The Oscillating Neutrino
(experiments)

Summary

- **Introduction : Neutrino masses and oscillations**

- **Neutrino sources and experiments:**
  reactors, accelerators, cosmic rays, sun

  Possible evidence for oscillations:
    Accelerators (LSND)
    Sun
    Cosmic Rays (atmospheric neutrinos)

- **Future**

- ***Main emphasis : atmospheric neutrinos (MACRO, Superkamiokande)***

- **Beautiful report** ***Los Alamos Science number 25 " Celebrating the Neutrino" (1998)190 pages it is free!!***

Introduction: Milestones in the Oscillating Neutrino

- 1930 Pauli : the "neutrons" to explain the missing energy
- 1934 Fermi : theory of beta decay and the word "neutrino"
- 1956 Reines and Cowan et al.: first direct detection of electron neutrino
- 1957 Pontecorvo : suggestion of neutrino oscillations
- 1963 Lederman Schwartz Steinberg detection of muon neutrino
- 1965 (Reines in South Africa and the KGF experiment in India) : first detection of atmospheric neutrinos
- 1968 Davis et al.: first detection of neutrinos from the SUN. Flux lower than expected.
- 1986 Beginning of the Atmospheric Neutrino Anomaly (IMB - Usa and then Kamiokande Japan)
- 1995 LSND experiment anomaly(Los Alamos)

- 1998 Evidence for Oscillations in the Atmospheric Neutrinos? (Superkamiokande, MACRO, Soudan2...)

Introduction: Direct Measurement of the Neutrino Masses

- based on the missing energy distributions experimental limitations due to the resolution of the energy measurement

- ν_e : Beta Decay

$$n \rightarrow p + e^- + \nu_e$$

$$(N,Z) \rightarrow (N-1,Z+1) + e^-$$

Tritium Beta decay using a magnetic spectrometer (Troitsk experiment)

$$\text{Tritium}(2,1) \rightarrow \text{Helium}(1,2) + e^-$$

$$m(\nu_e) < 3 \ \text{eV}/c^2 \quad (98\% \ \text{CL})$$

- ν_μ : $\pi \rightarrow \mu + \nu_\mu$ decay

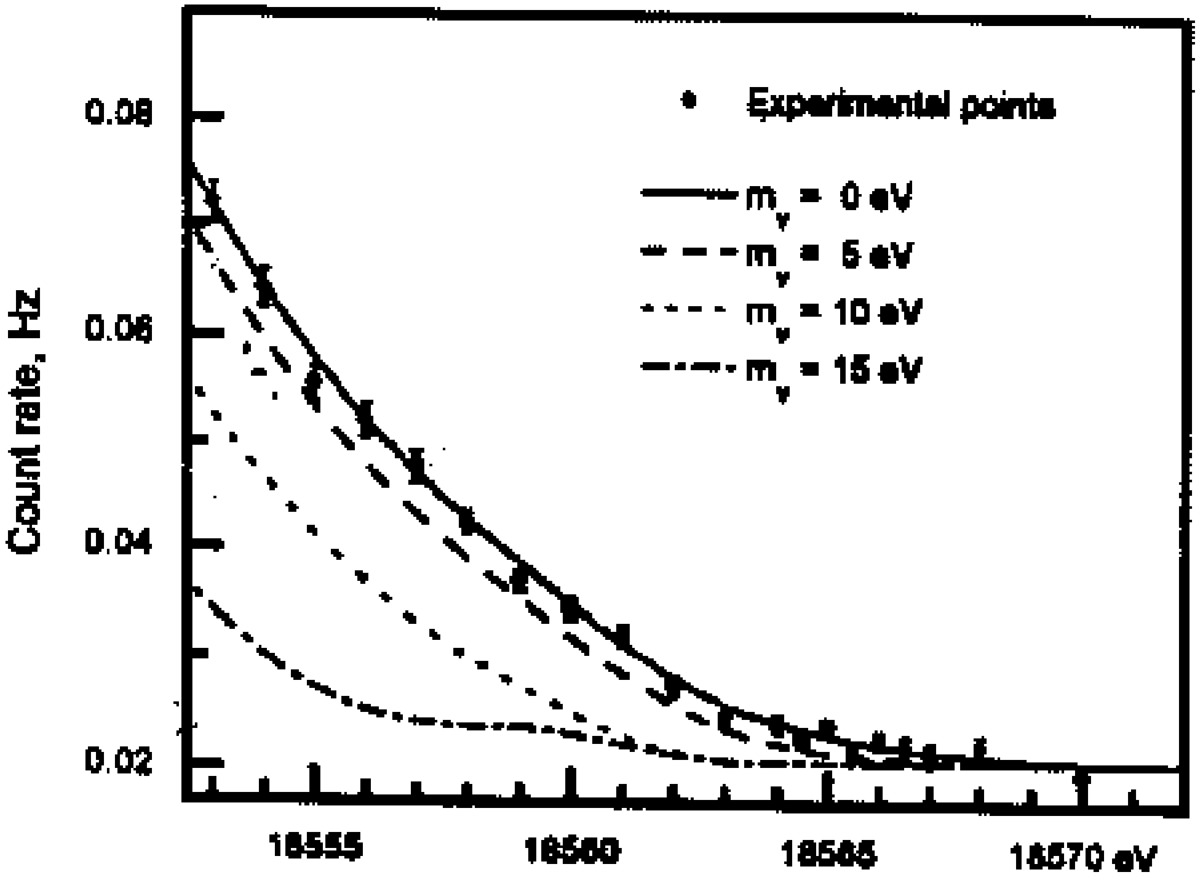
$$m(\nu_\mu) < 0.19 \ \text{MeV}/c^2 \quad (95\% \ \text{CL})$$

- ν_τ : $e^+ e^- \rightarrow \tau^+ \tau^-$

$\tau^+ \rightarrow 3 \pi^{+-} \nu_\tau$ and other decays

$$m(\nu_\tau) < 18.2 \ \text{MeV}/c^2 \quad (95\% \ \text{CL})$$

Introduction:
Direct Measurement of the Neutrino Masses
Tritium spectrum near the end point



Introduction:
The Oscillating Neutrino

- **Pontecorvo suggestion :**

if we postulate

1) Neutrino have different masses
2) The Weak eigenstate is a mixture of Mass Eingenstate then:

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

(θ is called mixing angle)

and the probability of oscillations for two neutrinos is :

$$Posc = \sin^2(2\theta)\sin^2\left(1.27\Delta \mathrm{m}^2 \frac{L}{E}\right)$$

(L in meters, E in MeV, $\Delta \mathrm{m}^2 = m_1^2 - m_2^2$ in (eV/c^2)^2

Introduction:
The Oscillating Neutrino

- The results of the experiments is usually given as function of the oscillation probability for two neutrinos, but the general case involves 3 neutrinos

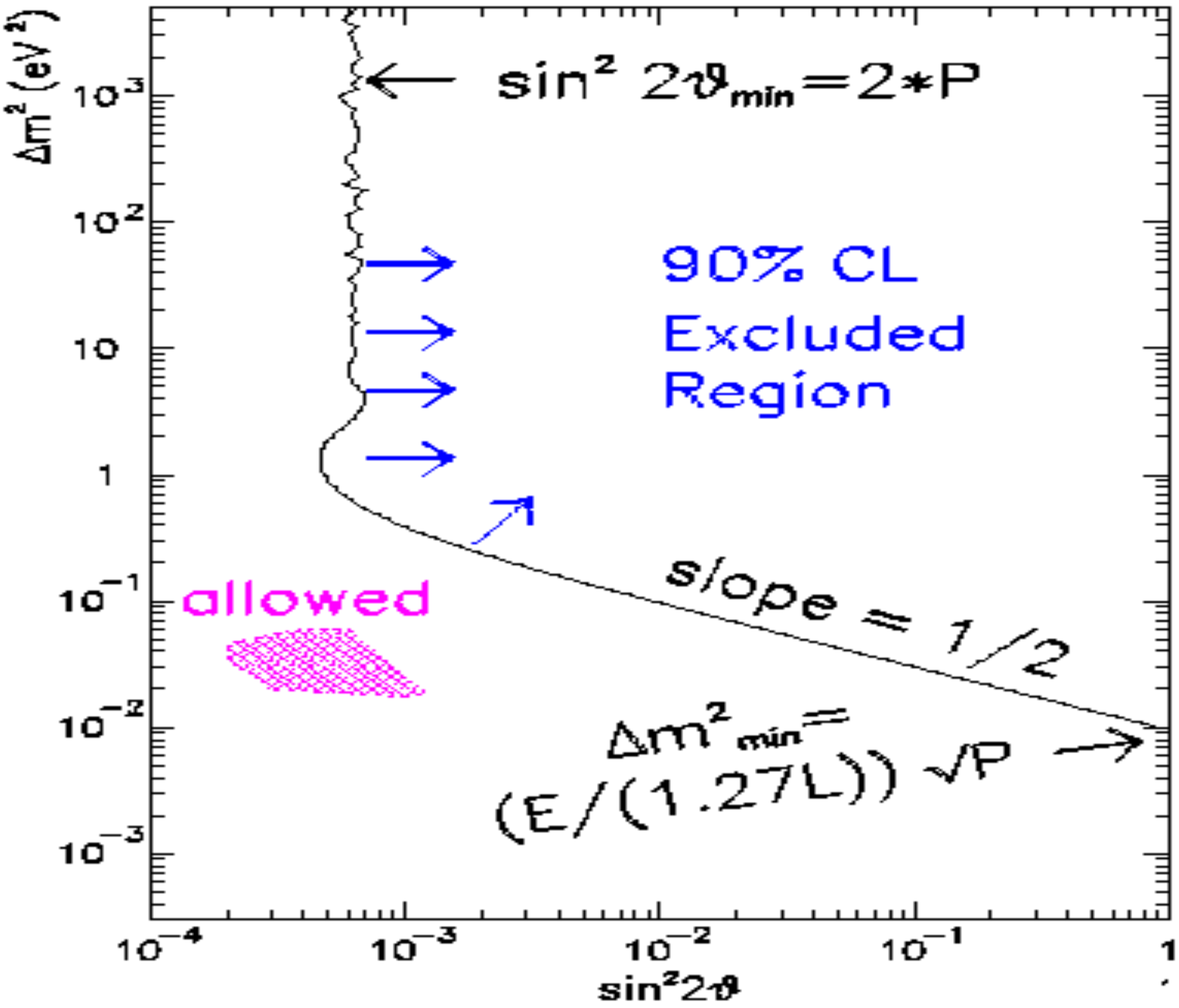
- Oscillating Neutrino crossing the Sun/Earth could have a "Matter Effect" (MSW).
This occurs when the two oscillating neutrinos have different interactions in the matter (for example the ν_e has interaction with electrons in the matter different from ν_μ.

- Neutrino oscillations and masses ==>> significant changes to the Standard Model

(==>> Fogli - Altarelli)

Introduction:
The Oscillation Plots

- *large* Δm^2 **due to the energy spread of a typical neutrino beams** $Posc = \dfrac{\sin^2(2\theta)}{2}$
- *small* Δm^2 $Posc = \sin^2(2\theta)\left(1.27\Delta m^2 \dfrac{L}{E}\right)^2$



- **the line is defined typically by $\chi^2 = \chi^2$min + x (x=4.5..)**
- **not well defined (Feldman Cousins) *also called exclusion plot* (for me is often a confusion plot)**

Neutrino sources and experiments

- **The experiments are of two kinds :**

a) appearance experiments : looking for neutrino of different kind respect to the beam
(LSND experiment)
Small values of the mixing angle can be measured
several combinations :
$\nu_\mu \nu_\tau$, $\nu_\mu \nu_e$

b) disappearance experiments : they measures the flux of neutrinos similar to the one in the beam
(solar and atmospheric)
Only large values of the mixing angle can be measured

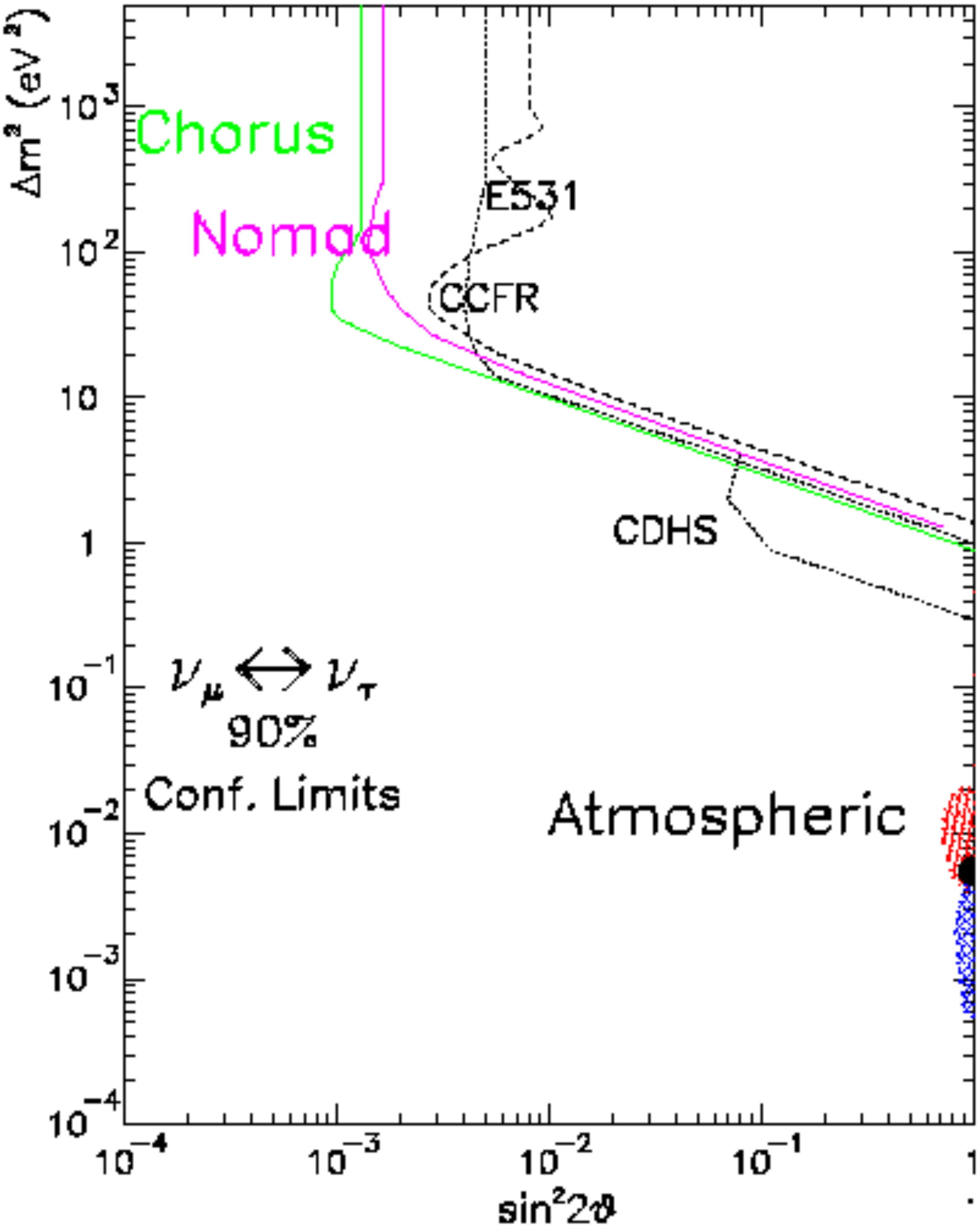
- **In both cases the behavior of the counting rates as function L/E is important to identify the oscillation pattern**

Neutrino sources and experiments

Source	Neutrino Beam	L meters	E MeV	Type	Δm^2 min (eV^2)
Reactors Chooz	$\bar{\nu}_e$	$10 \div 10^3$	3	dis.	$\approx 10^{-3}$
Accellerators low energies LSND	$\bar{\nu}_\mu$ ν_μ ν_e	30	70	app $\bar{\nu}_e$	$\approx 10^{-1}$
Accelerators high energy Nomad Chorus	ν_μ ν_e	10^3	$26 * 10^3$	app ν_τ	≈ 1
Atmospheric	$\bar{\nu}_\mu$ ν_μ $\bar{\nu}_e$ ν_e	$10^4 \div 10^7$	$100 \div 10^6$	dis	$\approx 10^{-4}$
Solar	ν_e	10^{11}	$0.1 \div 10$	dis	10^{-11}
Future : Long Base Line Beam	$\bar{\nu}_\mu$ ν_μ	10^6	10^4	app ν_τ dis	$\approx 10^{-3}$

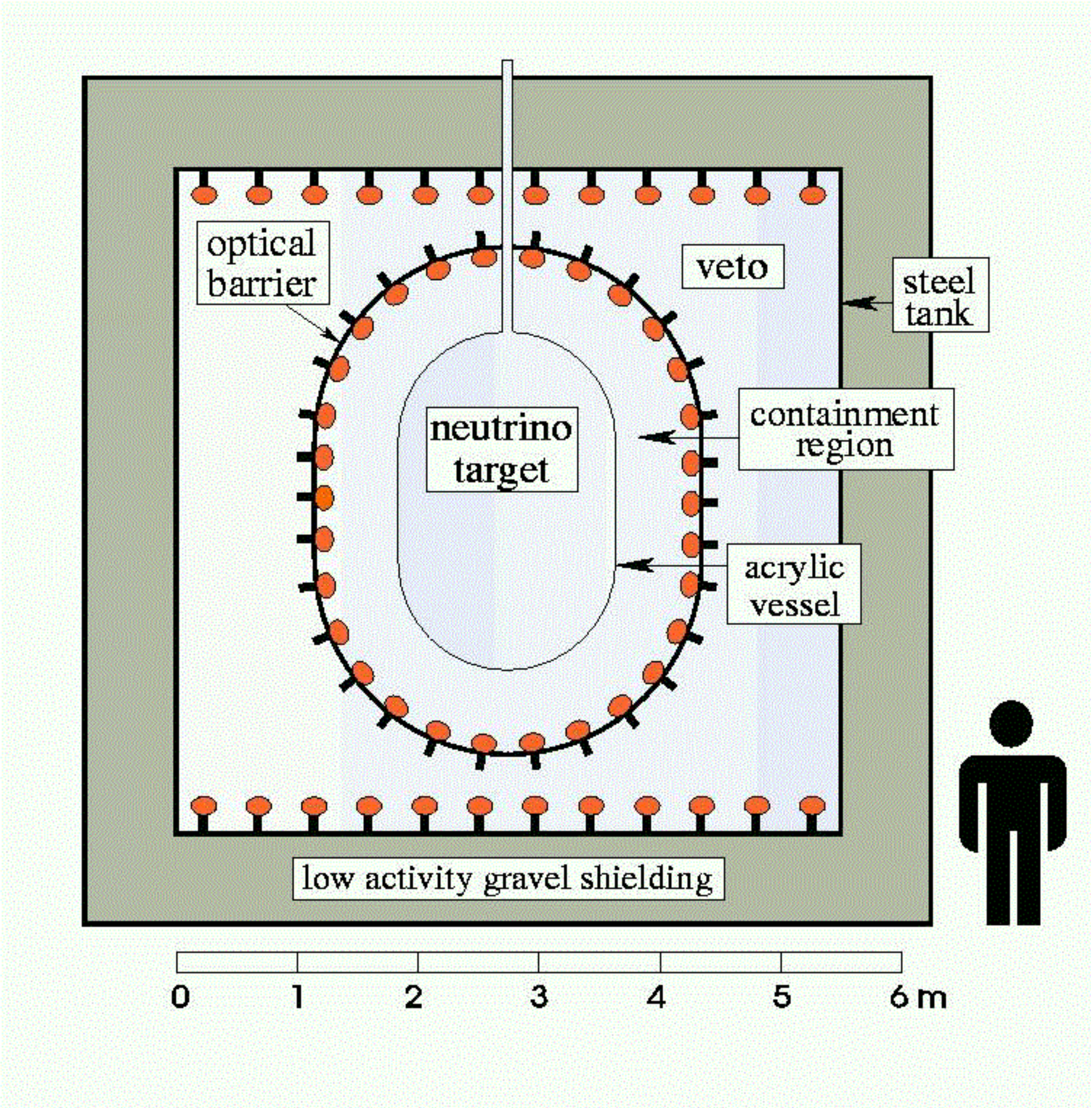
- **dis = disappearance, app= appearance**

Neutrino sources and experiments : negative results from accelerators ($\nu_\mu \rightarrow \nu_\tau$)



- The signature is a τ produced by ν_τ interaction

Neutrino at reactors Chooz
France Italy USA

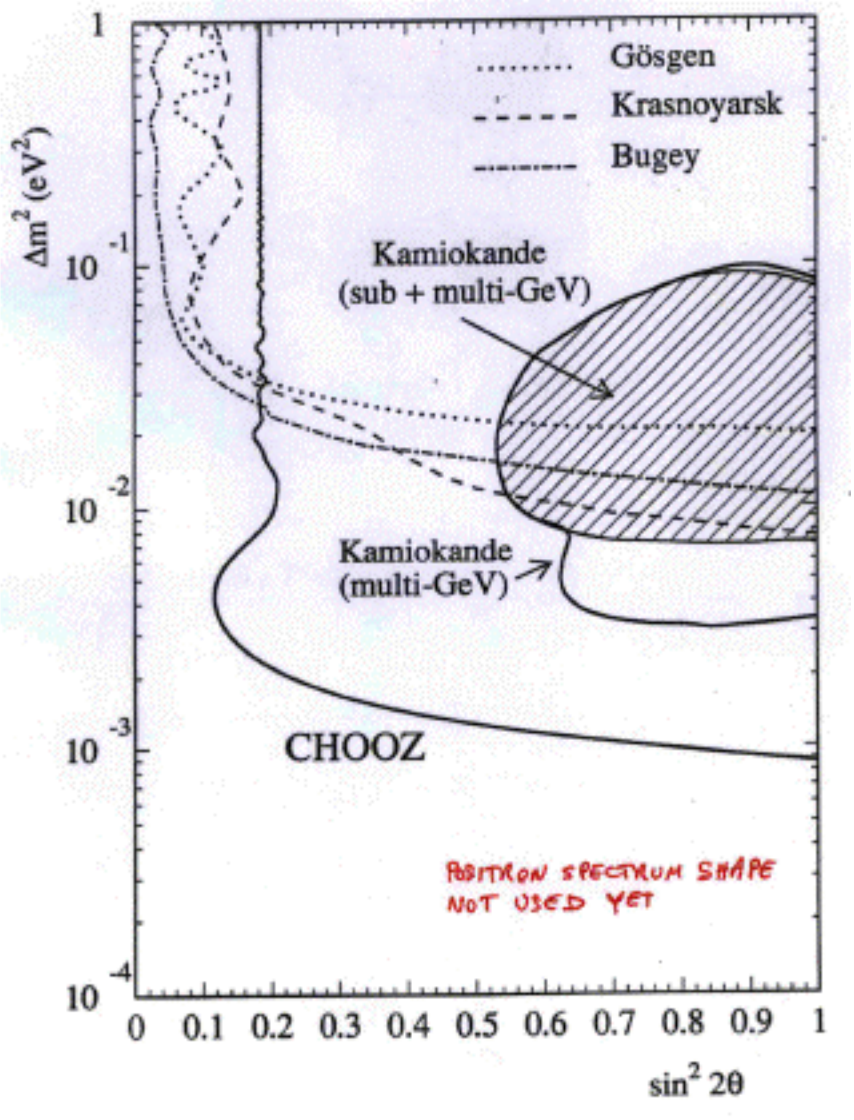


- Gd loaded liquid scintillator to have a good detections of neutrons ($\bar{\nu}_e$ p ==>> e^+ n)

  n capture after 30μsec with 8 Mev signal)

Neutrino sources and experiments : negative results from reactors

$(\nu_e \rightarrow \nu_x)$



POSITRON SPECTRUM SHAPE
NOT USED YET

Possible evidence for oscillations: LNSD results ($\nu_\mu \rightarrow \nu_e$)

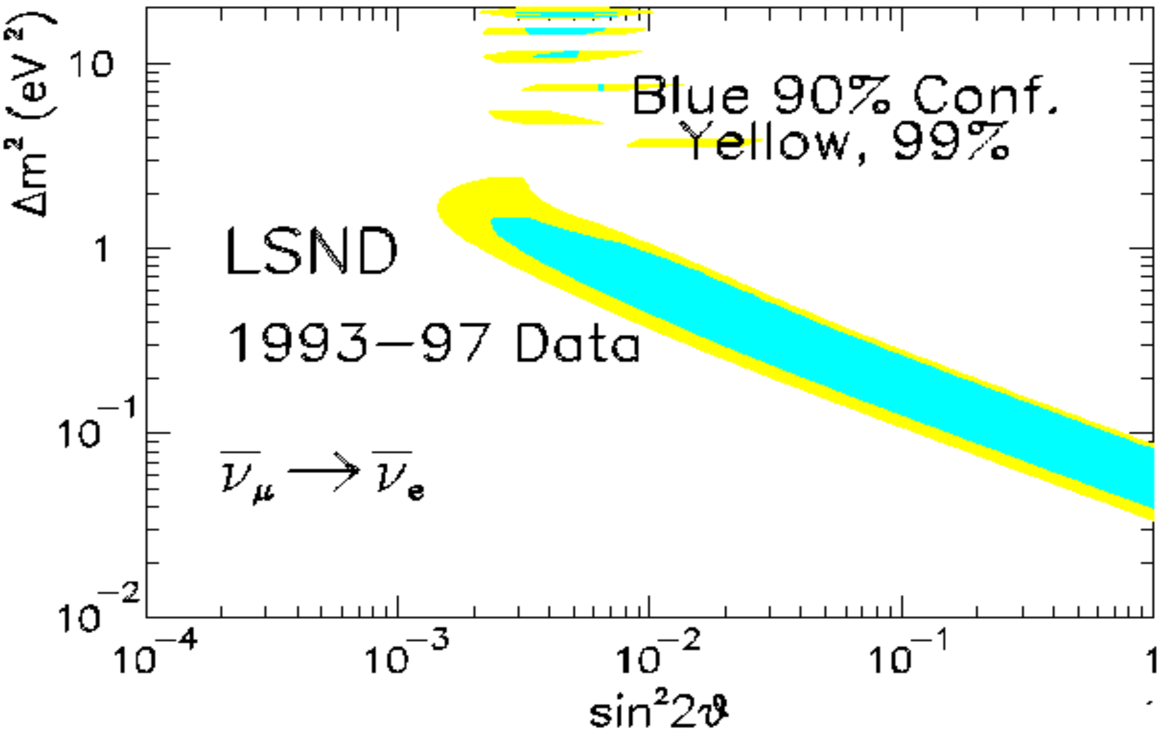
- **the only positive result using neutrino artificially produced**
- **Los Alamos : 800 MeV proton beam**
- **neutrino are produced at rest in the following way:**

$$\pi^+ \rightarrow \nu_\mu \; \mu^+$$

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

- **detection** $\boxed{\bar{\nu}_e}\; p \rightarrow e^+ n$

$$n\, p \rightarrow d\, \gamma \quad \text{(delayed 186 } \mu\text{sec)}$$



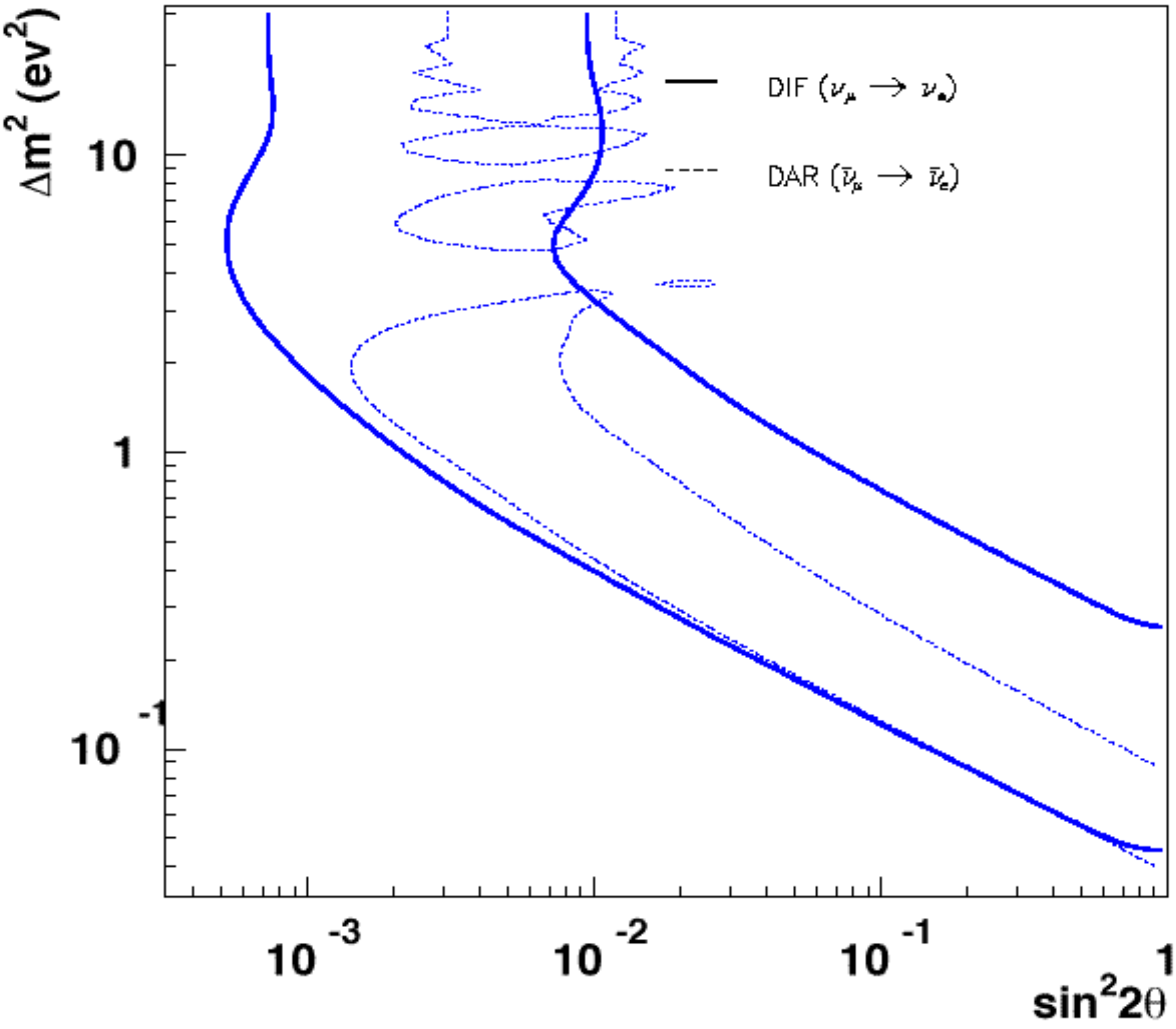
Fitted Excess	Background	Total Excess	Oscillation Probability
100.1±23.4	17.3±4.0	82.8±23.7	0.31±0.09±0.05%

Possible evidence for oscillations: LNSD results ($\nu_\mu \rightarrow \nu_e$)

- ν_μ neutrino are produced from π^+ decay in fligth
- detection of ν_e using quasi-elasting scattering:

$$\nu_e \, C \longrightarrow e \, N^*$$

- almost a different experiment : different L, higher energy neutrinos, different signature, different background



LNSD/Karmen disagreement?

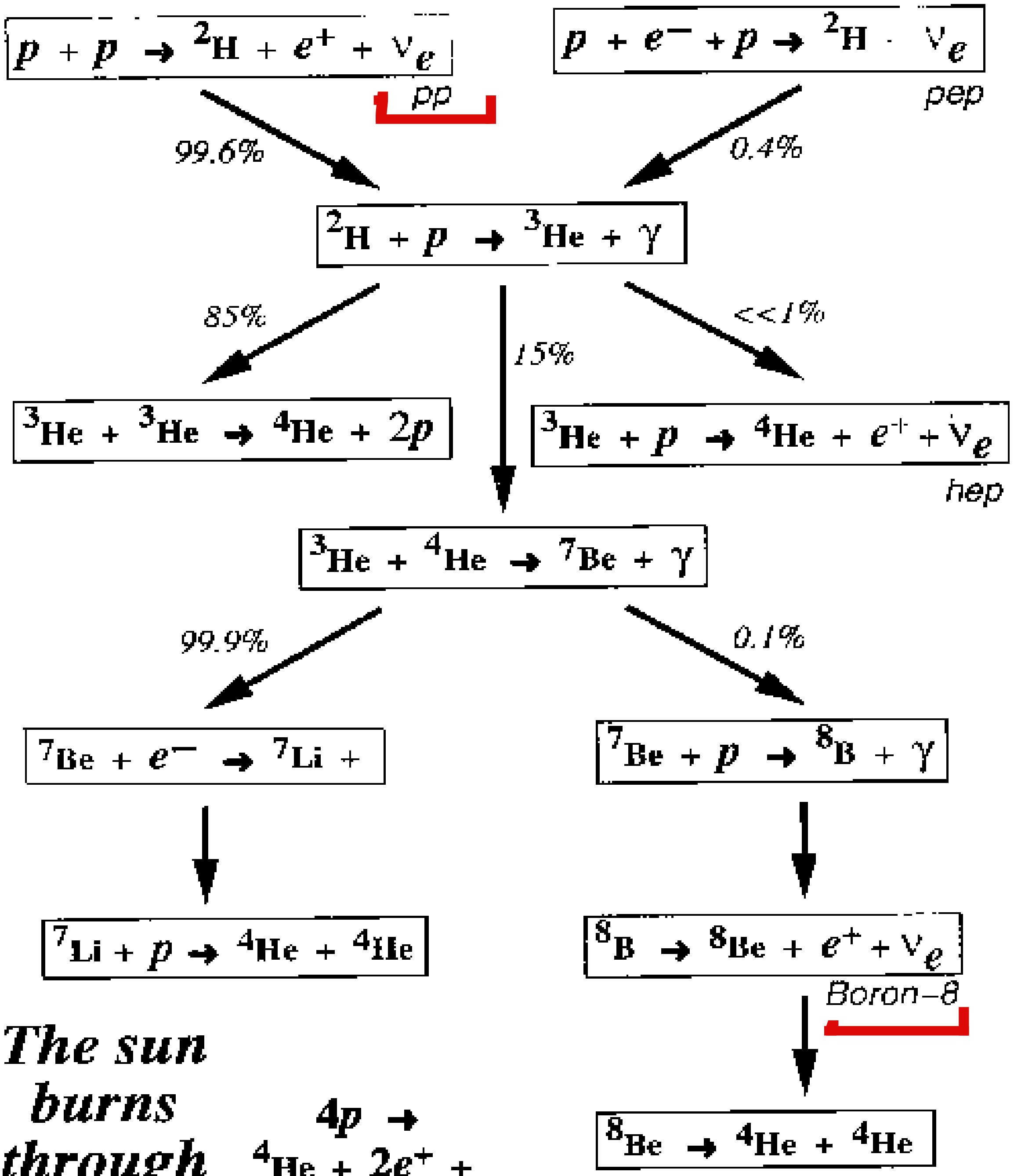
- Karmen 1 : detector similar to LSND
  10 times less statistics
  7.3 ± 7.0 event as excess consistent with LSND

- Karmen 2 : in progress
  Better veto shielding
  Expected Background 7.8 events
  3 events found
  oscillating signal expected ≈ 1 events (LSND)

- The interpretation depends on the statistical treatment of the data and to the way to give upper limits when the measured numbers are less than the expected background
- Nice paper of Feldman-Cousins on Phys Rev D 1998.
- If you believe to the background evaluation using the Feldman-Cousins preocedures

Karmen2 is inconsistent with LSND at 90% CL.

The Sun as Neutrino Source



$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

$p + e^- + p \rightarrow {}^2\mathrm{H}\ \ \nu_e$

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} +$

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

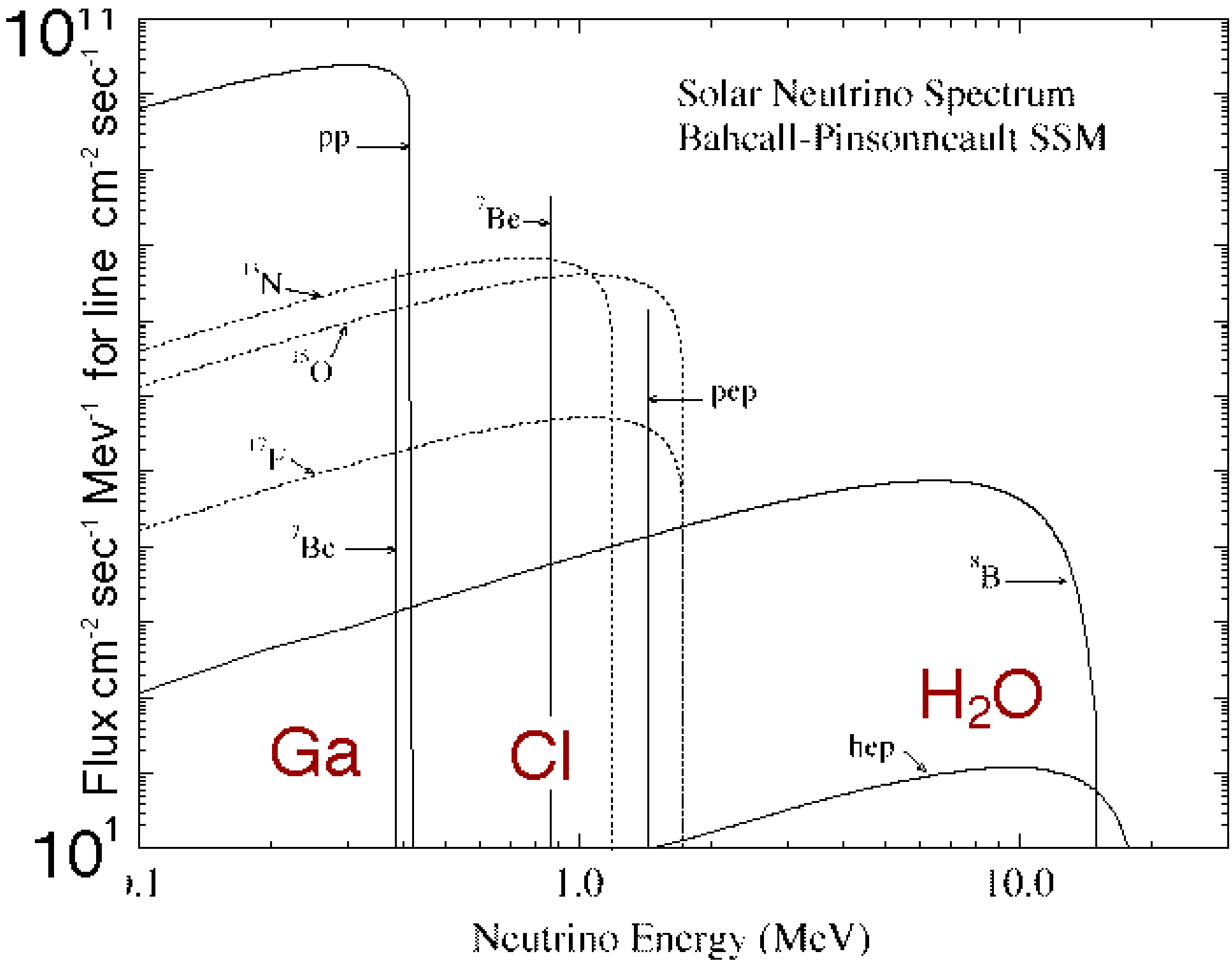
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$

${}^8\mathrm{Be} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

The sun burns through nuclear reactions

$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + \gamma$$

The Sun as Neutrino Source



- **Experiments**

Homestake(USA) Chlorine

ν_e + ^{37}Cl $\longrightarrow$ ^{37}Ar* + e$^-$ E$_{th}$=0.8 MeV

1 atom /day 25 years of data ^{37}Ar* τ =11 days

SAGE(Russia) and Gallex (Gran Sasso) Gallium

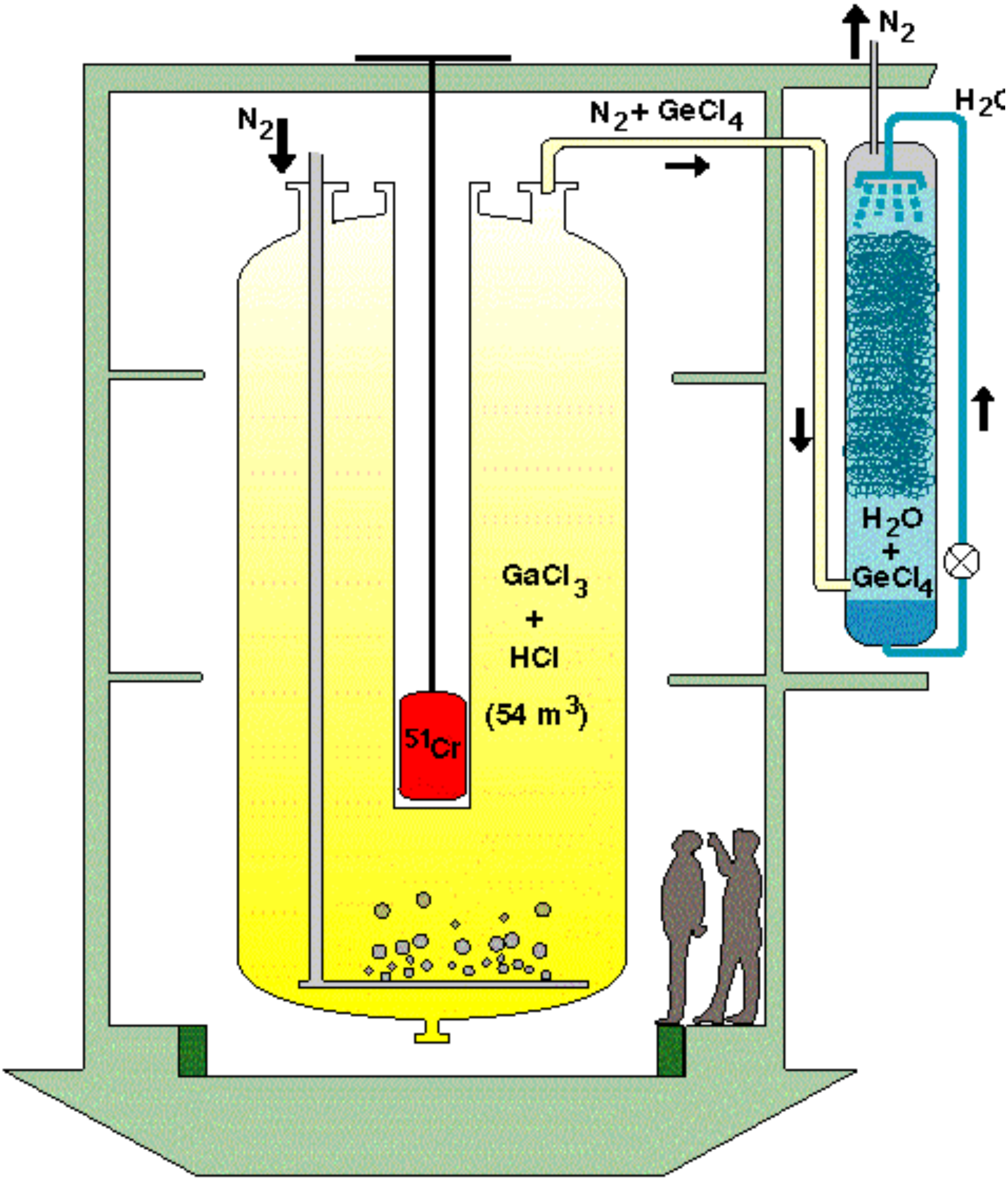
ν_e + ^{71}Ga $\longrightarrow$ ^{71}Ge* + e$^-$ E$_{th}$=0.23 MeV

1 atom/day ^{71}Ge* τ =35 days

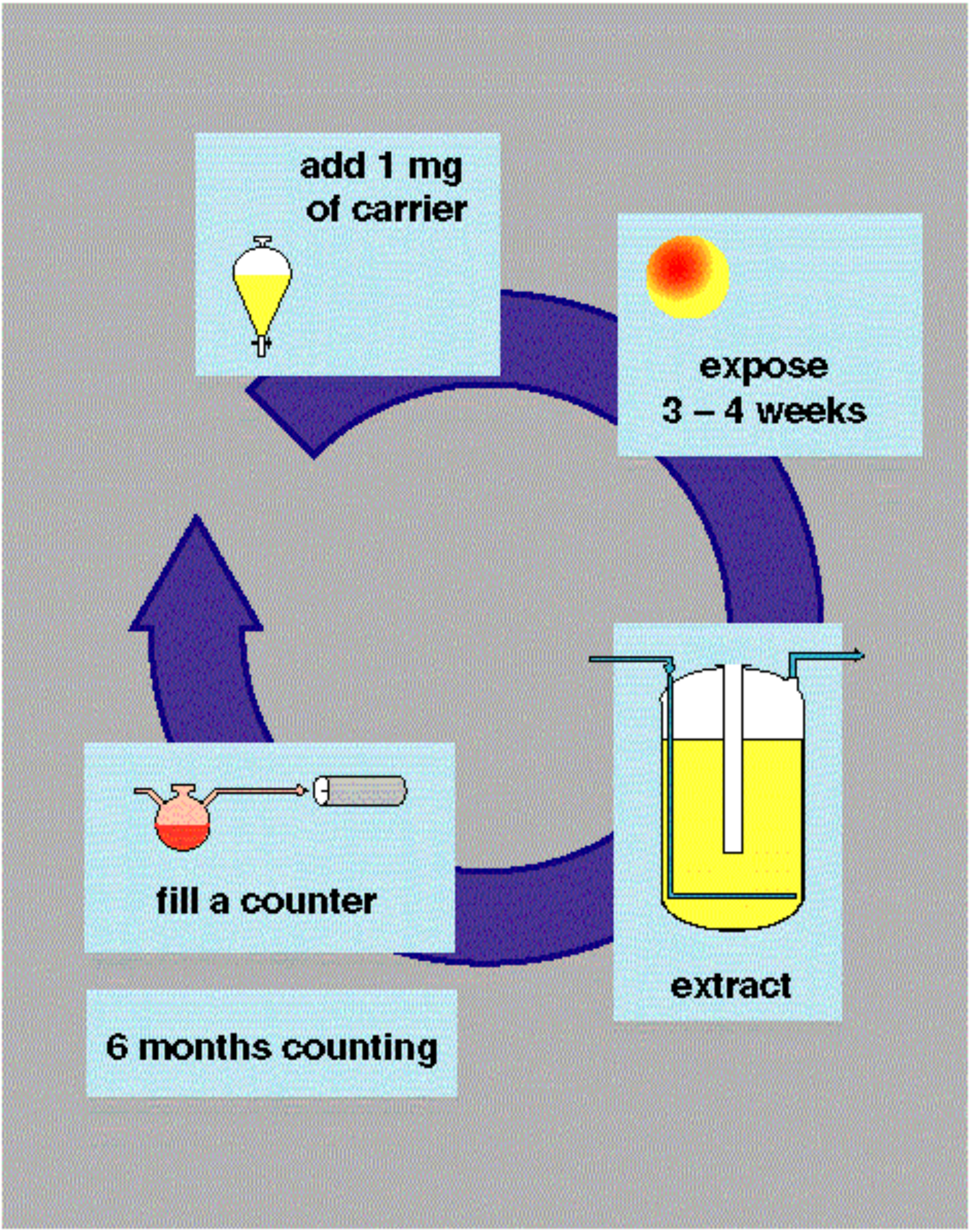
Kamiokande and SuperKamiokande (Japan)water

ν_e e $\longrightarrow$ ν_e e (elastic scattering) E$_{th}$=6.5 MeV

SUN
GALLEX at Gran Sasso



SUN
GALLEX at Gran Sasso



add 1 mg of carrier

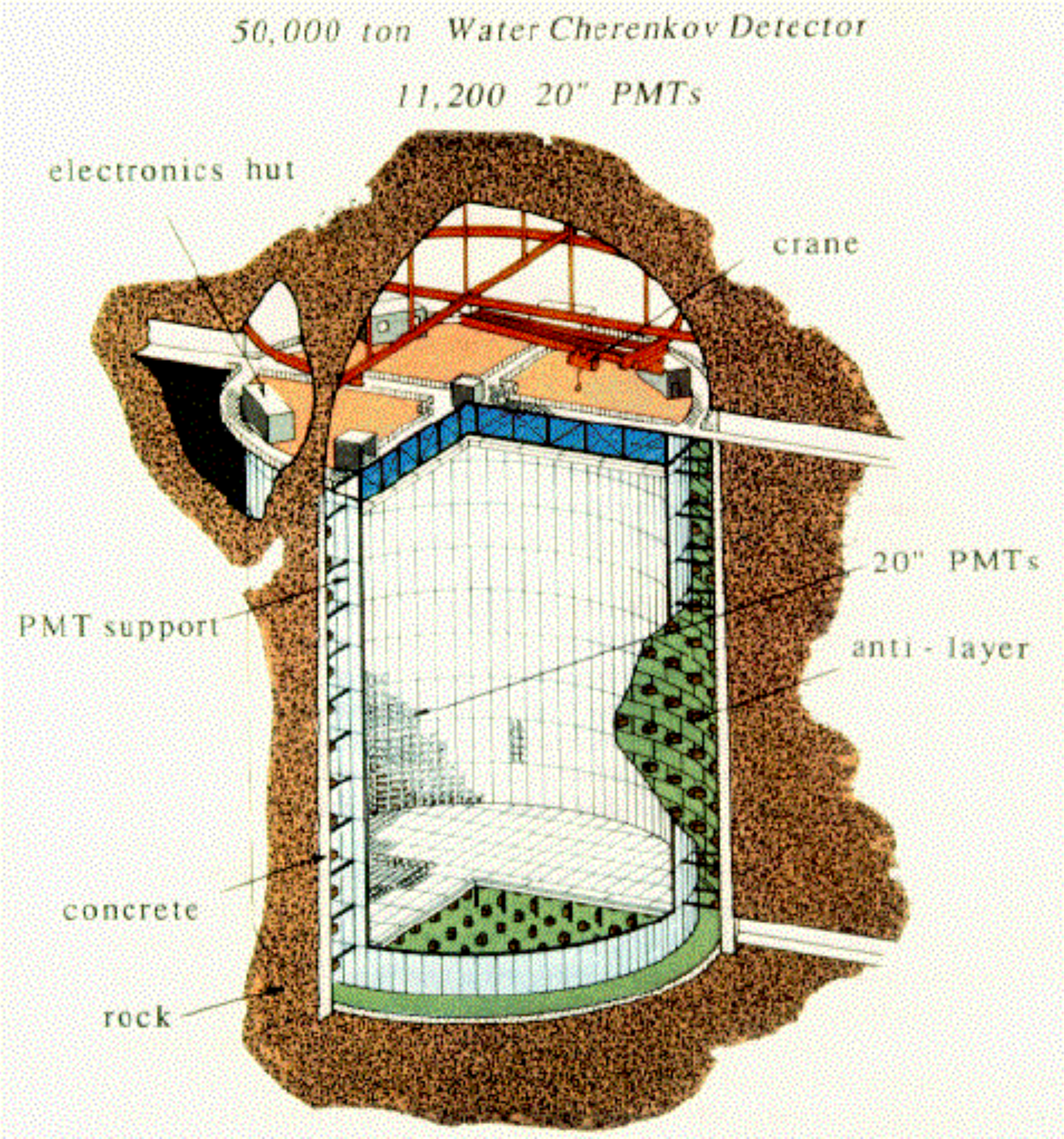
expose 3 – 4 weeks

extract

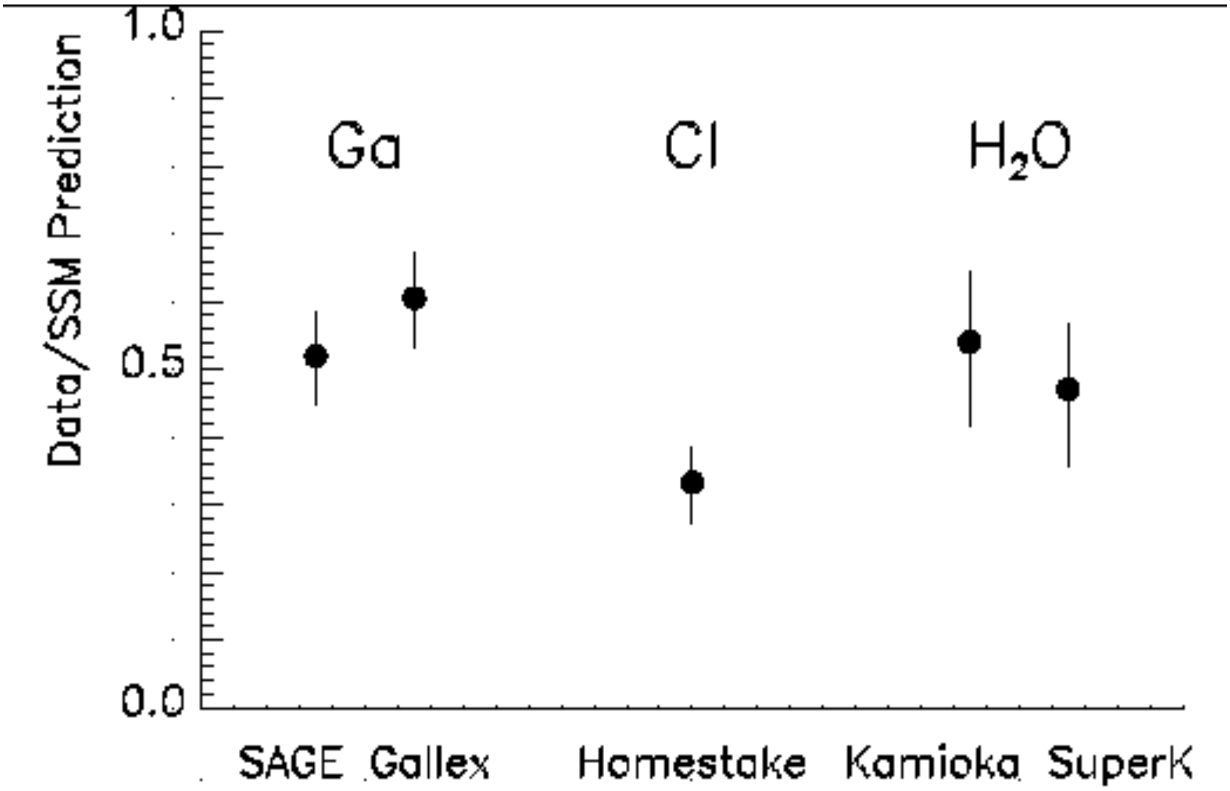
fill a counter

6 months counting

SUN
Superkamiokande



SUN : Neutrino flux measurements



ν source	> 0.23 MeV	> 0.8 MeV	> 7.0 MeV
pp	51%		
^{7}Be	28%	13%	
pep	2%	2%	
CNO	7%	5%	
^{8}B	12%	80%	100%

- **There is a ≈ 50% reduction of the measured flux respect expectations. How reliable are the expectations? A lot of theoretical work in the past years**

SUN : Theoretical Predictions

- **39 Experts agree on cross section and systematic**

Rev Mod Phys Oct 1998

- **Bahcal - Pinsonneault revised model 1998**

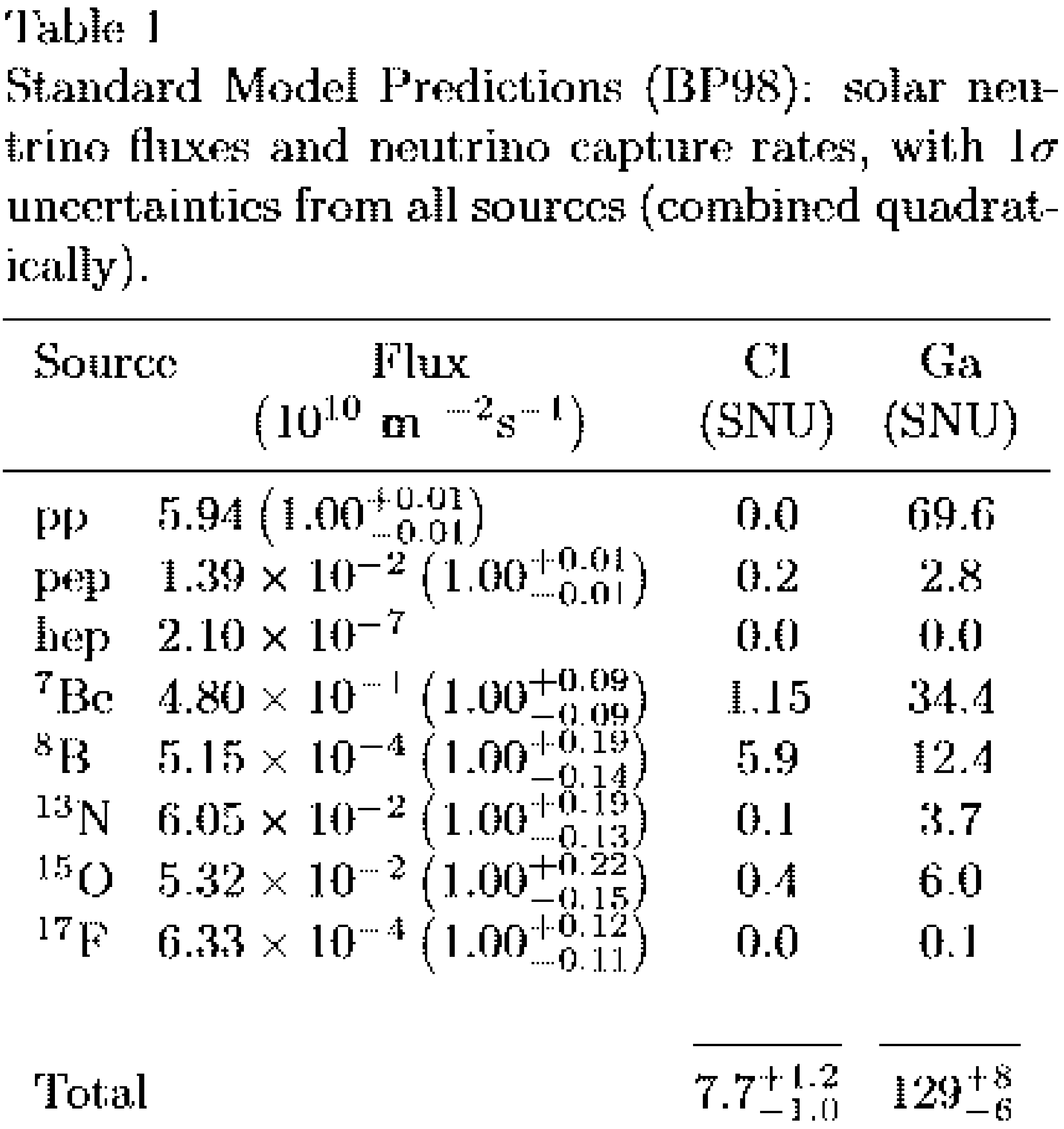
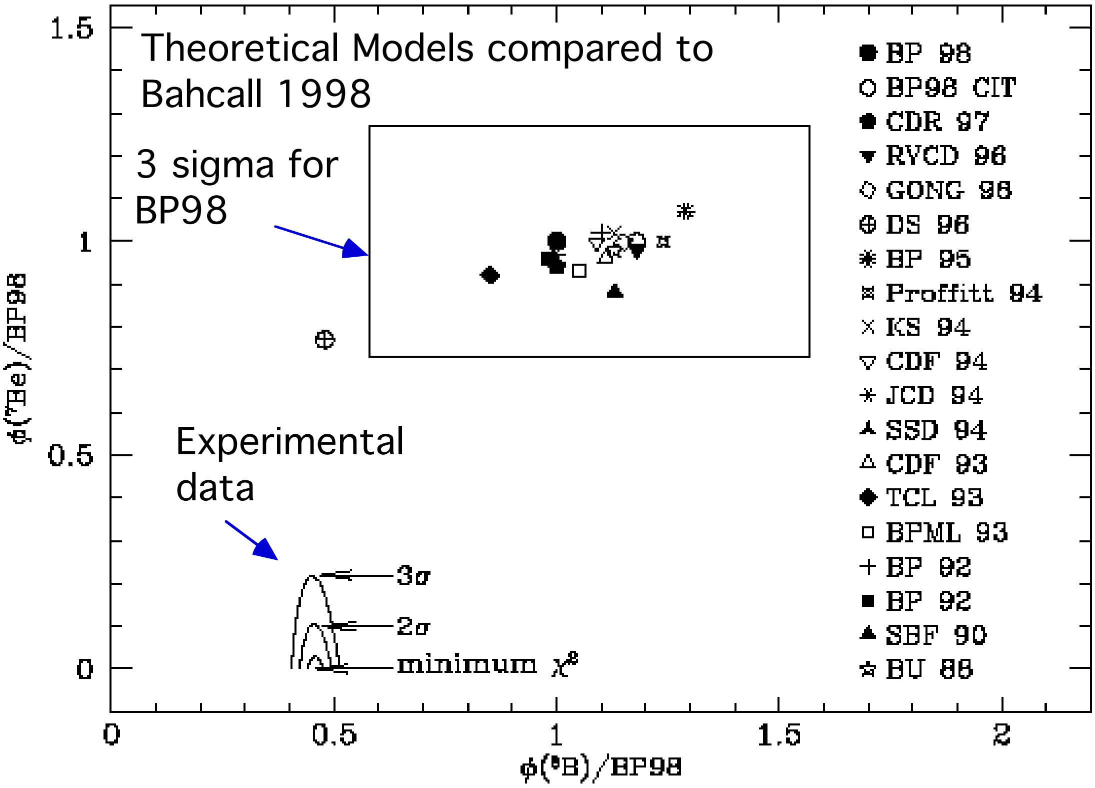


Table 1
Standard Model Predictions (BP98): solar neutrino fluxes and neutrino capture rates, with 1σ uncertainties from all sources (combined quadratically).

Source	Flux $(10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$	Cl (SNU)	Ga (SNU)
pp	$5.94\ (1.00^{+0.01}_{-0.01})$	0.0	69.6
pep	$1.39 \times 10^{-2}\ (1.00^{+0.01}_{-0.01})$	0.2	2.8
hep	2.10×10^{-7}	0.0	0.0
^{7}Be	$4.80 \times 10^{-1}\ (1.00^{+0.09}_{-0.09})$	1.15	34.4
^{8}B	$5.15 \times 10^{-4}\ (1.00^{+0.19}_{-0.14})$	5.9	12.4
^{13}N	$6.05 \times 10^{-2}\ (1.00^{+0.19}_{-0.13})$	0.1	3.7
^{15}O	$5.32 \times 10^{-2}\ (1.00^{+0.22}_{-0.15})$	0.4	6.0
^{17}F	$6.33 \times 10^{-4}\ (1.00^{+0.12}_{-0.11})$	0.0	0.1
Total		$7.7^{+1.2}_{-1.0}$	129^{+8}_{-6}

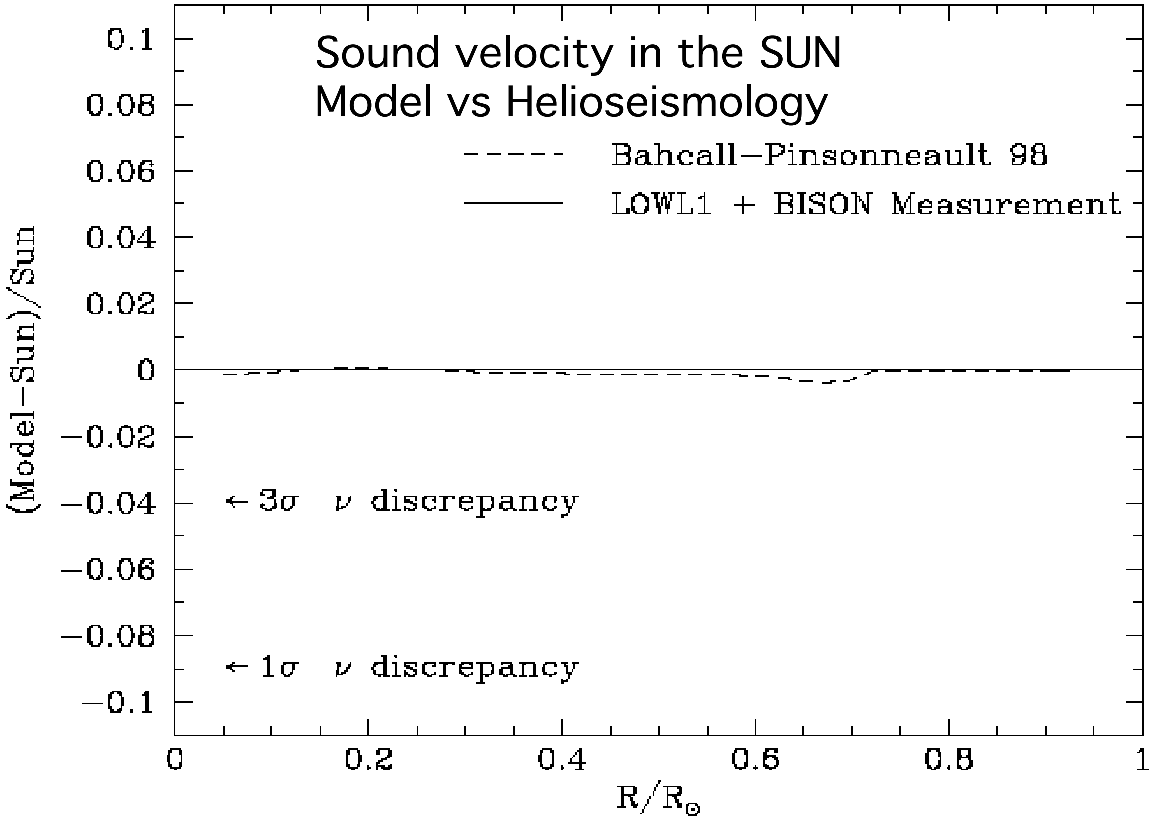
SUN-Theoretical Predictions



Theoretical Models compared to Bahcall 1998

3 sigma for BP98

Experimental data

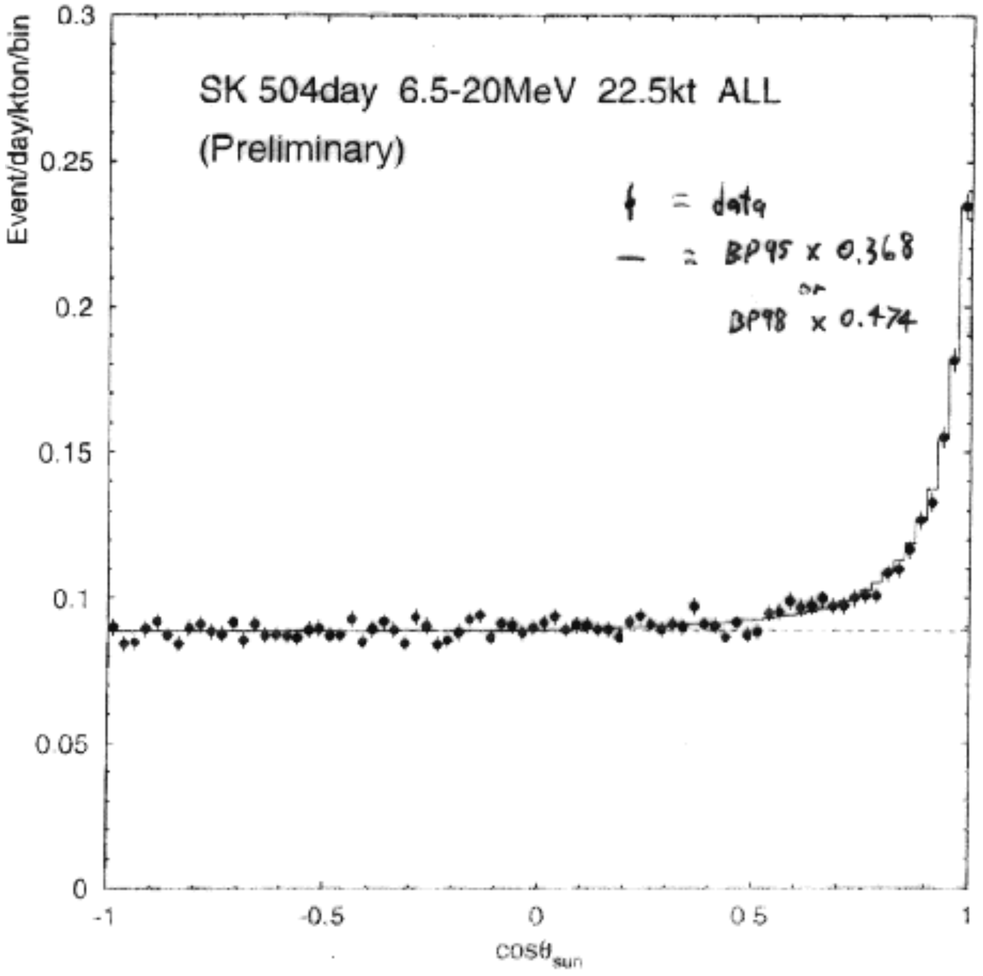


Sound velocity in the SUN
Model vs Helioseismology

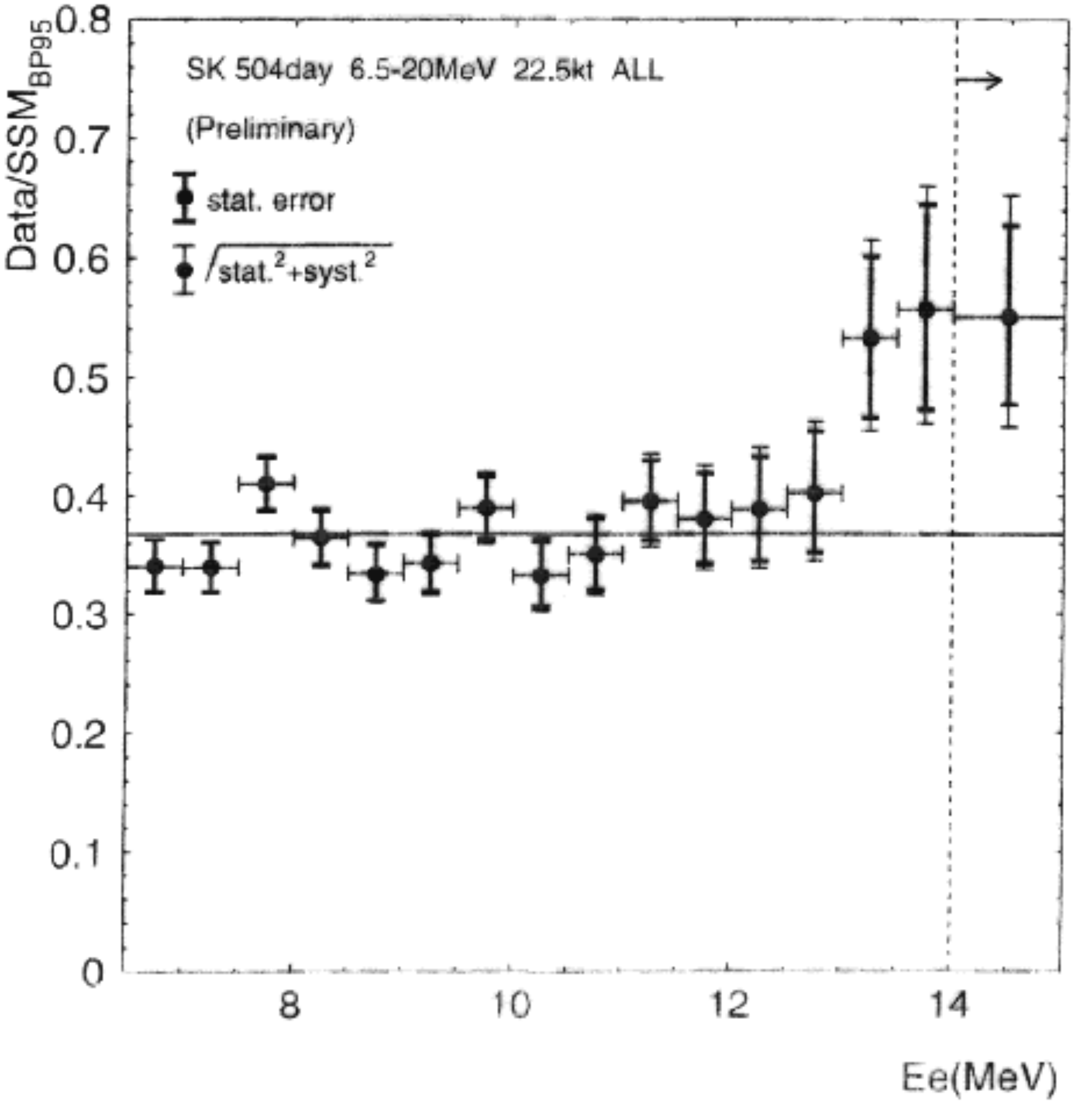
SUN- Superkamiokande

- 13.5 events/day more than 1 order of magnitude respect to past experiments
- enough statistic to look to day/night effects (to see matter effect) and to seasonal variations
no effect found

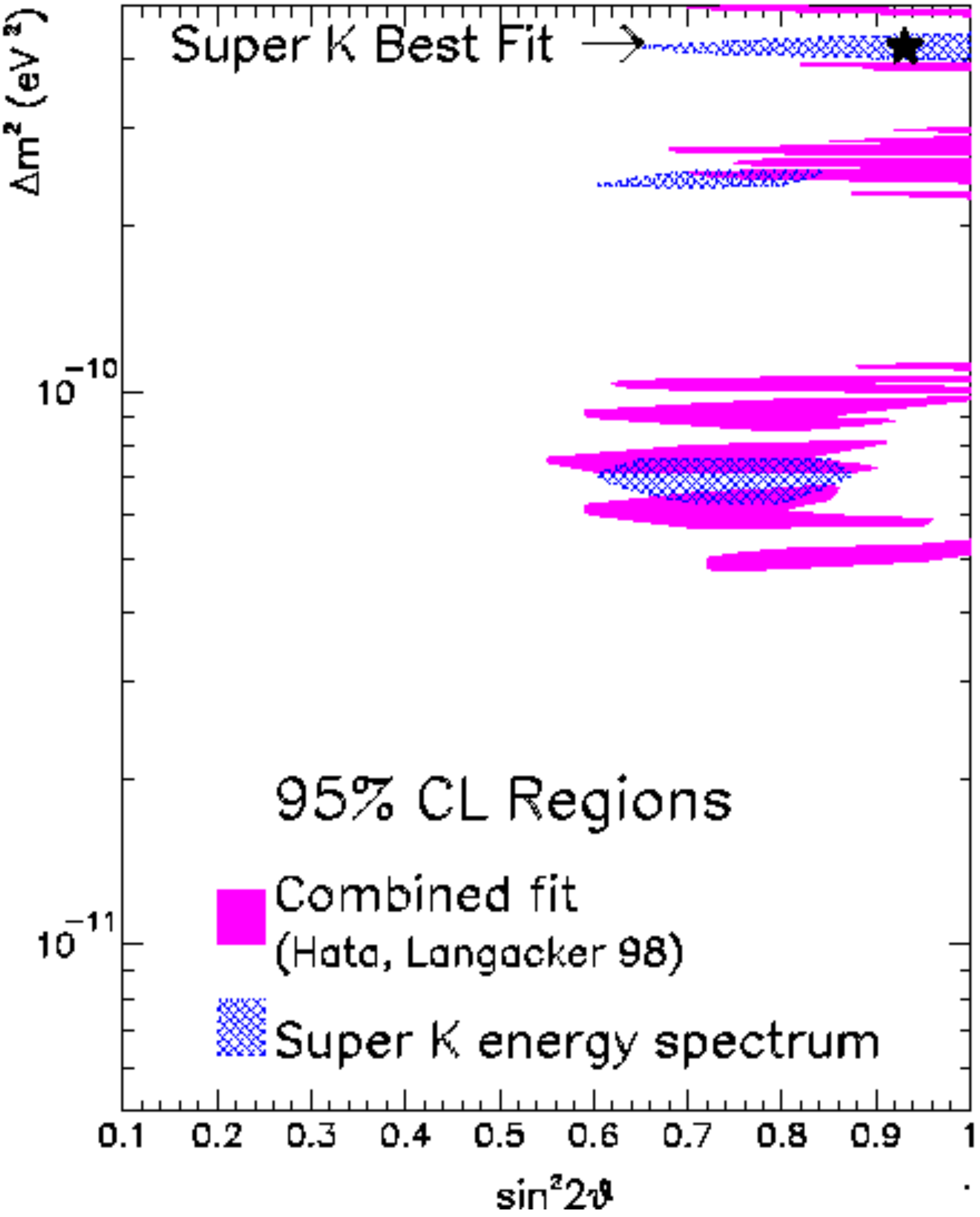
- electronic device ==>> possibility to measure the electron direction and to measure the energy



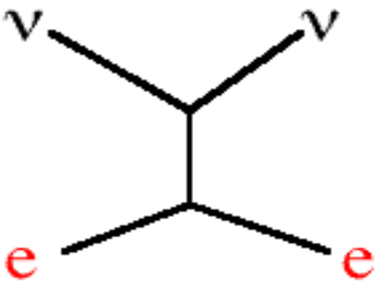
SUN- Superkamiokande energy distribution

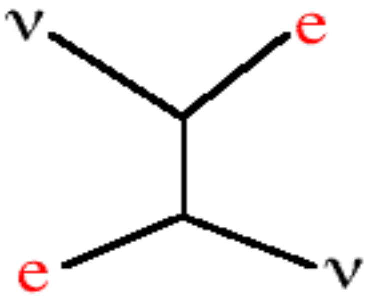


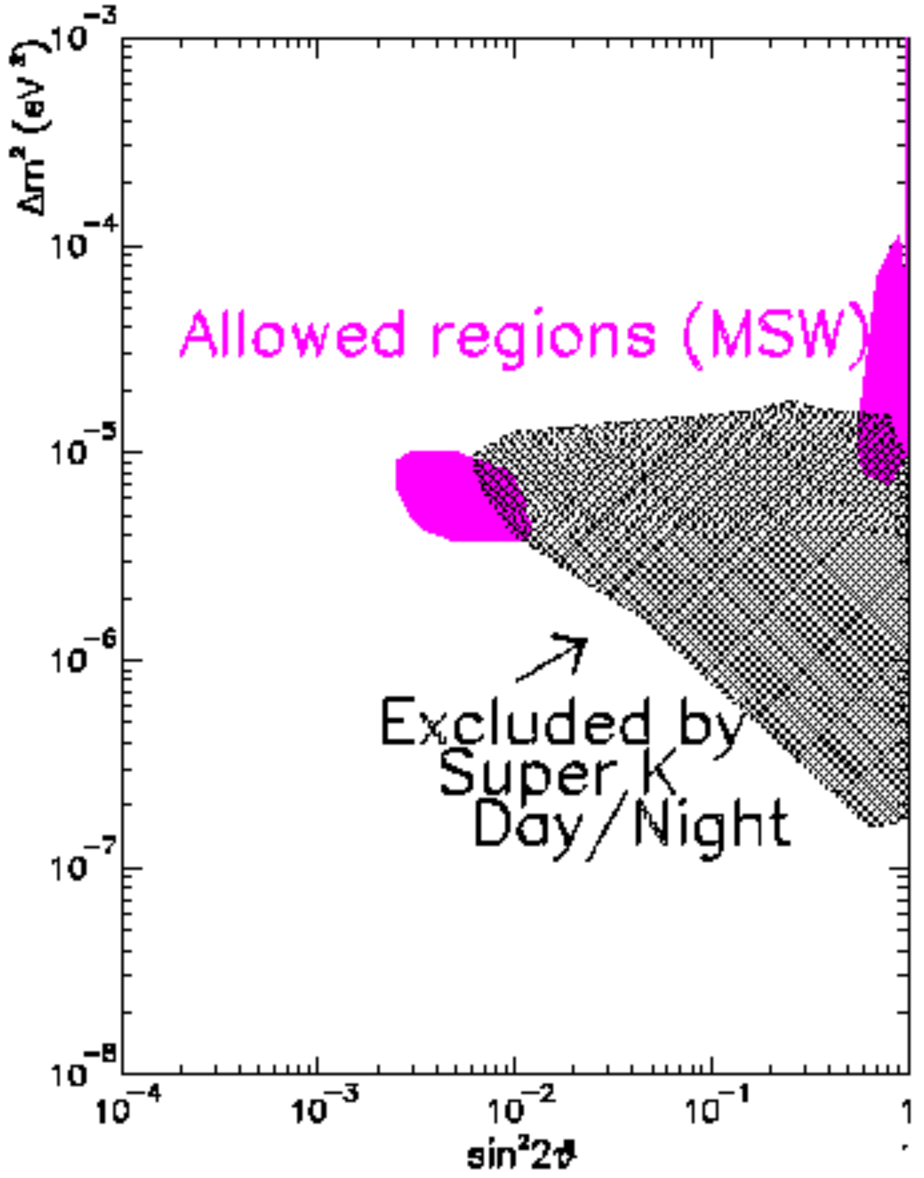
SUN- Superkamiokande Vacuum oscillations (just-so)



SUN- Superkamiokande Matter oscillations







SUN- Conclusions (Global Analysis of Bahcal Krastev Smirnov)

- **Input : all experiments + SK Energy dependence, Day/Night data**

- **Matter effect (MSW)**
Best solution Confidence Level=7%
$\Delta m^2 = 5 \times 10^{-6}$ eV^2 $\sin^2(\theta) = 5.5 \times 10^{-3}$
the large angle solution CL≈1%

- **Vacuum oscillations Confidence Level=6%**
$\Delta m^2 = 6.5 \times 10^{-11}$ eV^2 $\sin^2(\theta) = 0.75$

- **Standard Solar Models without oscillations inconsistent with the data at 20 σ**

Atmospheric neutrinos : the beam

- Neutrinos are produced in the hadronic cascade produced from the primary cosmic interacting in the atmosphere

- Basic scheme :

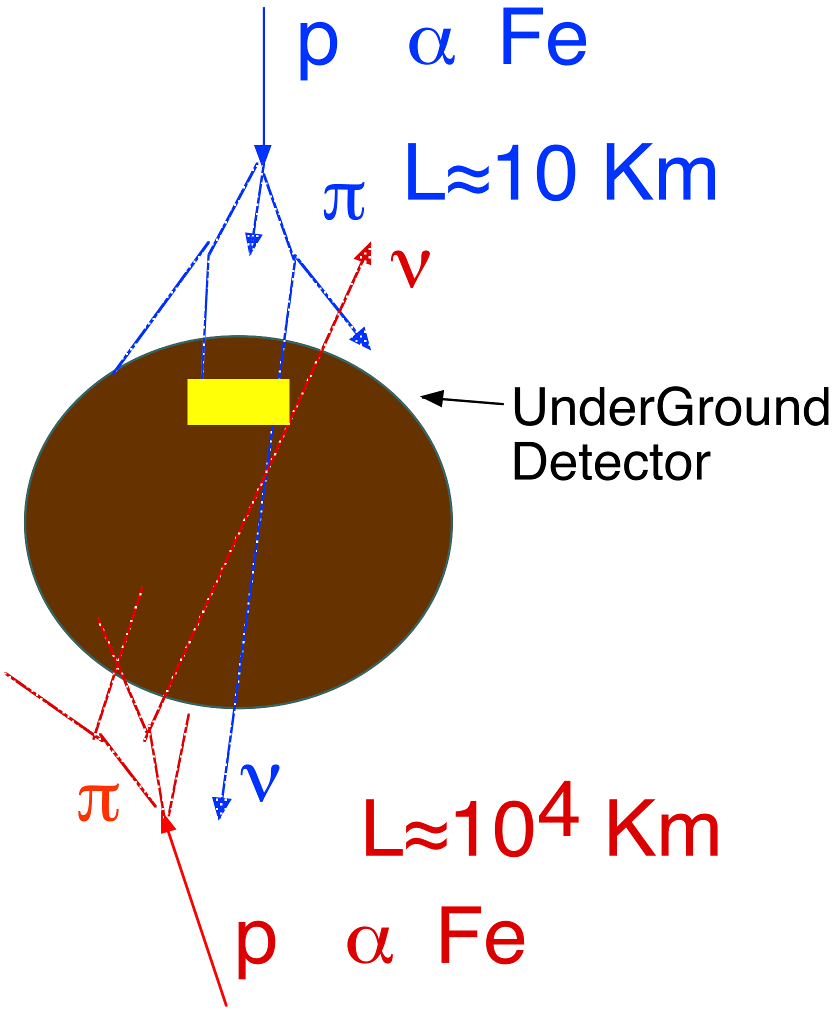
$$p+N \rightarrow n \quad \pi / k + ..$$

$$\pi / k \rightarrow \mu^{+} \quad (\mu^{-}) + \nu_{\mu} \quad (\nu_{\mu} \quad)$$

$$\mu^{+} \quad (\mu^{-}) \rightarrow e^{+} (e^{-}) + \nu_{e} (\nu_{e})$$

$$+ \nu_{\mu} \; (\nu_{\mu})$$

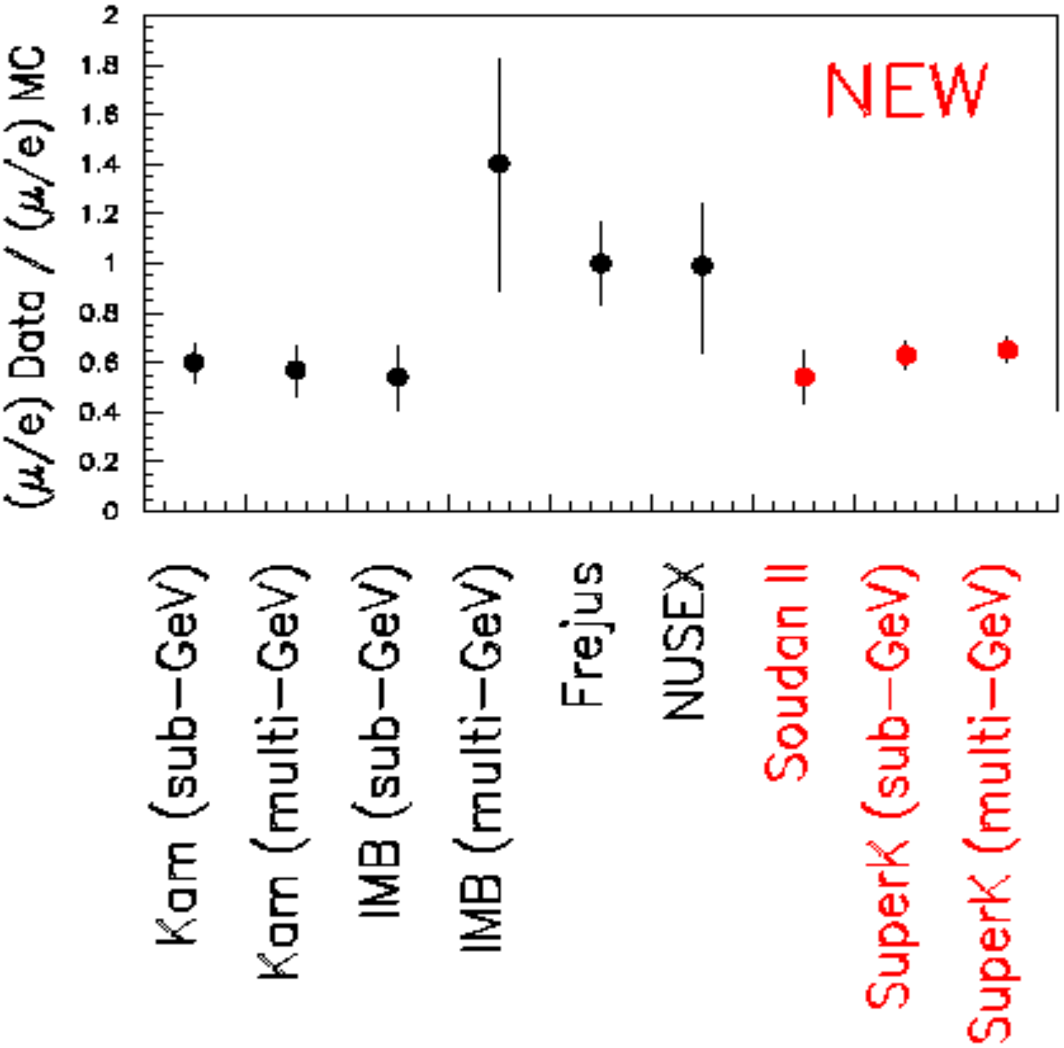
==>> at low energies about twice muon neutrinos respect to electron neutrinos.


p α Fe
π
L≈10 Km
ν
UnderGround Detector
π
ν
L≈10⁴ Km
p α Fe

The first Atmospheric neutrino anomaly

- The contained events with a single muon are less than expected compared with the events with a single electrons

$$\mathbf{R=}\ \frac{(\mu/e)data}{(\mu/e)MC}$$



- **Note : the "error " for R is from the binomial distribution**

Atmospheric neutrinos : Sources of uncertainties in a detailed calculation:

- **Experimental data on the cosmic ray spectra and nuclear composition**

- **Experimental data on proton-nucleus and nucleus-nucleus interaction (up to 1000 GeV)**

- **Data on the strength of the geomagnetic field (at low energies) , solar modulation**

- **Constraint from the measurement of the muon flux (as function of the height)**

- **At E >≈1 GeV the effect of the geo-magnetic field is small ==>>:**

- **UP-DOWN symmetry**

- **Angular Distributions are almost independent from the theoretical predictions**

- **R=** $\frac{(\mu/e)data}{(\mu/e)MC}$ **almost intependent from the theoretical predictions (±5%)**

Atmospheric neutrinos : the beam at low energies (≈1GeV)

Barr et al. (BGS) Honda et al. (HKHM) Bugaev and Naumov (BN) Battistoni et al (Fluka)

- **Significant** differences in the absolute flux calculation: for example for $\boxed{\nu}_\mu$ + $\boxed{\bar{\nu}}_\mu$ and energies between 0.4 and 1 GeV (flux normalized to BGS)

	Flux ($\boxed{\nu}_\mu + \boxed{\bar{\nu}}_\mu$)	ν_e/ν_μ
BGS	1	0.48
HKHM	0.90	0.49
BN	0.63	0.50
Fluka	0.86	0.48

- main difference : different treatment of pion production by the interactions of protons in the atmosphere.

- but practically **same value** for the ratio ν_e/ν_μ

- BGS theoretical error on R ≈ ± 5%
(warning theoretical errors are generally not gaussian)

- from muon flux measurement in the atmosphere (MASS experiment) Perkins $R = 0.49$ for $E = 1$ GeV

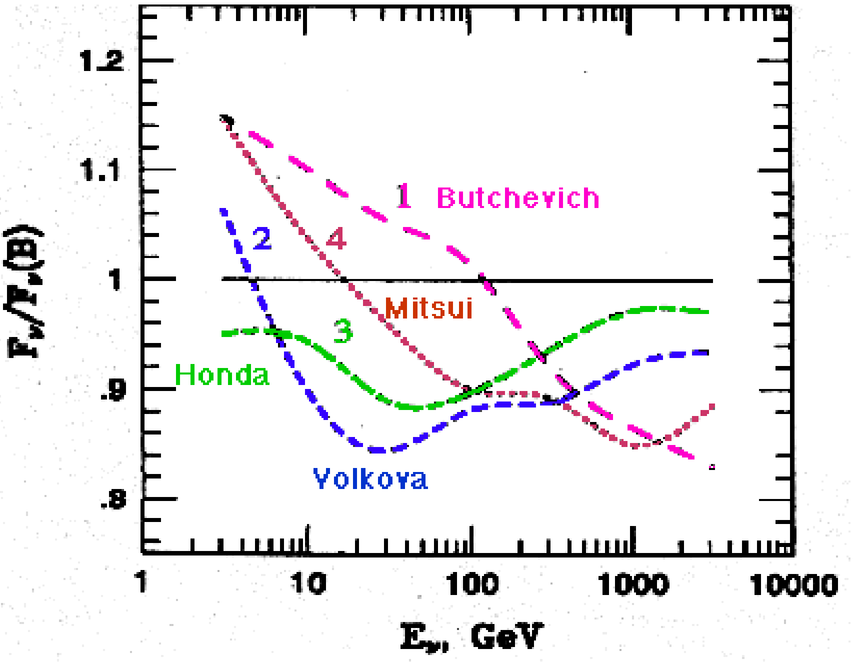
Atmospheric neutrinos : the beam at high energies (≈100 GeV)

- the contribution of the kaons is important (50% in the interval 10 < E < 1000)

- comparison of different calculation in a recent paper (Agrawal et al Phys Rev D 53)

- **18 %** estimated error on the flux in the interval
  10 < E < 1000,
  14% error with the muon flux measurement as
  constraint

- main sources of uncertainty : primary cosmic ray spectra and composition



Neutrino flux respect to the "Bartol" flux

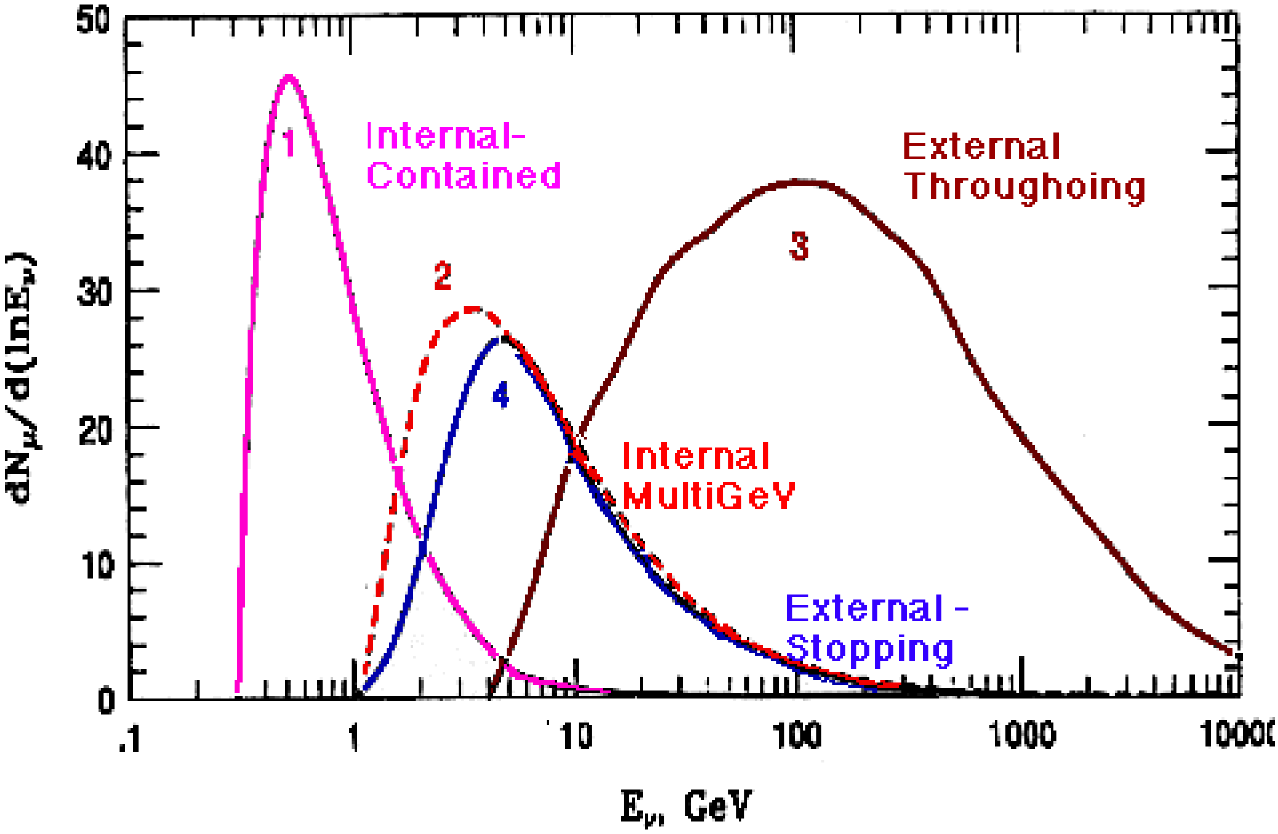
Roma III novembre 1998

Atmospheric neutrinos : Energies of interest

- The energy of the parent neutrino is dependent from the topology of detected events

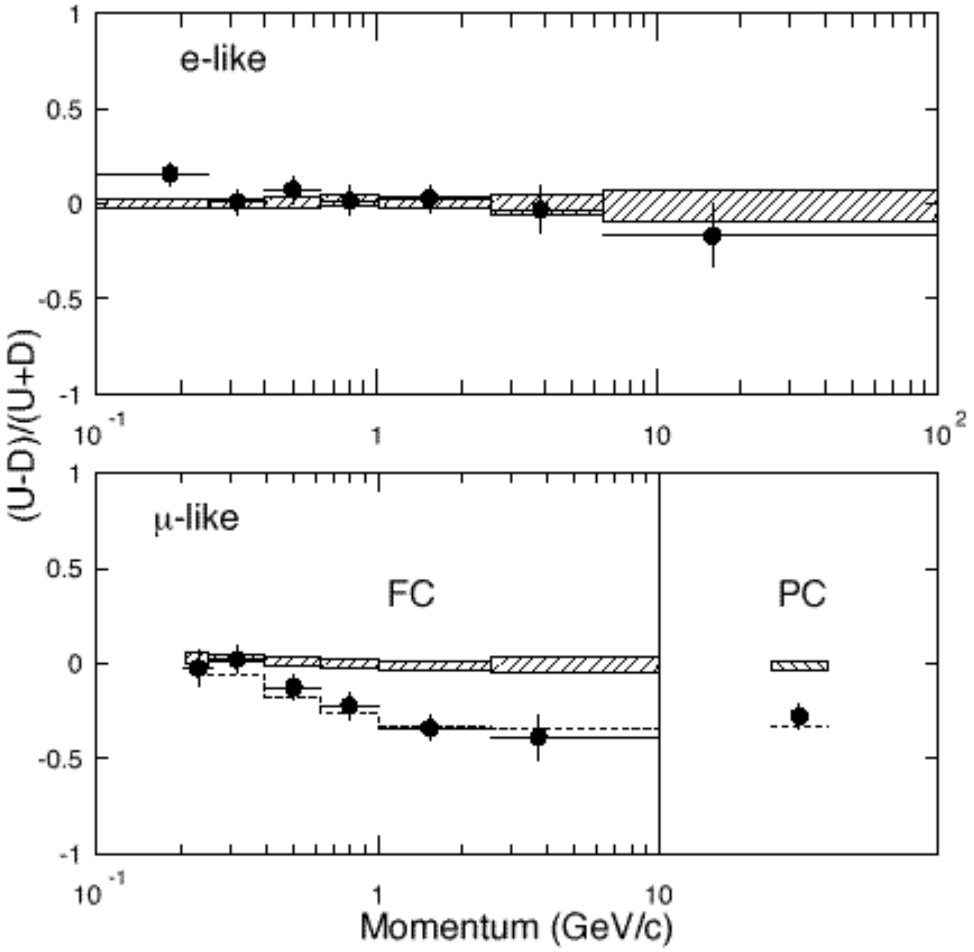
- Up to now four basic topology, neutrino energy .3 GeV- 1000 GeV

- "typical" parent neutrino distributions (Kamiokande cuts)



Atmospheric neutrinos : SuperKamiokande

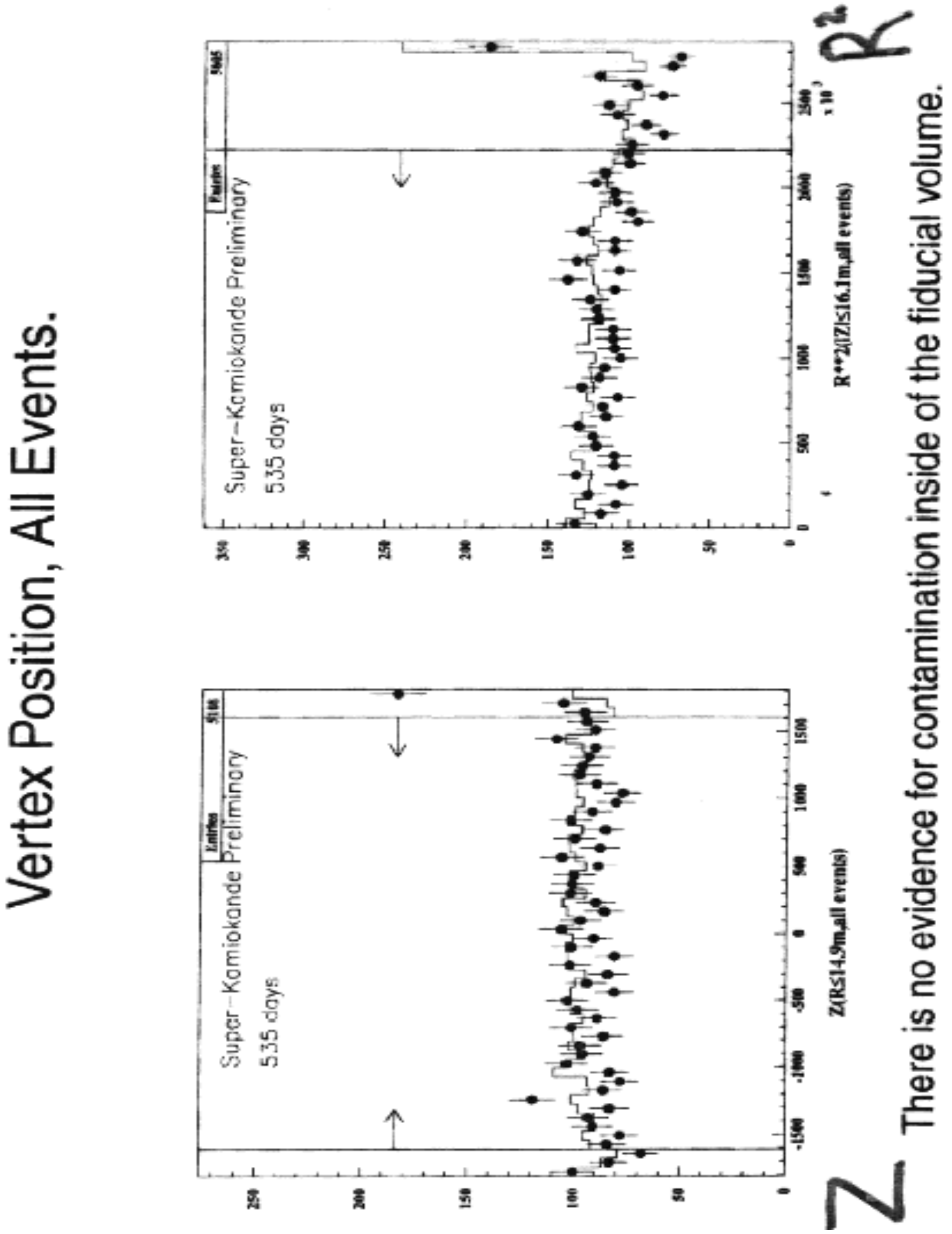
UP-DOWN $\nu\mu$ asymmetry



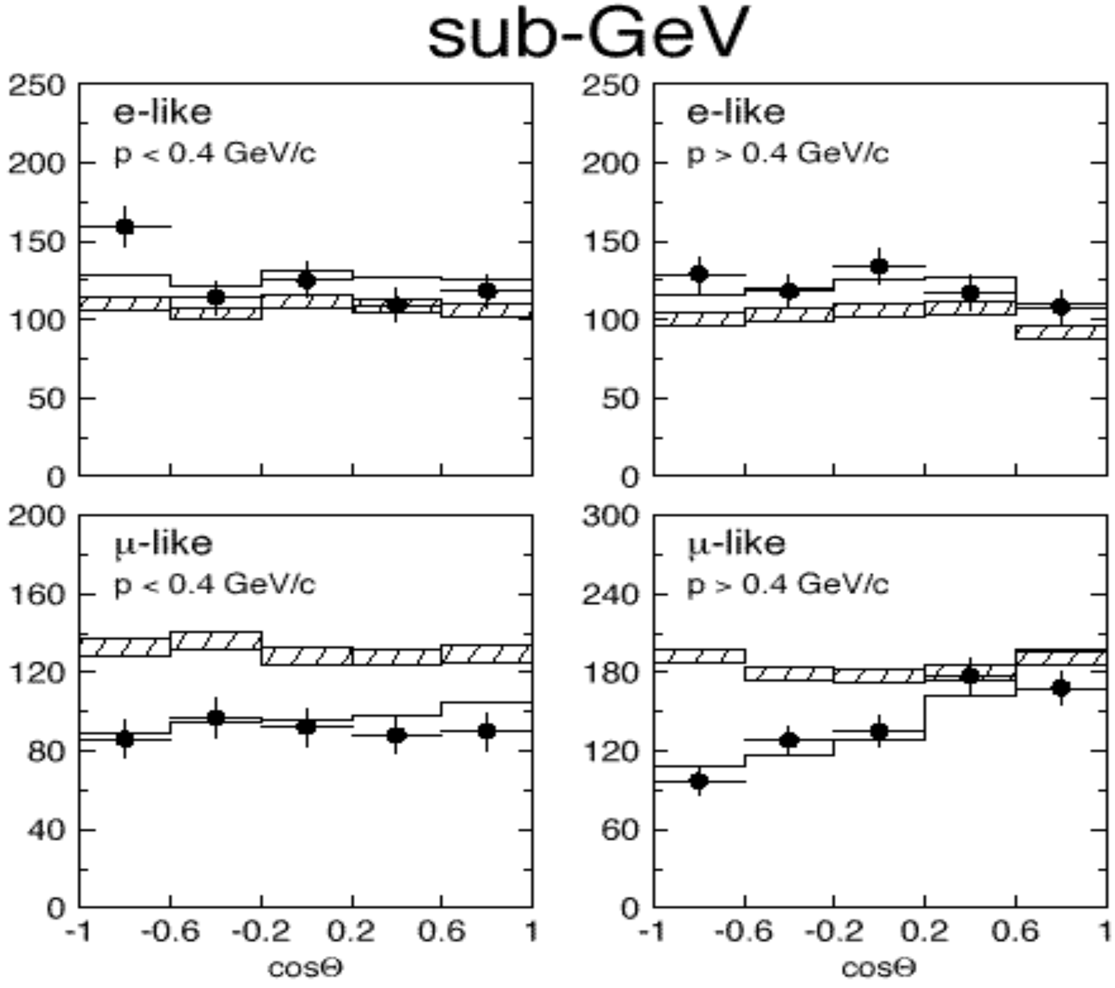
- **second anomaly : 6 sigma effect (multiGeV)**

SuperKamiokande: vertex measurement

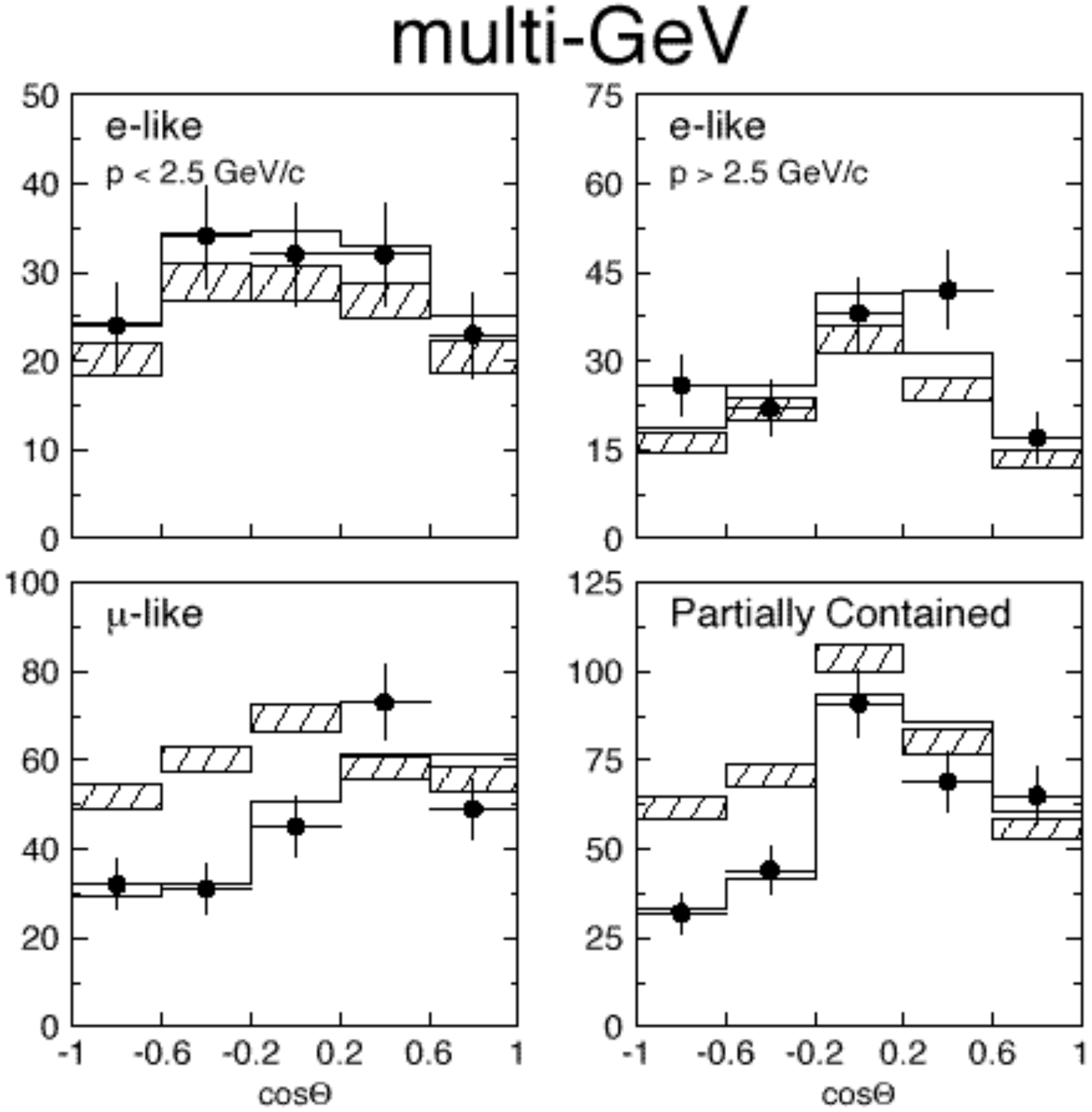
- **important for the discrimination of down-going internal events**



SuperKamiokande angular distributions



SuperKamiokande angular distributions



SuperKamiokande Global Fit L/E Plot

- data binned by particle type (e,μ) momentum (7), cos(θ) (5) for a total of 79 bins)
- 8 parameters to be minimized (normalization etc)
- scan in the grid Δm^2, $\sin^2(2\theta)$ (mixing)

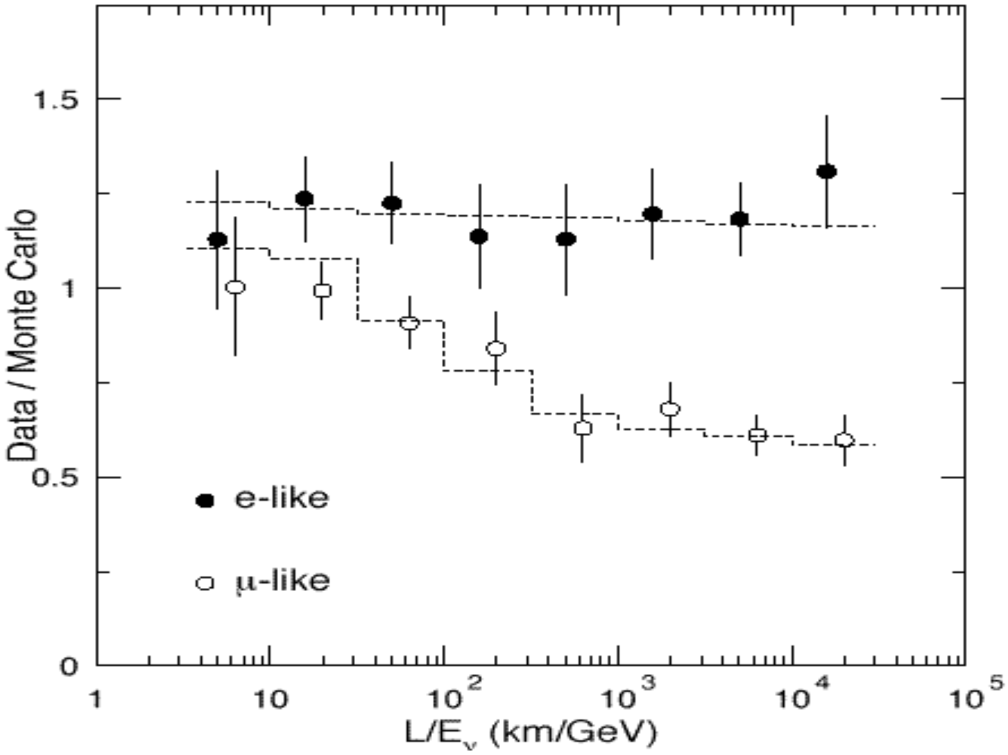
χ^2 no oscillations = 135/69 dof (warning not a true χ2)

- result for $\nu_\mu \rightarrow \nu_t$ oscillations

χ^2min=65.2/ 67 dof

- result for $\nu_\mu \rightarrow \nu_e$ oscillations

χ^2min= 87.8/67



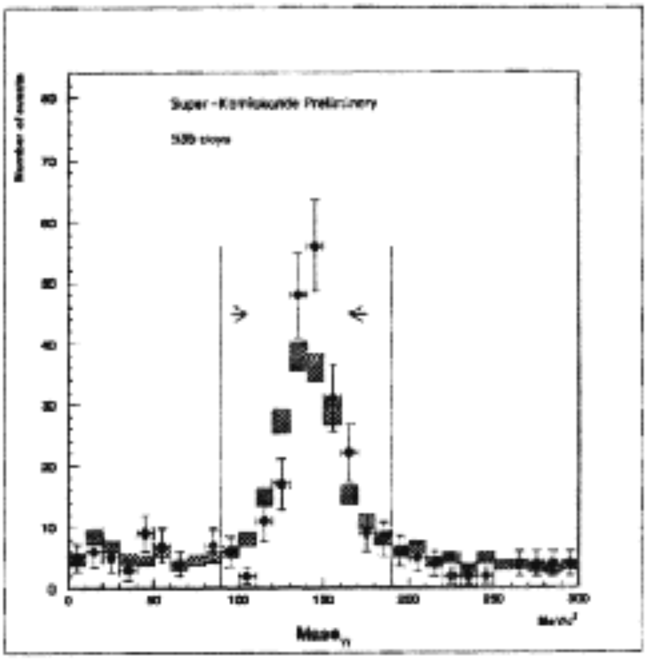
Discovery?

- additional evidence from stopping muons and thoroughgoing muons

SuperKamiokande Neutral currents

$$\nu_\mu \leftrightarrow \nu_\tau \text{ vs. } \nu_\mu \leftrightarrow \nu_{sterile}$$

- Single π^0 events are 80% neutral current.

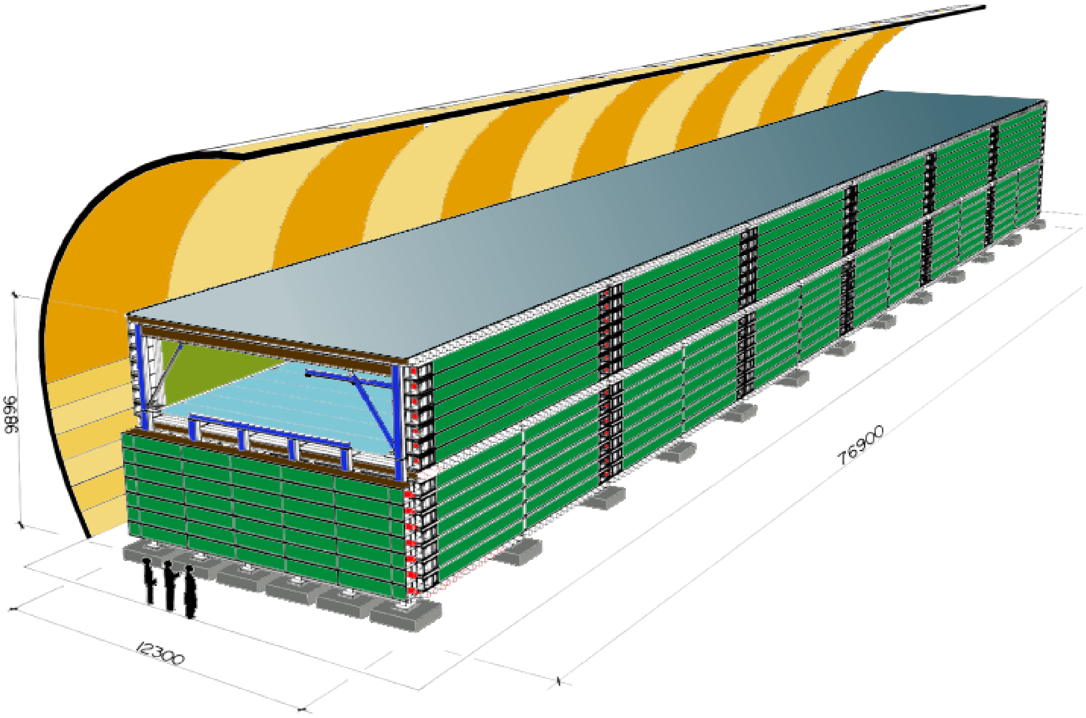


- Full $\nu_\mu \leftrightarrow \nu_{sterile}$ mixing reduces NC by $\sim 25\%$
- π^0/e-like
    - Theory Systematic: $\sim 20\%$
    - $\frac{(\pi^0/\text{e}-\text{like})_{\text{DATA}}}{(\pi^0/\text{e}-\text{like})_{\text{MC}}} =$
      $0.94 \pm 0.08(\text{stat.}) \pm 0.19(\text{prelim.sys})$

MACRO at GRAN SASSO

M onopole , **A** strophysics , and **C** osmic **R** ay **O** bservatory

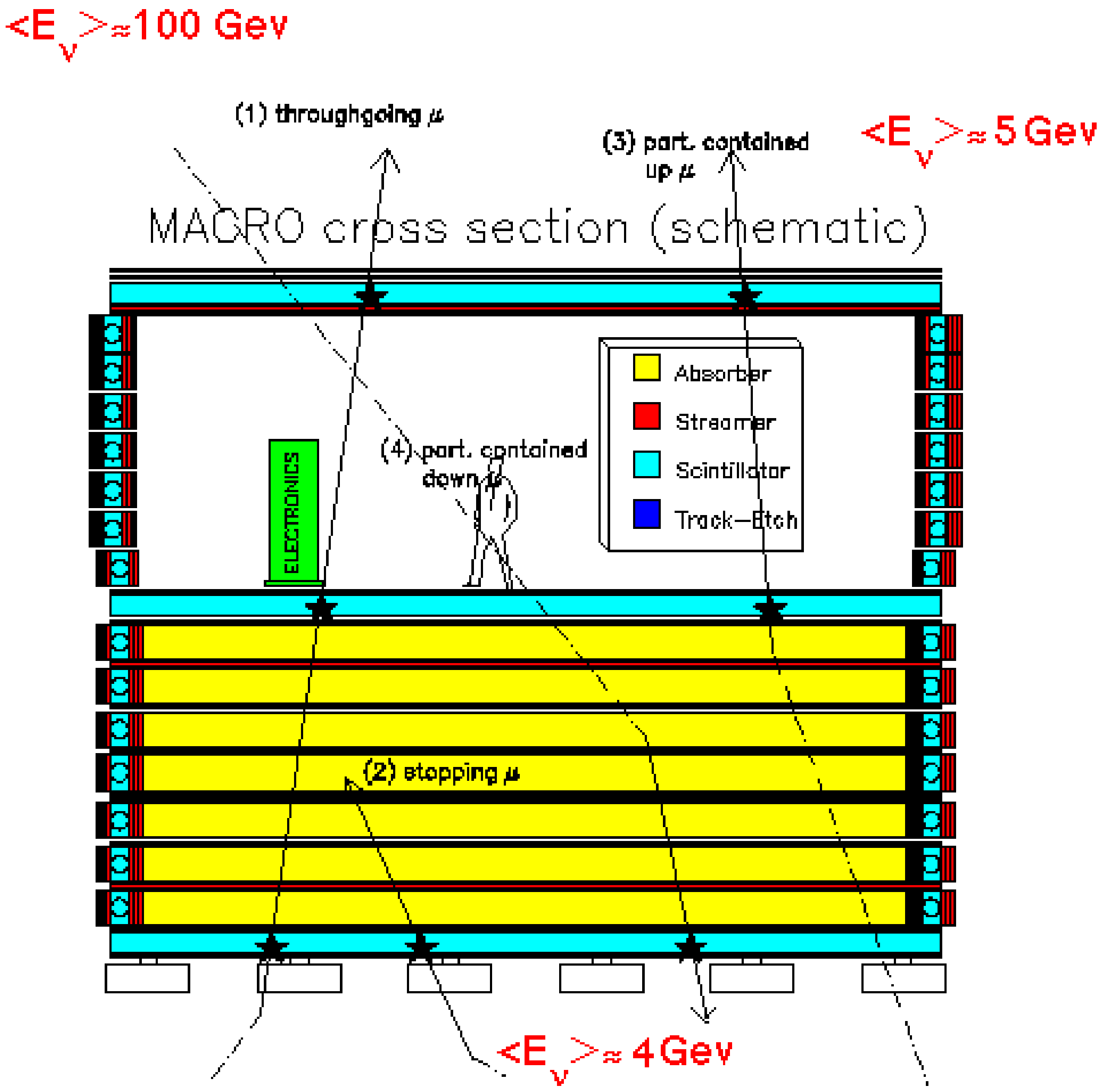
Main features of Macro as ν detector



- 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°)

More details in Nucl. Inst. and Meth. A324 (1993) 337.

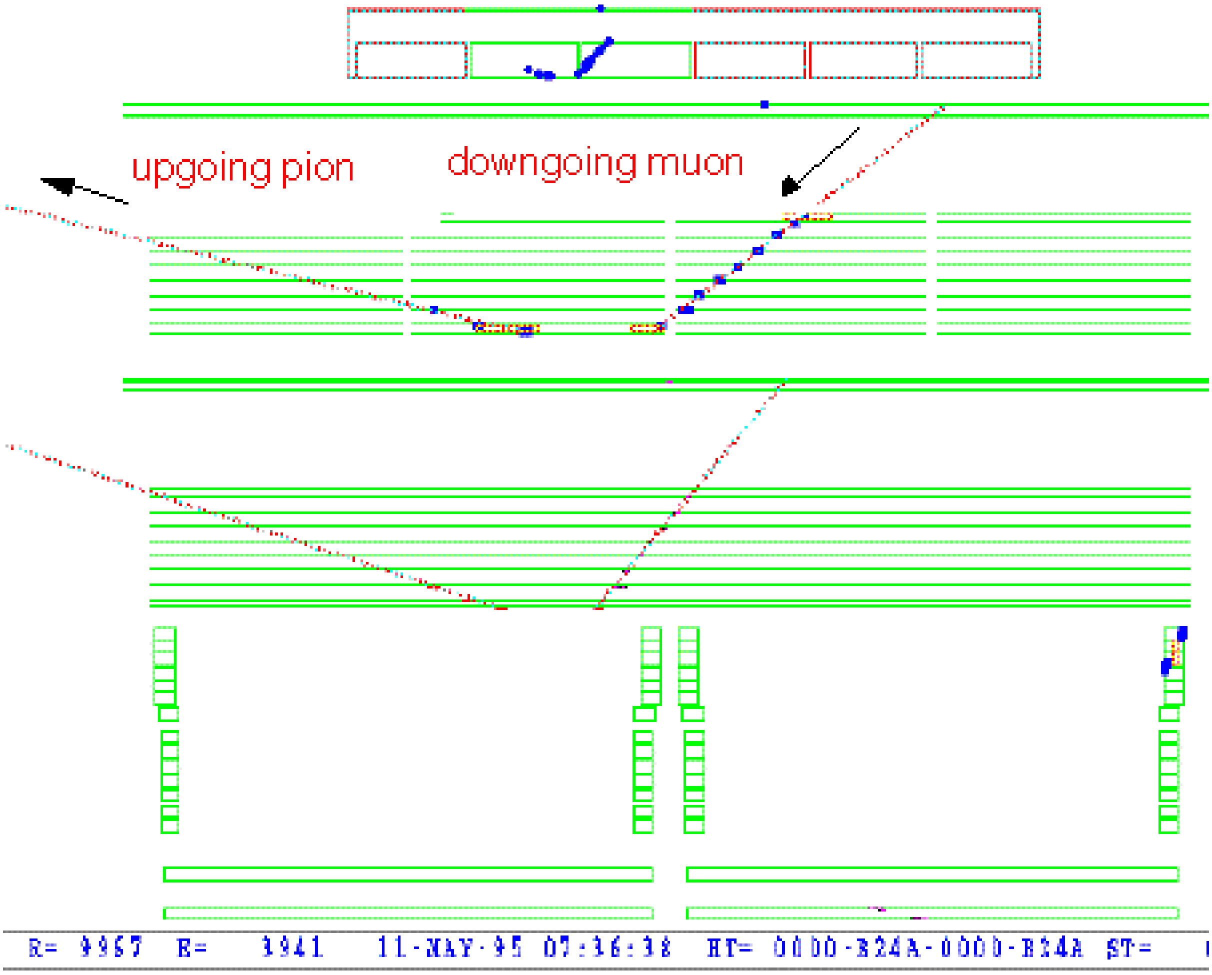
- MACRO can detect different categories of Neutrino produced Muons.



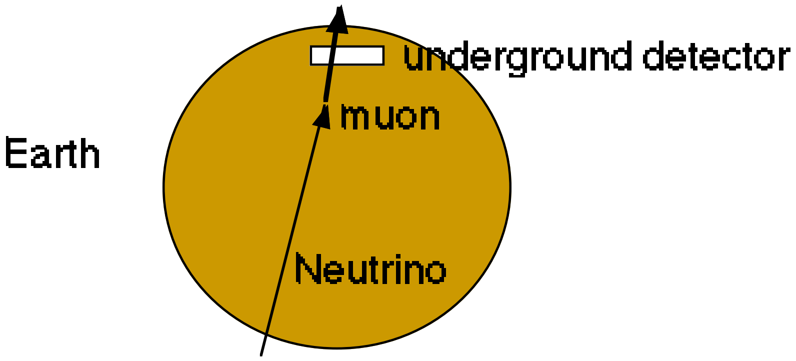
Pion production at large angle

- Pions produced at large angle from muon interaction in the rock around the detector are a possible source of background for stopping and throughgoing upgoing muons
- 243 upgoing particles + downgoing muons were found in 13.600 h

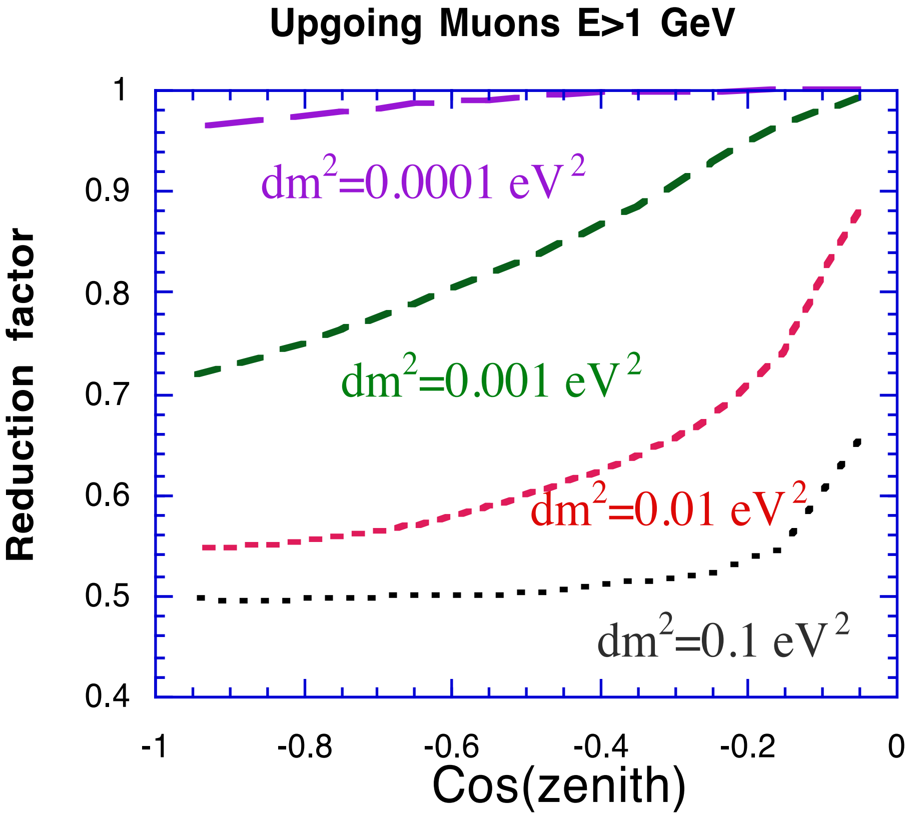
background in the stopping muon search (5%)
and in the through-goind (2%)



Upward-going (through-going) muons and neutrino oscillations



- Reduction factor for $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximum mixing

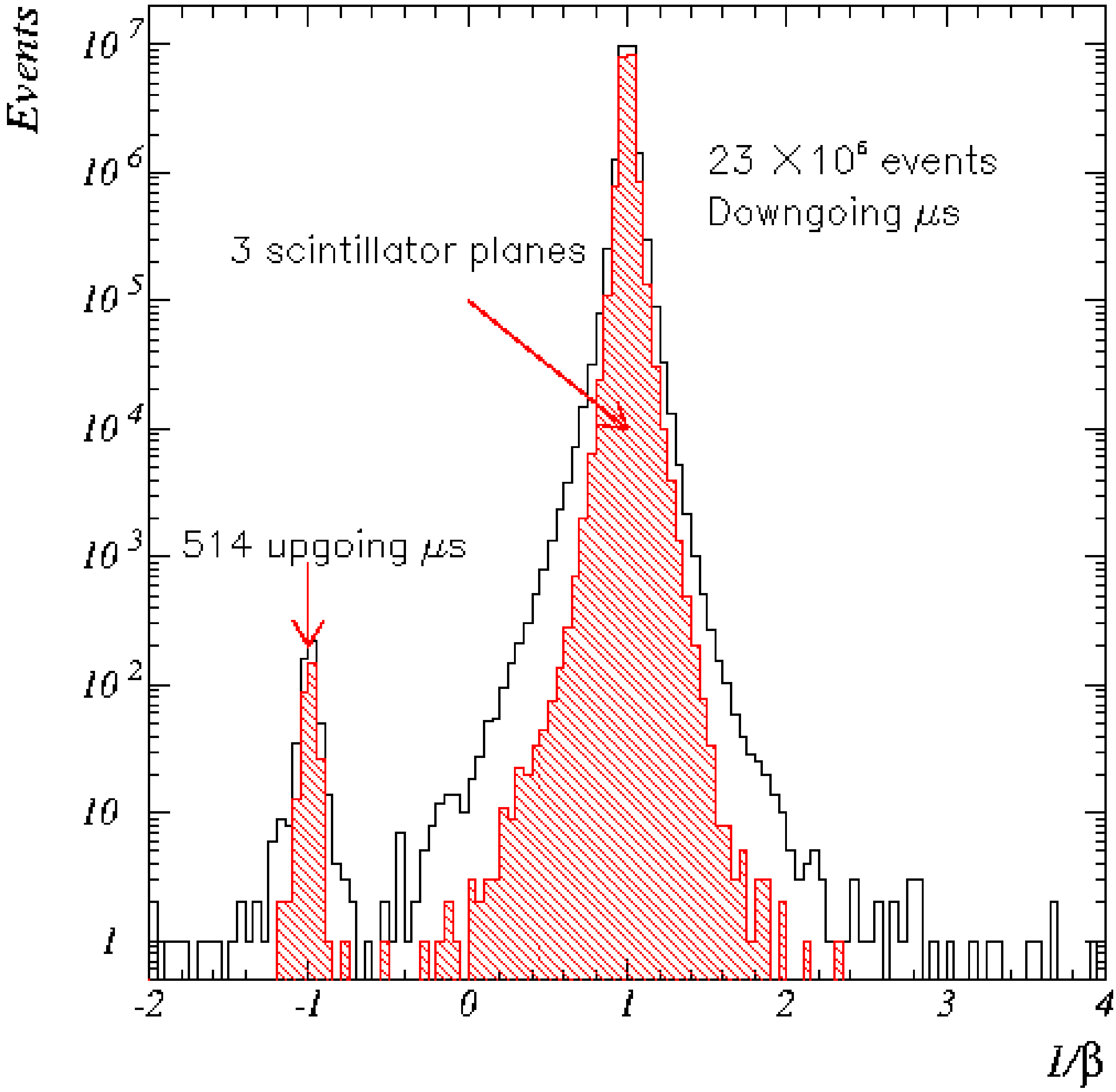


Upward-going (through-going) muons - 1/β distribution

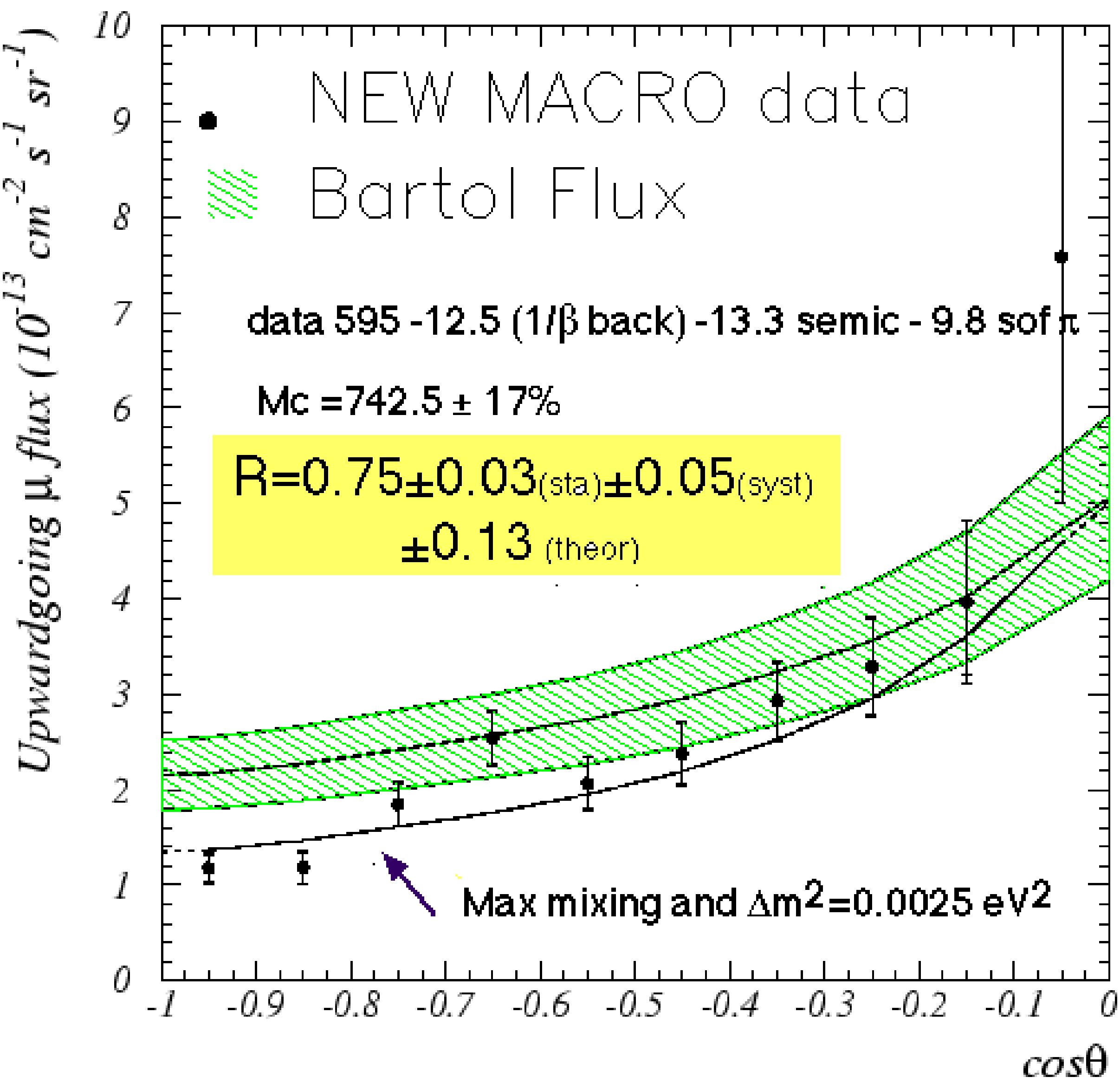
- **the time on the scintillators counters (measured with 0.5 nsec accuracy) is used to measure the flight direction of the tracks from the streamer tube chambers**

- **wrong time measurements are removed checking the position along the counters measured with the times**

- **data up to October 1998**



Upward-going (through-going) flux (MACRO)



- **from the shape only (predictions normalized to the data):**

χ^2 no oscillations = ≈24/8 dof (P≈ 0.2%)

best χ^2 with oscillations in the physical region
≈14.2/8 (P≈ 7.7%)

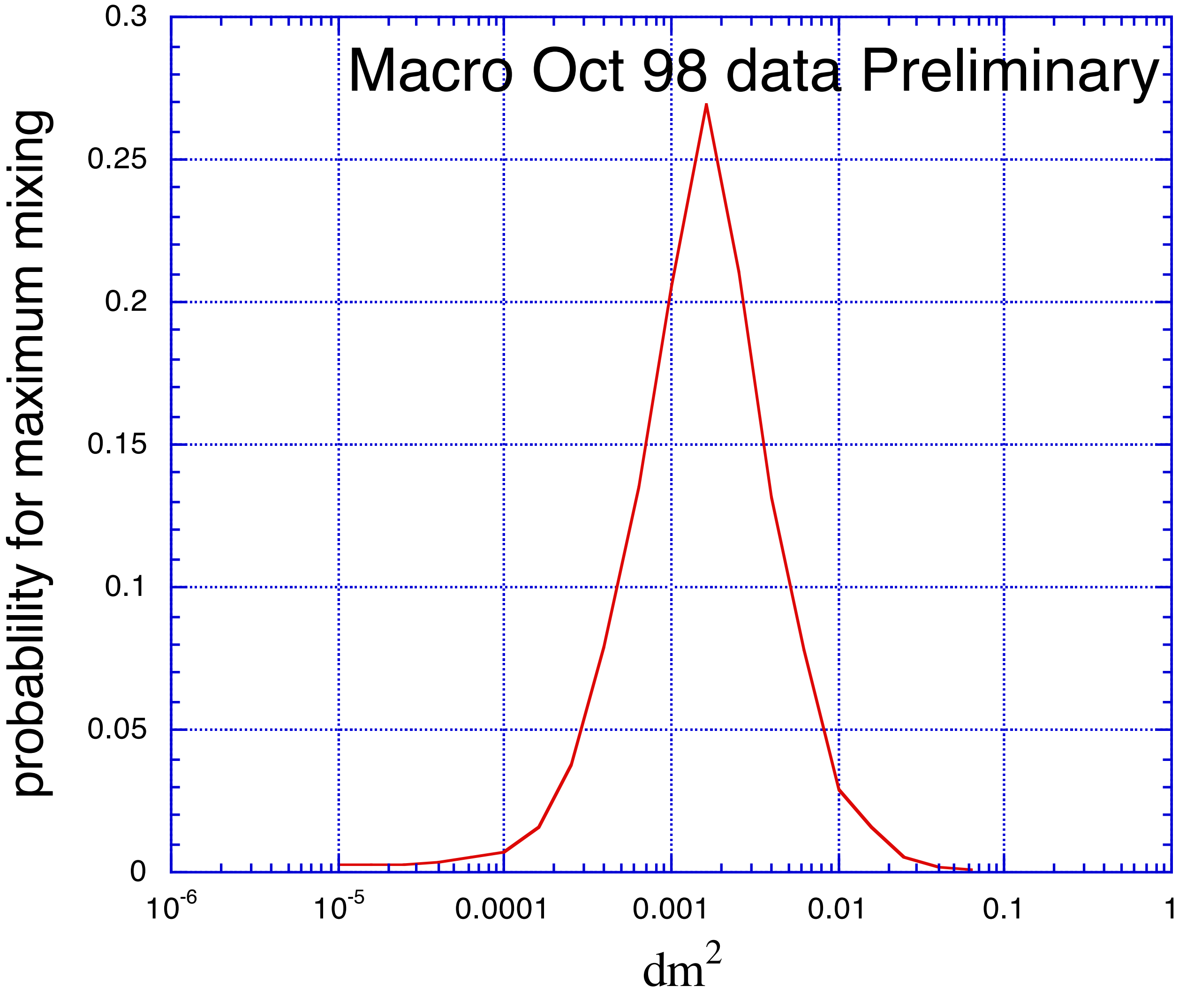
maximum mixing , Δm^2 around 0.002 eV^2

νμ -->> ντ

combining with the normalization:

P no oscillations ≈ 0.3% P with oscillations ≈ 27%

Upward-going (through-going) flux (MACRO)



Upmu in Other Experiments

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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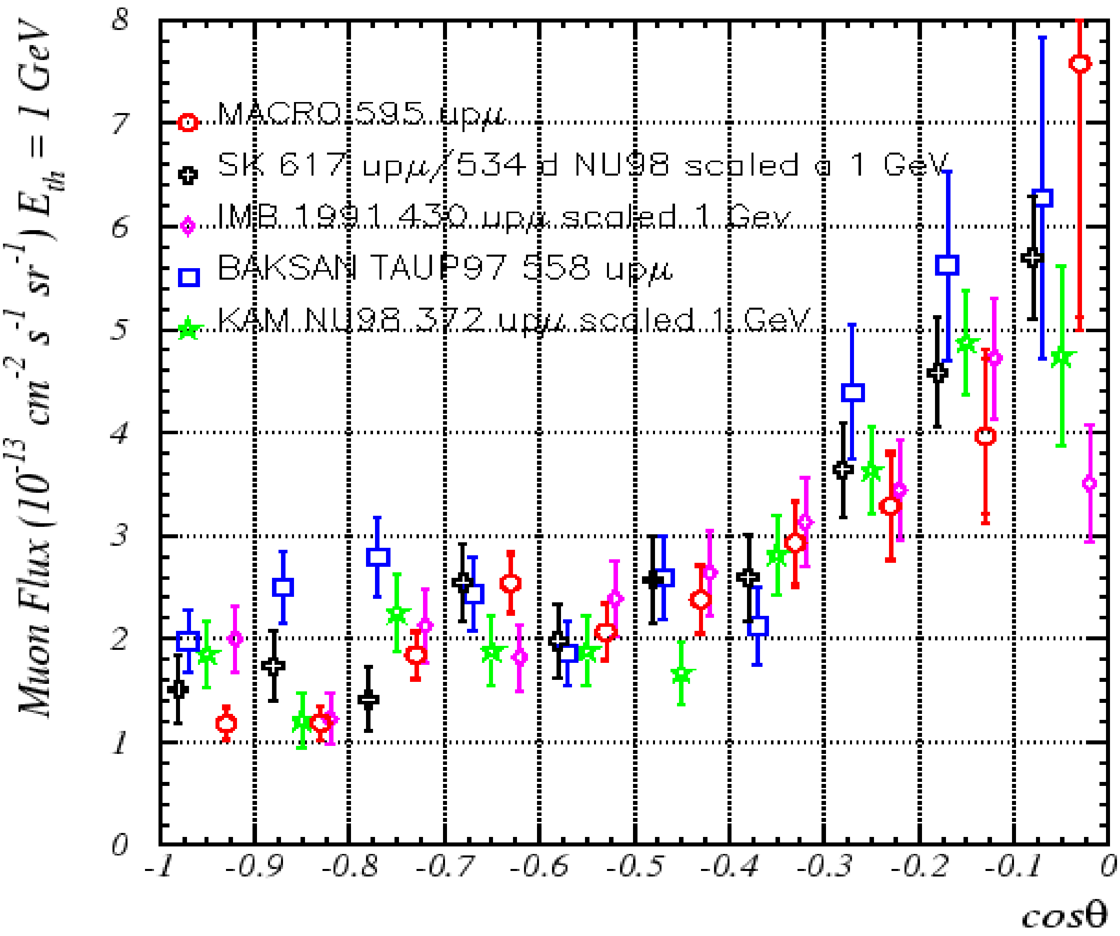


Atmospheric neutrinos : internal up events (MACRO)

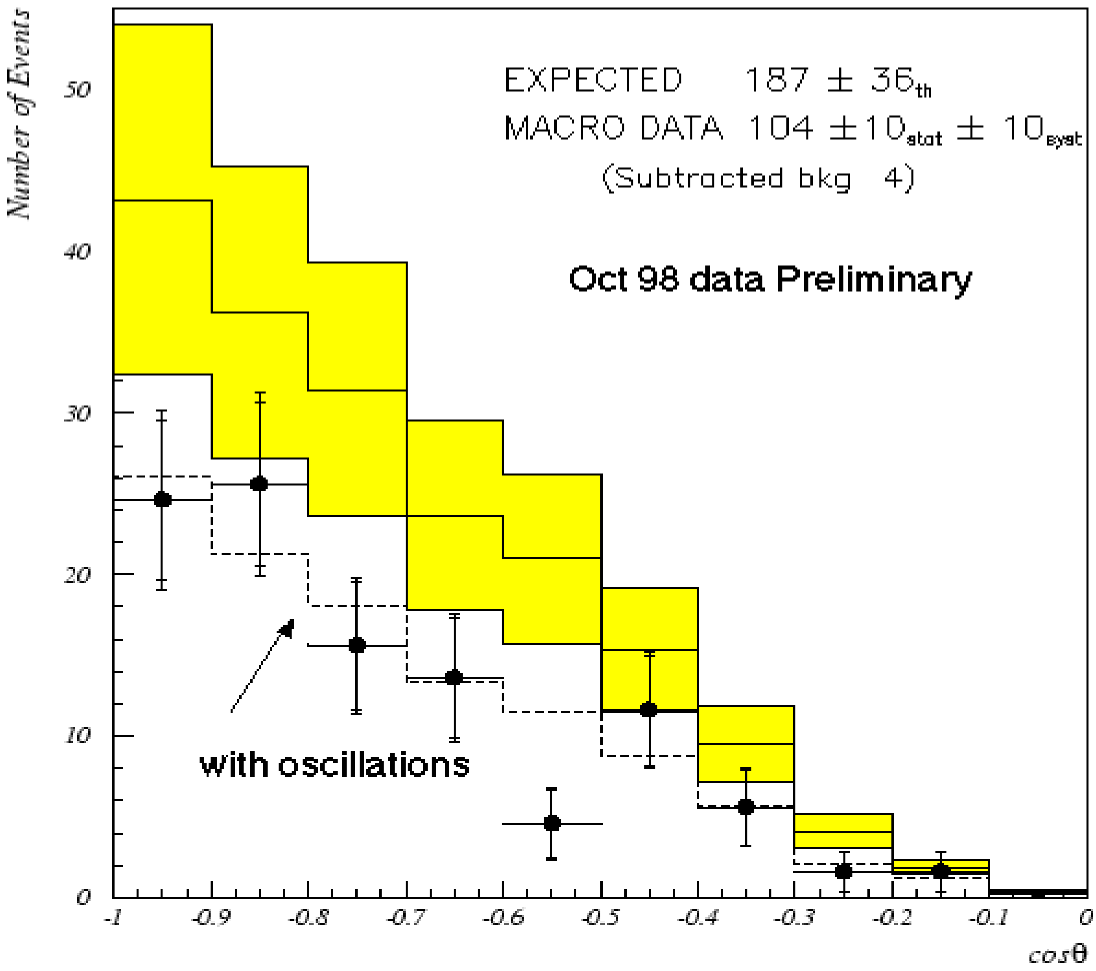
- **Similar cuts used in the through-going muon analysis with the addiction of :**

  Vertex containment cut

in order to remove the normal upward-going through-going muons (1% after this cut)

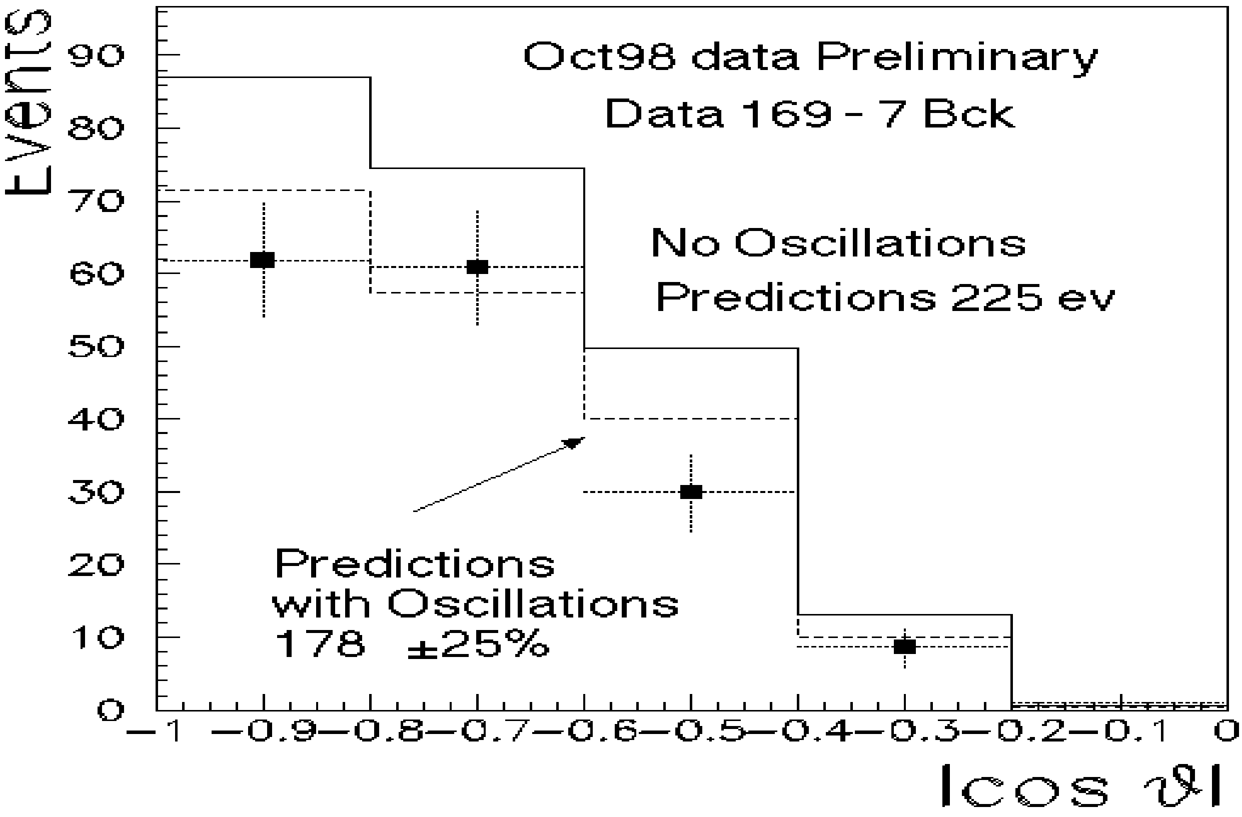
- **From the montecarlo simulation the event sample is an almost pure sample of single muon events**

  89% of the events are due to ν_μ


EXPECTED 187 ± 36th
MACRO DATA 104 ±10stat ± 10syst
(Subtracted bkg 4)
Oct 98 data Preliminary
with oscillations
Number of Events
0
10
20
30
40
50
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
cosθ

Atmospheric neutrinos : internal down +stopping events (MACRO)

- **almost 50% of downgoing events and 50% of upgoing events (n time information)**



- The double ratio of the low energy events is independent from the theoretical predictions. Only statistical errors and errors due to the acceptance (10% conservative for both analysis):

$$R = \frac{\frac{Data_{IUP}}{MC_{IUP}}}{\frac{Data_{IdwStop}}{MC_{IdwStop}}} = 0.77 \pm 0.14 \quad \text{(expected 1)}$$

- P no oscillations ≈8%

Summary for MACRO

MACRO **Upgoing Muons** (Through-going) :
E$\nu \approx$100 GeV

- Peak probability $\nu\mu$ --> $\nu\tau$ **27%**

(max mixing and $\delta m^2 \approx$ a few units in 10^{-3})

- Probability for No oscillations **0.3%**

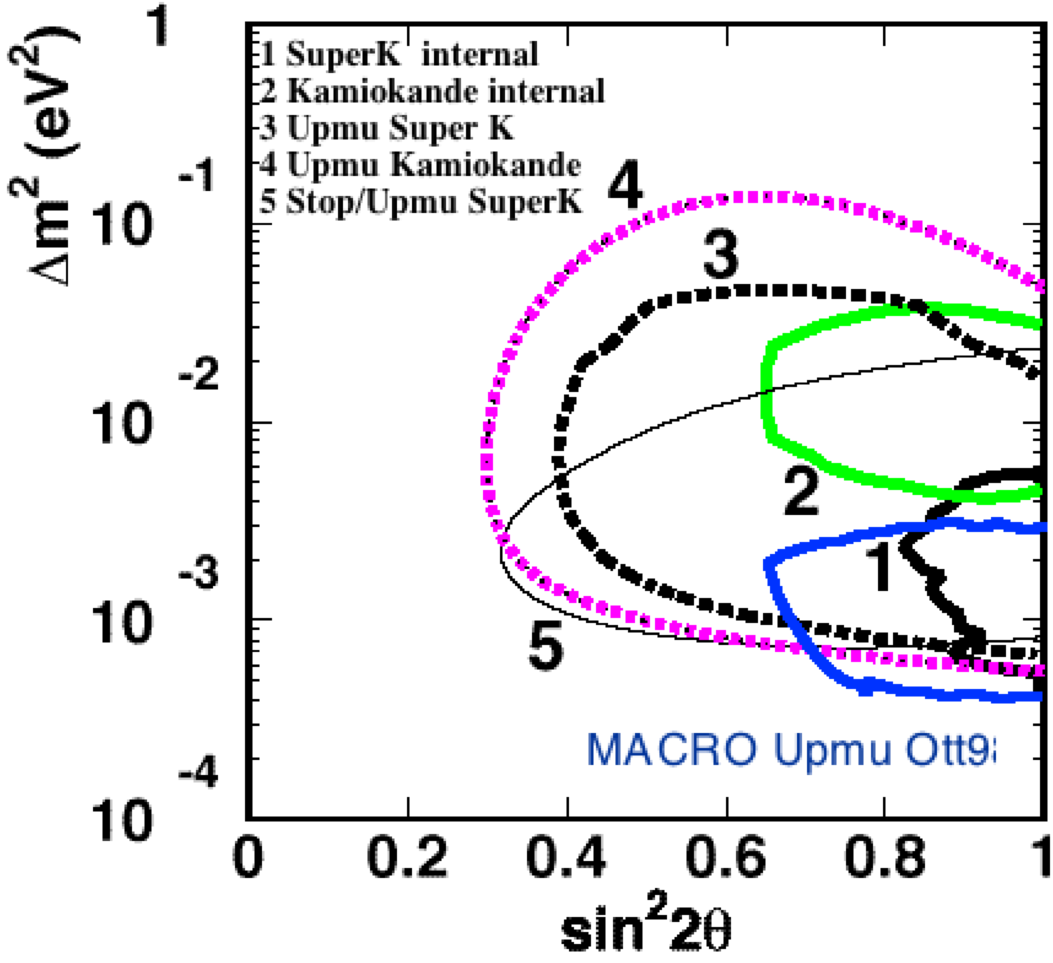
Low energy events: E$\nu \approx$4 GeV

	R=data/predict No Oscil	No oscillations	With oscillations $10^{-3}<\delta m^2<10^{-2}$
Internal Up	**0.56±0.15**	**1**	**0.58**
Internal Down + Stopping Up	**0.72±0.19**	**1**	**0.79**
Double Ratio	**0.77±0.14**	**1**	**0.73**

Conclusion: a $\nu\mu$ --> $\nu\tau$ with oscillation with maximum mixing is consistent with all the MACRO Data

Only Warning :
The peak probability for the angular distributions of the Upgoin Muons (Through-going) is low (7.7%) ==>> Statistical Fluctuation or Hidden Physics?

Evidence for oscillations: Atmospheric neutrinos Summary



- Negative results omitted

  Frejus : not in contradiction for low Δm2

  Baksan IMB in contradiction but wrong!

Evidence for oscillations: Summary

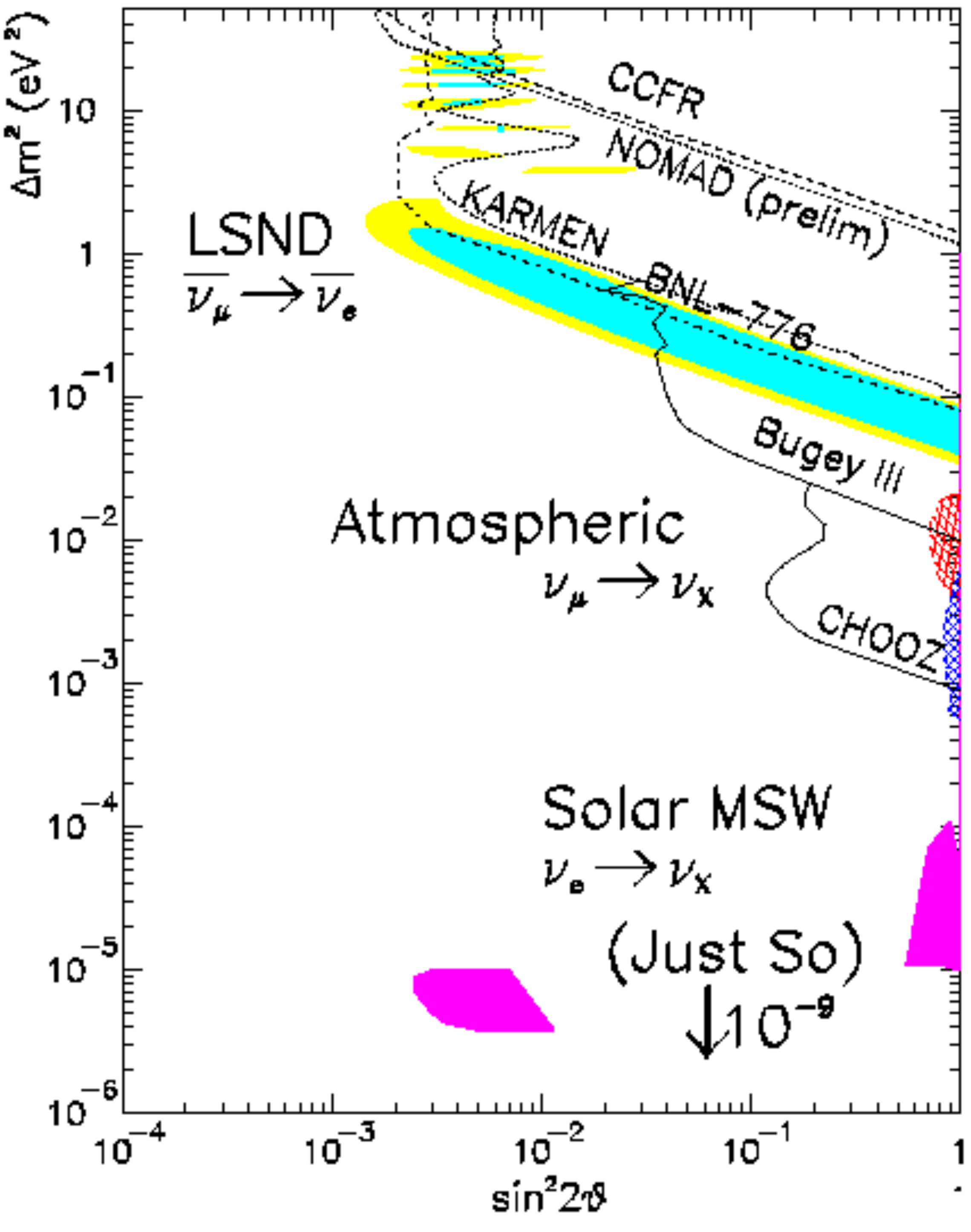


Figure 16: Allowed and excluded regions for $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftarrow$
oscillations.

Evidence for oscillations: Summary

Experiment	Anomaly	Probability $>5\sigma = 5.7\times10^{-5}$	≥ 2 Experiments with different techniques	L/E Signature
* LSND (accellerator)	$\overline{\nu_e}$ ν_e apper.	No	No	No
** SUN	ν_e disapper	Yes ?	Yes	No
*** Atmosperic	ν_μ disapper	Yes	Yes	Yes

- **Are all the experiments true?**
- **If the answer is yes the interpretation needs 3 neutrinos oscillations or a new neutrino (sterile)**

===>> next talks

Future

- **LSND anomaly**

1)MiniBone at Fermilab approved
data 2001
2) proposal at CERN (LoI 216)

- **SUN anomaly**

1)Borex (Gran Sasso) liquid scintillator
detection : electron scattering
low threshold
Be^7 neutrinos should see 0 ?
data 2000

2)Kamland (Kamioka)
similar to BOREX
+ reactor measurements using the nuclear power reactors in Japan
data 2000

3)SNO
1000 Tons D2O
detection: Cherenkov radiation
Helium-3 proportional counter tubes for neutrons

Charged Current	ne + d ----> p + p + e-
Neutral Current Reaction	nx + d ----> p + n + nx
Electron Scattering	e + nx ----> e- + nx

data 1999

Future
Atmospheric Neutrinos
and Long-Base line beams

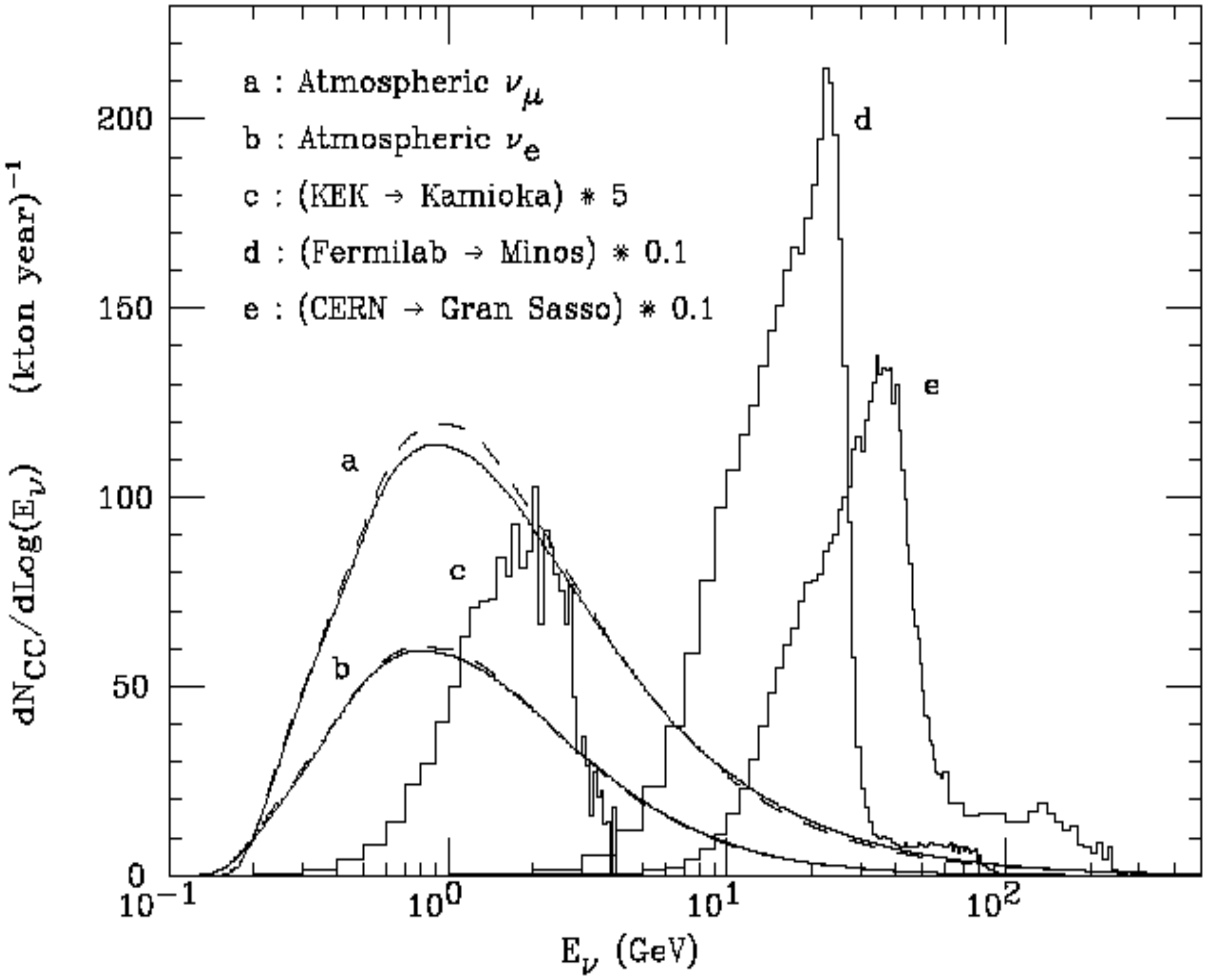


Figure 1: Energy distribution of interacting (with charged current) atmospheric neutrin and antineutrinos, and of the ν_μ in three LBL experiments. All calculations assume t absence of neutrino oscillations. For atmospheric neutrinos the solid (dashed) lines a calculated with the the Bartol [8] (Honda et. al. [9]) The scale of the vertical axis absolute, note however that the LBL fluxes are multiplied by constant factors.

Future
Atmospheric Neutrinos
and Long-Base line beams

- **two possibility for the experiments:**
  - **a) disappeance**
  - **b) TAU appearance**

- **The value of Δm^2 suggested by the atmospheric neutrino measurements is quite low.**
- **With the planned beam problems with appearance experiments if $\Delta m^2 \leq 10^{-3}$**

Beams

- **KEK (Japan) - Kamiokande E≈ 1-2 GeV L=250 Km**
  detector SuperKamiokande and near detectors
  low energy
  data 1999

- **Fermilab Soudan2 (USA) E≈10 GeV L=730 Km**
  detector MINOS appearance/disappearance
  approved but ...

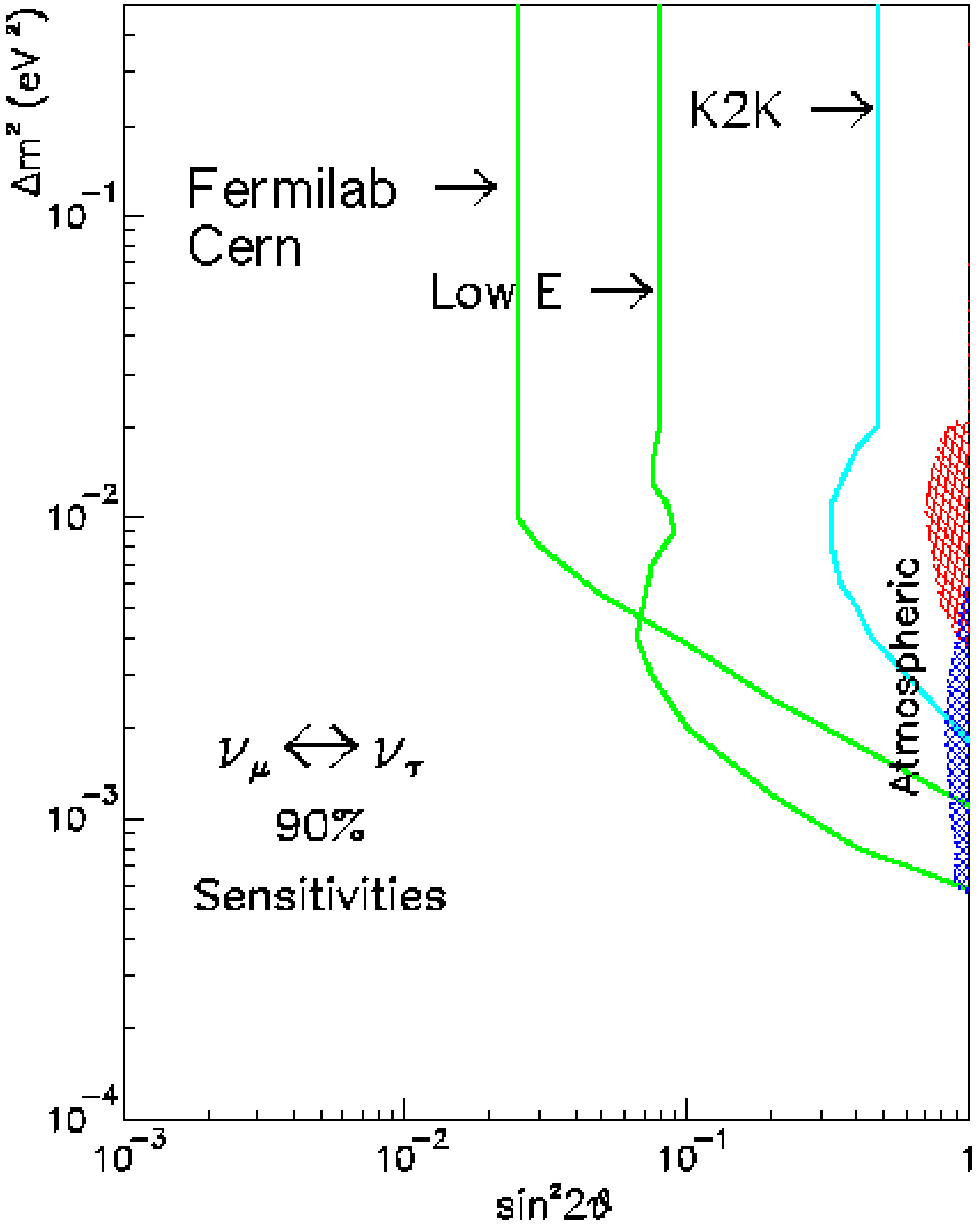
- **CERN - Gran Sasso E≈10 GeV L=730 Km**
  Recommended
  Proposed experiments Icarus, NOE, Aquarich, Opera, Nice

Scientific Committee recommendation:

appearance experiments

a new experiment for atmospheric neutrinos

Future



Future

- **Experiments are difficult and expensive**

but now :

Exiciting times for neutrino physics!

- **Fundamental questions.**

- **Long time scales**

- **very interesting challenges for young peoples**