7. Atmospheric neutrinos and Neutrino oscillations

Corso "**Astrofisica delle particelle**"
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Università di Bologna. A.a. 2011/12

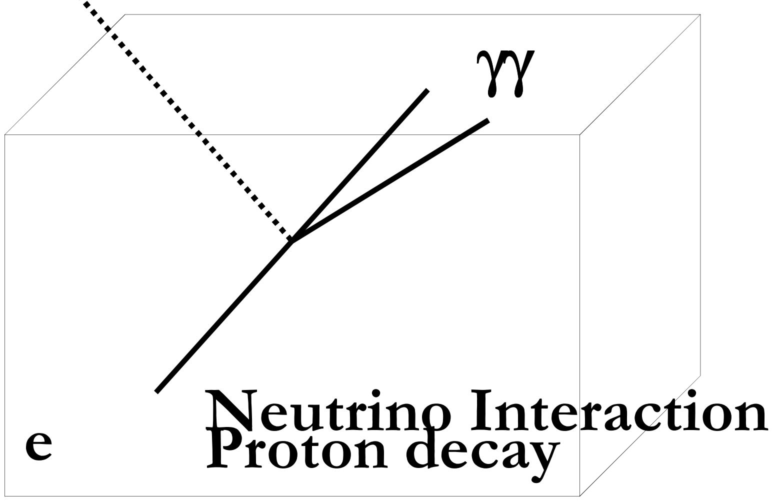
Outlook

- Some history
- Neutrino Oscillations
- How do we search for neutrino oscillations
- Atmospheric neutrinos
- 10 years of Super-Kamiokande
- Upgoing muons and MACRO
- Interpretation in terms on neutrino oscillations
    - Appendix: The Cherenkov light

7.1 Some history

- At the beginning of the '80s, some theories (GUT) predicted the proton decay with measurable livetime
- The proton was thought to decay in (for instance) $p \rightarrow e^+ \pi^0 \nu_e$
- Detector size: 10^3 m^3, and mass 1kt (=10^{31} p)
- The main background for the detection of proton decay were atmospheric neutrinos interacting inside the experiment

- Water Cerenkov Experiments (IMB, Kamiokande)
- Tracking calorimeters (NUSEX, Frejus, KGF)
- **Result: NO p decay ! But some anomalies on the neutrino measurement!**



7.2 Neutrino Oscillations

- Idea of neutrinos being massive was first suggested by B. Pontecorvo
- Prediction came from proposal of neutrino oscillations

Neutrinos are created or annihilated as W.I. eigenstates

$|\nu_e>$, $|\nu_\mu>$, $|\nu_\tau>$ =Weak Interactions (WI) eigenstats

$|\nu_1>$, $|\nu_2>$, $|\nu_3>$ =Mass (Hamiltonian) eigenstats

•Neutrinos propagate as a superposition of **mass** eigenstates

- **Weak eigenstates** $(\nu_e, \nu_\mu, \nu_\tau)$ **are expressed** as a combinations of the mass eigenstates (ν_1, ν_2, ν_3).
- These propagate with different frequencies due to their different masses, and different phases develop with distance travelled. ***Let us assume two neutrino flavors only.***
- The time propagation: $|\nu(t)\rangle = (|\nu_1\rangle, |\nu_2\rangle)$

$$\boxed{i\frac{d|\nu\rangle}{dt} = M|\nu(t)\rangle}$$

(eq.1)

$M =$ (2x2 matrix)

$$\begin{cases} M_{ii} = \sqrt{p^2 + m_i^2} \approx E_\nu + \dfrac{m_i^2}{2E_\nu} \\ M_{ij} = 0 \end{cases}$$

(eq.2)

Time propagation

eq.1 becames, using *eq.2)*

$$i\frac{d|\nu\rangle}{dt} = \left(E_\nu + \frac{m_i^2}{2E_\nu}\right)|\nu(t)\rangle$$

(eq.4)

whose solution is :

$$|\nu_i(t)\rangle = |\nu_i(0)\rangle e^{-i\varpi_i t}$$

(eq.5)

with

$$\varpi_i = \left(E_\nu + \frac{m_i^2}{2E_\nu}\right)$$

During propagation, the phase difference is:

$$\Delta\Phi_i = \frac{(m_2^2 - m_1^2)\cdot t}{2E_\nu}$$

(eq.6)

Time evolution of the “physical” neutrino states:

- Let us assume two neutrino flavors only (i.e. the electon and the muon neutrinos).
- They are linear superposition of the n1,n2 eigenstaten:

$$|\nu_e> = \cos\theta\,|\nu_1> + \sin\theta\,|\nu_2>$$

θ = mixing angle

$$|\nu_\mu> = -\sin\theta\,|\nu_1> + \cos\theta\,|\nu_2>$$

(eq.3)

- Using eq. 5 in eq. 3, we get:

$$\left|v_e\right\rangle = \cos\theta\left|v_1(0)\right\rangle e^{-i\varpi_1 t} + \sin\theta\left|v_2(0)\right\rangle e^{-i\varpi_{2i} t}$$

$$\left|v_\mu\right\rangle = -\sin\theta\left|v_1(0)\right\rangle e^{-i\varpi_1 t} + \cos\theta\left|v_2(0)\right\rangle e^{-i\varpi_{2i} t}$$

(eq.7)

- At t=0, eq. 7 becomes:

$$\boxed{\begin{aligned}
\left|\nu_e\right\rangle &= \cos\theta\left|\nu_1(0)\right\rangle + \sin\theta\left|\nu_2(0)\right\rangle \\
\left|\nu_\mu\right\rangle &= -\sin\theta\left|\nu_1(0)\right\rangle + \cos\theta\left|\nu_2(0)\right\rangle
\end{aligned}}$$

(eq.8)

- By inversion of eq. 8:

$$\boxed{\begin{aligned}
\left|\nu_1(0)\right\rangle &= \cos\theta\left|\nu_e(0)\right\rangle - \sin\theta\left|\nu_\mu(0)\right\rangle \\
\left|\nu_2(0)\right\rangle &= \sin\theta\left|\nu_e(0)\right\rangle + \cos\theta\left|\nu_\mu(0)\right\rangle
\end{aligned}}$$

(eq.9)

- For the experimental point of view (accelerators, reactors), a pure muon (or electron) state a t=0 can be prepared. For a pure ν_μ beam, eq. 9:

$$\boxed{\begin{aligned}
\left|\nu_1(0)\right\rangle &= -\sin\theta\left|\nu_\mu(0)\right\rangle \\
\left|\nu_2(0)\right\rangle &= \cos\theta\left|\nu_\mu(0)\right\rangle
\end{aligned}}$$

(eq.10)

The time evolution of the ν_μ state of eq. 8:

$$\left|\nu_\mu\right\rangle = \sin^2\theta\left|\nu_\mu(0)\right\rangle e^{-i\varpi_1 t} + \cos^2\theta\left|\nu_\mu(0)\right\rangle e^{-i\varpi_{2i} t}$$

(eq.11)

By definition, the probability that the state at a given time is a ν_μ is:

$$P_{\nu_\mu \nu_\mu} \equiv \left|\left\langle \nu_\mu^0 \middle| \nu_\mu^t \right\rangle\right|^2$$

(eq. 12)

- Using eq. 11, the probability:

$$P_{\nu_\mu \nu_\mu} \equiv \left|\left\langle \nu_\mu^0 \middle| \nu_\mu^t \right\rangle\right|^2 = \sin^4\theta + \cos^4\theta + \\ + \sin^2\theta \cos^2\theta \left(e^{i(\varpi_1-\varpi_2)t} + e^{-i(\varpi_1-\varpi_2)t}\right)$$

(eq. 13)

i.e. using trigonometry rules:

$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[\frac{(\varpi_1-\varpi_2)t}{2}\right]$$

(eq. 14)

Finally, using eq.5: $\varpi_i = \left(E_\nu + \frac{m_i^2}{2E_\nu} \right)$

$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2 \left[\frac{(m_2^2 - m_1^2)t}{4E_\nu} \right]$$

(eq. 15)

With the following substitutions in eq.15:

- **the neutrino path length L=ct (in Km)**
- **the mass difference $\Delta m^2 = m_2^2 - m_1^2$ (in eV^2)**
- **the neutrino Energy Eν (in GeV)**

$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2 \left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu} \right]$$

(eq. 16)

To see "oscillations" pattern:

$$\theta \neq 0$$

$$\left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu} \right] \approx \frac{\pi}{2}$$

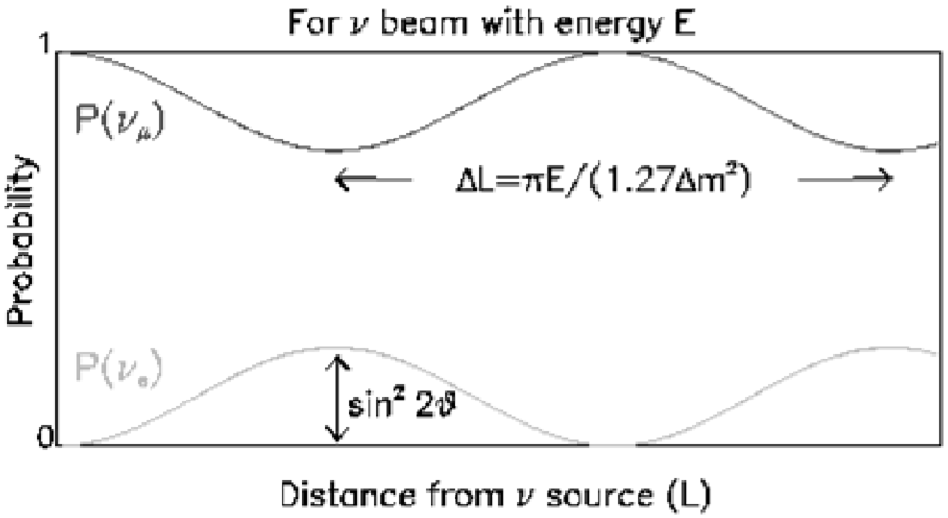
7.3 How do we search for neutrino oscillations?

...Depends Upon Two Experimental Parameters:

- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:

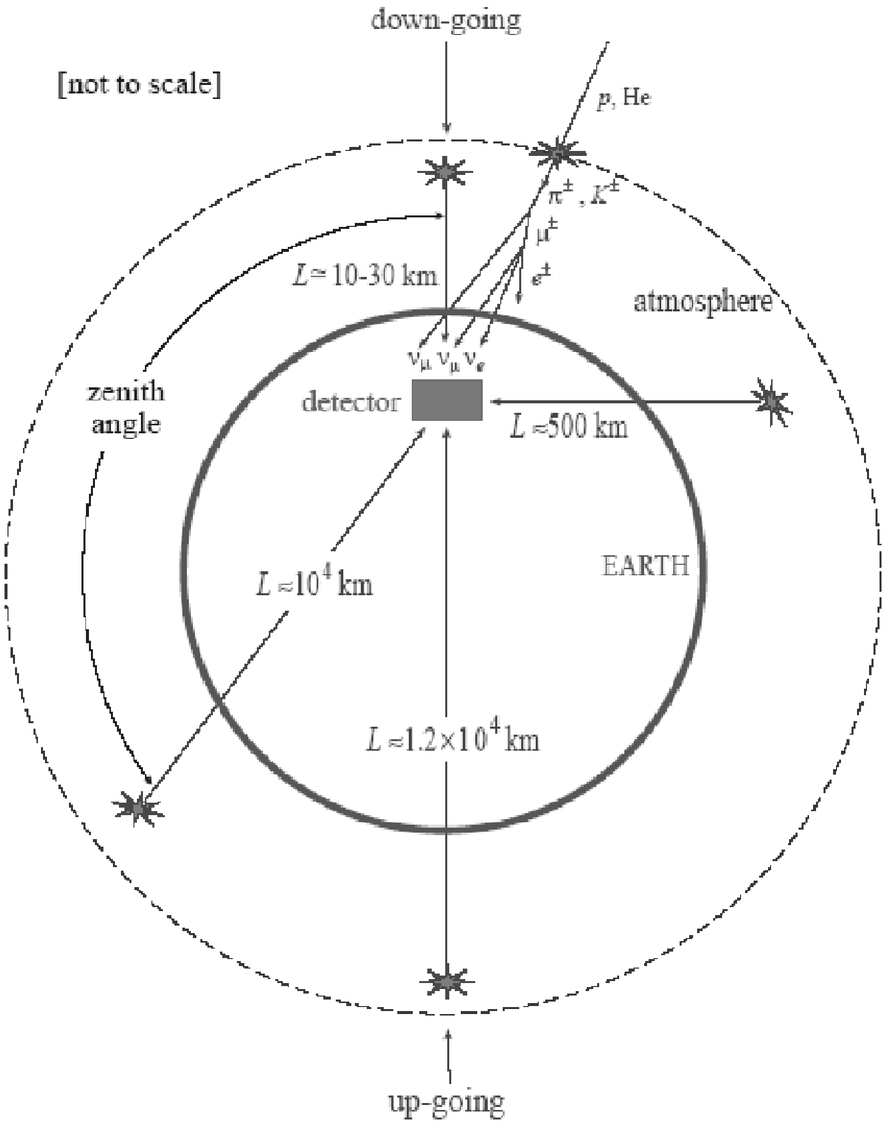
- $\Delta m^2 = m_2^2 - m_1^2$
- $\sin^2 2\theta$



The Δm^2 and $\sin^2 2\theta$ accessible
to ν_μ oscillation experiments
are set by the L, E, and ν_μ intensity available.

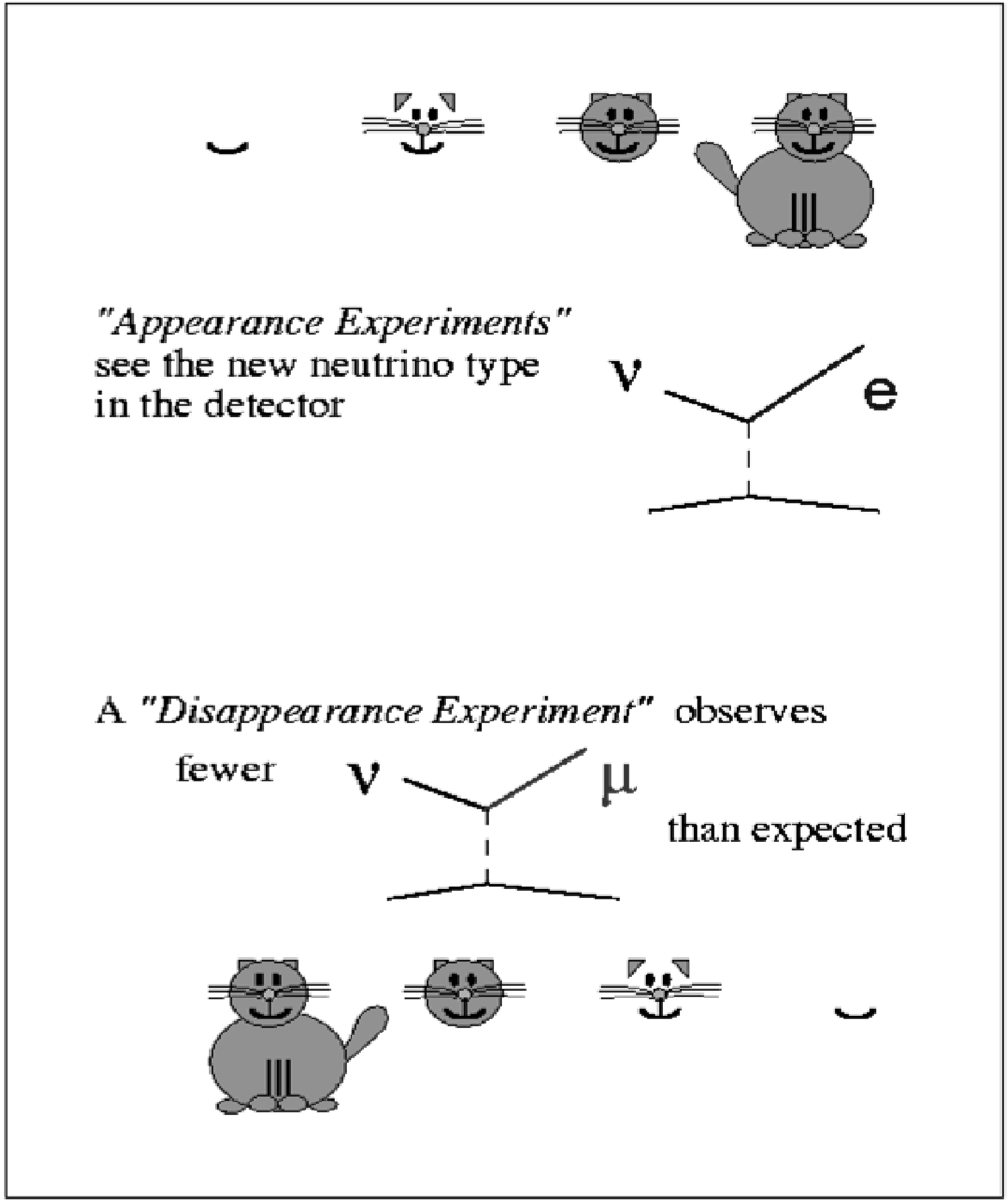
..with atmospheric neutrinos

- Δm^2, $\sin^2 2\Theta$ → from Nature;
- $E\nu$ = experimental parameter (energy distribution of neutrino giving a particular configuration of events)
- L = experimental parameter (neutrino path length from production to interaction)



$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[1.27\frac{\Delta m^2 \cdot L}{E_\nu}\right]$$

Appearance/Disappearance



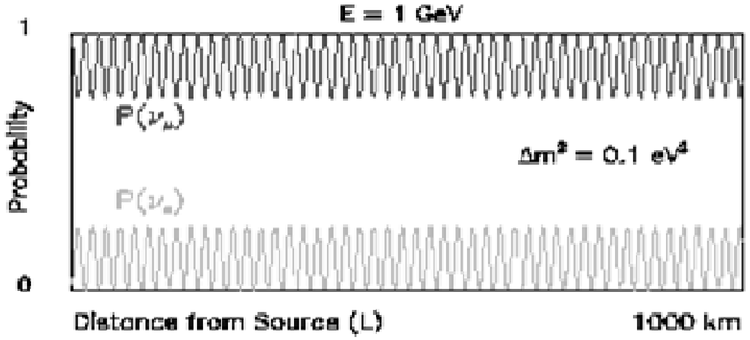
"Appearance Experiments" see the new neutrino type in the detector

A *"Disappearance Experiment"* observes fewer ν_μ than expected

$$\boxed{P_{\nu_\mu\nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[1.27\frac{\Delta m^2 \cdot L}{E_\nu}\right]}$$

- Small $\Delta m^2 \rightarrow$ small P_{osc}
  Unless the experiment has large L/E to compensate!

- Large $\Delta m^2 \rightarrow$ oscillations happen rapidly
  For a single ν energy:



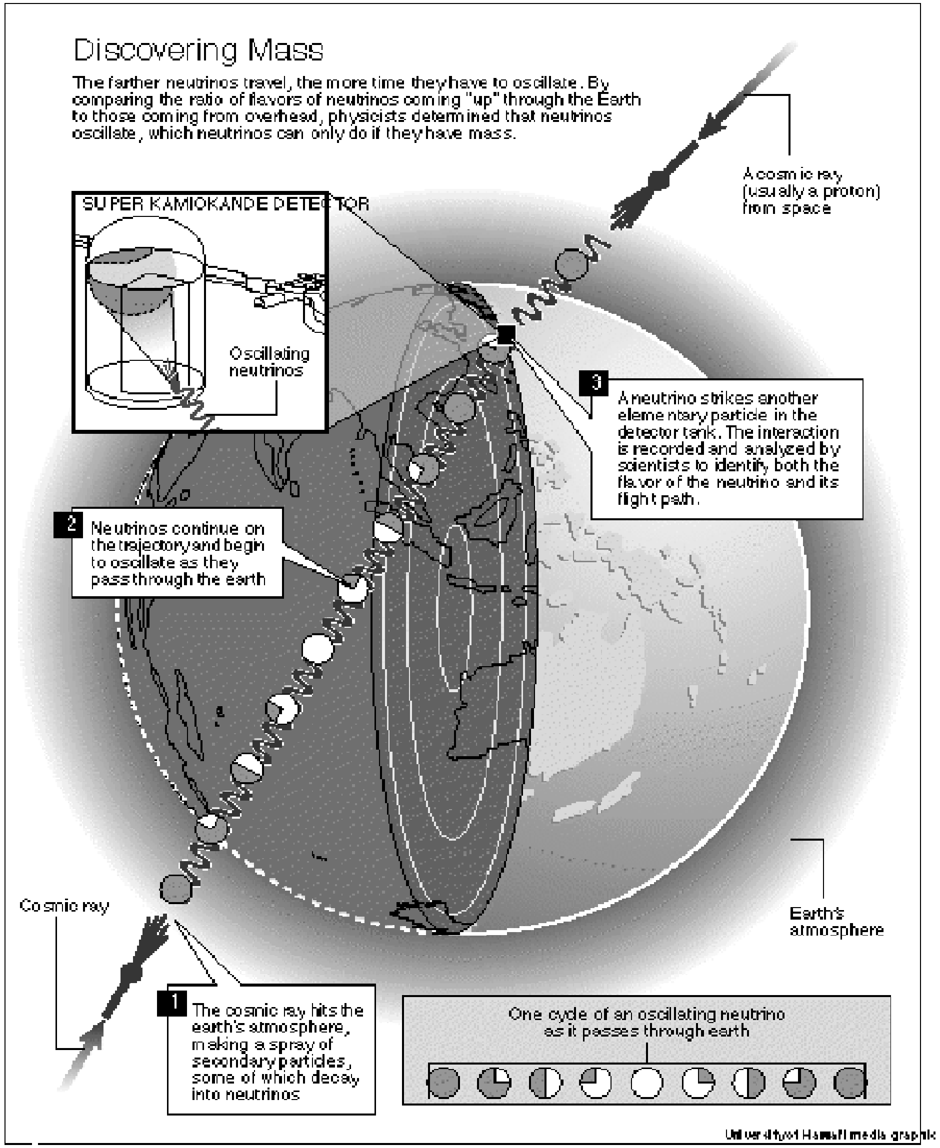
But beams have a wide E range,
detectors have finite resolution and large size:

. $$\langle \sin^2(1.27\Delta m^2 L/E)\rangle = 1/2$$

By choosing L/E too large,
You can lose sensitivity to Δm^2

- Small $\sin^2 2\theta \rightarrow$ small probability,
  So an experiment needs high statistics

7.4- Atmospheric neutrinos



Discovering Mass

The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.

1 The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos

2 Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth

3 A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.

One cycle of an oscillating neutrino as it passes through earth

University of Hawaii media graphic

The recipes for the evaluation of the atmospheric neutrino flux-

$$\pi^+ \to \mu^+ + \nu_\mu$$

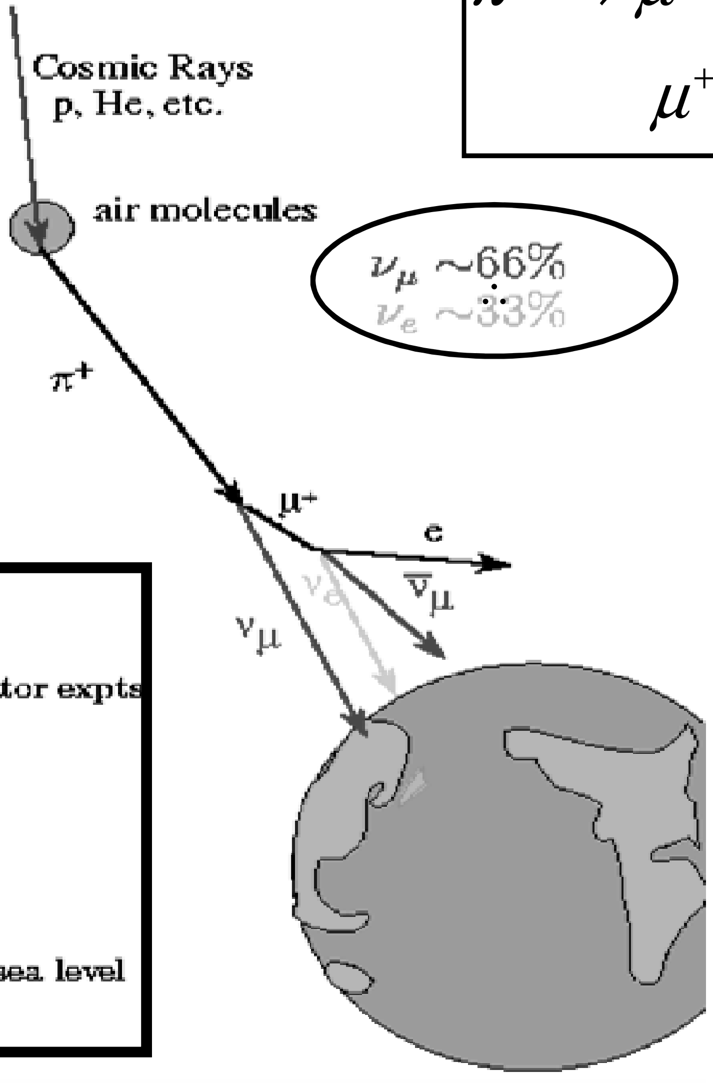
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

The Atmospheric Neutrino flux

We cannot measure the flux
of incoming neutrinos.
We have to rely on Monte Carlo...

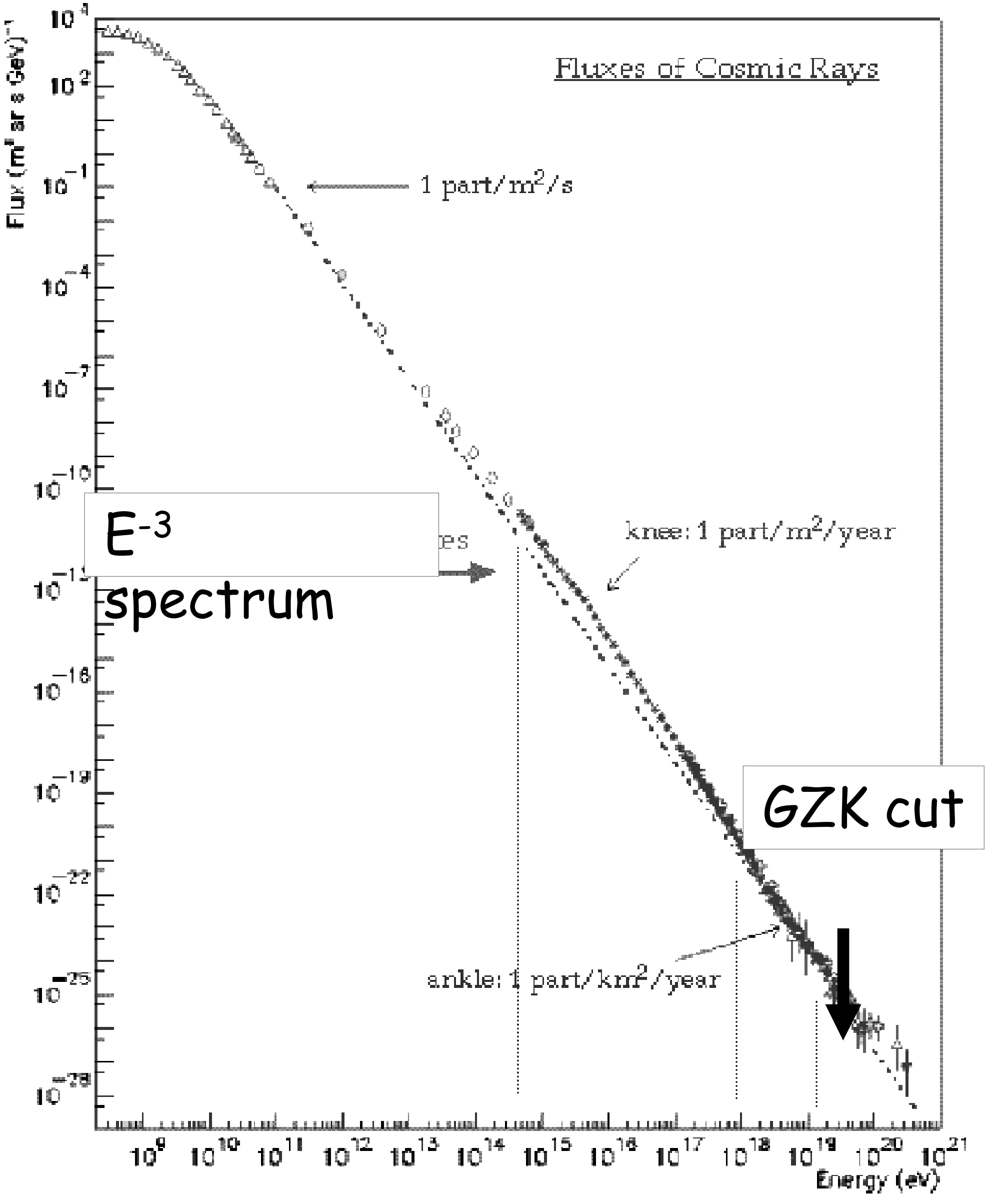
The flux Monte Carlos:

- Flux of primary cosmics from atmospheric expts
- Secondary production from accelerator expts
- Geomagnetic effects are included
- "1-dimensional" model
- Nuclear effects are not included
- Detector position is assumed to be sea level



$\nu_\mu \sim 66\%$
:
$\nu_e \sim 33\%$

i) The primary spectrum



$E < 10^{15}$ eV
Galactic

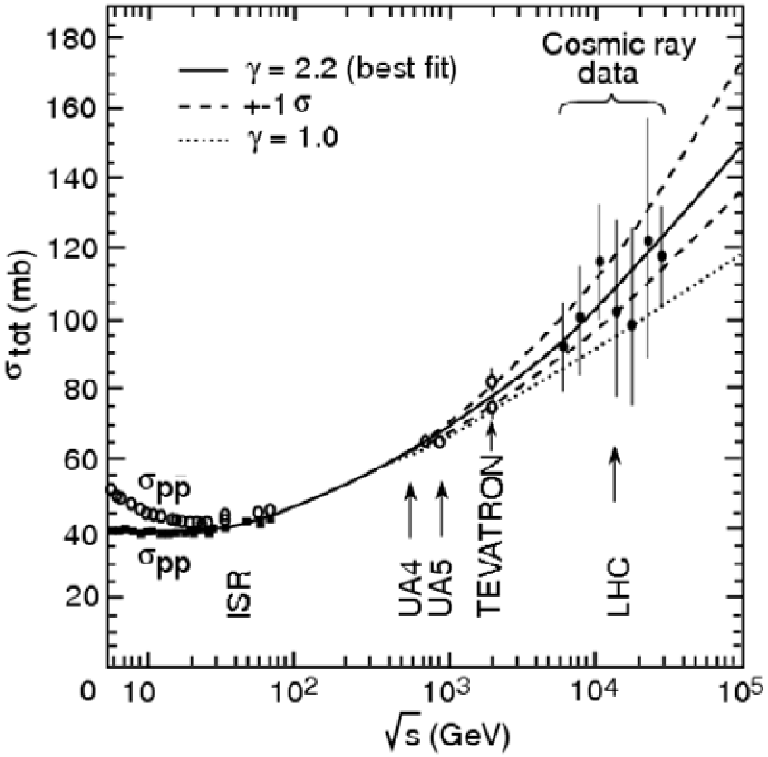
$5.\ 10^{19} < E < 3.\ 10^{20}$ eV

$10^{15} < E < 10^{18}$ eV
galactic ?

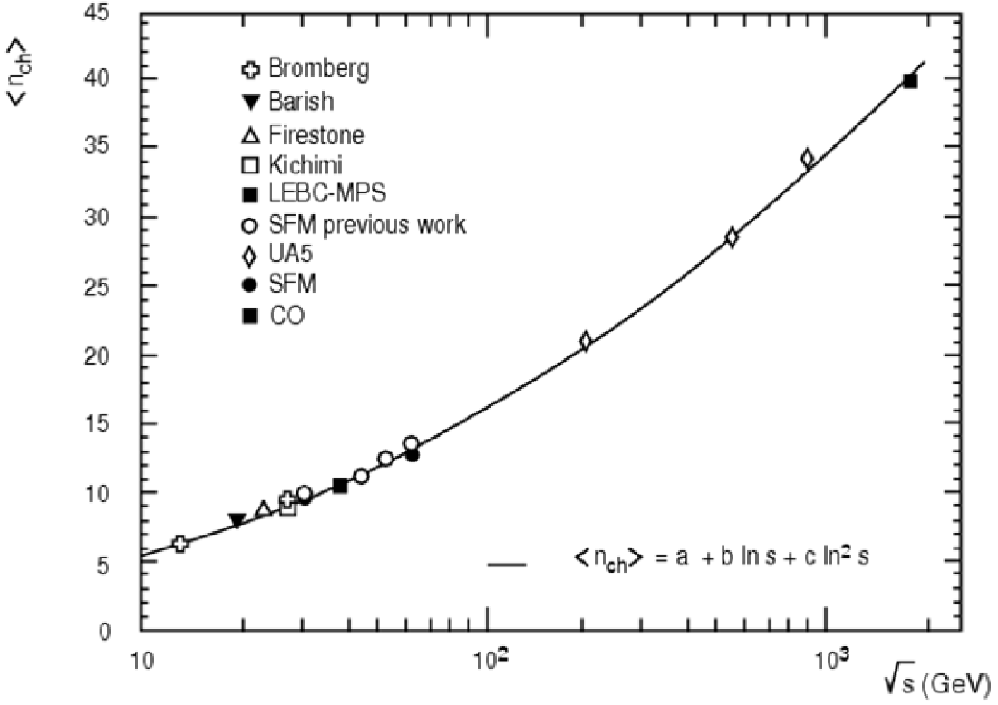
$E \geq 5.\ 10^{19}$ eV
Extra-Galactic?
Unexpected?

ii)- CR-air cross section

It needs a model of nucleus-nucleus interactions



pp Cross section versus center of mass energy.

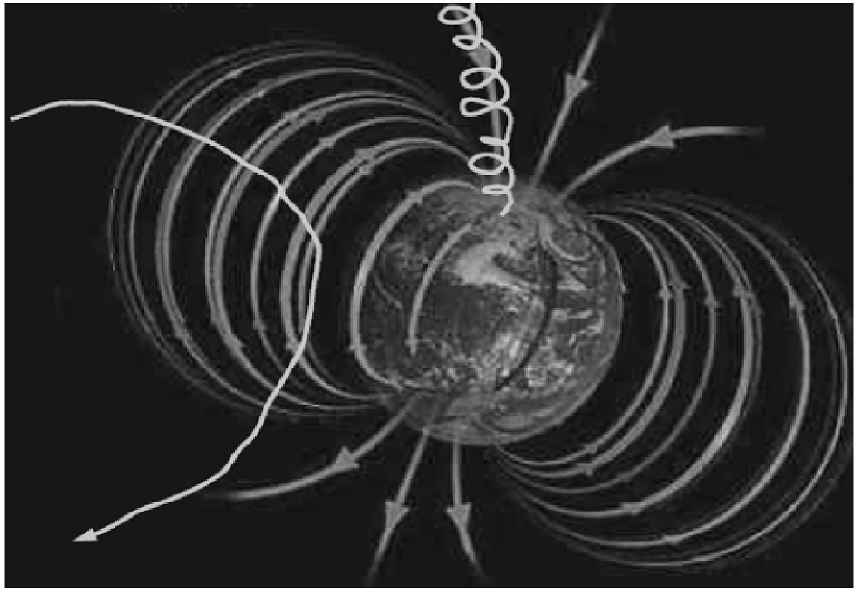


Average number of charged hadrons produced in pp (and $\bar{p}p$) collisions versus center of mass energy

iii) Model of the atmosphere

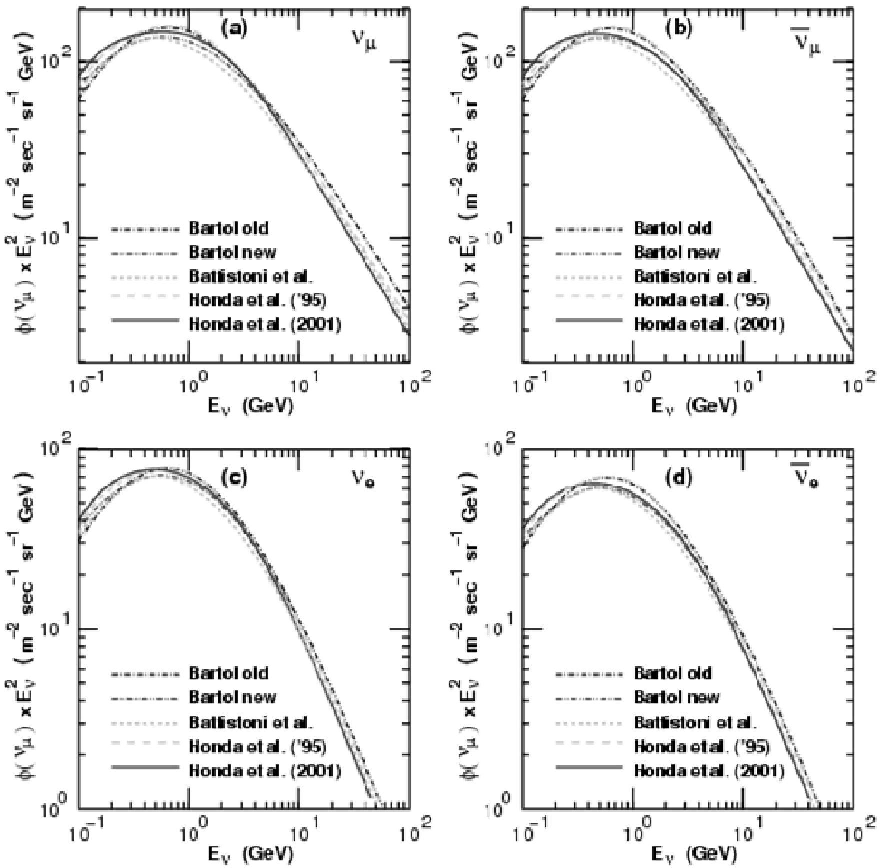
ATMOSPHERIC NEUTRINO PRODUCTION:

- high precision 3D calculations,
- refined geomagnetic cut-off treatment (also geomagnetic field in atmosphere)
- elevation models of the Earth
- different atmospheric profiles
- geometry of detector effects

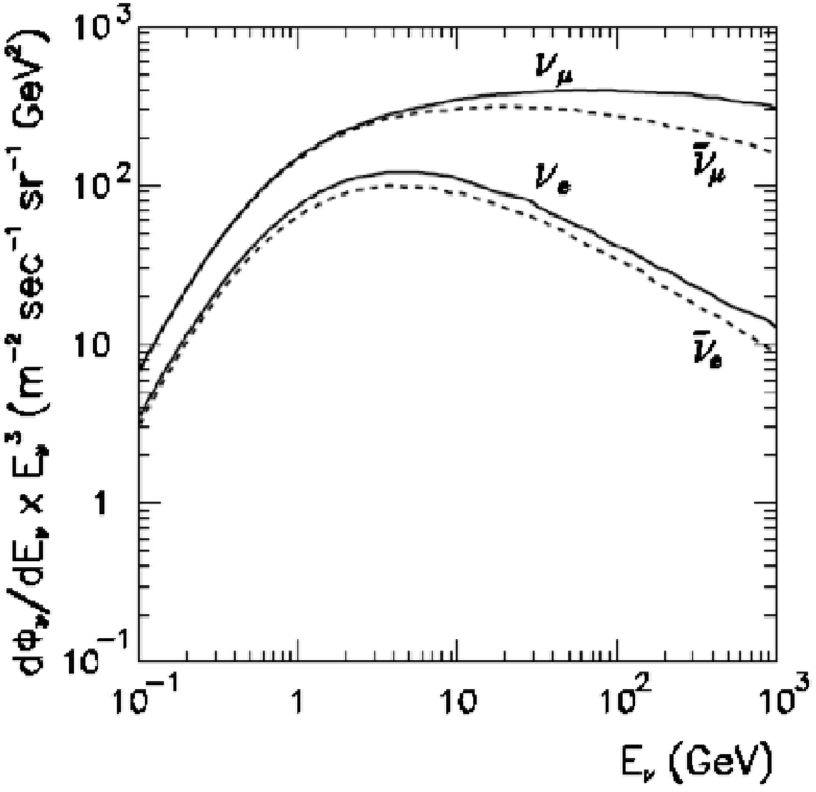


Output: the neutrino (ν_e,ν_μ) flux

Comparison of neutrino flux calculations

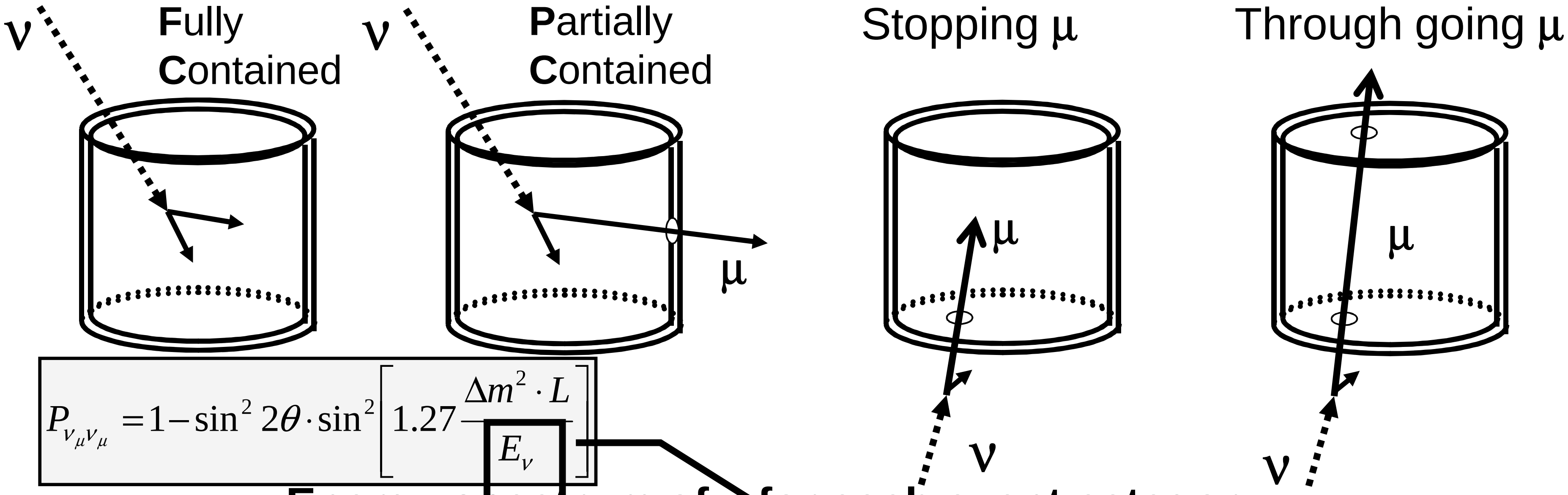


gure 18: Comparison of neutrino flux calculations for the location of Kamiol



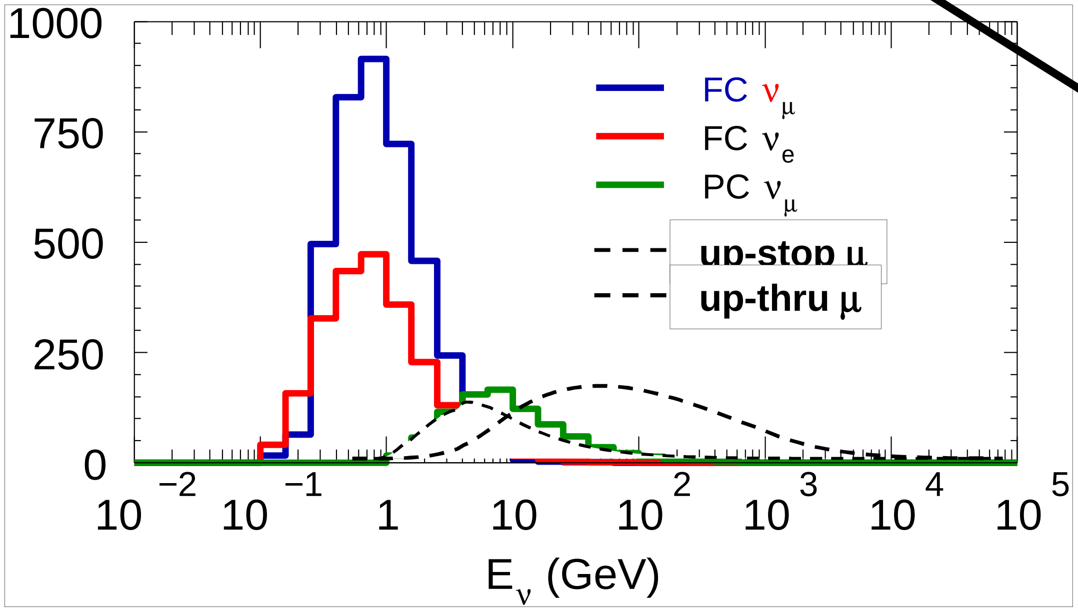
See for instance the FLUKA MC: http://www.mi.infn.it/~battist/neutrino.html

iv) The Detector response



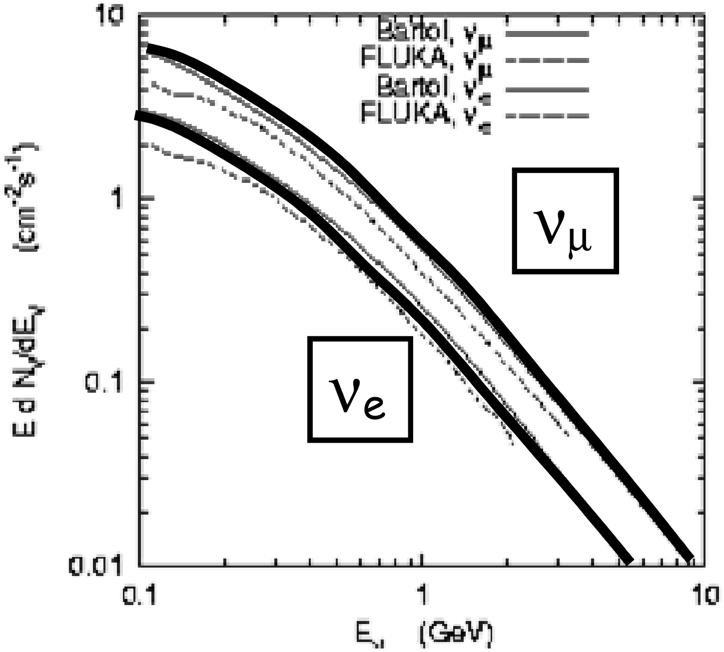
$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[1.27\frac{\Delta m^2 \cdot L}{\boxed{E_\nu}}\right]$$

Energy spectrum of ν for each event category



Energy spectrum (from Monte Carlo) of atmospheric neutrinos seen with different event topologies (SuperKamiokande)

Rough estimate: how many ‘Contained events’ in 1 kton detector



1. Flux: $\Phi_\nu \sim 1$ cm^{-2} s^{-1}
2. Cross section (@ 1GeV): $\sigma_\nu \sim 0.5\ 10^{-38}$ cm^2
3. Targets M= 6 10^{32} (nucleons/kton)
4. Time t= 3.1 10^7 s/y

$N_{int} = \Phi_\nu$ (cm^{-2} s^{-1}) x σ_ν (cm^2)x M (nuc/kton) x t (s/y) ~

~ 100 interactions/ (kton y)

7.5 10 years of Super-Kamiokande

SK-I

1996.4 Start data taking

1998 Evidence of atmospheric ν oscillation (SK)

1999.6 K2K started

2001 Evidence of solar ν oscillation (SNO+SK)

2001.7 data taking was stopped
for detector upgrade

2001.11 Accident
partial reconstruction

SK-II

2002.10 data taking was resumed

2005 Confirm ν oscillation by accelerator ν (K2K)

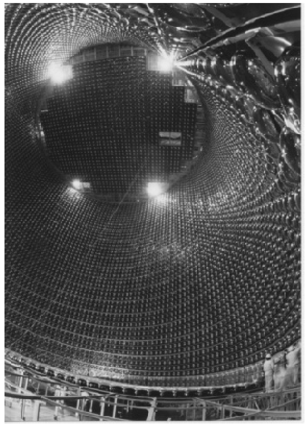
2005.10 data taking stopped for full reconstruction

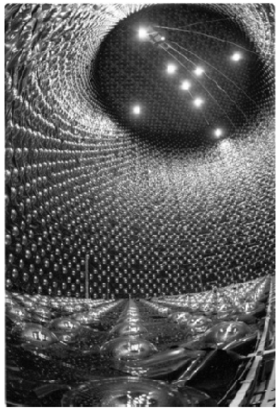
SK-III

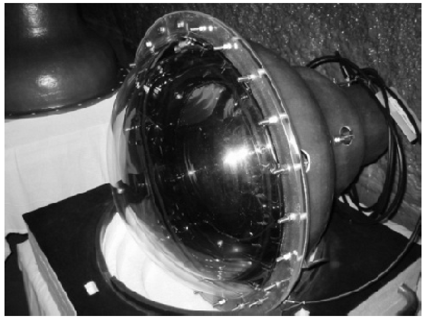
2006.7 data taking was resumed

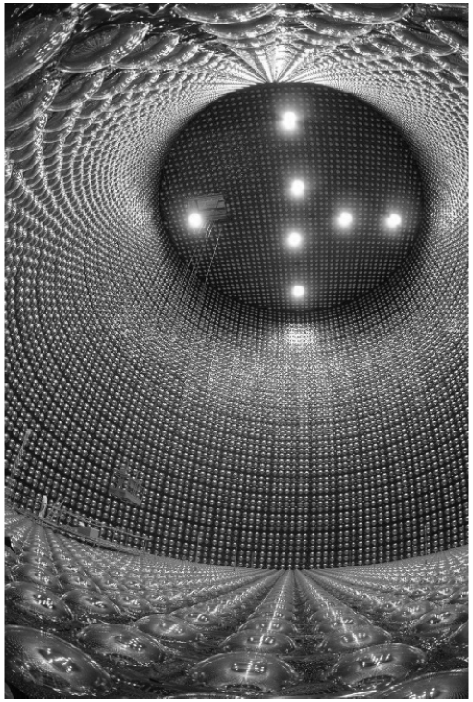
SK-IV

2009 data taking

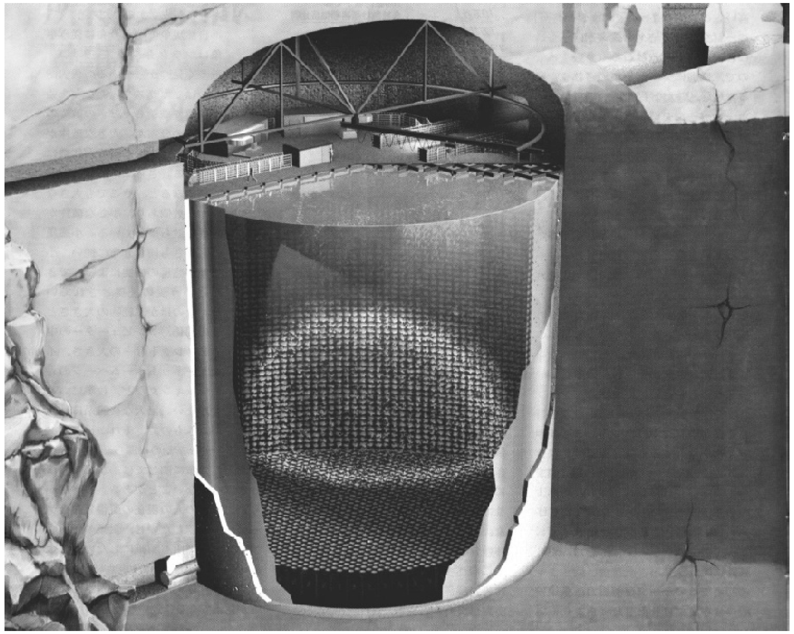


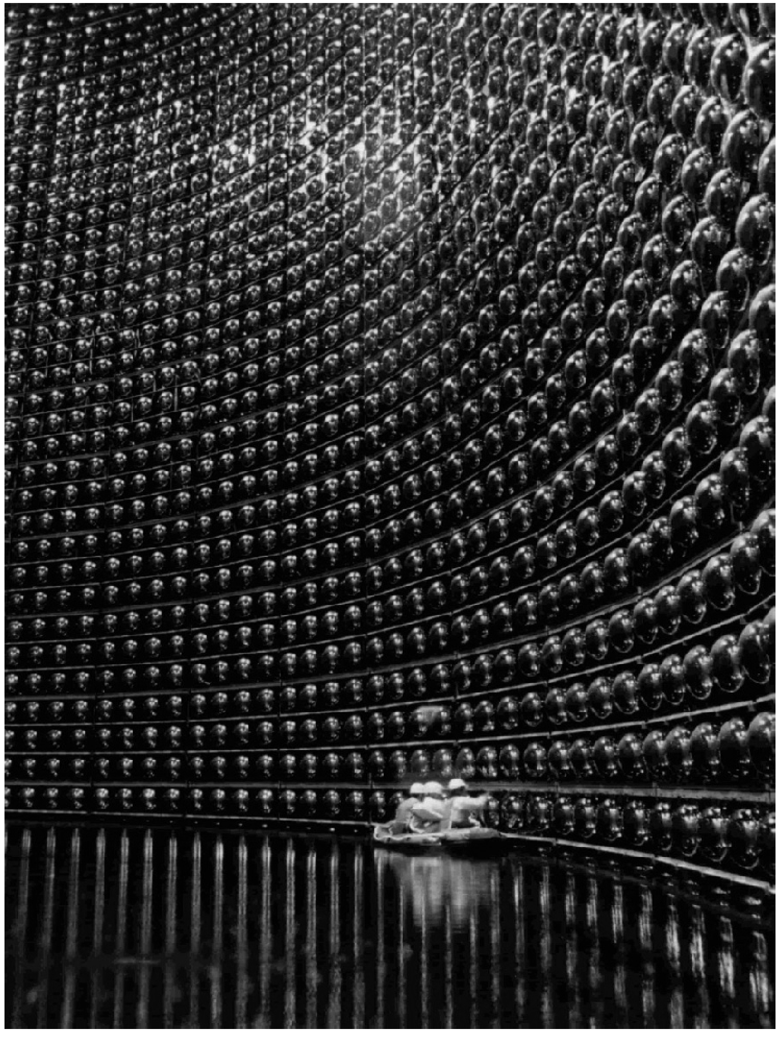






Measurement of contained events and SuperKamiokande (Japan)

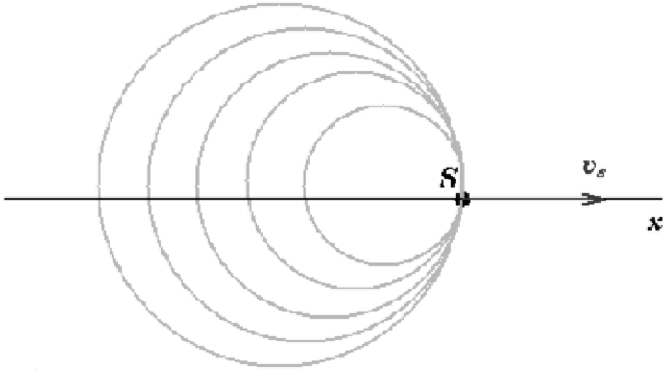


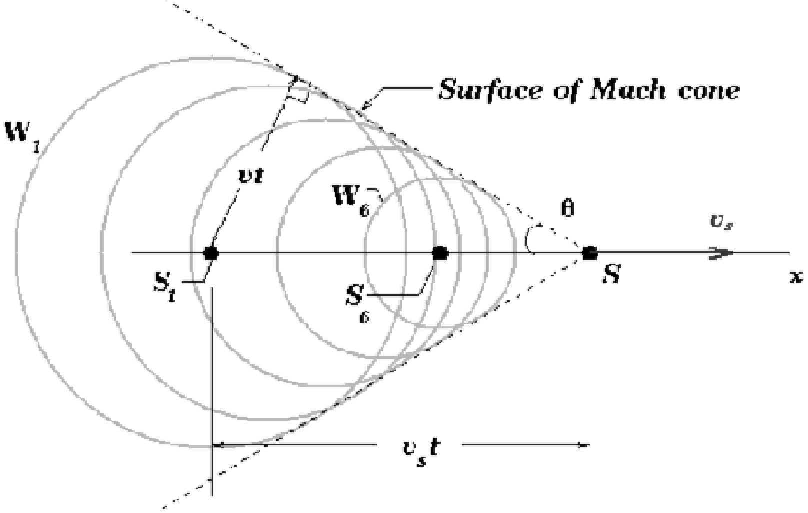


- 1000 m Deep Underground
- 50.000 ton of Ultra-Pure Water
- 11000 +2000 PMTs

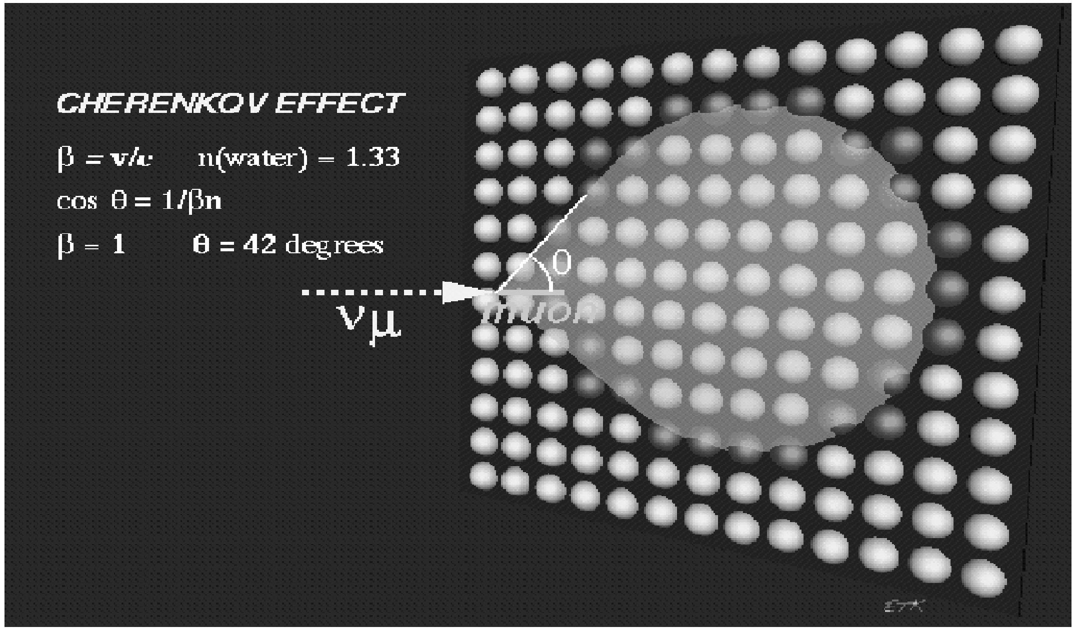
Cherenkov Radiation

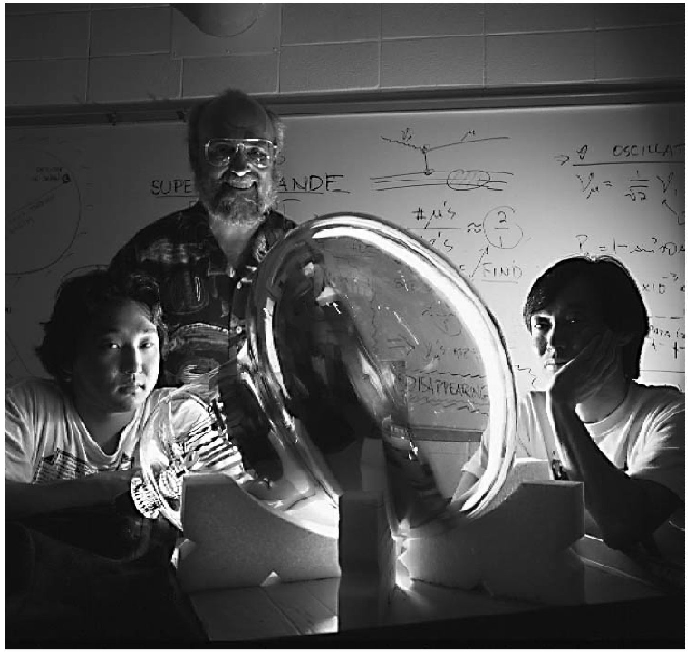
- As a charged particle travels, it disrupts the local electromagnetic field (EM) in a medium.
- Electrons in the atoms of the medium will be displaced and polarized by the passing EM field of a charged particle.
- Photons are emitted as an insulator's electrons restore themselves to equilibrium after the disruption has passed.
- In a conductor, the EM disruption can be restored without emitting a photon.
- In normal circumstances, these photons destructively interfere with each other and no radiation is detected.
- However, when the disruption travels faster than light is propagating through the medium, the photons constructively interfere and intensify the observed Cerenkov radiation.





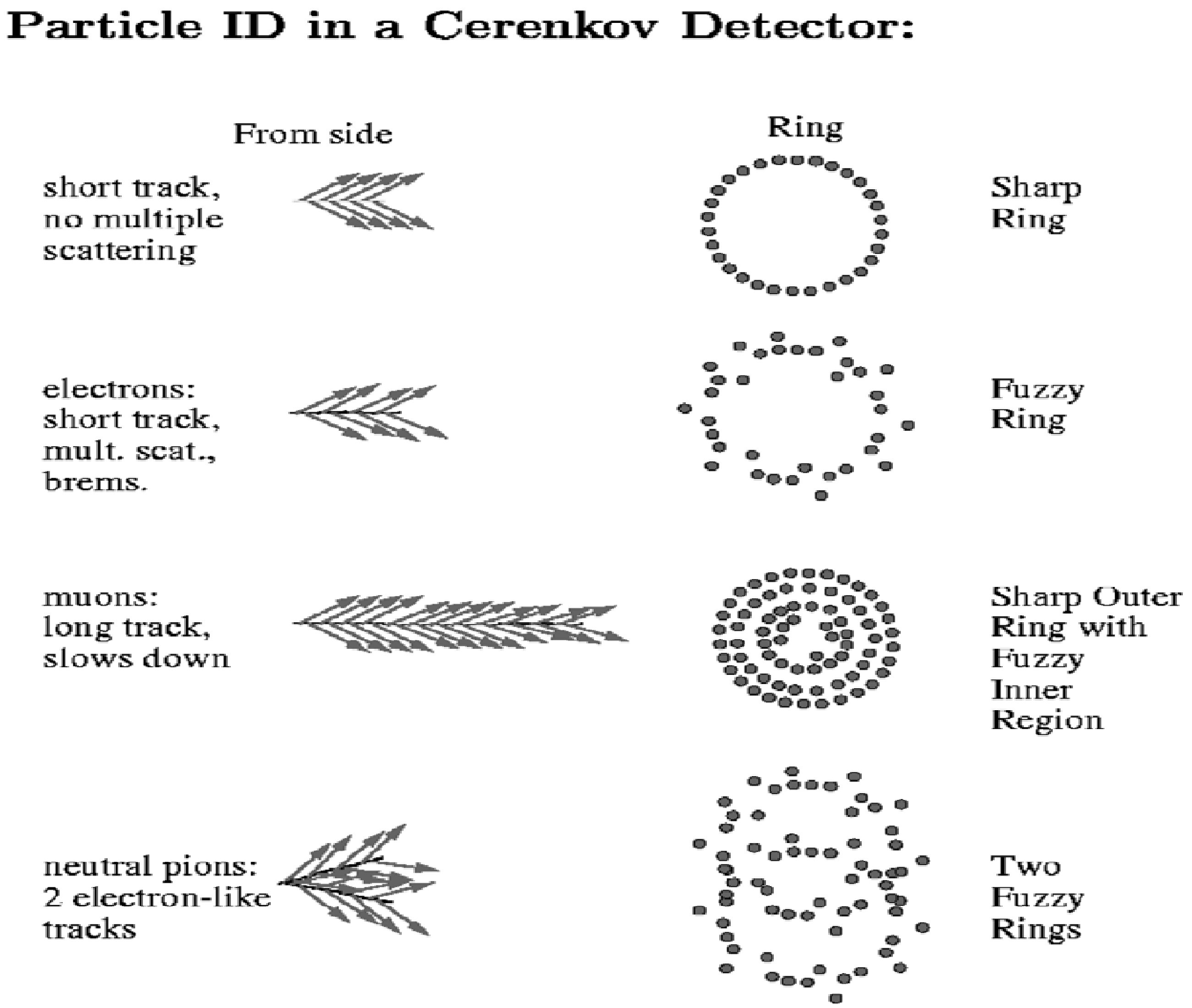
Cherenkov Radiation



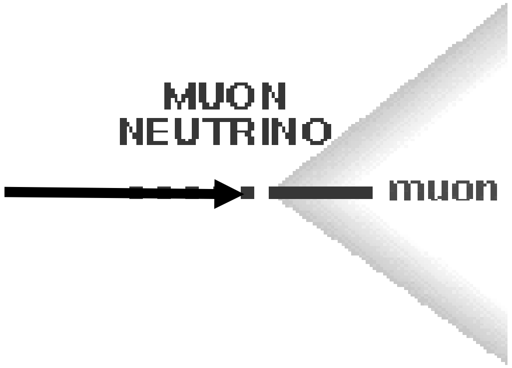


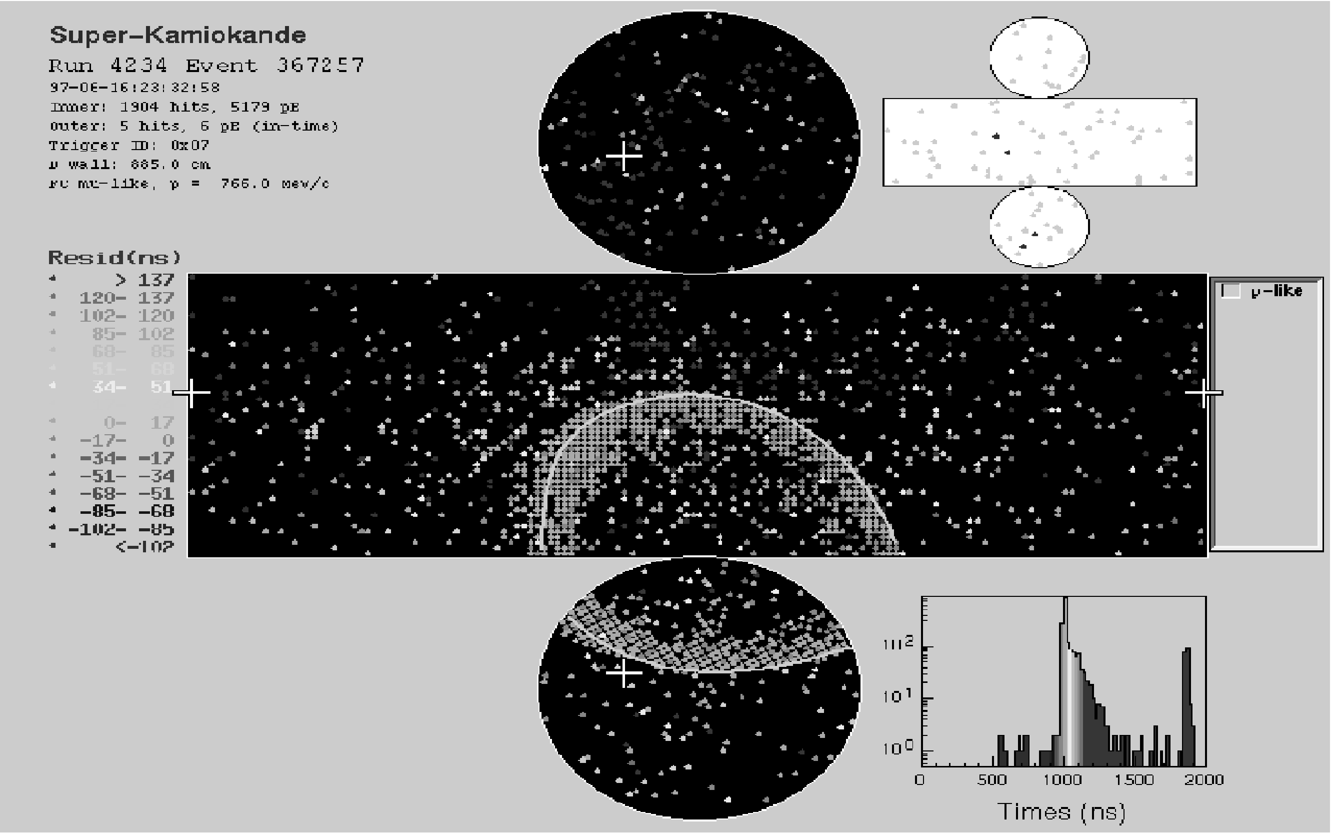
One of the 13000
PMTs of SK

How to tell a ν_μ from a ν_e : Pattern recognition



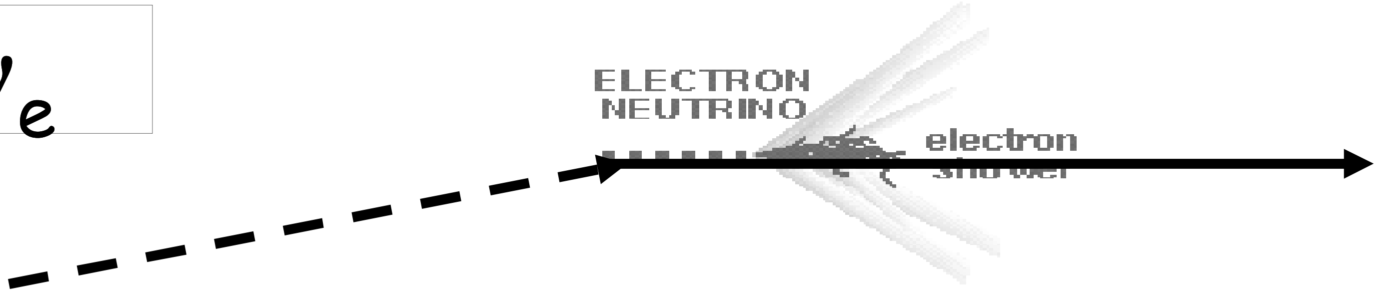
ν_μ

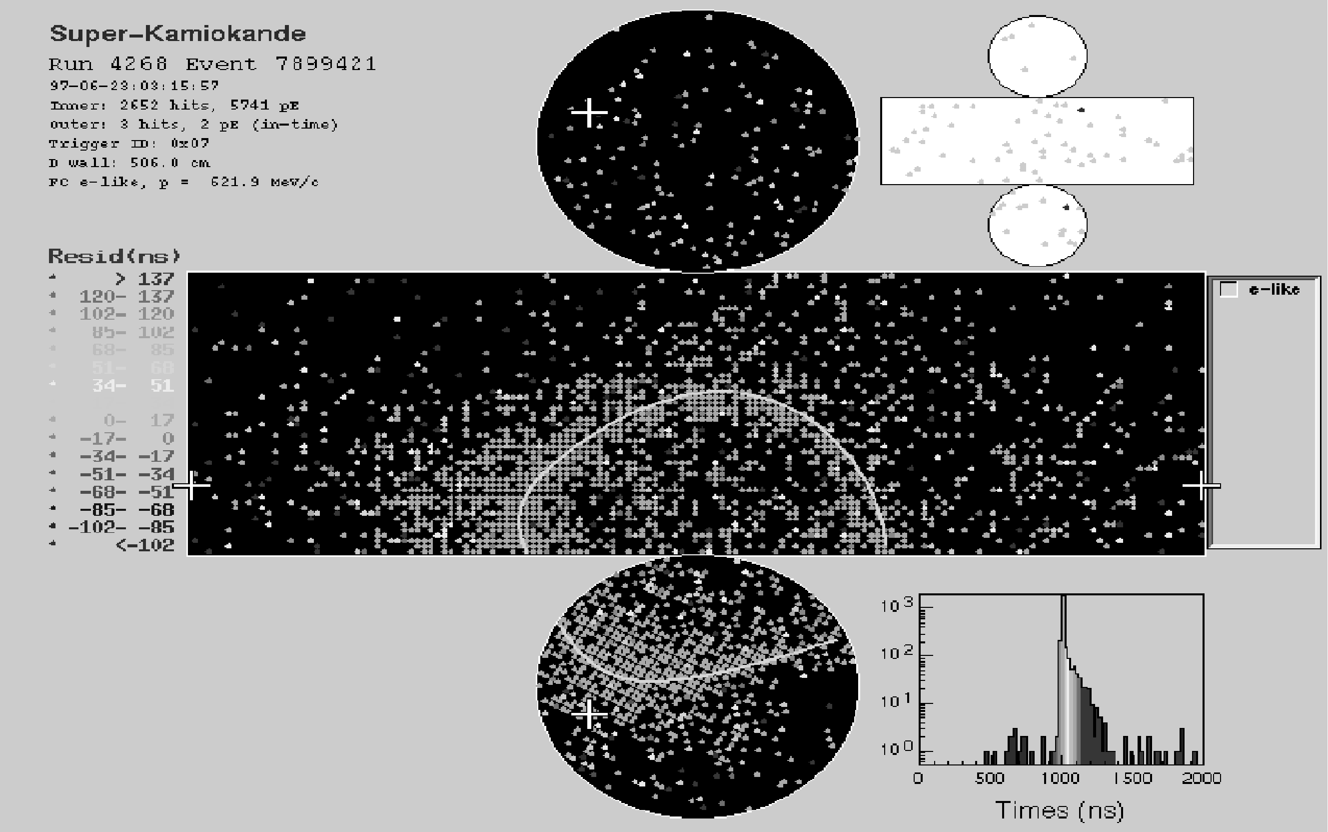




```
Super-Kamiokande
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
Outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
ν wall: 885.0 cm
fc mu-like, p =  766.0 mev/c
```

ν_e

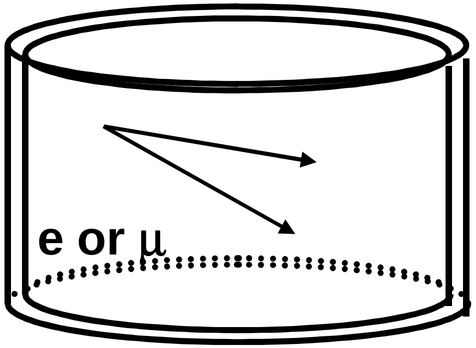




```
Super-Kamiokande
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p =  621.9 MeV/c
```

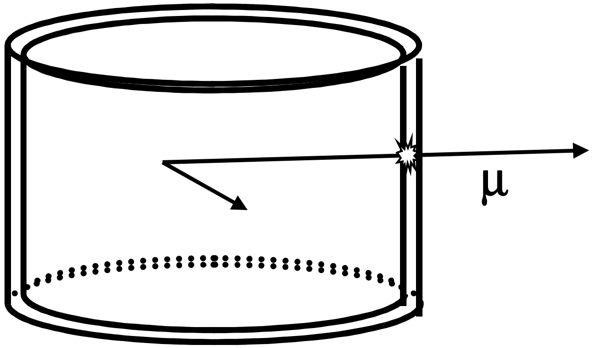
Contained event in SuperKamiokande

Fully Contained (FC)



No hit in Outer Detector

Partially Contained (PC)



One cluster in Outer Detector

Reduction

Automatic ring fitter
Particle ID
Energy reconstruction

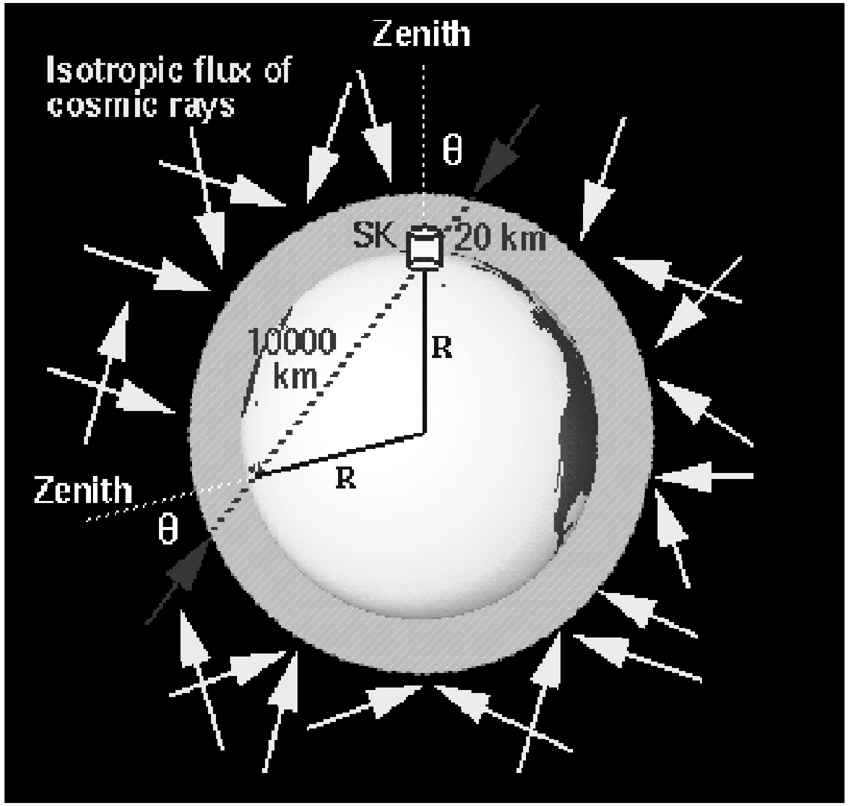
Fiducial volume (>2m from wall, 22 ktons)
E_{vis} > 30 MeV (FC), > 3000 p.e. (~350 MeV) (PC)

Fully Contained
8.2 events/day
E_{vis}<1.33 GeV : Sub-GeV
E_{vis}>1.33 GeV : Multi-GeV

Partially Contained
0.58 events/day

Contained events. The up/down symmetry in SK and ν_μ/ν_e ratio.

Up/Down asymmetry interpreted as neutrino oscillations

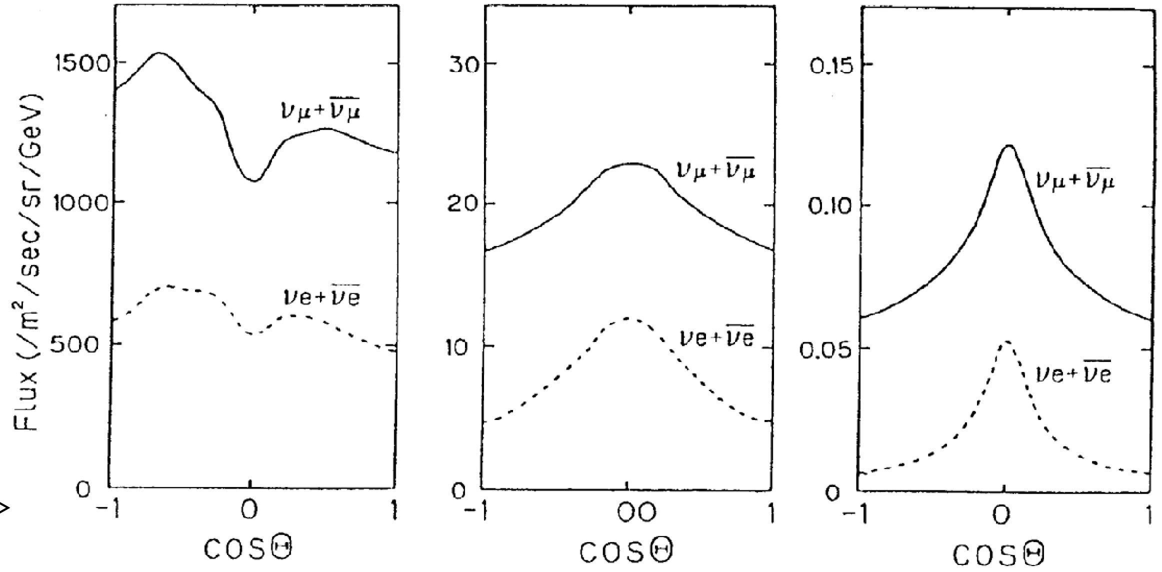


Expectations: events inside the detector.

For E_ν > a few GeV,

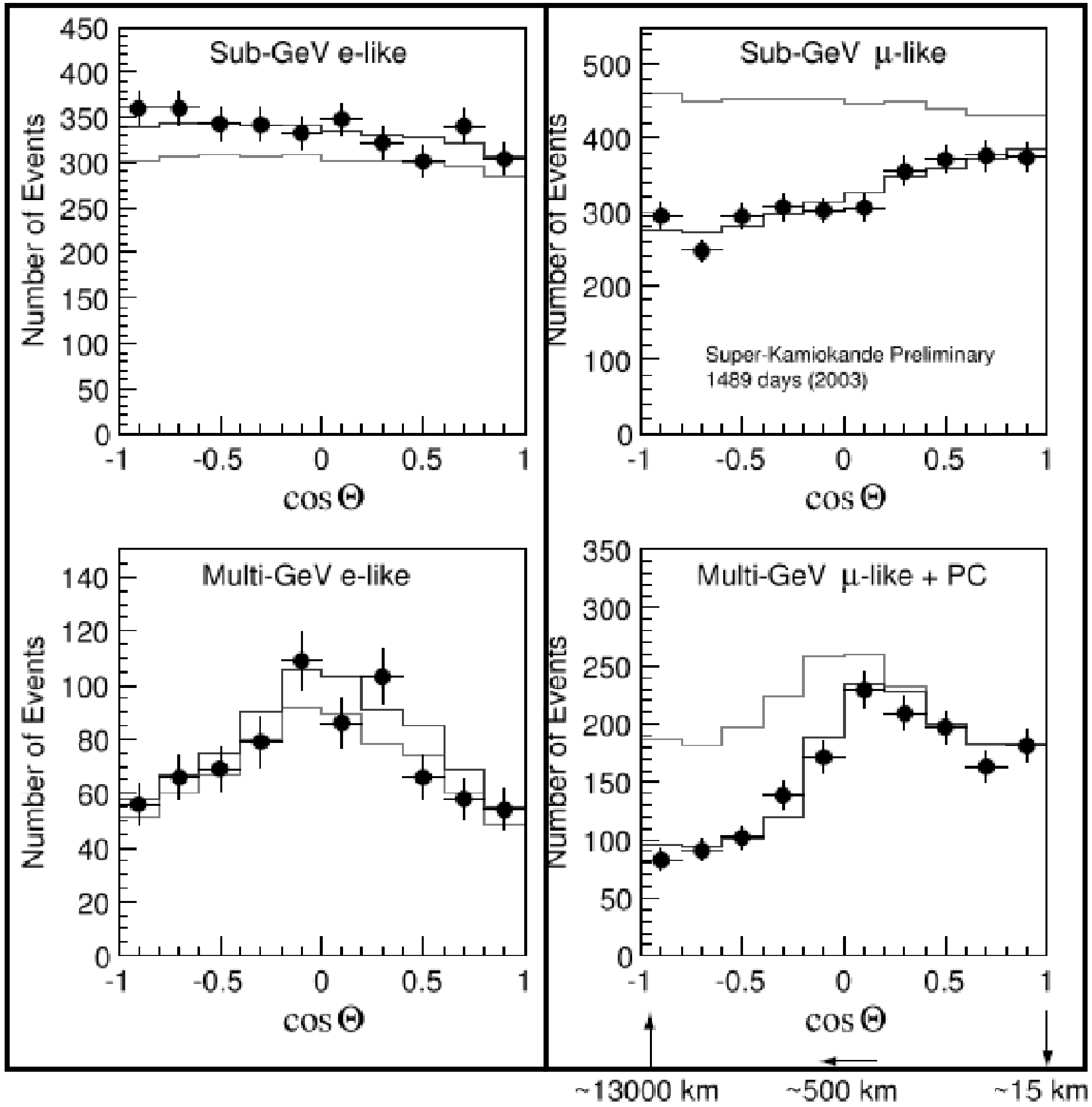
Upward / downward = 1

Eν=0.5GeV **Eν=3 GeV** **Eν=20 GeV**



Zenith angle distribution

SK:1289 days (79.3 kty)



Zenith angle distributions for e-like and μ-like contained atmospheric neutrino events in SK. The lines show the best fits with (red) and without (blue) oscillations; the best-fit is $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1.00$.

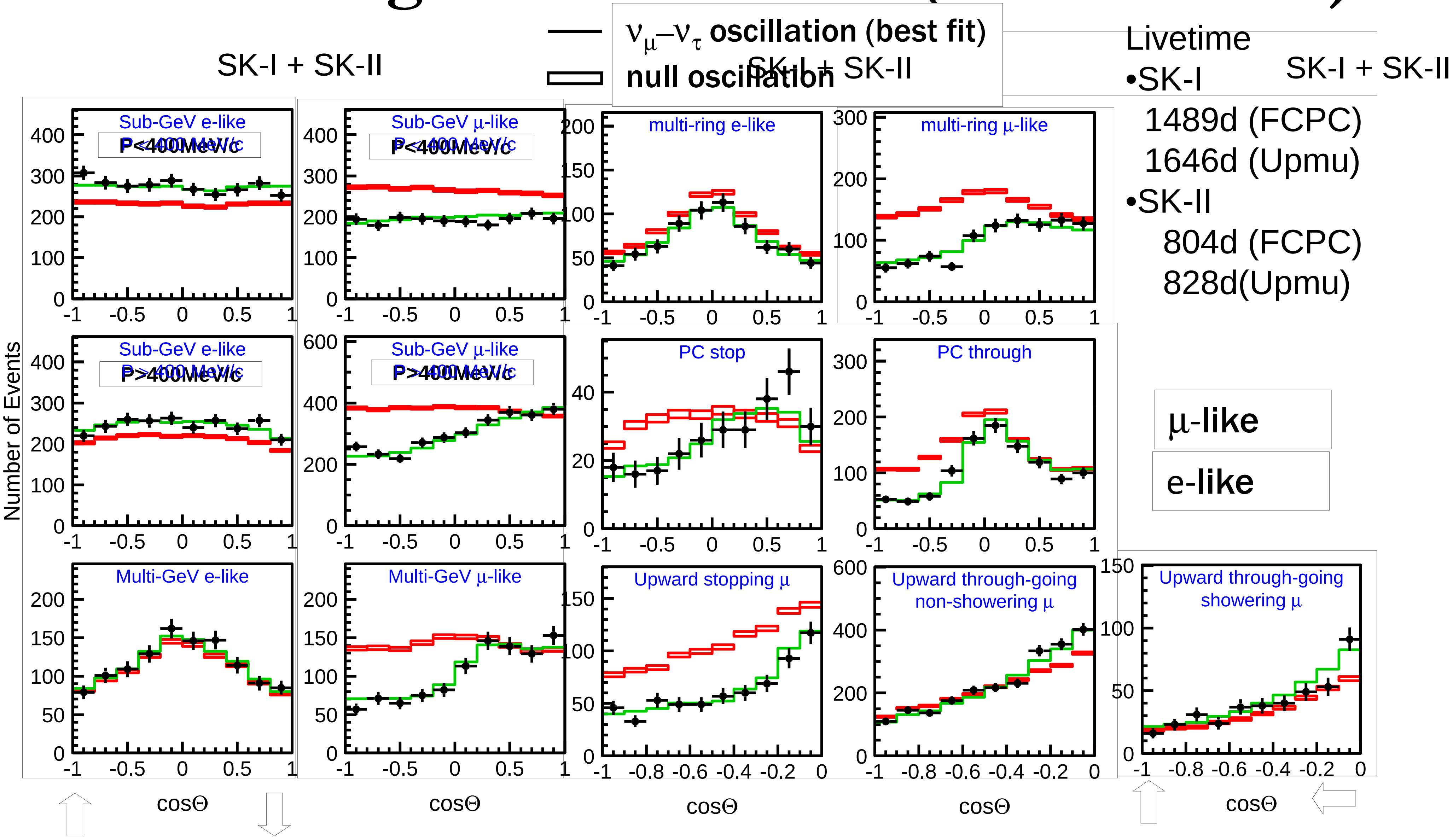
- Electron neutrinos = DATA and MC (almost) OK!

- Muon neutrinos = Large deficit of DATA w.r.t. MC !

DATA

$$\frac{(\mu/e)_{\mathrm{Data}}}{(\mu/e)_{\mathrm{MC}}} = 0.638 \pm 0.017 \pm 0.050$$

Zenith Angle Distributions (SK-I + SK-II)



Livetime
- SK-I
  1489d (FCPC)
  1646d (Upmu)
- SK-II
  804d (FCPC)
  828d(Upmu)

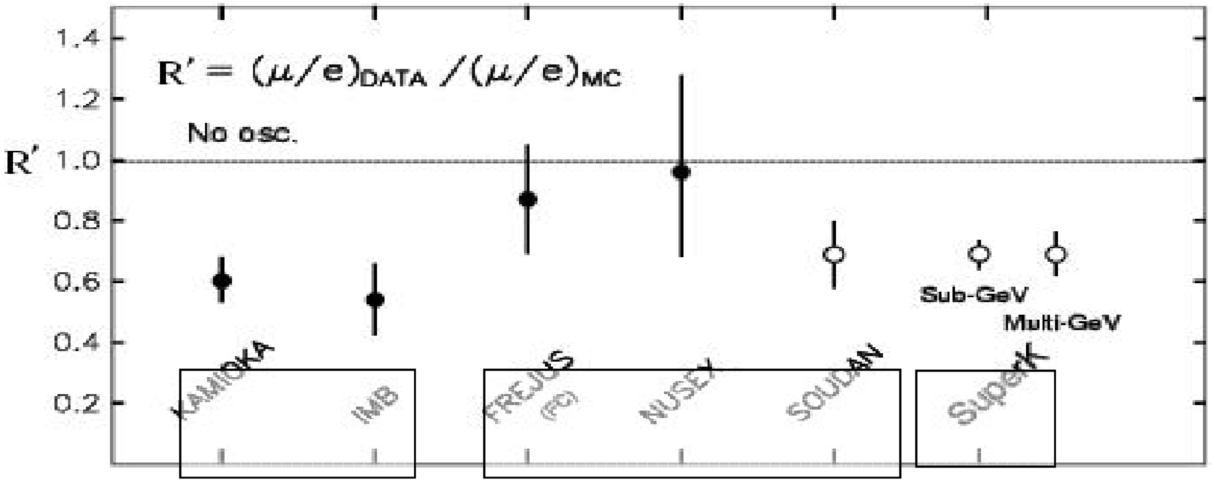
NOTE: All topologies, last results (September 2007)

Atmospheric Neutrino Anomaly

Summary results since the mid-1980's:

$$R' = \frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$$

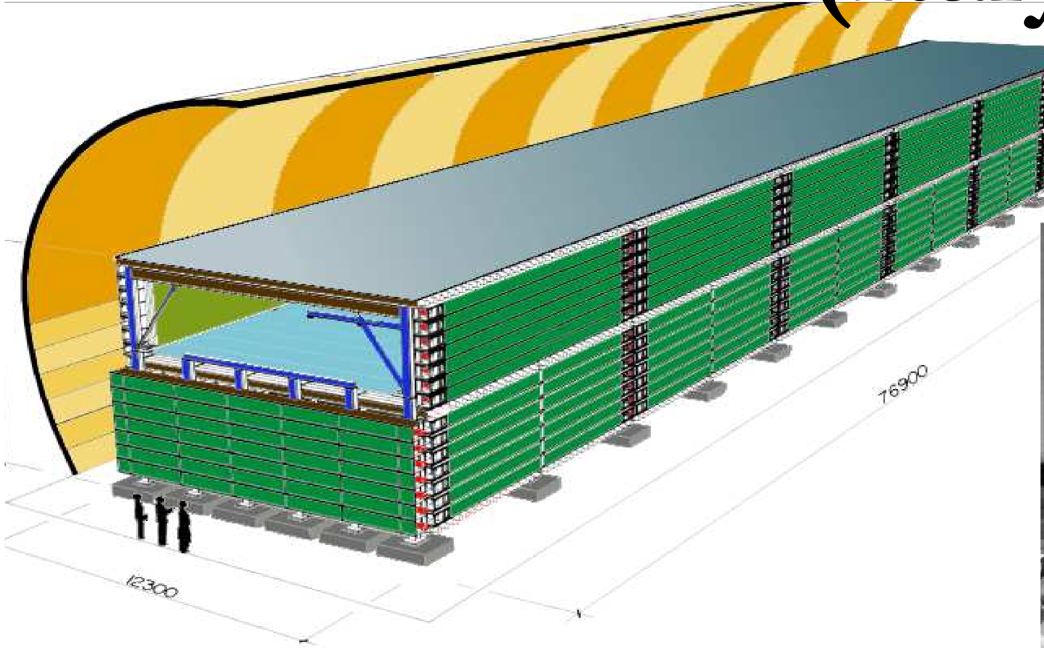
Double ratio between the number of detected and expected $\nu\mu$ and νe

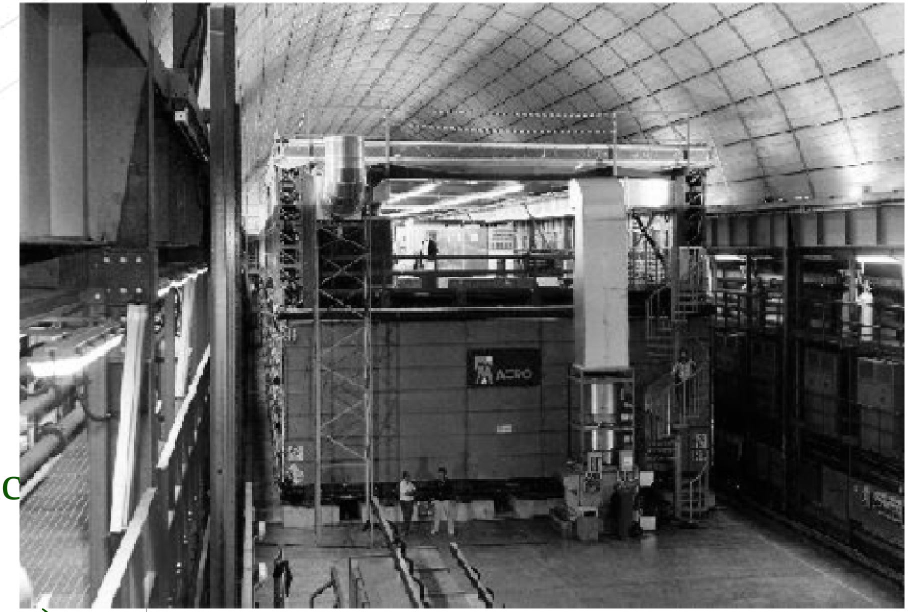


Calorimetric

Water Cherenkov

7.6 Upgoing muons and MACRO (Italy)

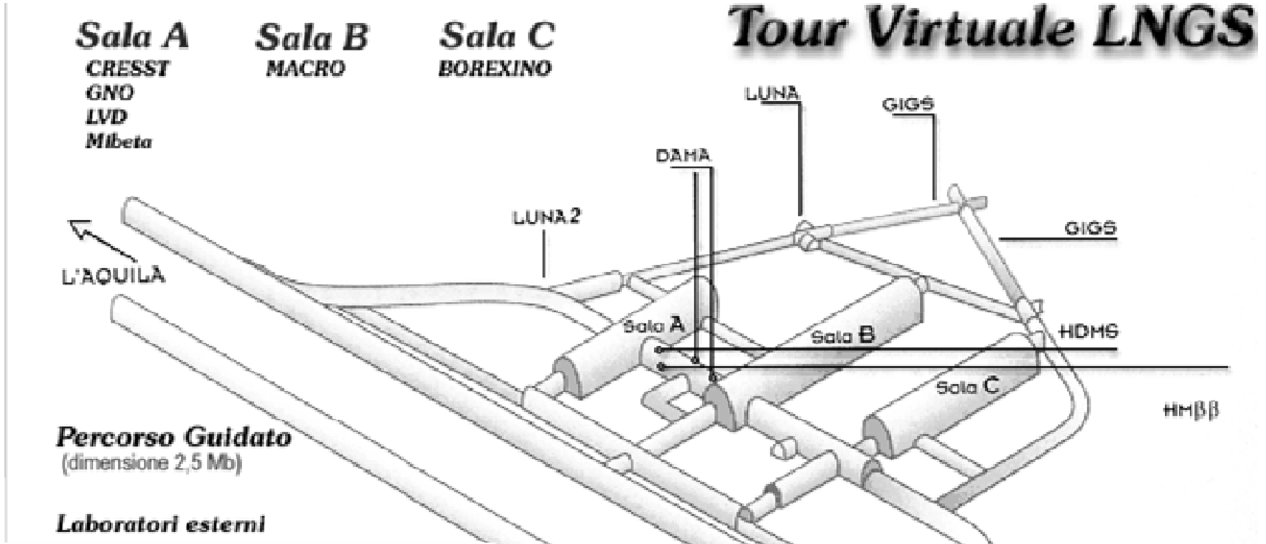




- Large acceptance (~10000 m^2sr for an isotropic flux)
- Low downgoing μ rate (~10^{-6} of the surface rate)
- ~600 tons of liquid scintillator to measure T.O.F. (time resolution ~500psec)
- ~20000 m^2 of streamer tubes (3cm cells) for tracking (angular resolution < 1°)

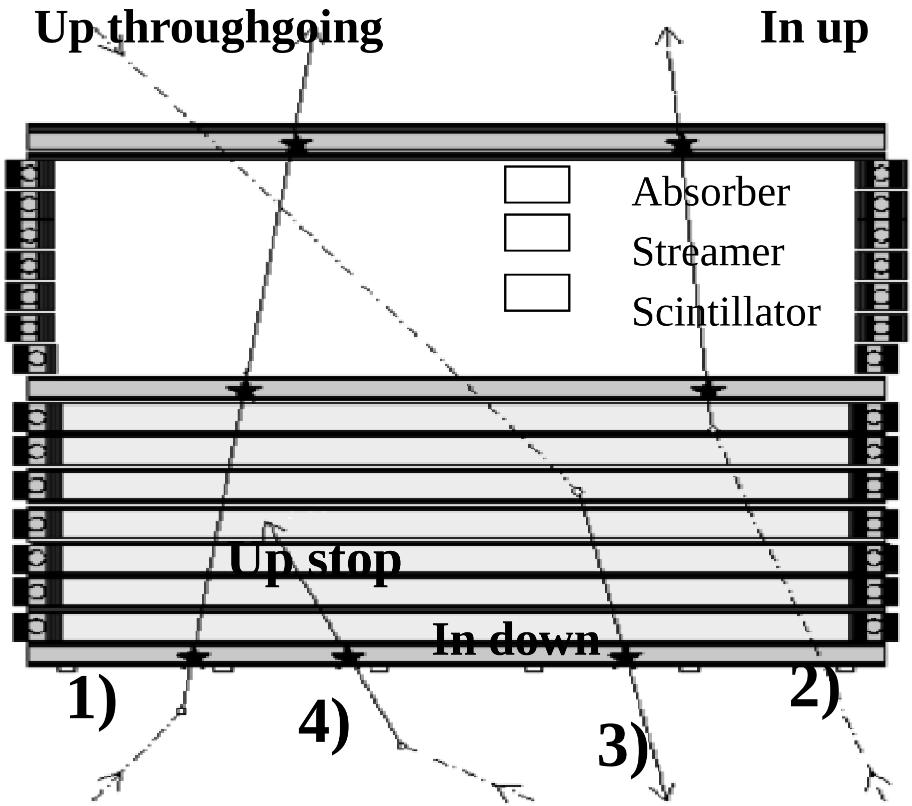
† **R.I.P December 2000**

The Gran Sasso National Labs



http://www.lngs.infn.it/

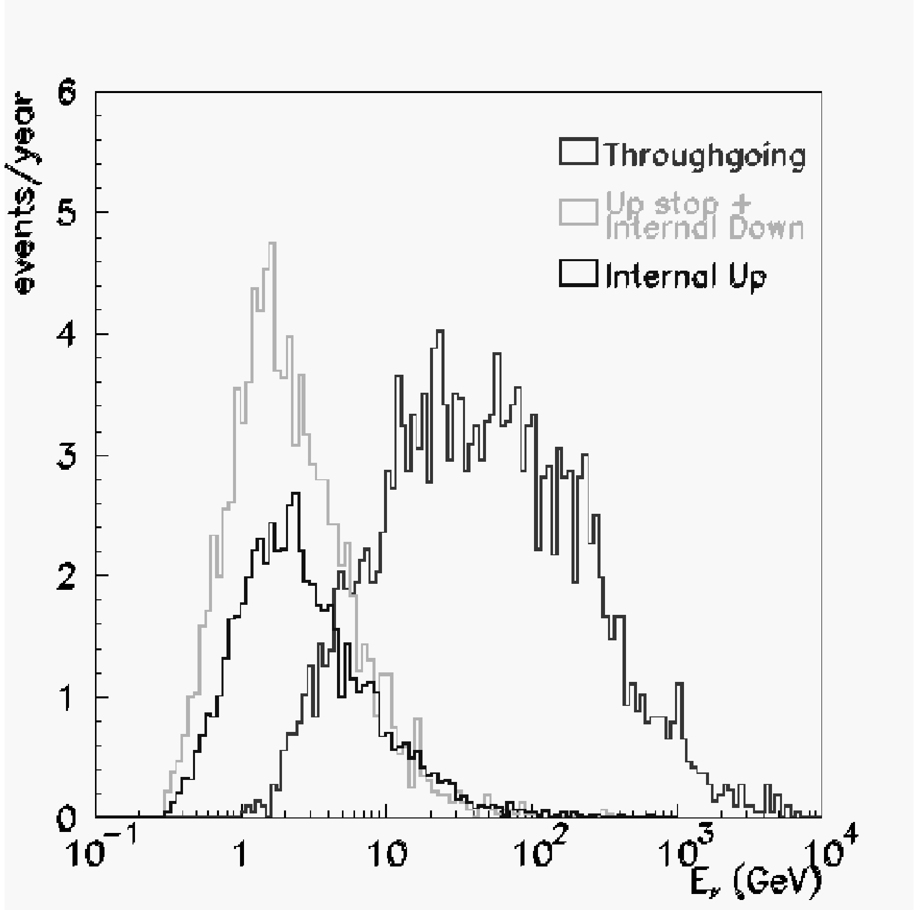
Neutrino event topologies in MACRO



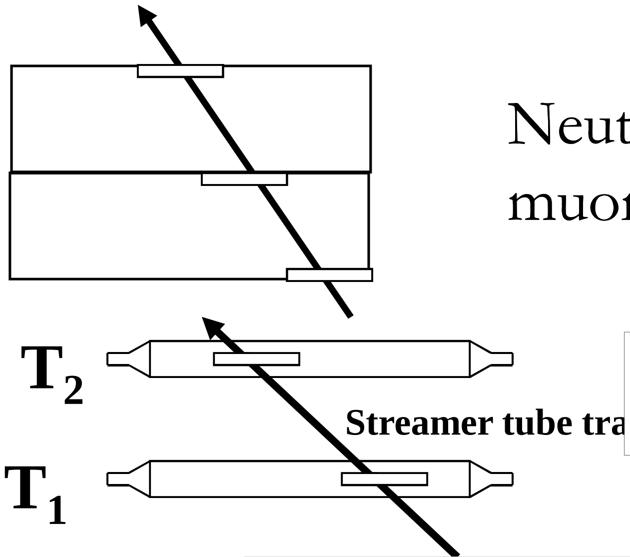
- ***Liquid scintillator counters***, (3 planes) for the measurement of **time** and **dE/dx**.
- ***Streamer tubes*** (14 planes), for the measurement of the track position;
- Detector mass: 5.3 kton
- Atmospheric muon neutrinos produce upward going muons
- Downward going muons ~ 10^6 upward going muons
- Different neutrino topologies

Energy spectra of ν_μ events in MACRO

- <E>~ 50 GeV throughgoing μ
- <E>~ 5 GeV, Internal Upgoing (IU) μ;
- <E>~ 4 GeV , internal downgoing (ID) μ and for upgoing stopping (UGS) μ;



Neutrino induced events are upward throughgoing muons, Identified by the time-of-flight method



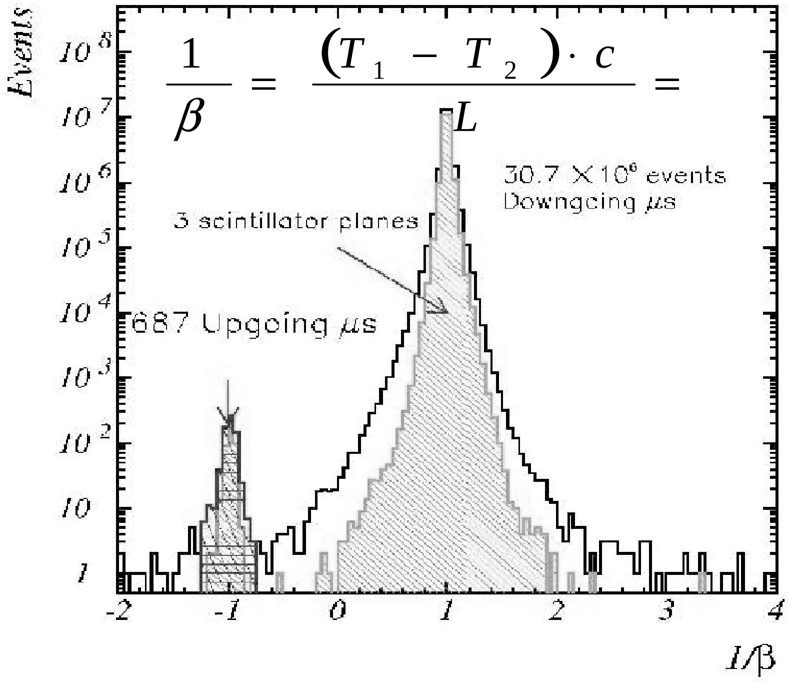
$$\frac{1}{\beta} = \frac{(T_1 - T_2)\cdot c}{L} = $$

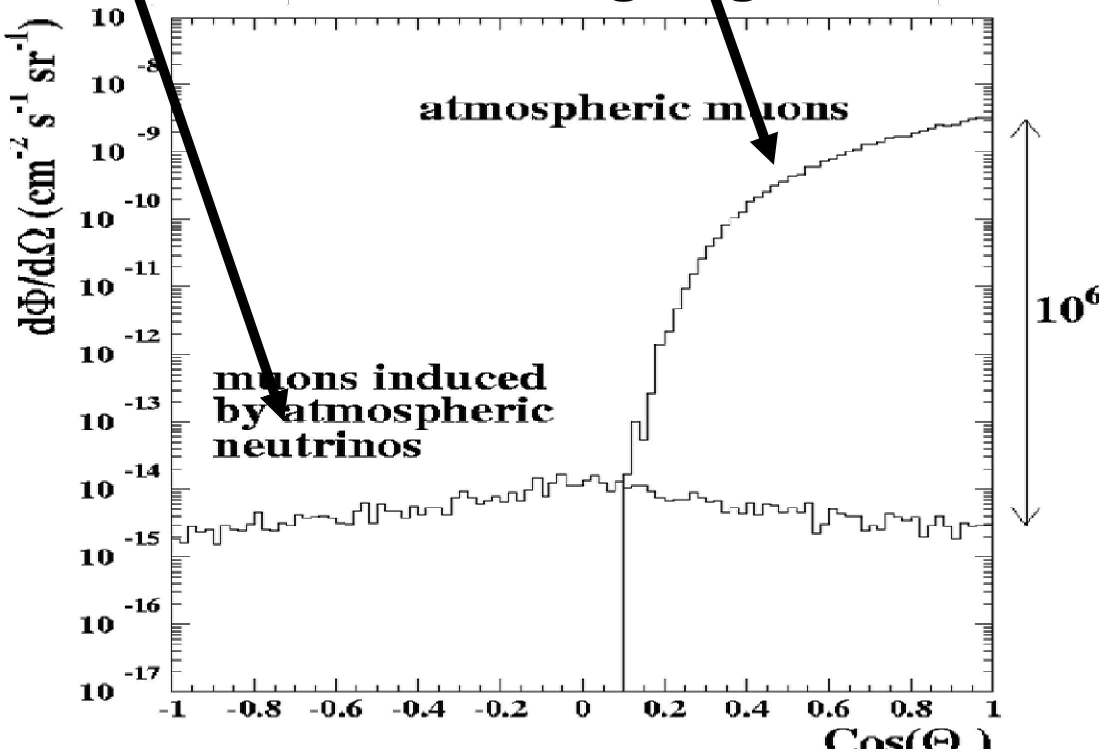
+1 μ↓

-1 μ↑

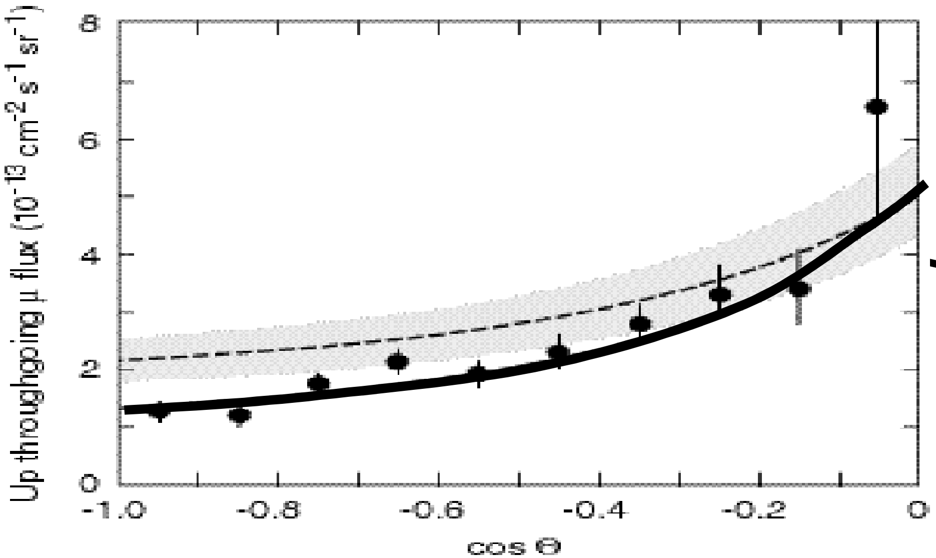
μ from ν: upgoing

Atmospheric μ: downgoing



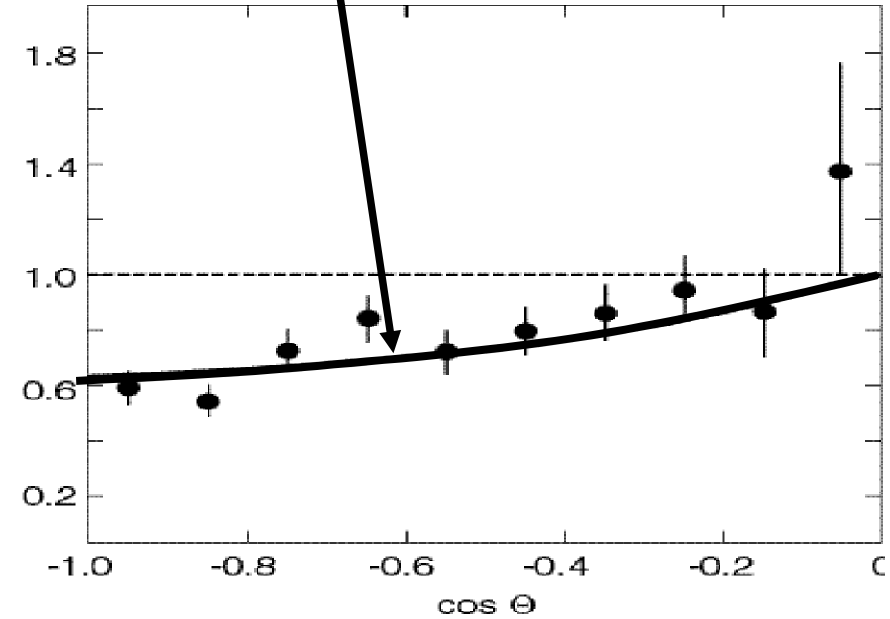


MACRO Results: event deficit and distortion of the angular distribution



- - - - No oscillations

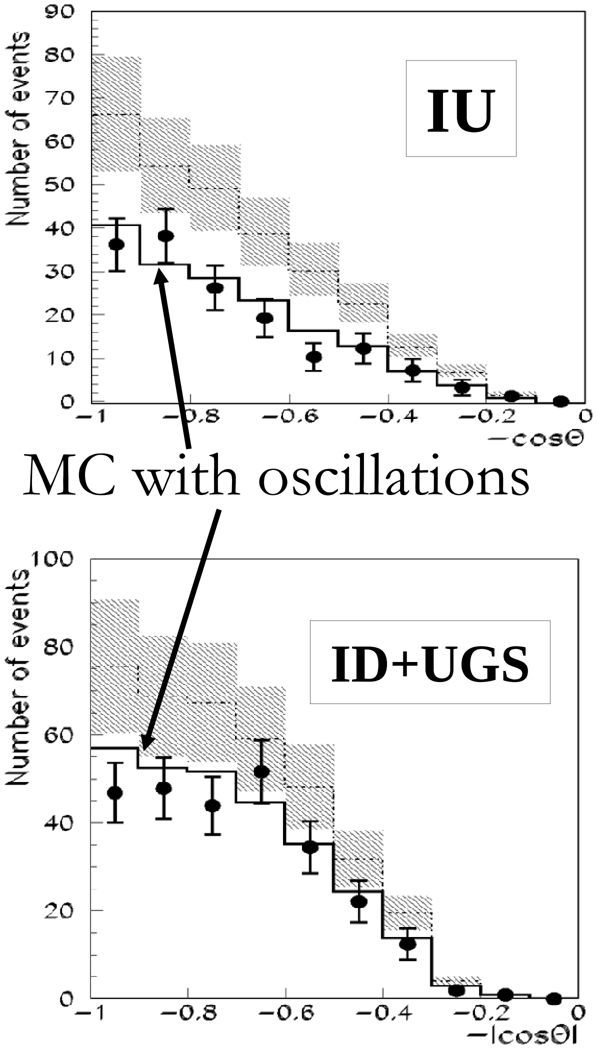
—— Best fit $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2 $\sin^2 2\theta = 1.00$



Observed= 809 events
Expected= 1122 events (Bartol)

<u>Observed/Expected</u>
<u>= </u>$0.721 \pm 0.050_{(stat+sys)} \pm 0.12_{(th)}$

MACRO Partially contained events



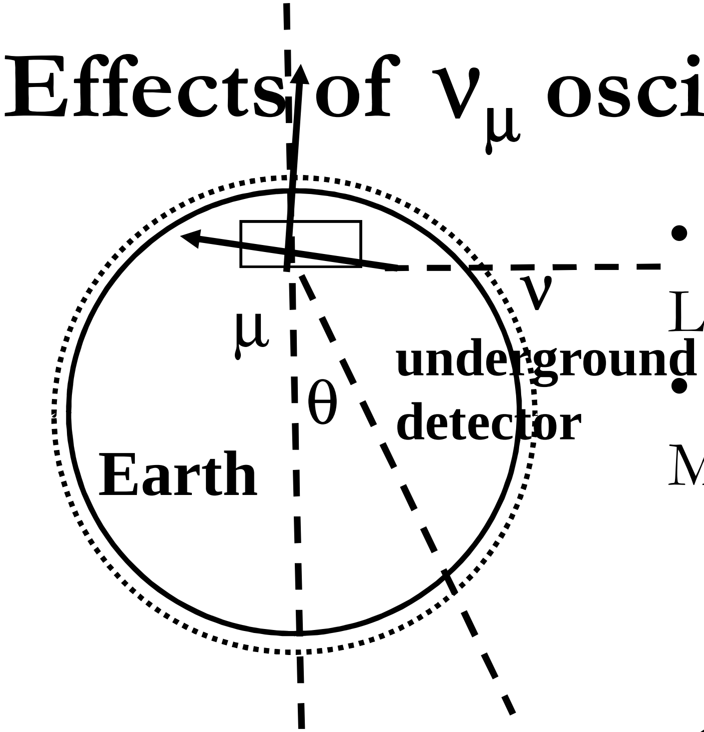
MC with oscillations

Obs. 154 events
Exp. 285 events
Obs./Exp. = 0.54±0.15

Obs. 262 events
Exp. 375 events
Obs./Exp. = 0.70±0.19)

consistent with up throughgoing muon results

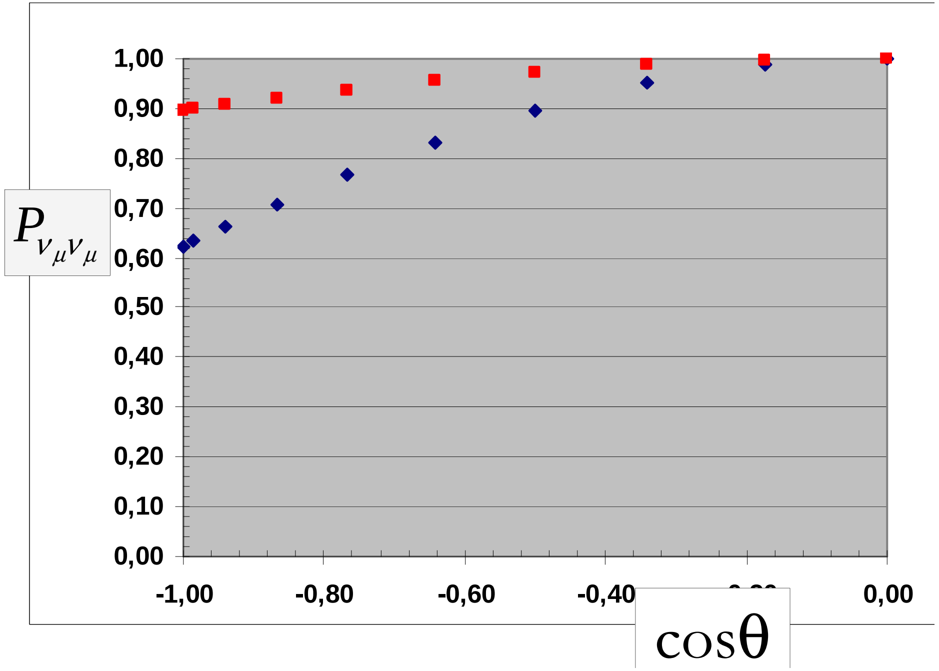
Effects of ν_μ oscillations on upgoing events



- If θ is the zenith angle and D= Earth diameter L=Dcosθ
- For throughgoing neutrino-induced muons in MACRO, Eν = 50 GeV (from Monte Carlo)

$$P_{\nu_\mu\nu_\mu} = 1-\sin^2 2\theta \cdot \sin^2\left[1.27\frac{\Delta m^2 \cdot L}{E_\nu}\right]$$

0	-1,000	0,62	0,89
-10	-0,985	0,63	0,90
-20	-0,940	0,66	0,91
-30	-0,866	0,71	0,92
-40	-0,766	0,77	0,94
-50	-0,643	0,83	0,96
-60	-0,500	0,89	0,97
-70	-0,342	0,95	0,99
-80	-0,174	0,99	1,00
-90	0,000	1,00	1,00



Oscillation Parameters

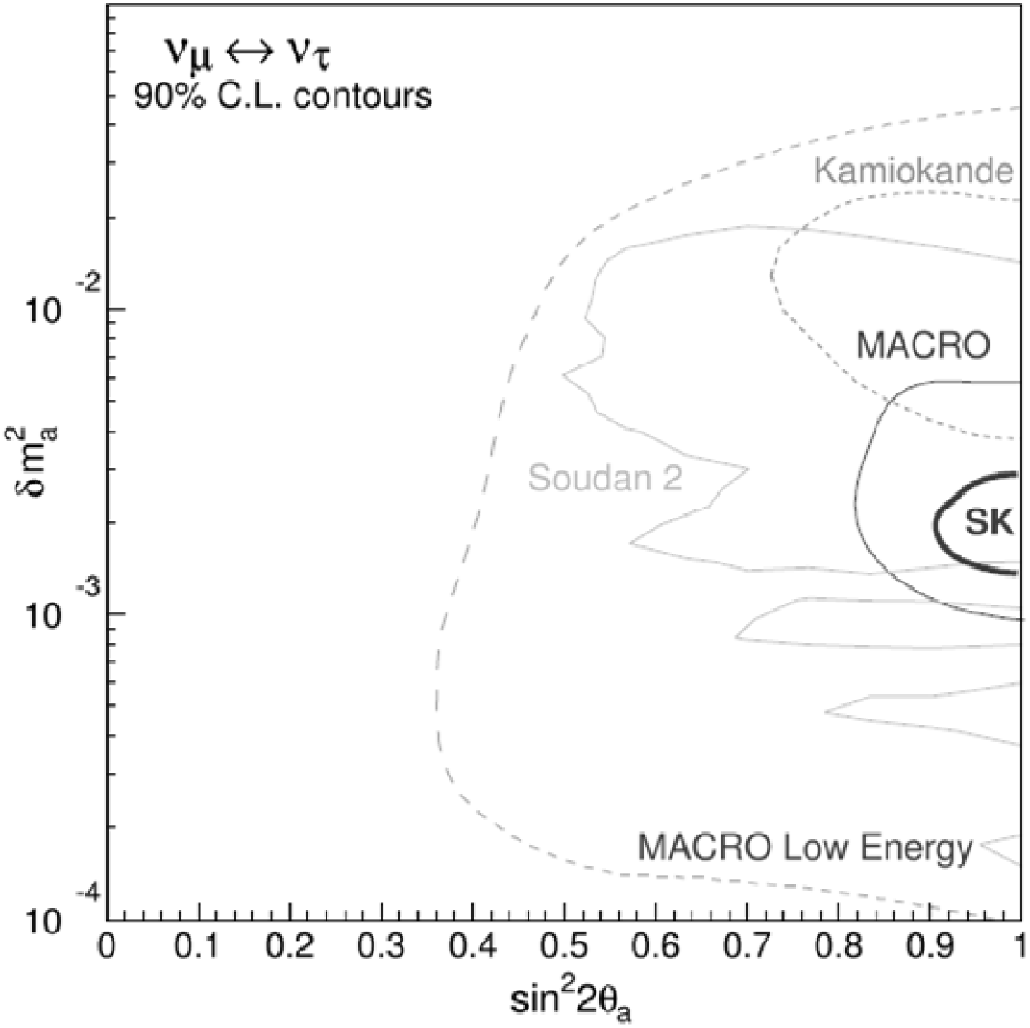
- The value of the "oscillation parameters" $\sin^2\theta$ and Δm^2 correspond to the values which provide the best fit to the data
- Different experiments → different values of $\sin^2\theta$ and Δm^2
- The experimental data have an associated error. All the values of ($\sin^2\theta$, Δm^2) which are compatible with the experimental data are "allowed".
- The "allowed" values span a region in the parameter space of ($\sin^2\theta$, Δm^2)

$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu}\right]$$

$1.9 \times 10^{-3}\ \mathrm{eV}^2 < \Delta m^2 < 3.1 \times 10^{-3}\ \mathrm{eV}^2$

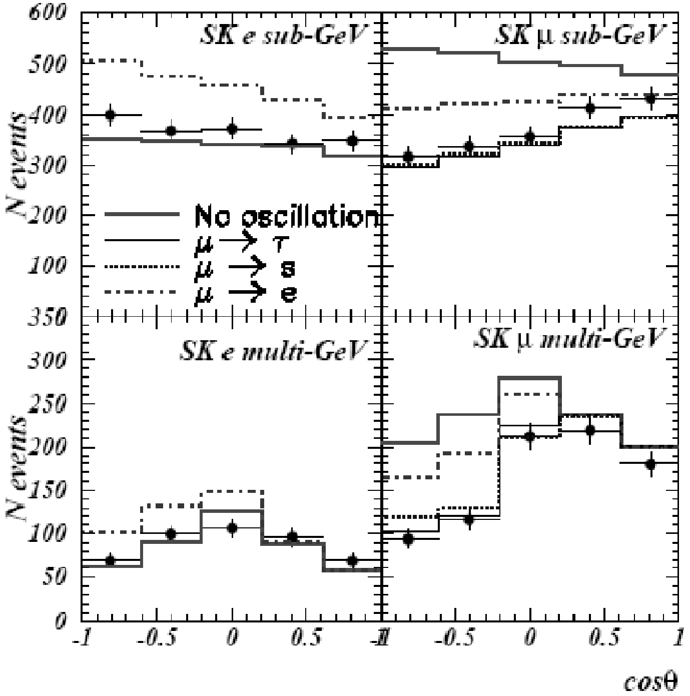
$\sin^2 2\theta > 0.93$ (90% CL)

“Allowed” parameters region

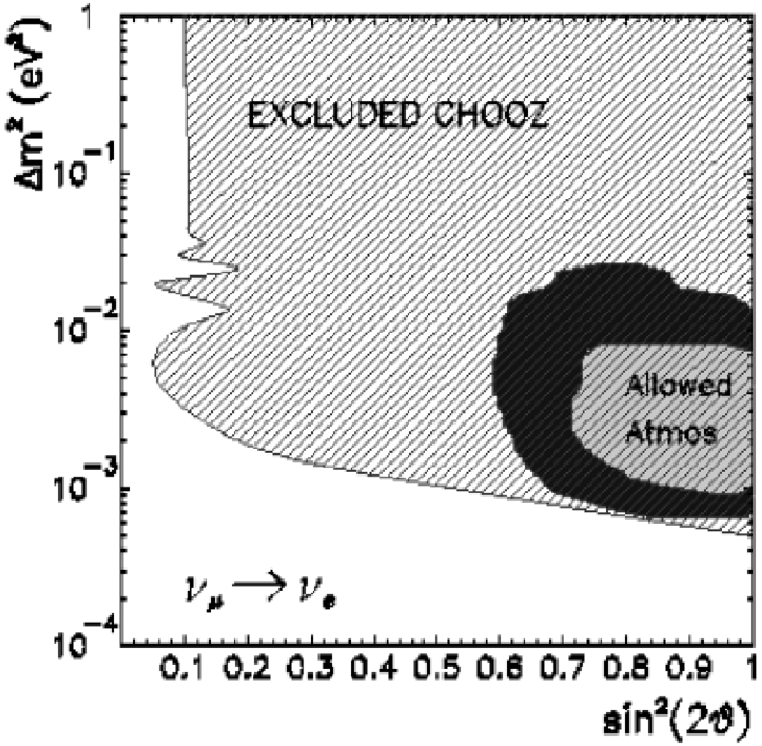


90% C. L. allowed regions for $\nu_\mu \rightarrow \nu_\tau$ oscillations of atmospheric neutrinos for Kamiokande, SuperK, Soudan-2 and MACRO.

Why not $\nu_\mu \rightarrow \nu_e$?

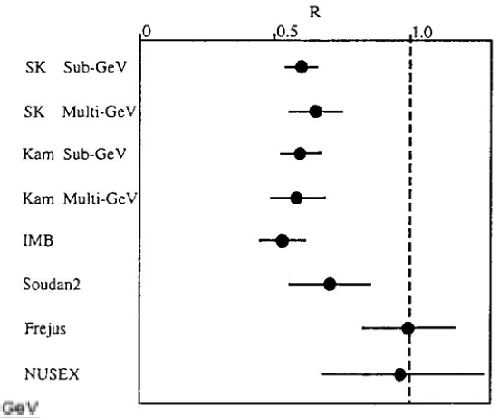


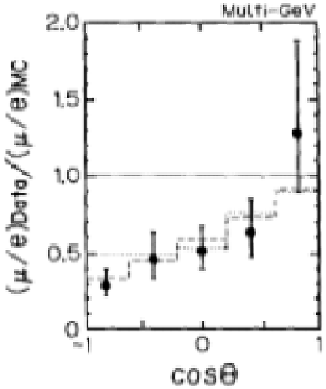
Apollonio et al., CHOOZ Coll., Phys.Lett.B466,415

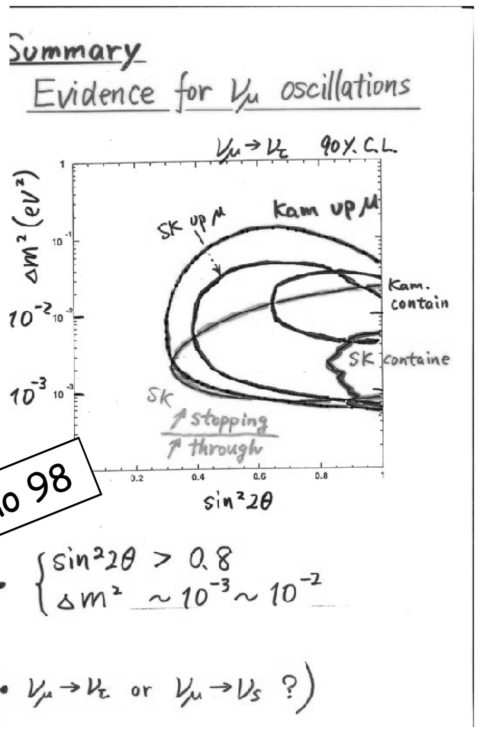


ν_μ disappearance: History

- Anomaly in $R=(\mu/e)_{observed}/(\mu/e)_{predicted}$
  - Kamiokande: PLB 1988, 1992
  - Discrepancies in various experiments
- Kamiokande: Zenith-angle distribution
  - Kamiokande: PLB 1994
- Super-Kamiokande/MACRO: Discovery of ν_μ oscillation in 1998
  - Super-Kamiokande: PRL 1998
  - MACRO, PRL 1998
- K2K: First accelerator-based long baseline experiment: 1999 – 2004 Confirmed atmospheric neutrino results
  - Final result 4.3σ: PRL 2005, PRD 2006
- MINOS: Precision measurement: 2005 -
  - First result: PRL2006






Summary

Evidence for ν_μ oscillations

$$\bullet \begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$$

$(\bullet\ \nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?$)$

Kajita: Neutrino 98

See for review:

- The “Neutrino Industry”
  - **http://www.hep.anl.gov/ndk/hypertext/**
- Janet Conrad web pages:
  - **http://www.nevis.columbia.edu/~conrad/nupage.html**
- Fermilab and KEK “Neutrino Summer School”
  - **http://projects.fnal.gov/nuss/**
- Torino web Pages:
  - **http://www.nu.to.infn.it/Neutrino_Lectures/**
- Progress in the physics of massive neutrinos, hep-ph/0308123

Appendice:
La radiazione Cerenkov

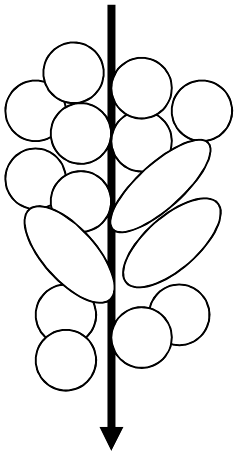
Effetto Cerenkov

Per una trattazione classica dell'effetto Cerenkov:

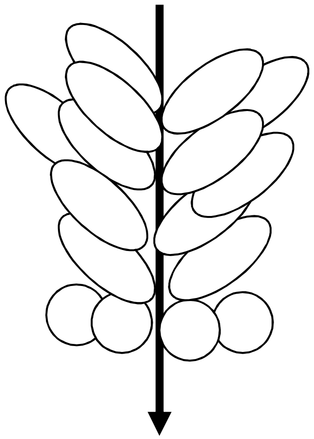
Jackson : Classical Electrodynamics, cap 13 e par. 13.4 e 13.5

La radiazione Cerenkov e' emessa ogniqualvolta una particella carica attraversa un mezzo (dielettrico) con velocita' $\beta c = v > c/n$, dove v e' la velocita' della particella e n l'indice di rifrazione del mezzo.

Intuitivamente: la particella incidente polarizza il dielettrico → gli atomi diventano dei dipoli. Se $\beta > 1/n$ → momento di dipolo elettrico → emissione di radiazione.

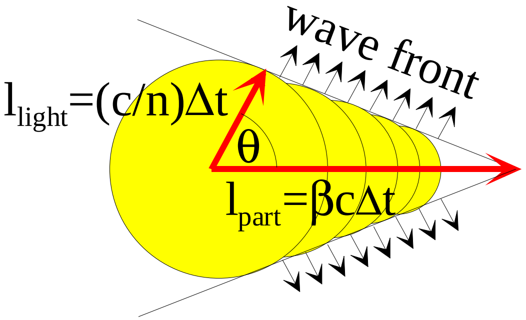


$\beta<1/n$

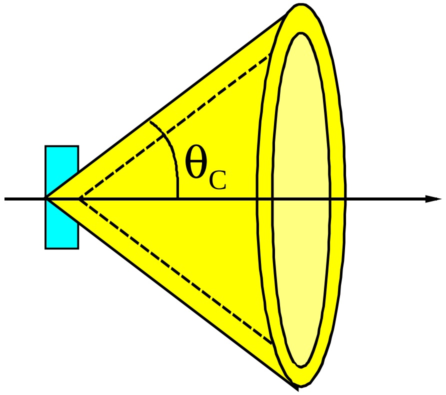


$\beta>1/n$

L’ angolo di emissione θ_c puo’ essere interpretato qualitativamente come un’onda d’urto come succede per una barca od un aereo supersonico.



$$\boxed{\cos\theta_C=\frac{1}{n\beta}} \quad \text{with } \underline{n=n(\lambda)\geq 1}$$

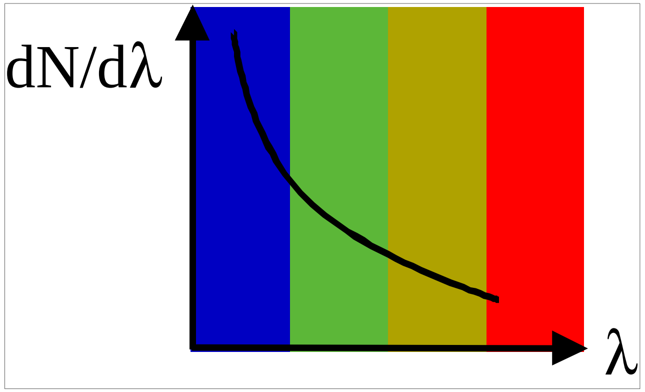


Esiste una velocita’ di soglia $\beta_s = 1/n \rightarrow \theta_c \sim 0$

Esiste un angolo massimo $\theta_{max} = \arccos(1/n)$

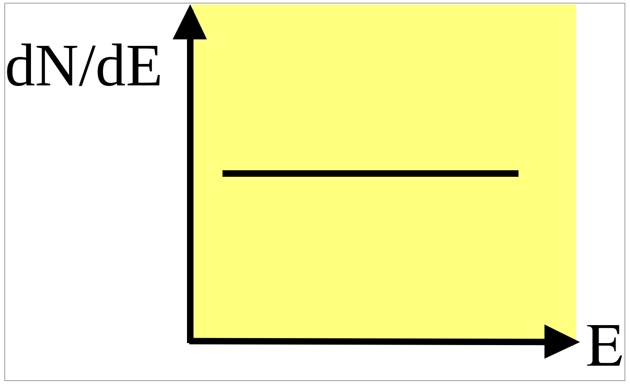
La $\cos(\theta) = 1/\beta n$ e’ valida solo per un radiatore infinito, e’ comunque una buona approssimazione ogniqualvolta il radiatore e’ lungo $L >> \lambda$ essendo λ la lunghezza d’onda della luce emessa

Numero di fotoni emessi per unita' di percorso e intervallo unitario di lunghezza d'onda. Osserviamo che decresce al crescere della λ



$$\frac{d^2N}{dxd\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$

$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2} \quad \text{with } \lambda = \frac{c}{\nu} = \frac{hc}{E} \qquad \frac{d^2N}{dxdE} = const.$$



Il numero di fotoni emessi per unita' di percorso non dipende dalla frequenza

$$-\frac{dE}{dx} = z^2\alpha\frac{\hbar}{c}\int\omega\left(1-\frac{1}{\beta^2 n^2(\omega)}\right)d\omega$$

L' energia persa per radiazione Cerenkov cresce con β. Comunque anche con β → 1 e' molto piccola.

Molto piu' piccola di quella persa per collisione (Bethe Block), al massimo 1% .

medium	n	θ_{max} (β=1)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

1) Esiste una soglia per emissione di luce Cerenkov

2) La luce e’ emessa ad un angolo particolare

→Facile utilizzare l’effetto Cerenkov per identificare le particelle.

Con 1) posso sfruttare la soglia → Cerenkov a soglia.

Con 2) misurare l’angolo → DISC, RICH etc.

La luce emessa e rivelabile e’ poca.

Consideriamo un radiatore spesso 1 cm un angolo $\theta_c = 30^o$ ed un $\Delta E = 1$ eV ed una particella di carica 1.

$$\frac{dN}{dE\,dx} = \frac{z^2\alpha}{\hbar c}\sin^2\vartheta_c$$

$$\Rightarrow \quad N_{ph} = 370\cdot\sin^2\vartheta_c\cdot L\cdot\Delta E = 370\times 0.25 = 92.5$$

Considerando inoltre che l’efficienza quantica di un fotomoltiplicatore e’ ~20% → $N_{pe}=18$ → fluttuazioni alla Poisson