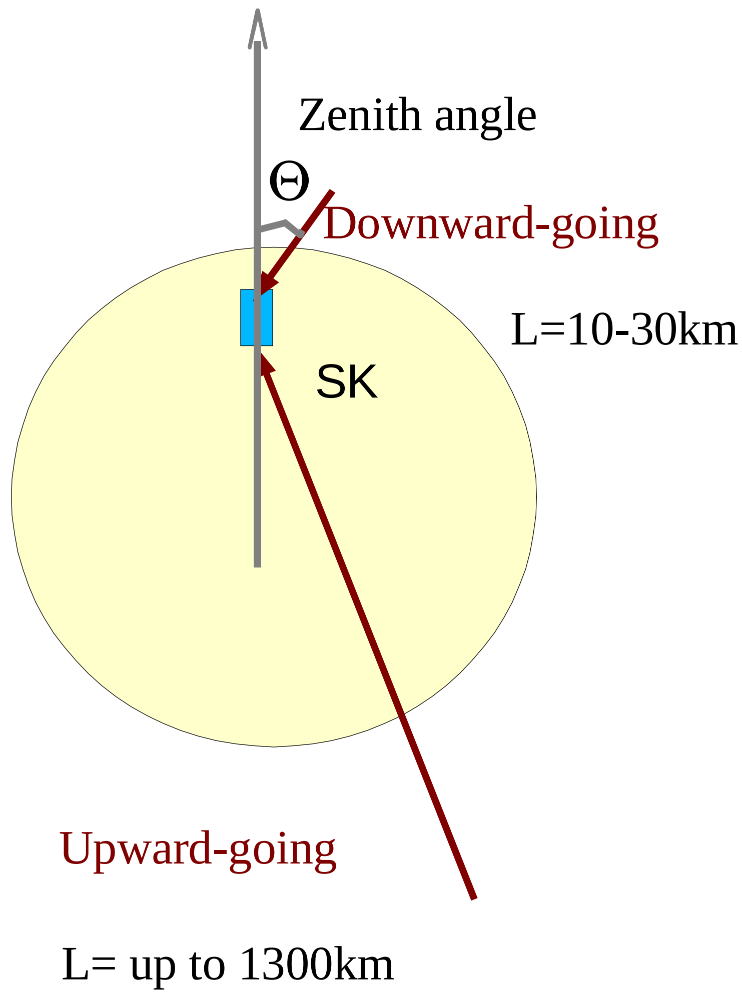
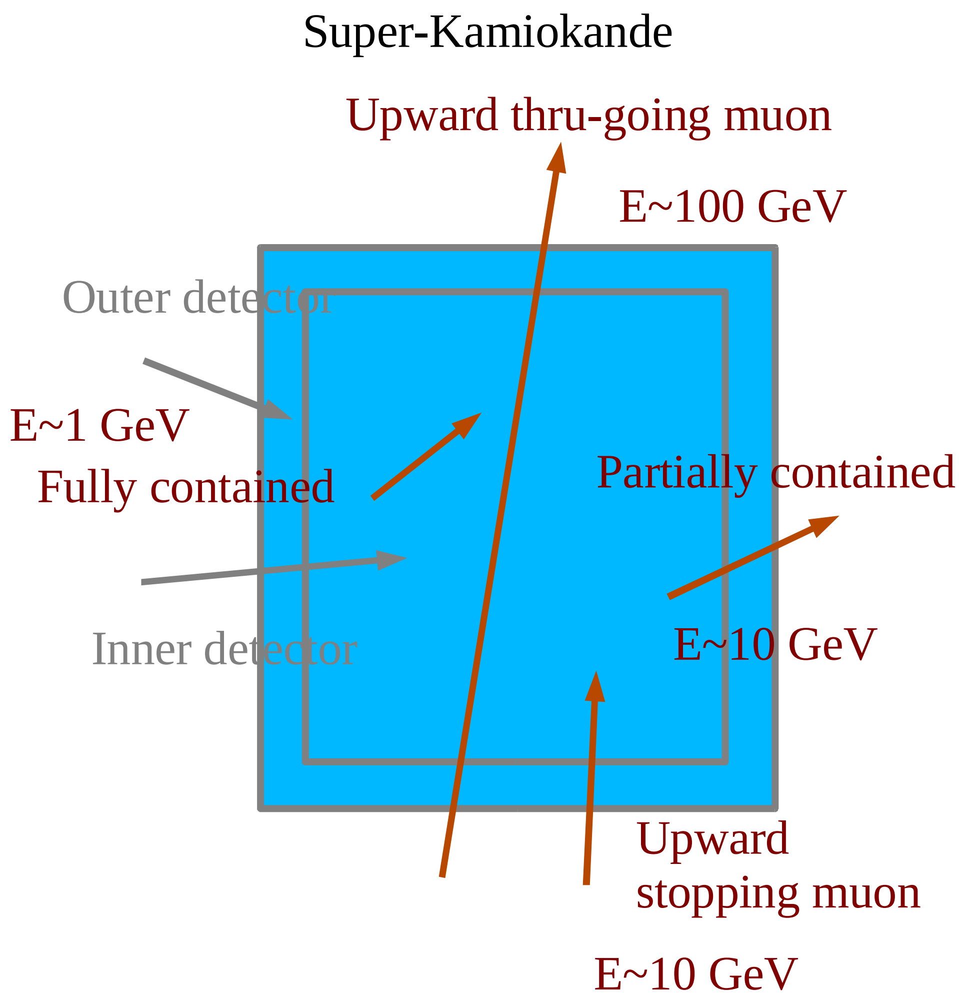
- Introduction

- Neutrino oscillation
  - 2 flavor oscillation
    - $\nu_\mu \rightarrow \nu_\tau$ (disappearance mode)
    - $\nu_\mu \rightarrow \nu_\tau$ (appearance mode)
  - Oscillation to admixture state
    - $\nu_\mu \rightarrow \nu_\tau + \nu_s$ (mixture of tau and sterile neutrino)
  - 3 flavor oscillation
    - $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$

- Neutrino decay

Introduction





•Neutrino Oscillation

- 2 flavor oscillation: $\nu_\mu \rightarrow \nu_\tau$ disappearance

Oscillation probability:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

Δm^2 in eV^2, L in km, E in GeV

First indication (Kamiokande, IMB):

Smaller ν_μ/ν_e ratio than expected

- SK 1489 day data $(\mu/e)_{data}/(\mu/e)_{MC}$

	stat.	sys.
SubGeV	.638(.647)+.016-.016	+-.050 Honda (Bartol)
MultiGeV	.629(.652)+.034-.032	+-.092 Honda (Bartol)

- Soudan 2 data $(\mu/e)_{data}/(\mu/e)_{MC}$

.68+-.11+-.006 (stat. .11, sys. .006)

2flavor oscillation

•Neutrino Oscillation

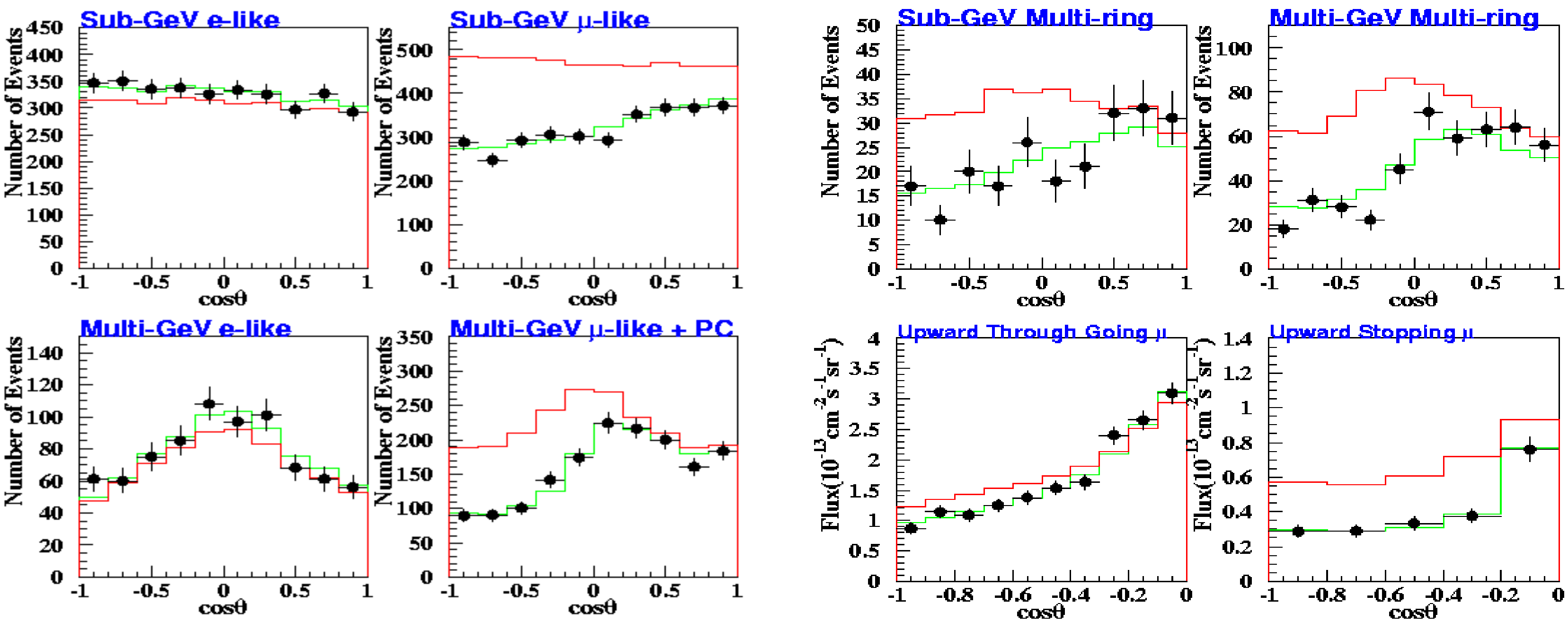
- 2 flavor oscillation: $\nu_\mu \rightarrow \nu_\tau$ disappearance

Further evidences: zenith angle distribution

MC expected No oscillation

MC expected Best fit with osc.

SK zenith angle distributions

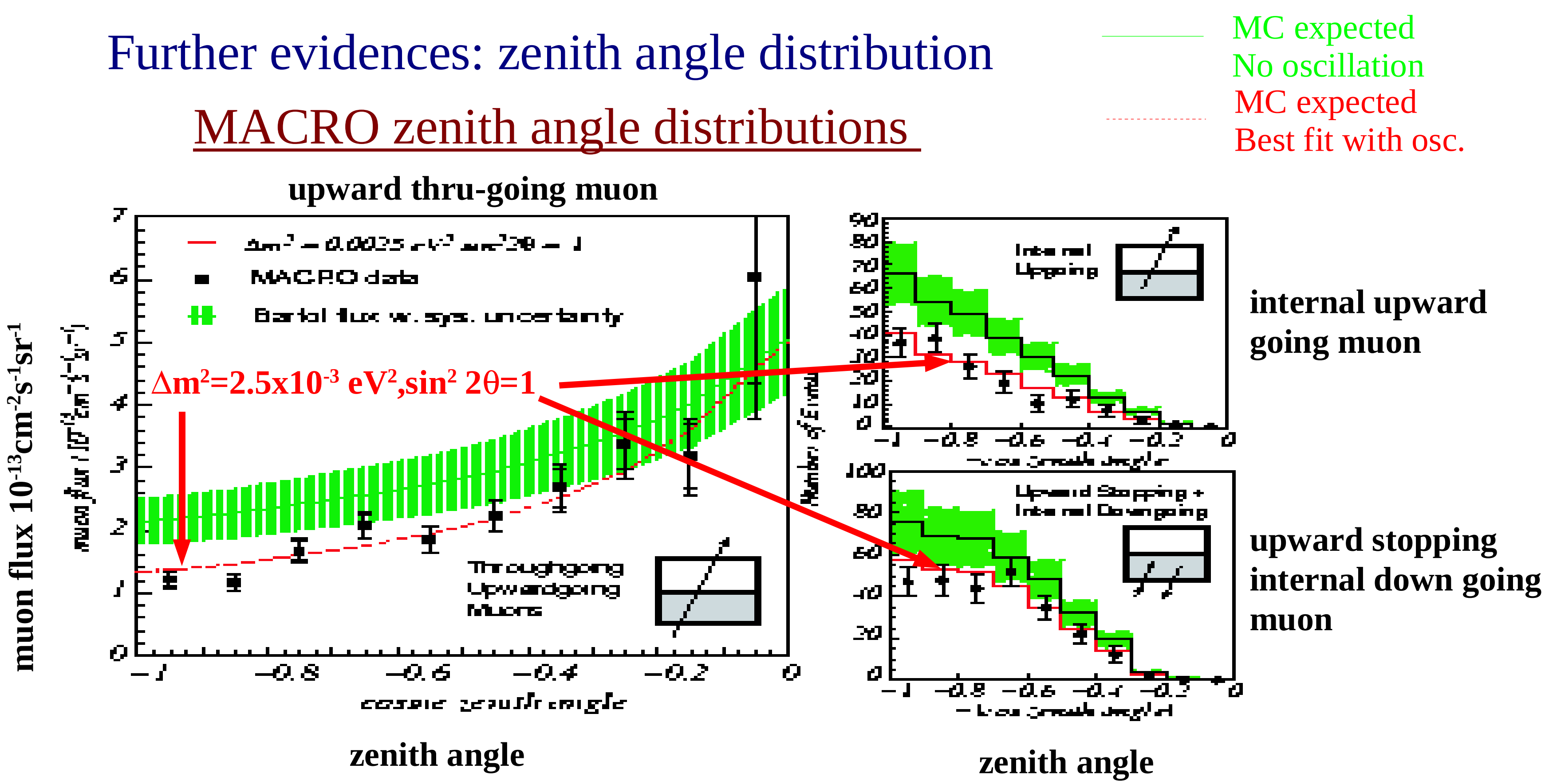


•Neutrino Oscillation

- 2 flavor oscillation: $\nu_\mu \rightarrow \nu_\tau$ disappearnce

Further evidences: zenith angle distribution

MACRO zenith angle distributions

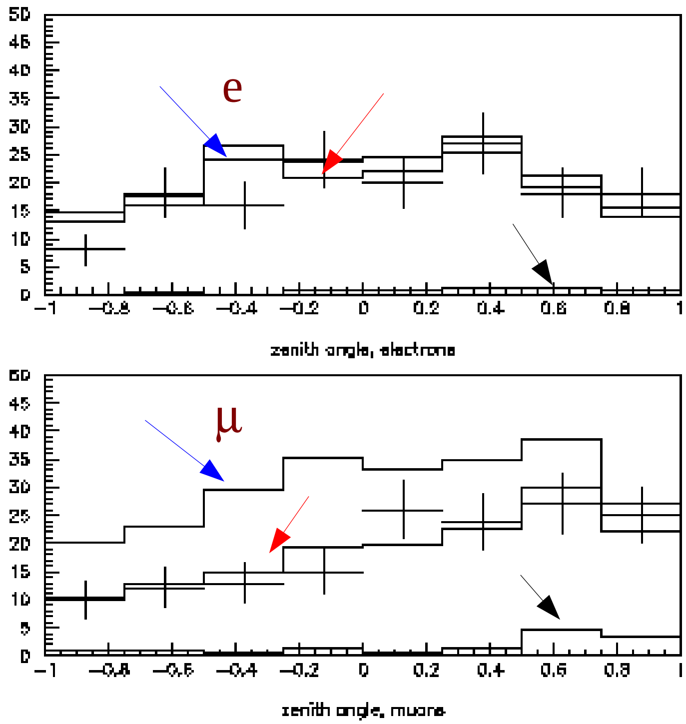


•Neutrino Oscillation

- 2 flavor oscillation: $\nu_\mu \rightarrow \nu_\tau$ disappearnce

Further evidences: zenith angle distribution

Soudan 2 zenith angle distributions



Best fit,osc

MC, no osc

Background

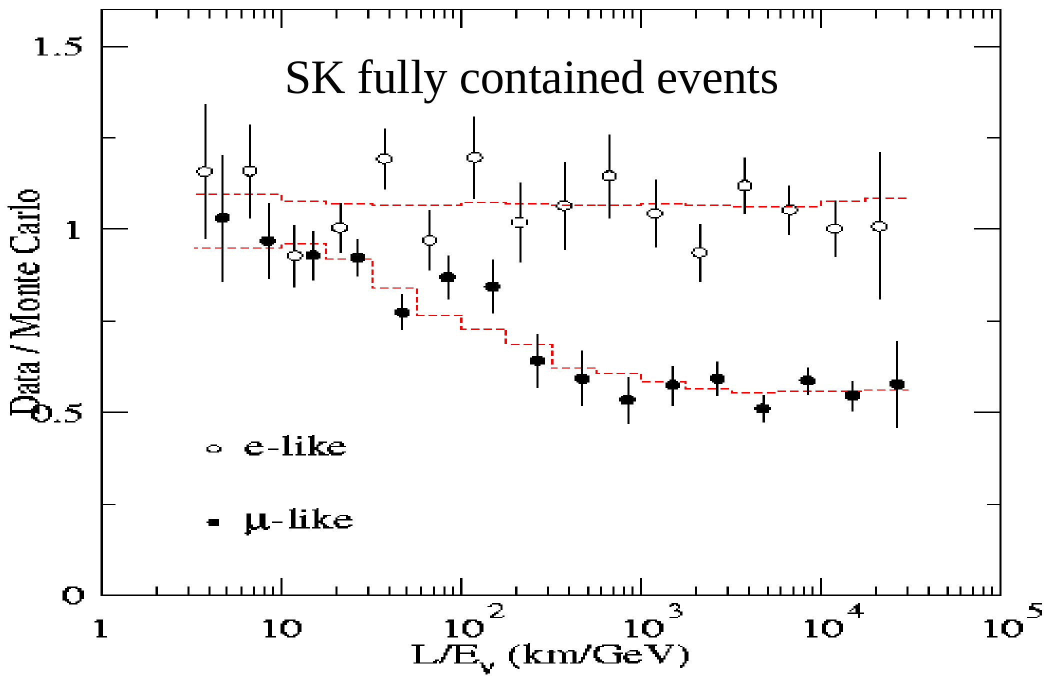
•Neutrino Oscillation

- 2 flavor oscillation: $\nu_\mu \to \nu_\tau$ disappearance

Further evidences: L/E distribution

SK L/E distribution

MC expected
Best fit with osc.



•Neutrino Oscillation

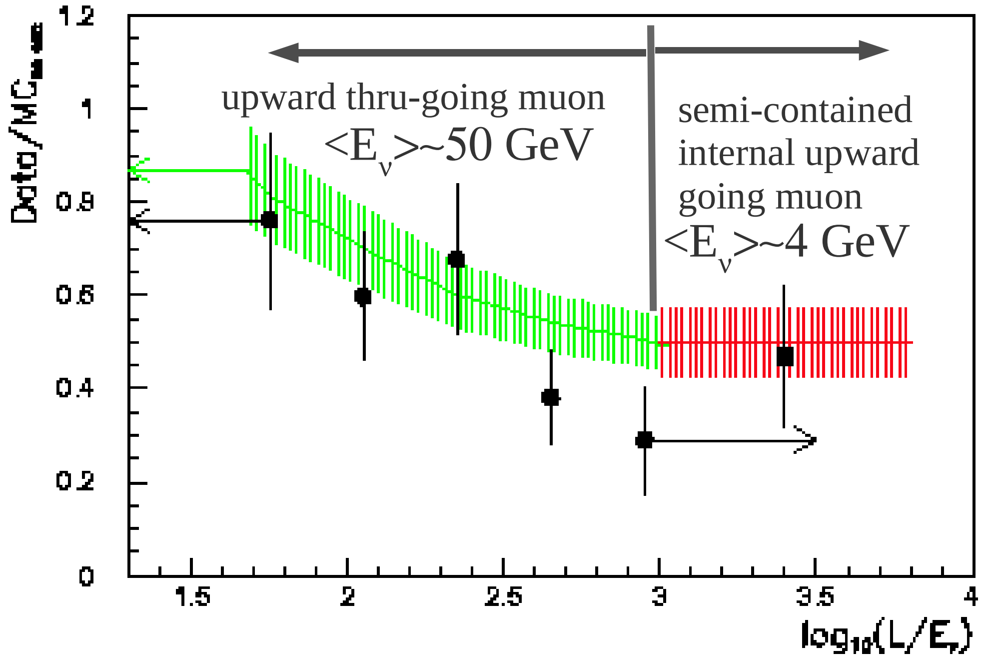
- 2 flavor oscillation : $\nu_\mu \rightarrow \nu_\tau$ disappearance

Further evidences: L/E distribution

MACRO L/E distribution

Best fit with oscillation

Best fit with oscillation

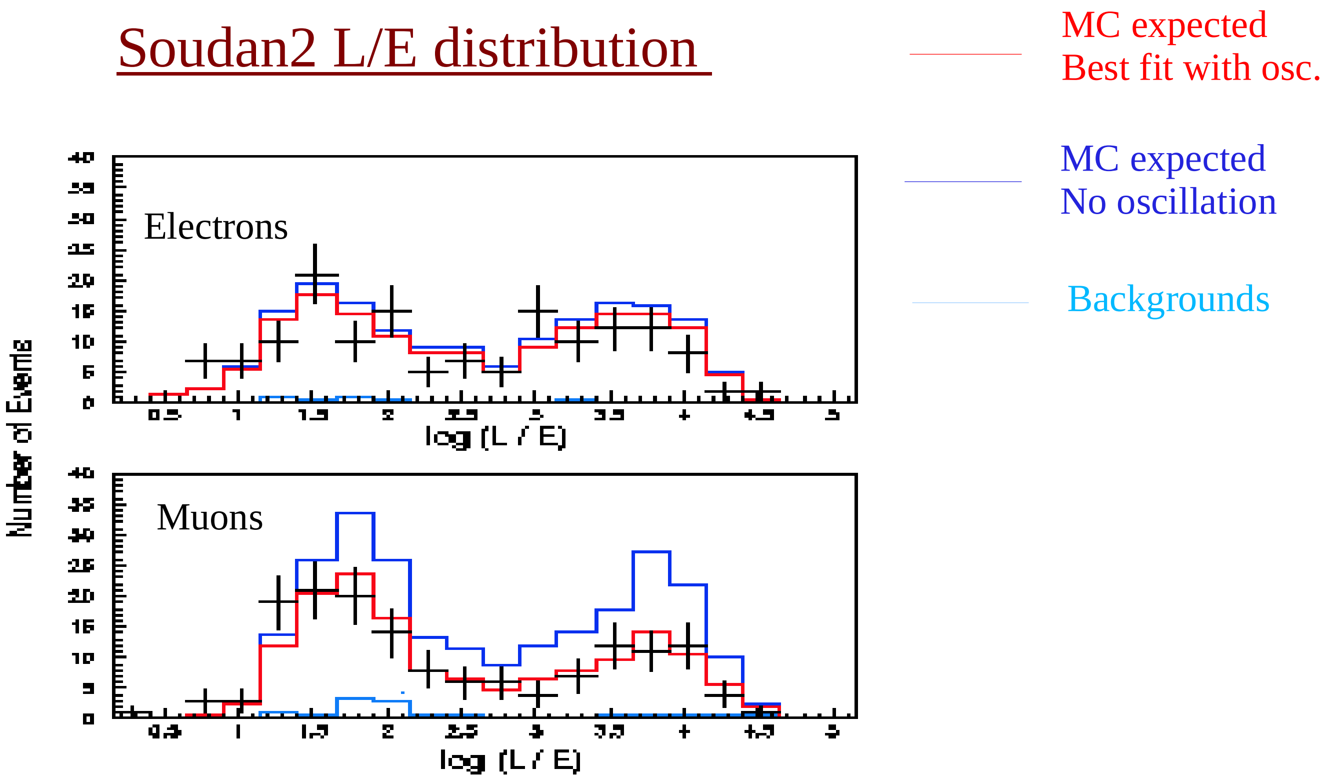


•Neutrino Oscillation

- 2 flavor oscillation: $\nu_\mu \rightarrow \nu_\tau$ disappearance

Further evidences: L/E distribution

Soudan2 L/E distribution

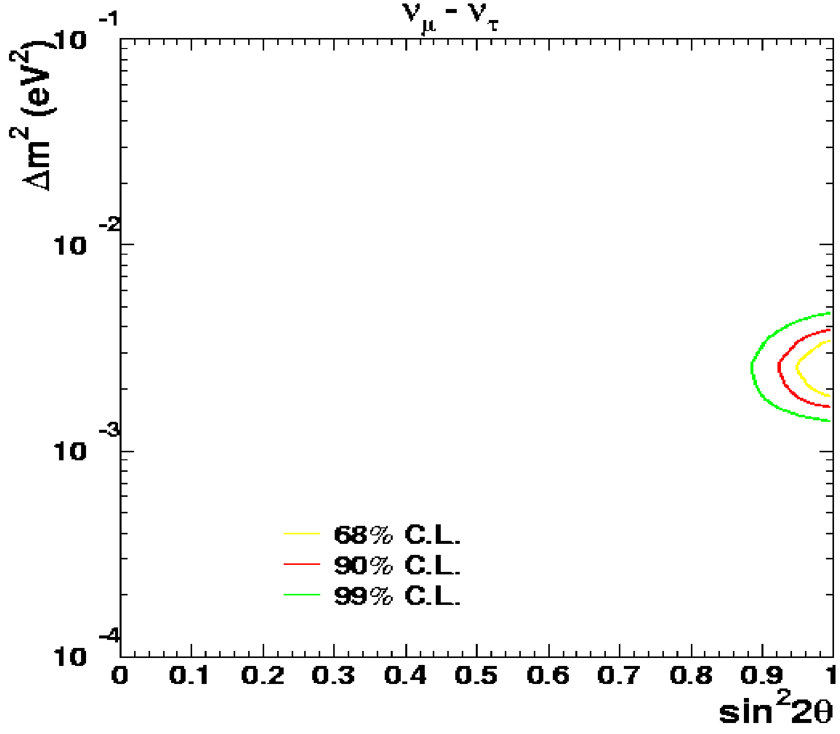


•Neutrino Oscillation

- 2 flavor oscillation: $\nu_\mu \rightarrow \nu_\tau$ disappearance

Oscillation parameters:

SK FC+PC+multi-Ring+upmu



$\nu_\mu \rightarrow \nu_\tau$ oscillation

Best fit

$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 $\sin^2 2\theta = 1.0$

χ^2_{min} =163.2/170 d.o.f

No oscillation

χ^2_{min} =456.5/172 d.o.f

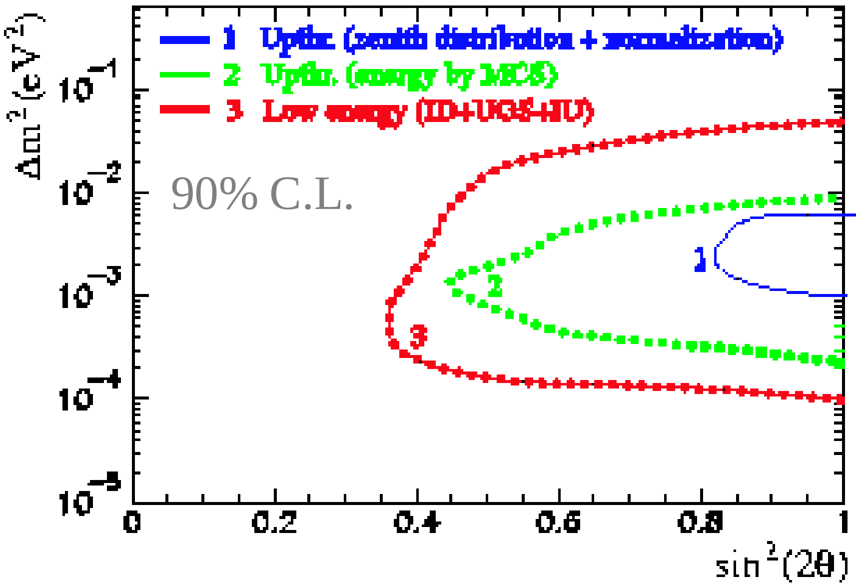
•Neutrino Oscillation

- 2 flavor oscillation: $\nu_\mu \rightarrow \nu_\tau$ disappearance

Oscillation parameters:

MACRO up-thru mu+lowE mu

$\nu_\mu \rightarrow \nu_\tau$ oscillation



Low energy muon

Upward thru-going muon: zenith angle+normalization

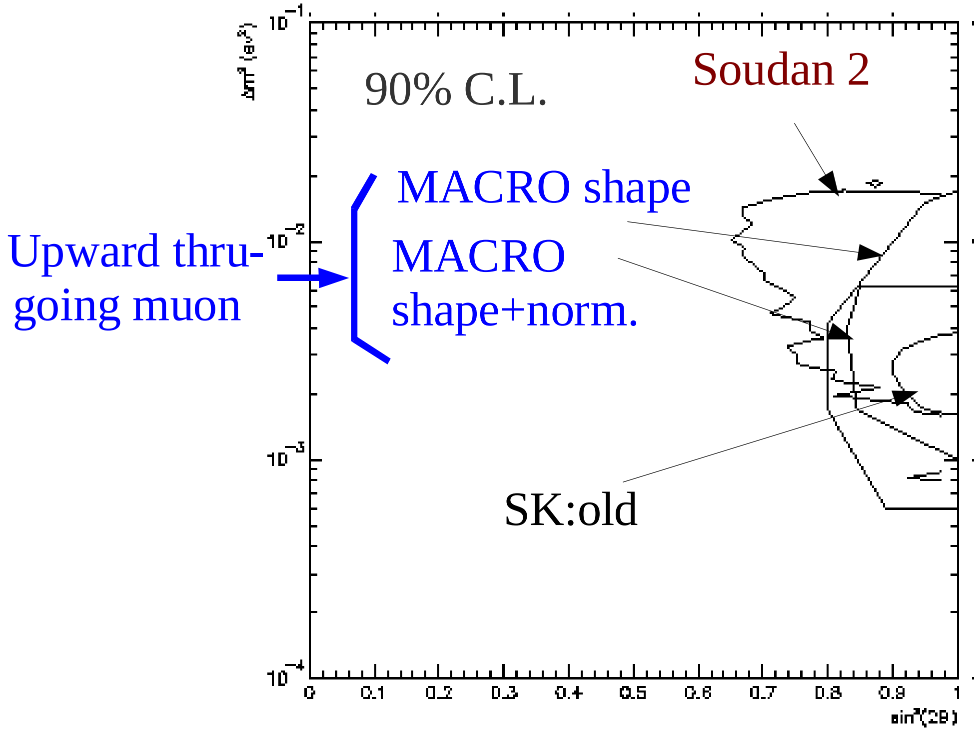
Upward thru-going muon: with energy by multi-Coulomb scattering

•Neutrino Oscillation

- 2 flavor oscillation: $\nu_\mu \rightarrow \nu_\tau$ disappearance

Oscillation parameters:

SK+MACRO+Soudan 2

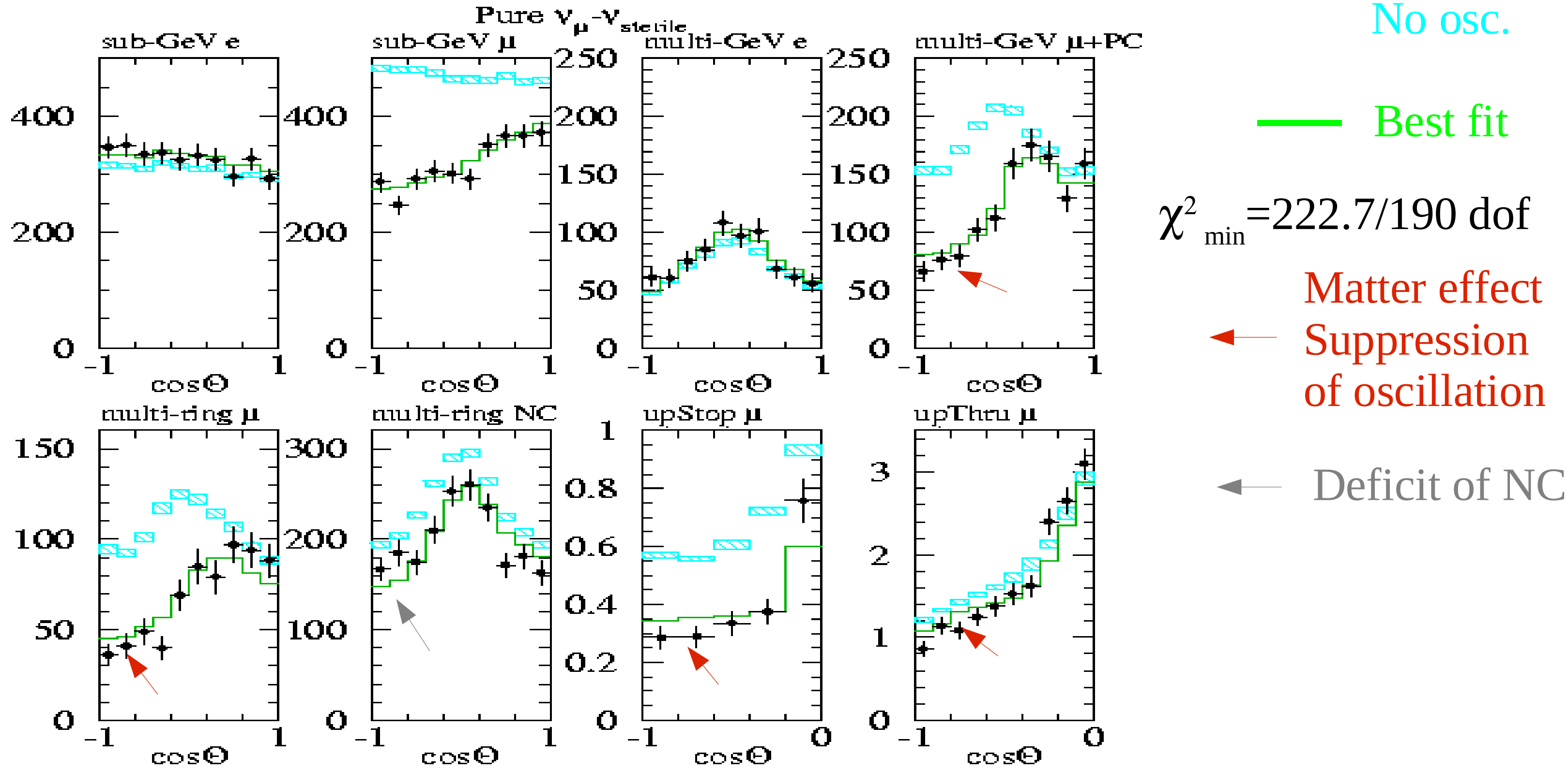


$\nu_\mu \rightarrow \nu_\tau$ oscillation

•Neutrino Oscillation

- Oscillation to admixture state: $\nu_\mu \rightarrow \cos\xi\ \nu_\tau + \sin\xi\ \nu_s$

$\nu_\mu \rightarrow \nu_s\ \sin^2\xi=1$



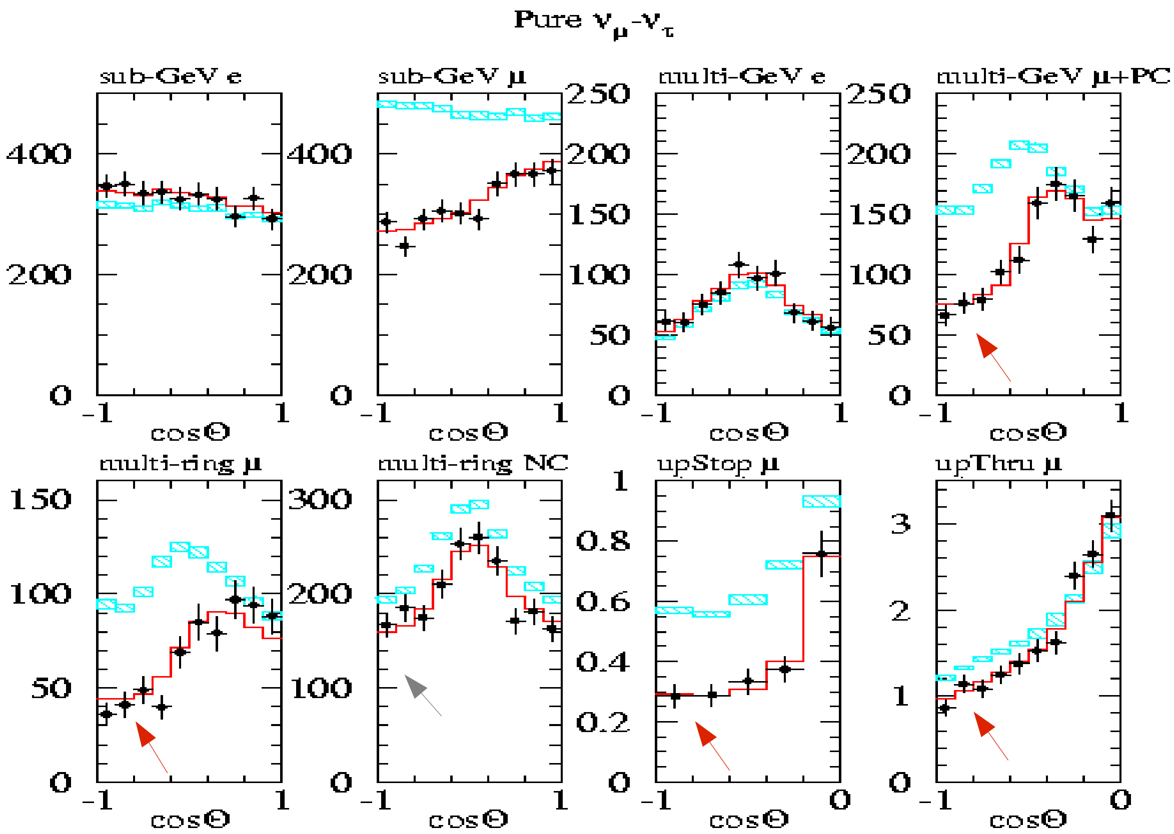
χ^2_{min}=222.7/190 dof

oscillation to admixture state

•Neutrino Oscillation

- Oscillation to admixture state: $\nu_\mu \rightarrow \cos\xi\ \nu_\tau + \sin\xi\ \nu_s$

$\nu_\mu \rightarrow \nu_\tau\ \sin^2\xi = 0$



MC
No osc.

Best fit

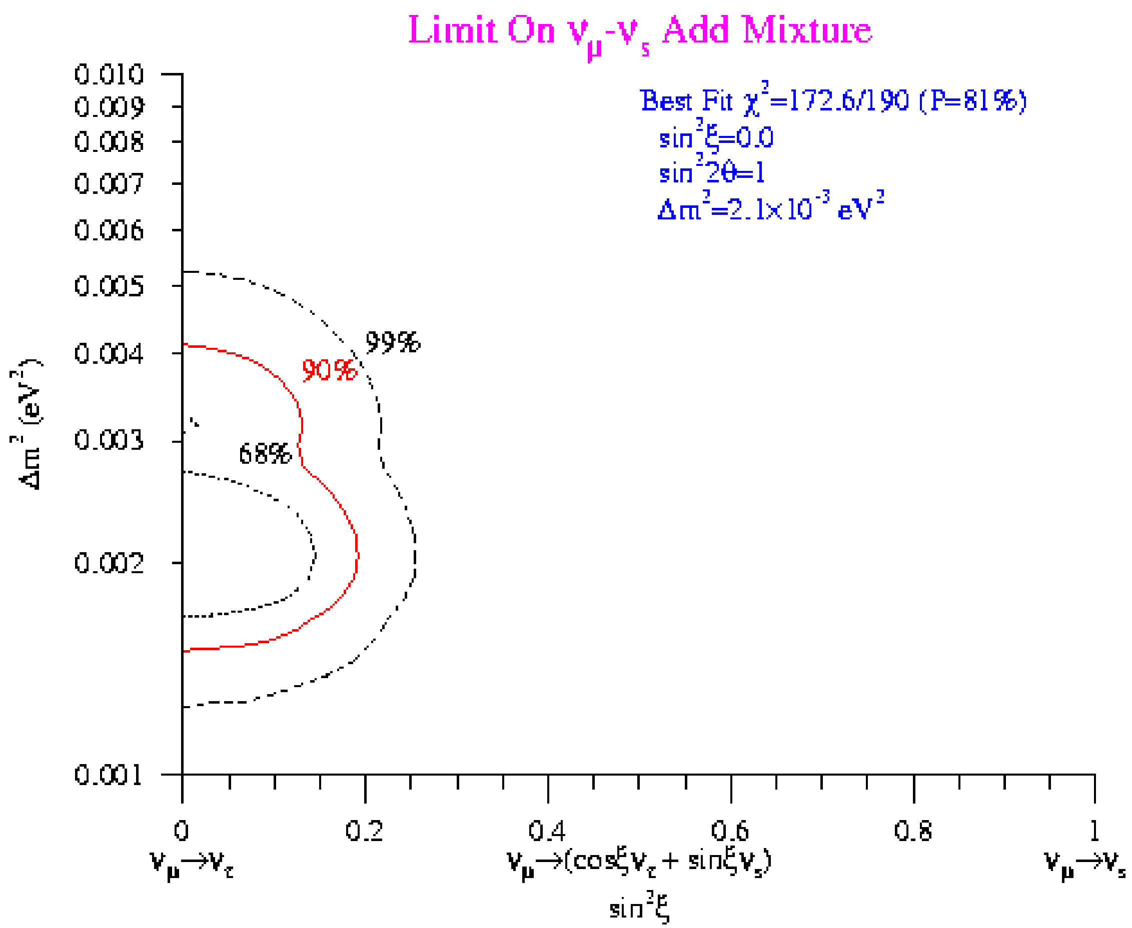
χ^2_{min}=172.6/190 dof

Matter effect;
Suppression
of oscillation
in sterile case

Deficit of NC
in sterile case

•Neutrino Oscillation

- Oscillation to admixture state: $\nu_\mu \rightarrow \cos\xi\ \nu_\tau + \sin\xi\ \nu_s$



χ^2_{min}=172.6/190 dof

$\sin^2\xi$=0.0

$\sin^2 2\theta$=1.0

$\Delta m^2 = 2.1\text{x}10^{-3}\ eV^2$

•Neutrino Oscillation

• $\nu_\mu \to \nu_\tau$ appearance : SK

Three independent but correlated analyses:

→
- Shape analysis based on energy flow + likelihood
- Standard variables + likelihood
- Standard variables + neural network

τ events appear mostly in multi-ring e-like events because:

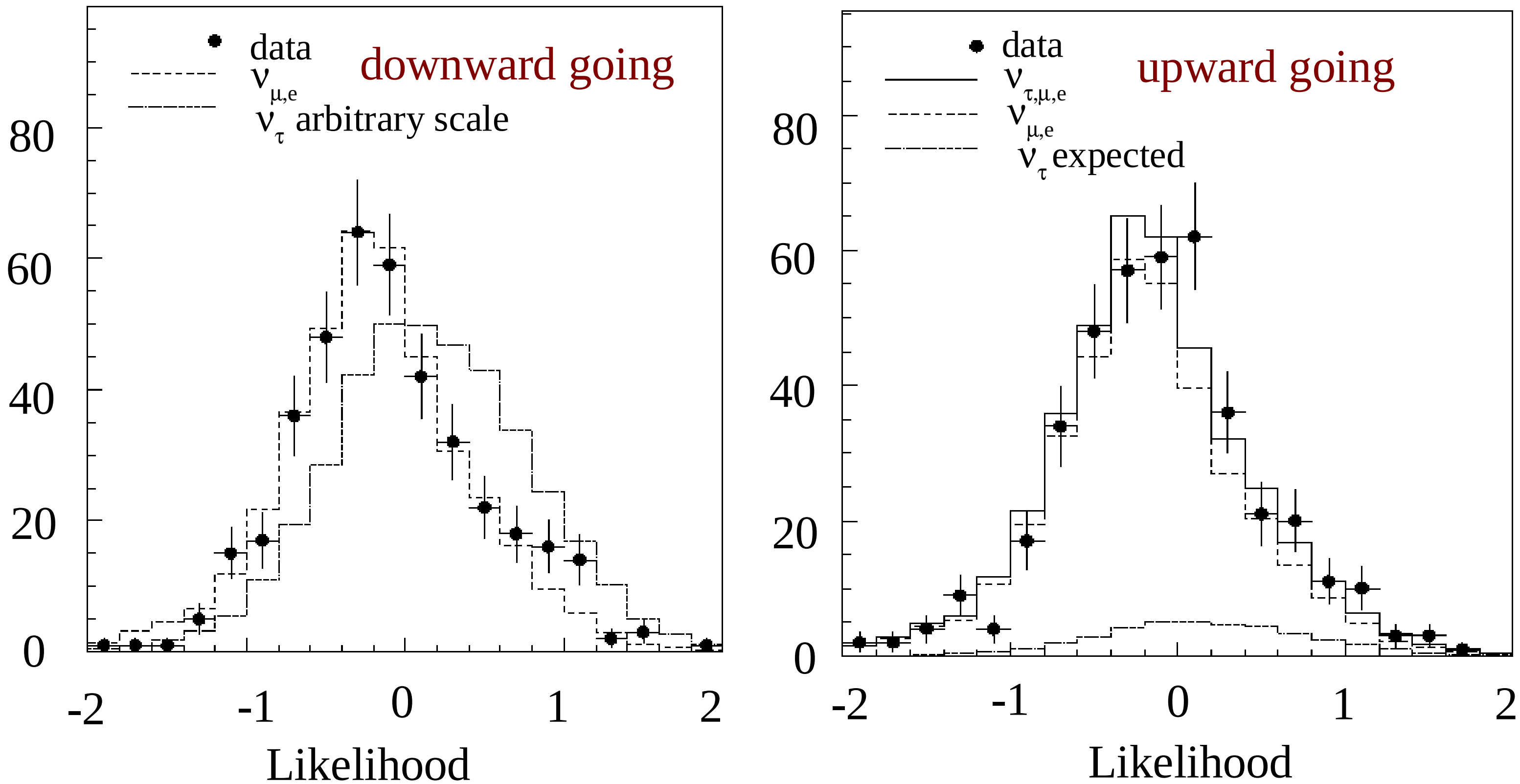
- Majority of τ decays are multi-prong events 3.3 πs per event
- τ is much heavier than electron or muon-> DIS-> more particles 6.1 πs per event
- Clusters of particles look like electrons 82% showering

tau appearance

•Neutrino Oscillation

- $\nu_\mu \rightarrow \nu_\tau$ appearance : SK (preliminary)

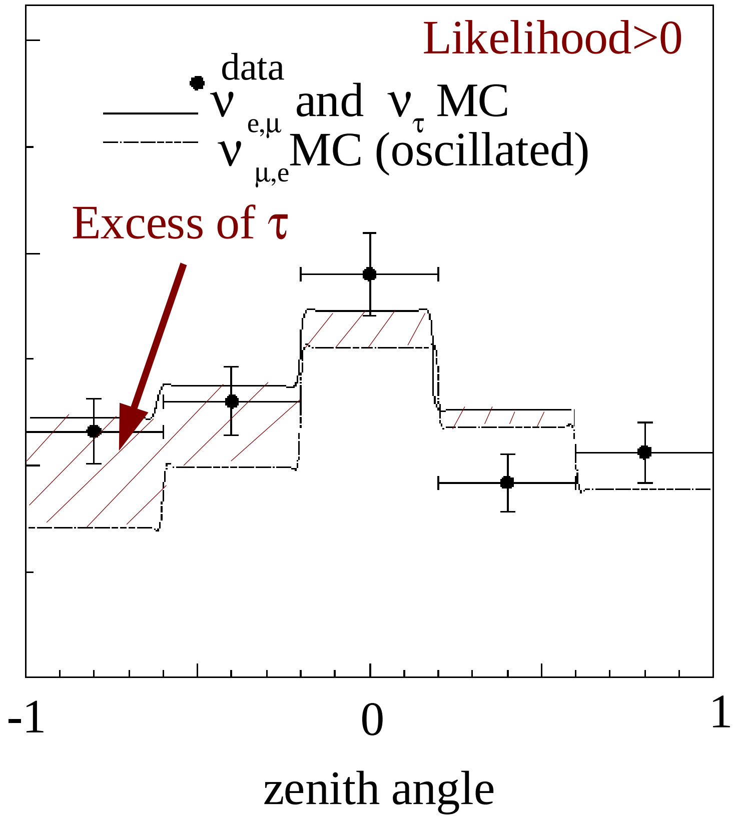
Shape /energy flow analysis: Likelihood



•Neutrino Oscillation

- $\nu_\mu \rightarrow \nu_\tau$ appearance : SK (preliminary) 1489 days

Zenith angle distribution after all cuts



Fitted τ excess : 43.4 +15-14 events

τ produced : 135 +47-44 events

$\nu_{\mu,e}$ normalization:1.05+-0.13

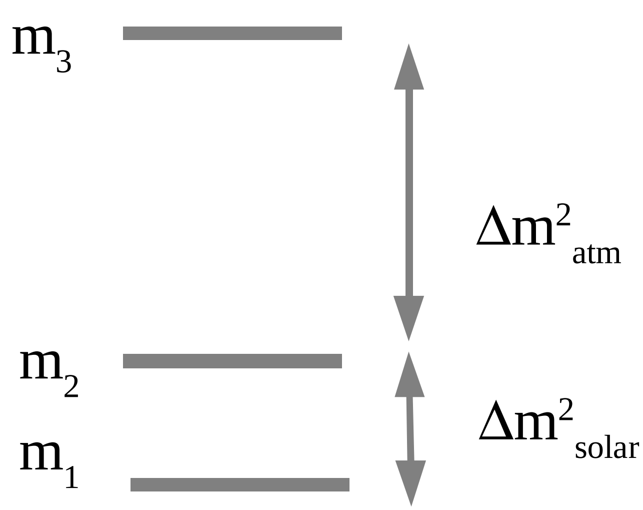
Fitted Δm^2 :2.5+4.0-1.5x10^{-3} eV^2

All the methods give consistet results

3 flavor oscillation

•Neutrino Oscillation

3 flavor oscillation



Basic assumption:

- $\Delta m^2_{23} = \Delta m^2_{atm} > \sim 10^{-3}\ eV^2$
- $\Delta m^2_{12} = \Delta m^2_{solar} = \sim 0\ eV^2$

Oscillation parameters:

- $\Delta m^2 = \Delta m^2_{23} = \Delta m^2_{13}, \theta_{13}, \theta_{23}$

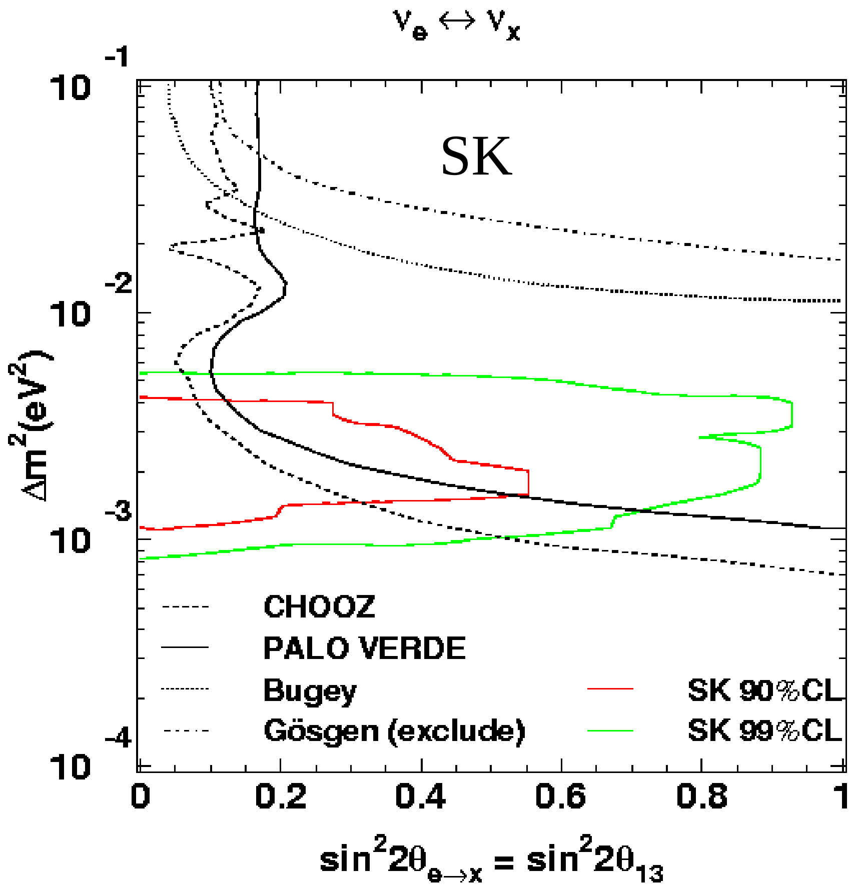
Oscillation probabilities:

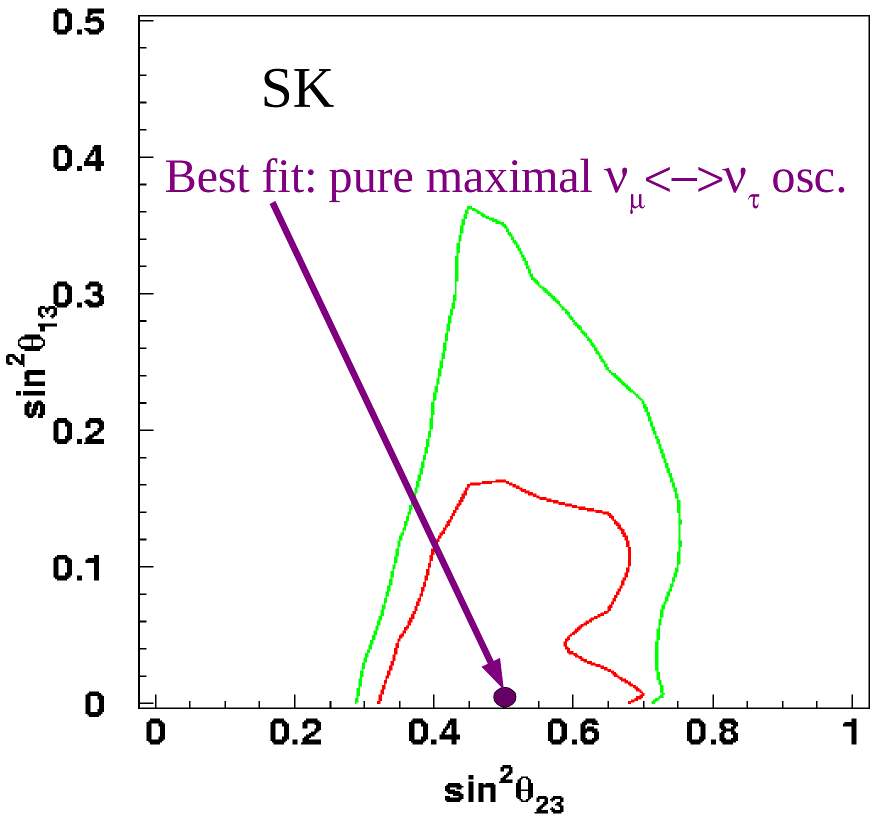
- $P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\Delta m^2 L/E)$
- $P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2 L/E)$
- $P(\nu_\tau \to \nu_e) = \sin^2 2\theta_{13} \cos^2\theta_{23} \sin^2(1.27\Delta m^2 L/E)$

•Neutrino Oscillation

3 flavor oscillation

Data : a similar sample to those used for 2 flavor oscillation analysis





•Neutrino Decay

- Neutrino mixing + decay

Models:

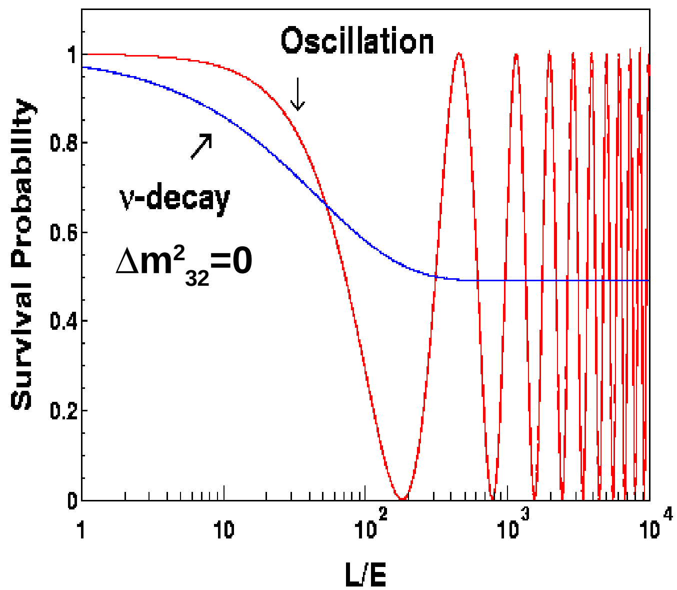
- $\nu_1 \sim \nu_e$
- $\nu_\mu \sim \sin\theta\ \nu_2 + \cos\theta\ \nu_3$
- ν_3 decays to a state with which it does not mix ν_4 (Δm^2_{32}=0)
- ν_3 decays to ν_2 (Δm^2_{32}=+oo)

Survival probability:

$$P(\nu_\mu \to \nu_\mu) =$$

$$[cos^2\theta + sin^2\theta \cdot exp(-\frac{m_3}{2\tau_3}\frac{L}{E})]^2(\Delta m^2_{32} = 0)$$

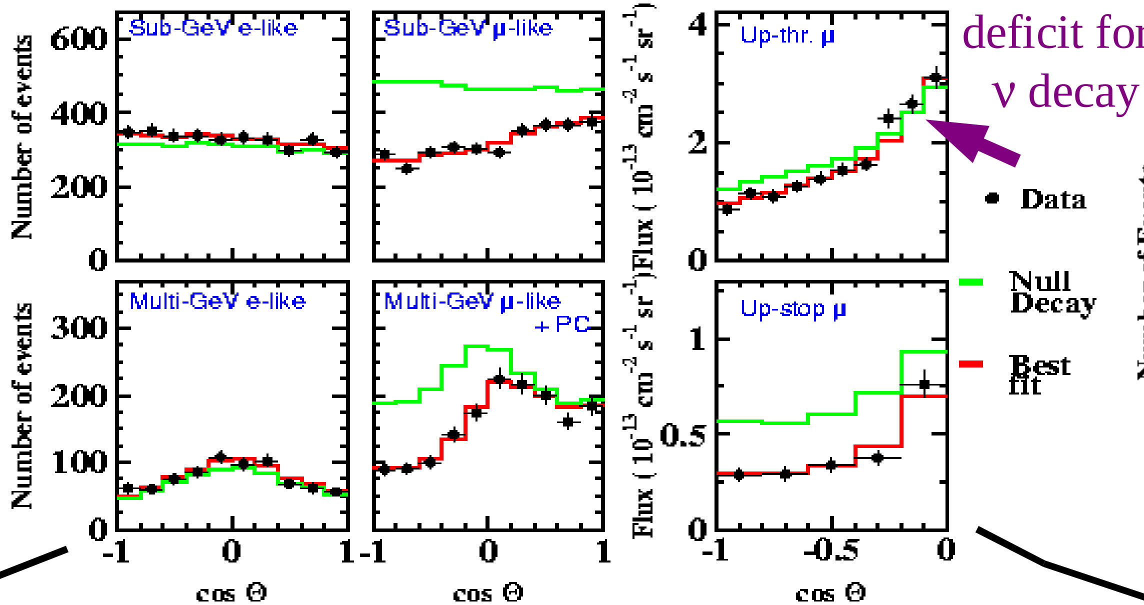
$$sin^4\theta + cos^4\theta \cdot exp(-\frac{m_3}{2\tau_3}\frac{L}{E})(\Delta m^2_{32} = \infty)$$

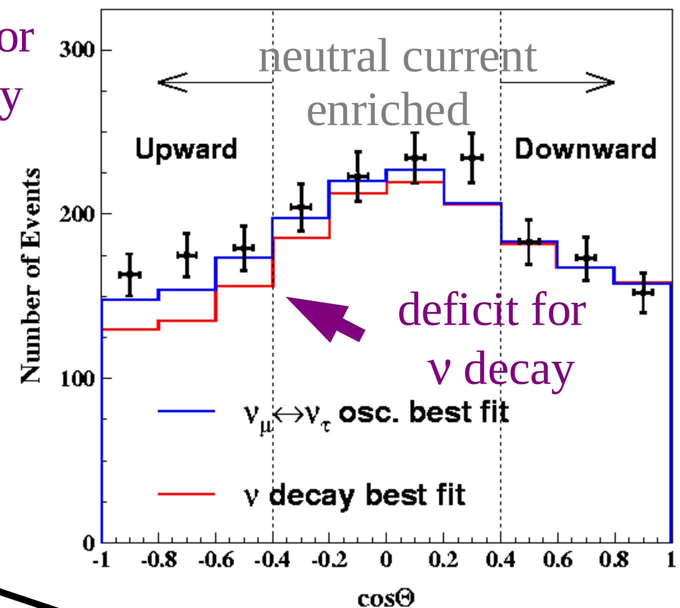


•Neutrino Decay

- Neutrino mixing + decay

$\Delta m^2_{32}=0$; zenith angle distributions





$\Delta m^2_{32}=0$

$\chi^2_{min}=141.5/152$ dof

$\sin^2\theta=0.33$

$m_3/\tau_3=1.0\times10^{-2}$ GeV/km

$\Delta m^2_{32}=\infty$

$\chi^2_{min}=209.9/152$ dof

$\sin^2\theta=0.48$

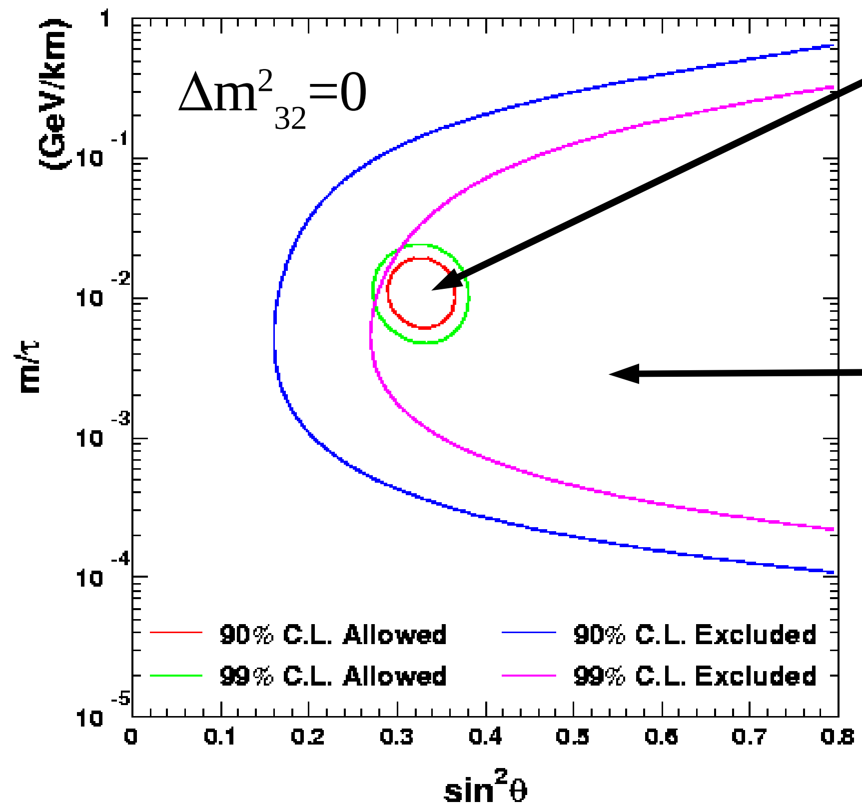
$m_3/\tau_3=3.2\times10^{-2}$ GeV/km

oscillation

$\chi^2_{min}=136.7/152$ dof

•Neutrino Decay

- Neutrino mixing + decay



Allowed region:
FC 1-ring+PC+upmu

+

Excluded region:
NC enriched

99% CL allowed region almost excluded by 99% excluded region

•Conclusions

- Atmospheric neutrino anomaly observed by IMB,Kamiokande and Super-Kamiokande are also confirmed by Soudan 2 and MACRO which employed different detector technologies
- $\nu_\mu <-> \nu_\tau$ oscillation seems the primary source of of the anomaly as observed by SK and confirmed by Soudan 2 and MACRO
- Contribution of sterile neutrino is quite small
- Neutrino decay hypothesis is more or less excluded
- SK began to be sensitive to $\nu_\mu <-> \nu_\tau$ appearance events
- SK has enough sensitivity to do three-generation neutrino oscillation analysis