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SCHOOL ON
NON-ACCELERATOR PHYSICS
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# LARGE EXISTING UNDERGROUND DETECTORS (2)

BY

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LARGE EXISTING UNDERGROUND DETECTORS
PART II

# CONTAINED EVENTS IN GeV RANGE

- NUCLEON DECAY EXPERIMENTS
  - General features
  - Channel per channel analysis
  - Results
- ATMOSPHERIC NEUTRINOS
  - Interest of Atmospheric $\overset{(-)}{\nu}$'s
  - Expected effects & possible exotic phenomena.
  - Results
- SEARCH FOR EXTRA-TERRESTRIAL $\overset{(-)}{\nu}$'s in "VERTEX-CONTAINED" EVENTS.
- SUMMARY & PERSPECTIVES

## NUCLEON DECAY

GRAND UNIFIED THEORIES
⇓
QUARKS & LEPTONS IN SAME MULTIPLETS
⇓
QUARKS → LEPTONS TRANSITIONS
(BOSONS WITH $M_x \sim 10^{14}$ GeV)
⇓
PROTON DECAY
BOUND NEUTRON DECAY
} $N \rightarrow \ell^+ +$ meson(s)
$N \rightarrow \bar{\nu} +$ meson(s)

$\underset{\text{LIFETIME}}{\tau}$ ($\propto M_x^4$) WAS FIRST PREDICTED AT THE LEVEL OF $10^{31}$ years

THIS MOTIVATED DETECTORS WITH MASSES $\gtrsim$ 1000 tonnes.

EXPECTED NUMBER OF EVENTS IN A DECAY-MODE WITH BRANCHING RATIO B :

$$N = f \times 6\ 10^{23} \times 10^{9} \times M_F \times T \times \frac{B \times \varepsilon}{\tau}$$

- $f$ : FRACTION OF THE RELEVANT NUCLEON, $\frac{p}{p+n}$ OR $\frac{n}{p+n}$
- $6\ 10^{23} \times 10^{9}$ : NUMBER OF NUCLEONS / 1000 tonnes
- $M_F$ : FIDUCIAL MASS IN kilotonnes
- $T$ : EXPOSURE TIME

$\varepsilon$ = OVERALL EFFICIENCY
- BRANCHING RATIO(S) OF FINAL STATE MESON(S).
- RE-INTERACTION OF "FINAL" STATE PARTICLES IN NUCLEUS.
- TRIGGER + DETECTION + SELECTION CRITERIA

## 1. NUCLEON DECAY: GENERAL FEATURES

### A- THE BACKGROUND OF ATMOSPHERIC $\nu$'s.

COSMIC-RAY AIR SHOWERS PRODUCE

$$\begin{cases} \nu_\mu \ \bar{\nu}_\mu \text{'s FROM } \pi \ \& \ K \text{ DECAYS} \\ \nu_e \ \bar{\nu}_e \text{'s FROM } \mu \text{ DECAYS MAINLY.} \end{cases}$$

THESE NEUTRINOS (FROM ALL DIRECTIONS) SOMETIMES INTERACT WITHIN THE DETECTOR

RATE $\sim$ 100 events / 1000 tonnes / year

MOST OF THOSE EVENTS CANNOT BE CONFUSED WITH NUCLEON DECAYS AND ARE REMOVED BY SELECTION CRITERIA :

- EVENT MUST BE FULLY CONTAINED
- TOPOLOGICAL REQUIREMENTS (depends on decay-mode of interest)
- KINEMATICAL CONSTRAINTS ($E \approx M$ for modes with a charged lepton) $\Delta E/E$, Angular resolution

FOR LARGE EXISTING DETECTORS (IMB, KAMIOKANDE II & FRÉJUS) AND FOR MOST OF THE MODES, THE REMAINING BACKGROUND RATE $R_B \sim$ several events / 1000 tonnes / year depending on the decay-modes.

In some favourable cases, it is significantly lower. ($e^+\pi^0$, $e^+\eta^0$)

### B. KEY-PARAMETERS OF A NUCLEON-DECAY EXPERIMENT

LOWER BOUND ON $\tau/B$ FOR A NUCLEON DECAY MODE.

2 CASES :

- MODES WITH A NEGLIGIBLE BACKGROUND.

0 Events observed

$$\tau/B > f \ \frac{6 \cdot 10^{32}}{2.30} \ |M_F \cdot T| \ |\varepsilon|$$

(90% C.L.)

$f$: fraction of the relevant nucleon; $M_F \cdot T$: luminosity in kilotonnes x years; $\varepsilon$: efficiency (overall)

- MODES WITH A SIGNIFICANT BACKGROUND.

Number of observed candidates is compatible with background expect$^n$

$R_B$ = BACKGROUND RATE / kilotonne / year

$$\tau/B > f \ \frac{6. \ 10^{32}}{1.65} \sqrt{\frac{M_F \cdot T}{R_B}} \ \varepsilon$$

(90% C.L.)

---

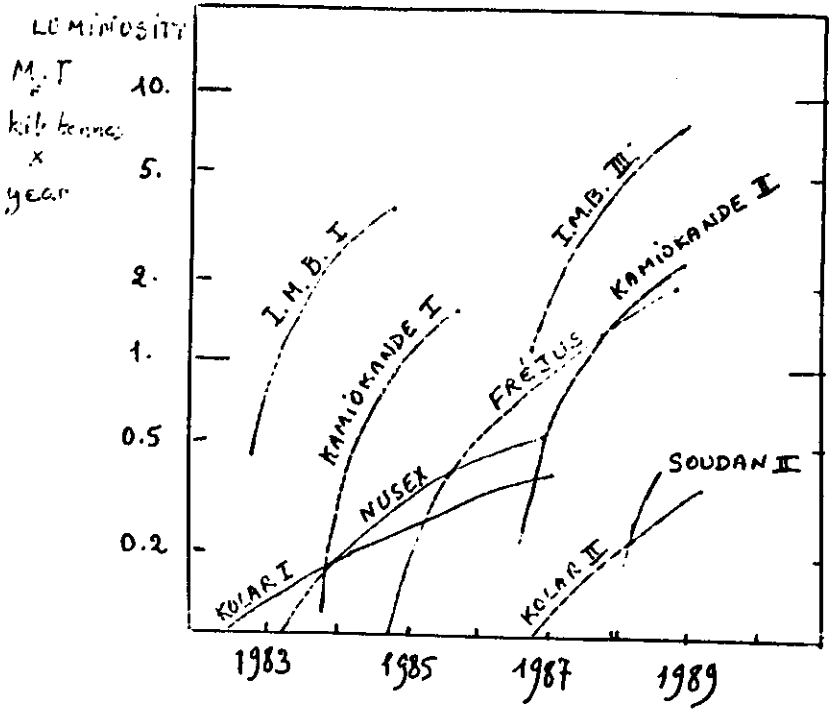
KEY-PARAMETERS :

- $M_F \cdot T$ (kilotonnes x years)
- $\varepsilon$ OVERALL EFFICIENCY PER DECAY MODE
- $R_B$ BACKGROUND RATE PER DECAY MODE

## C. NUCLEON DECAY : DETECTORS & LUMINOSITY

PRESENT SENSITIVITY ~ 11000 tonnes x years (ALL EXPERIMENTS)

| WATER CHERENKOV | TRACKING CALORIMETERS |
|---|---|
| + LARGE MASSES (e.g. IMB : 3300 tonnes fiducial mass) | + HIGH SPATIAL RESOL$^{n}$ (multi-track / multi-vertex) |
| + SENSE OF TRACK DIRECT$^{n}$ | + BETTER $\pi/\mu$ DETECTION AT $E \sim 100-200$ MeV |
| + FREE PROTONS | + SOUDAN II : $dE/dx$ |




## 2. NUCLEON DECAY : CHANNEL PER CHANNEL ANALYSIS

- DEFINE SELECTION CRITERIA FOR THE RELEVANT CHANNEL.
  1). RECONSTRUCT VERTEX.
    - REQUIRE VERTEX TO BELONG TO FID$^{L}$ VOLUME
    - REQUIRE ALL TRACKS TO BE CONFINED IN DETECTOR. ("FULLY CONTAINED" EVENTS)
  2) TOPOLOGICAL CRITERIA
    - Number of rings / prongs
    - Showering vs. Non Showering
    - Possible $\mu \to e$ decay signal.
  3) KINEMATICAL CRITERIA.
    - Modes with a charged lepton : $\Sigma E_i$, $|\Sigma \vec{p}_i|$, Total effective mass
    - Meson effective mass (e.g. $\gamma\gamma$ mass compatible with $m_{\pi^0}$).
    - Opening angle between tracks (e.g. $\gamma\gamma$ angle for $\eta^0 \to \gamma\gamma$)

  * $N \to \ell^{\pm}$ + meson more constrained
  $\Sigma E_i \simeq M$, $|\Sigma \vec{p}_i|$ IN FERMI MOMENTUM RANGE
  ... BUT NUCLEAR EFFECTS
  (FINAL STATE PARTICLES MAY INTERACT WITHIN TARGET NUCLEUS)

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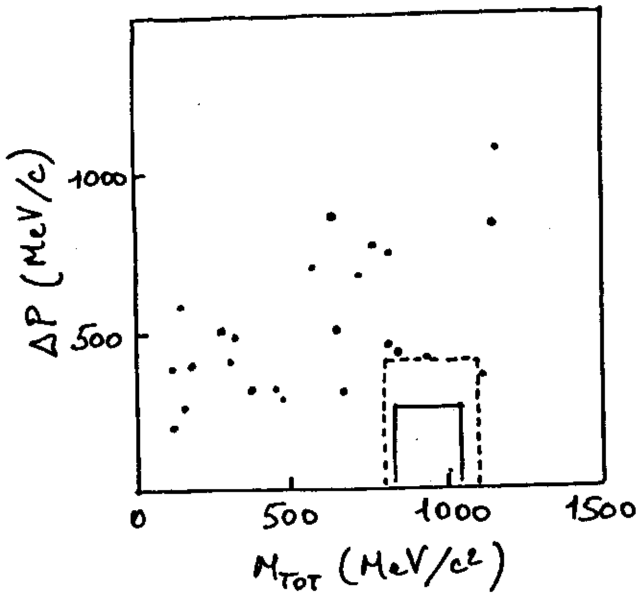
  SAMPLE OF EXP$^{L}$ CANDIDATE(S)

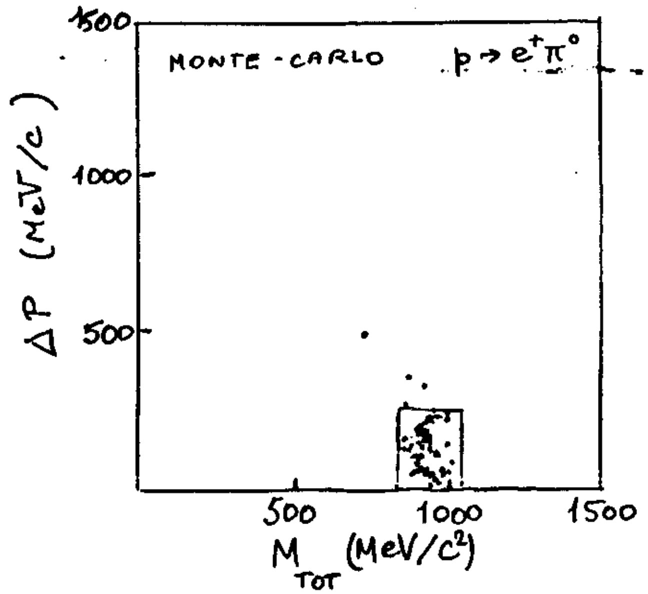


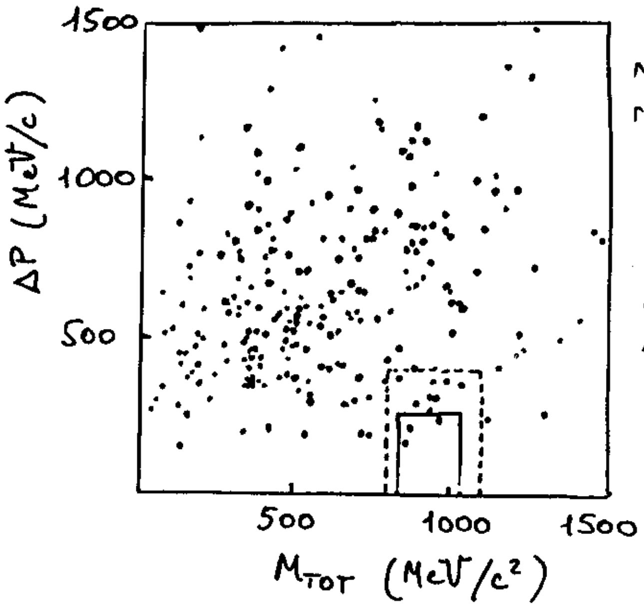

KAMIOKANDE II (≥2 RING DATA)

DATA SAMPLE : 1.18 kilotonnes x years

- μ-DECAY
- NO μ-DECAY

MODES WITH A CHARGED LEPTON




NEUTRINO MONTE-CARLO

≥ 2 Rings

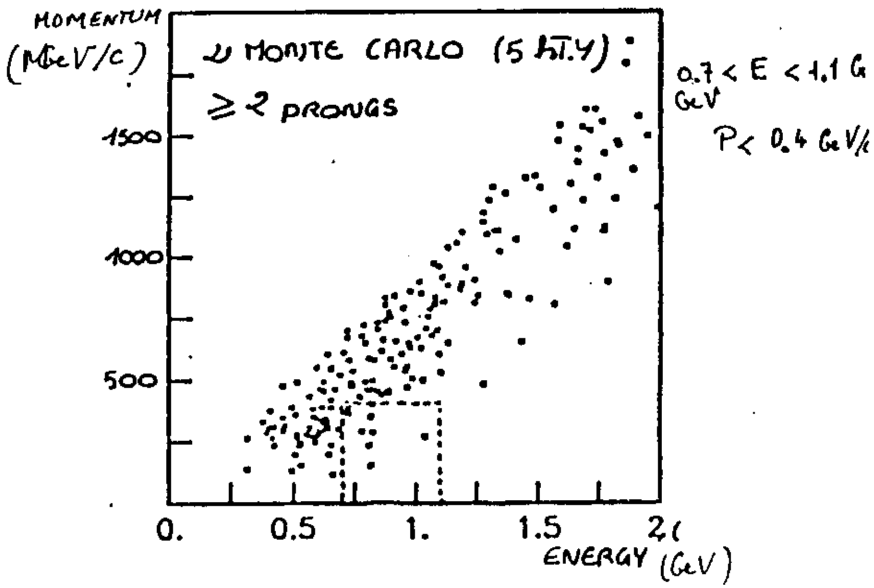
8.8 kilotonnes x years

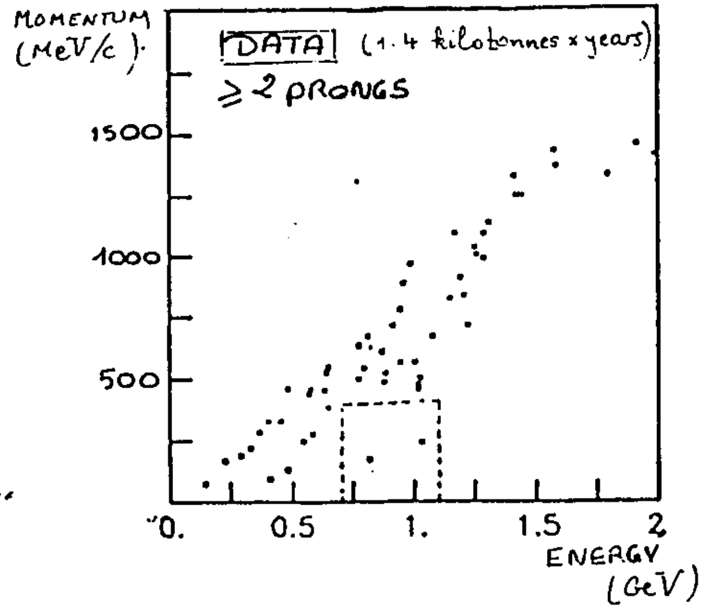
- No μ DECAY
- μ DECAY

KAMIOKANDE II : KINEMATICAL CRITERIA

NUCLEON DECAY INTO CHARGED LEPTON + MESONS

FRÉJUS KINEMATICAL ANALYSIS

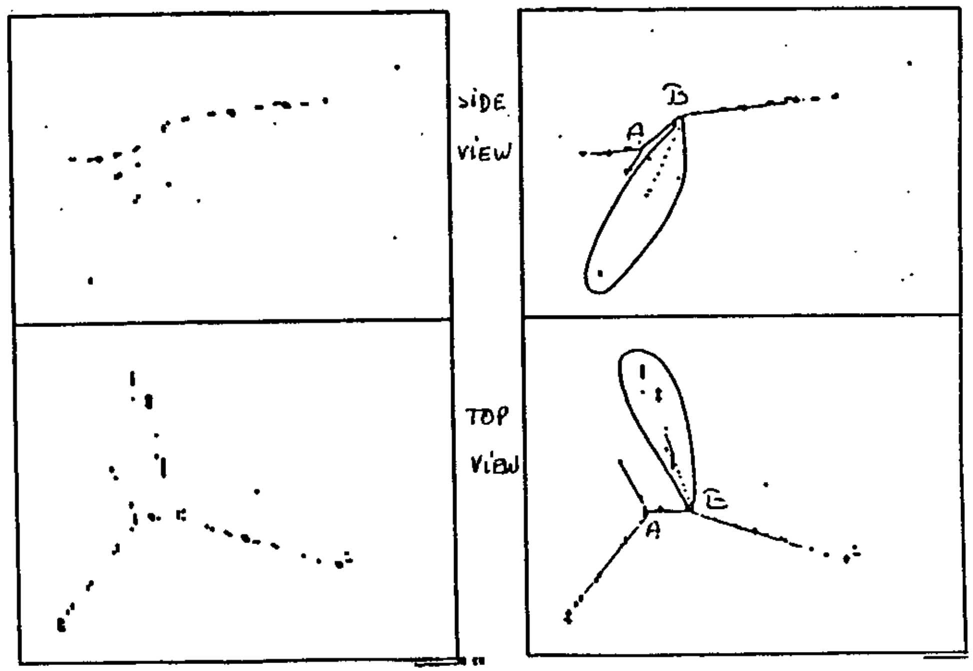



NUCLEON DECAY INTO CHARGED LEPTON + MESONS

1st FRÉJUS CANDIDATE

RUN 1378 - EVT. 420 : 2 VERTICES A AND B




VERTEX A : $E = 1020$ MeV, $P = 230$ MeV/c — Candidate for $p \to \mu^+ \underbrace{\pi^+\pi^-}_{\rho}$

VERTEX B : $E = 1020$ MeV, $P = 430$ MeV/c — Candidate for $p \to e^+ \underbrace{\pi^+\pi^-}_{\rho}$

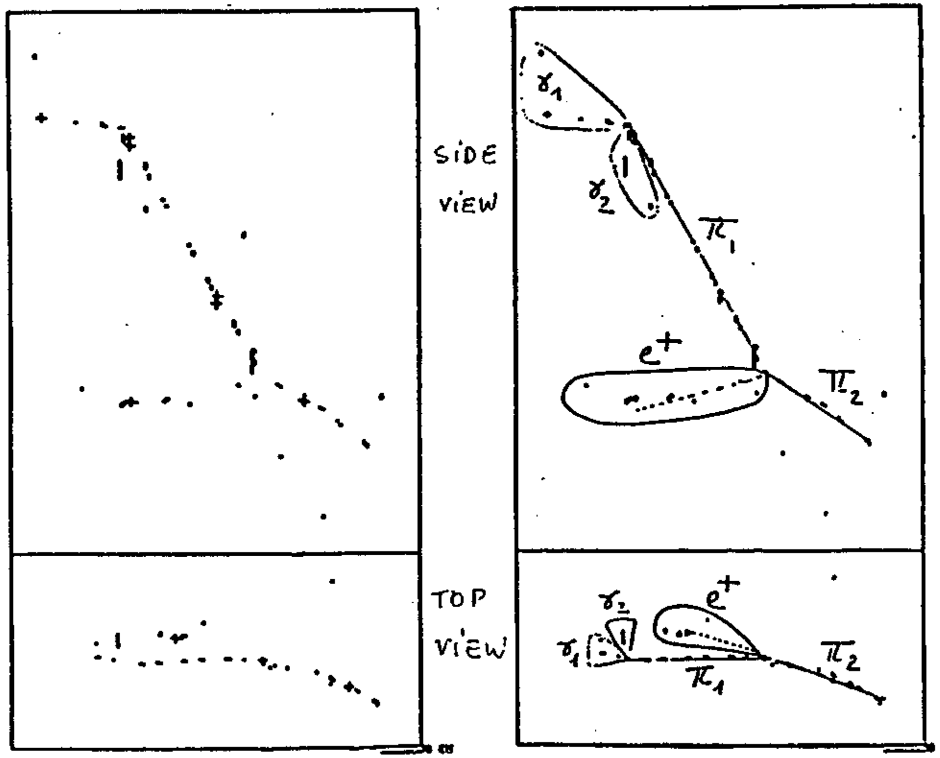
EXPECTED "BACKGROUND" IN THESE MODES (1.4 kt·year)

- 0.8 EVT. $p \to e^+ \rho^0$
- 0.9 EVT $p \to \mu^+ \rho^0$

## NUCLEON DECAY INTO CHARGED LEPTON + MESONS

### 2nd FRÉJUS CANDIDATE

RUN 2833 - EVENT 346




$E = 815$ MeV

$P = 180$ MeV/c

Candidate for $p \to e^+ \underbrace{\pi^+\pi^-}_{\rho^0}$

EXPECTED BACKGROUND IN THIS MODE ~ 0.8 EVENT (1.4 kilotonne·year)

## NUCLEON DECAY INTO $\bar{\nu}$ + MESONS

e.g. $p \to K^+ \bar{\nu}$

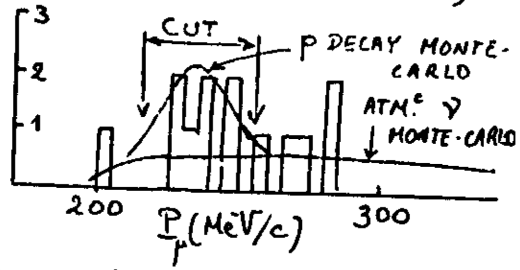
$K^+$ DECAYS AT REST INTO A MONO-ENERGETIC $\mu^+$ 236 MeV/c

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

KAMIOKANDE II

$K^+$ NOT VISIBLE (BELOW CHERENKOV THRESHOLD)

1 RING
MUON-LIKE
1 $\mu$-DECAY
CUT IN $P_\mu$




3 CANDIDATES
2 EXPECTED BACKGROUND EVENTS

FRÉJUS

$K^+$ is VISIBLE in 30% OF SIMULATED $p \to \bar{\nu} K^+$ EVENTS

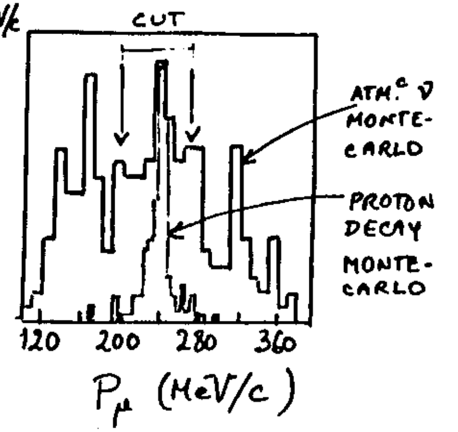
200 MeV/c $\leq P_\mu \leq$ 270 MeV/c

300 MeV/c $\leq P_K \leq$ 500 MeV/c

$(\mu, K)$ ANGLE > 30°

1 CANDIDATE

1 EXPECTED BACKGROUND EVENT



- **SIMULATE THE RELEVANT DECAY MODE**

1) "FINAL" STATE PARTICLES (after meson decays)

2) NUCLEAR EFFECTS : final state HADRONS MAY INTERACT IN TARGET NUCLEUS
   - elastic scattering : modify $|\Sigma \vec{p}_i|$
   - charge exchange, absorption } modify topology

   * UNCERTAINTIES IN NUCLEAR MODELS

3) HADRON SECONDARY INTERACTIONS IN THE DETECTOR → SECONDARY VERTEX

4) DETECTOR RESPONSE
   NEEDS A GOOD MONITORING OF TRIGGER AND DETECTION EFFICIENCIES

5) SCAN THE SIMULATED EVENTS, WITH THE SAME CRITERIA AS THE EXPERIM^L ONES (take account of possible misidentifications of main vertex or of final particles)

| SAMPLE OF "MONTE-CARLO" N-DECAY EVENTS SATISFYING SELECTION CRITERIA. |
|---|

⇓

| OVERALL EFFICIENCY $\varepsilon$ |
|---|

- **ESTIMATE THE BACKGROUND RATE OF ATMOSPHERIC NEUTRINOS.**

1) CALCULATION OF THE NEUTRINO FLUX :
   ~ 20% - 30% ACCURACY
   Geomagnetic effects ← depend on site latitude
   Solar modulation "

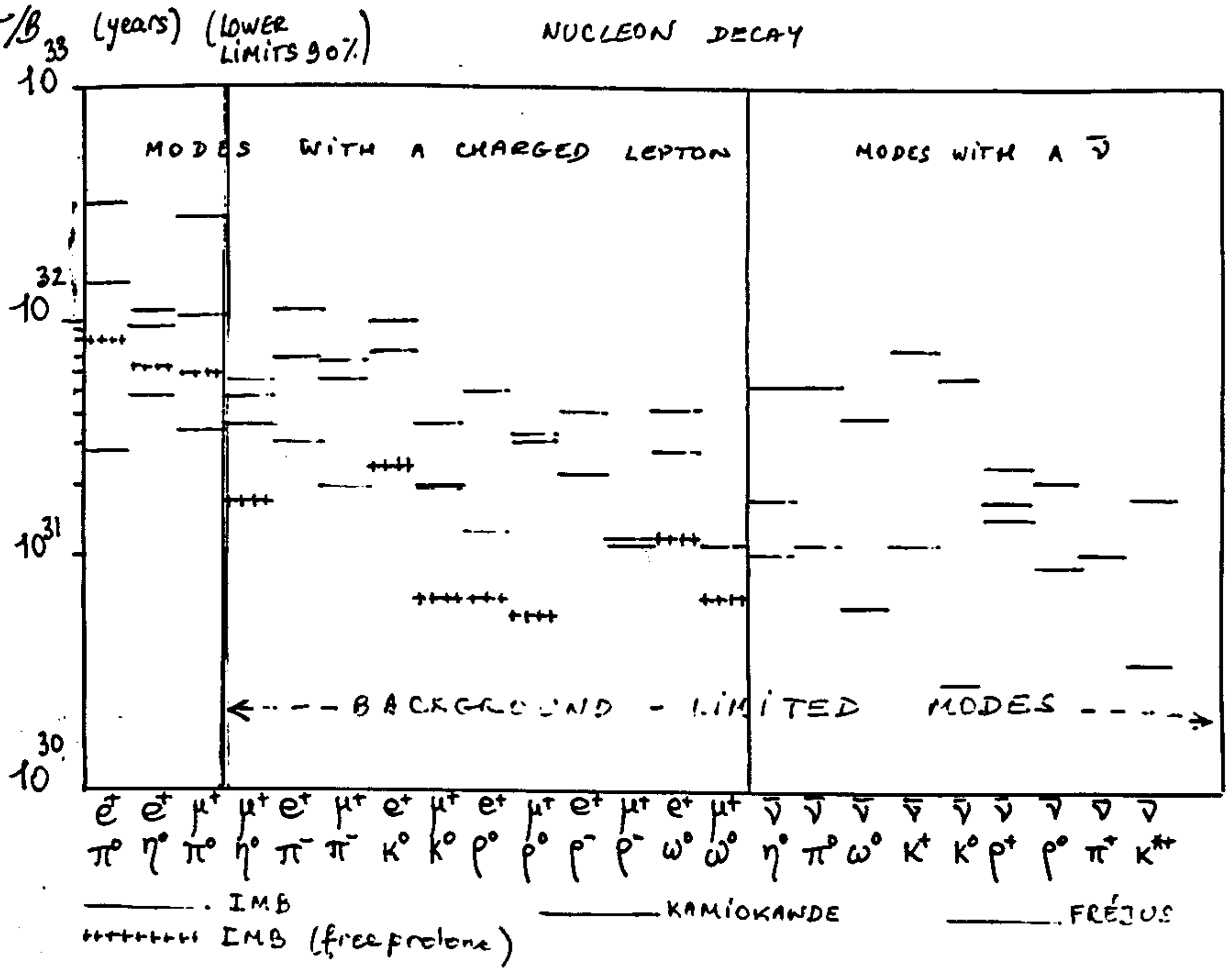
2) TWO POSSIBLE WAYS :

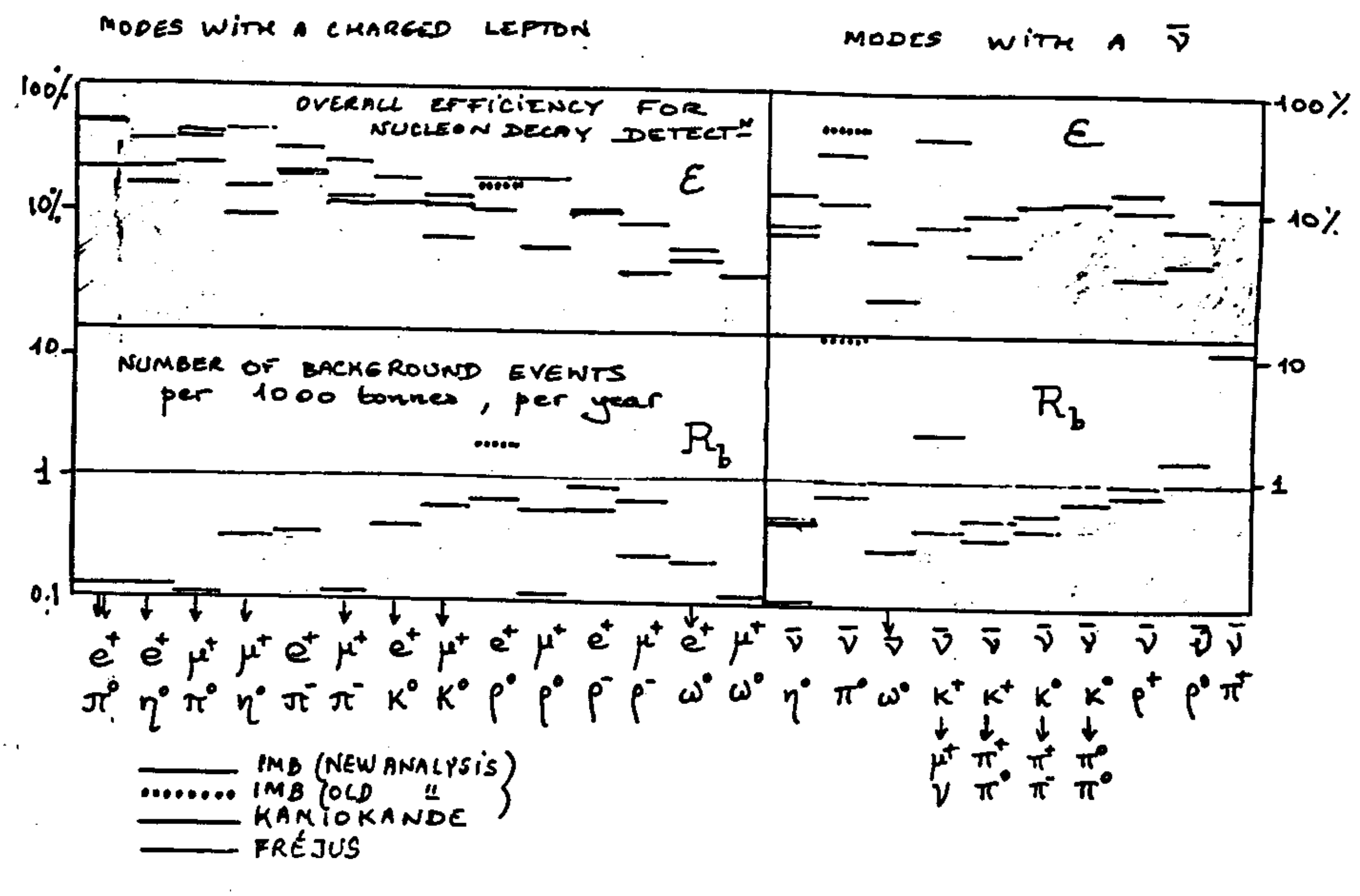
| SIMULATION | DIRECT USE |
|---|---|
| BASED ON ACCELERATOR $\nu$ EXPERIMENTS | OF ACCELERATOR DATA (IF DETECTORS ARE SIMILAR) |

CERN PS / ANL / BNL

| SIMULATION | DIRECT USE |
|---|---|
| • NUCLEAR EFFECTS<br>• SECONDARY INTER^NS<br>• DETECTOR RESPONSE<br>• SCAN AS NUCLEON DECAY CANDIDATES (detected protons interpreted as $\pi/\mu$) | • ANALYZE EVENTS AS N-DECAY CANDIDATES<br>• WEIGHT EVENTS TO TAKE ACCOUNT OF { - DIFF^CE IN SPECTRA; - DETECTOR SIZE & POSITION / BEAM }<br>• CORRECT FOR $\nu_e$'s (very few in acceler^r beams) |
| IMB, KAMIOKANDE, FRÉJUS | NUSEX, FRÉJUS<br>FRÉJUS USED THE AACHEN-PADOVA EXP^T at CERN : 4000 $\nu_\mu$'s, 1000 $\bar{\nu}_\mu$'s<br>EQUIV^T TO 90 kilotonnes x years |

| BACKGROUND RATE PER kilotonne x year $R_B$ |
|---|


τ/B (years) (LOWER LIMITS 90%)
NUCLEON DECAY
MODES WITH A CHARGED LEPTON
MODES WITH A ν̄
BACKGROUND - LIMITED MODES
IMB
IMB (free proton)
KAMIOKANDE
FRÉJUS


MODES WITH A CHARGED LEPTON
MODES WITH A ν̄
OVERALL EFFICIENCY FOR NUCLEON DECAY DETECTN
ε
NUMBER OF BACKGROUND EVENTS per 1000 tonnes, per year
$R_b$
IMB (NEW ANALYSIS)
IMB (OLD ")
KAMIOKANDE
FRÉJUS

## 3. PRESENT RESULTS ON N-DECAY

- BACKGROUND-FREE MODES ($\tau/B$ LIMITS in $10^{32}$ years)

| | $p \to e^+\pi^0$ | $p \to e^+\eta^0$ | $p \to \mu^+\pi^0$ |
|---|---|---|---|
| IMB | > 3.2 | > 1.0 | > 2.7 |
| KAMIOKA | > 1.9 | > 1.1 | > 1.5 |
| FRÉJUS | > 0.5 | > 0.38 | > 0.45 |

$\tau/B$ BEYOND $10^{32}$ years

- OTHER MODES

BACKGROUND & CANDIDATES AT THE LEVEL OF 0.5 ÷ 2 EVT/kilotonne for EFFICIENCIES OF 10 ÷ 20% (CHARGED LEPTON)
5 ÷ 10% (FINAL $\bar{\nu}$)

LIMITS 10 ÷ 30 TIMES LOWER THAN FOR $e^+\pi^0$

e.g. $p \to \bar{\nu} K^+$

KAMIOKA > 3.9 ÷ 6.4 $\times 10^{31}$ years

FRÉJUS > $1.5 \times 10^{31}$ years

PRESENT CANDIDATES : RATES COMPATIBLE WITH BACKGROUND

Only lower limits on $\tau/B$.

e.g. MODES $N \to \ell^+ +$ Meson

| | | | |
|---|---|---|---|
| IMB (New analysis) | 4600 t.yr. | 5 cand. | 1.1 / kt.yr |
| KAMIOKANDE I | 1300 t.yr. | 5 cand. | 3.8 / kt.yr |
| KAMIOKANDE II | 1180 t.yr. | 0 cand. | < 1.9 / kt.yr |
| FRÉJUS | 1400 t.yr. | 2 cand. | 2 / kt.yr (expected Backg. rate) |

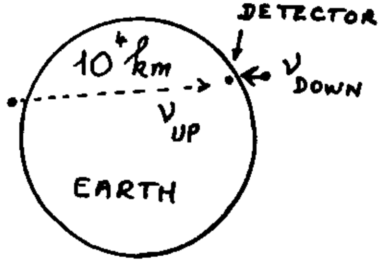
- PRESENT DETECTOR HAVE REACHED A BACKGROUND RATE AT THE LEVEL OF $\sim 1 \div 2 \; 10^{-2}$ OF ATMOSPHERIC $\nu$ INTERACTIONS

- IF A BETTER REJECTION IS ACHIEVED IN FUTURE EXPERIMENTS, THE NEUTRINO BACKGROUND MUST BE KNOWN VERY ACCURATELY. NEUTRINO RUNS AT ACCELERATORS WITH STATISTICS OF $\sim 10^5$ $\nu$ INTERACTIONS WILL BE NEEDED.

# ATMOSPHERIC NEUTRINOS ($\nu, \bar{\nu}$)

BESIDES NUCLEON DECAY BACKGROUND, ...

WHY ARE THEY INTERESTING ?




$$\frac{\nu_e, \bar{\nu}_e}{\nu_\mu, \bar{\nu}_\mu}$$

- PART OF THOSE NEUTRINOS HAVE BEEN PRODUCED $\sim 10^4$ km AWAY
  PROPAGATION TIME $\sim 1/30$ s
  POSSIBILITY TO EXPLORE :
  - $\nu$ OSCILLATIONS
    - in vacuo (Bilenky, Pontecorvo)
    - in matter (Mikheïev, Smirnov, Wolfenstein).
  - $\nu_\mu$ DECAY
- ARE THEY ALL FROM ATMOSPHERIC ORIGIN ?

  Extra-terrestrial $\nu$ events in GeV range?

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COMPARISON WITH MONTE-CARLO CALCULATIONS BASED ON $\nu$ PHYSICS IN GeV RANGE KNOWN FROM ACCELERATOR DATA
(BNL, ANL, CERN-PS $\nu$ exp'ts )

BUT ...

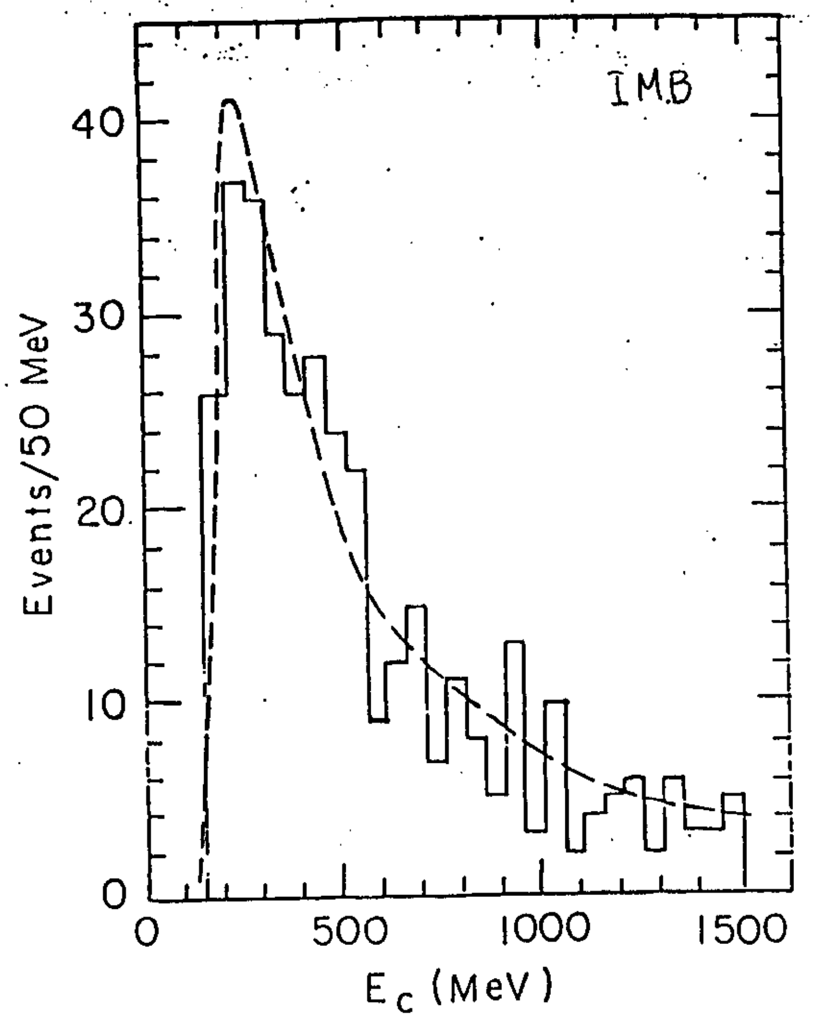
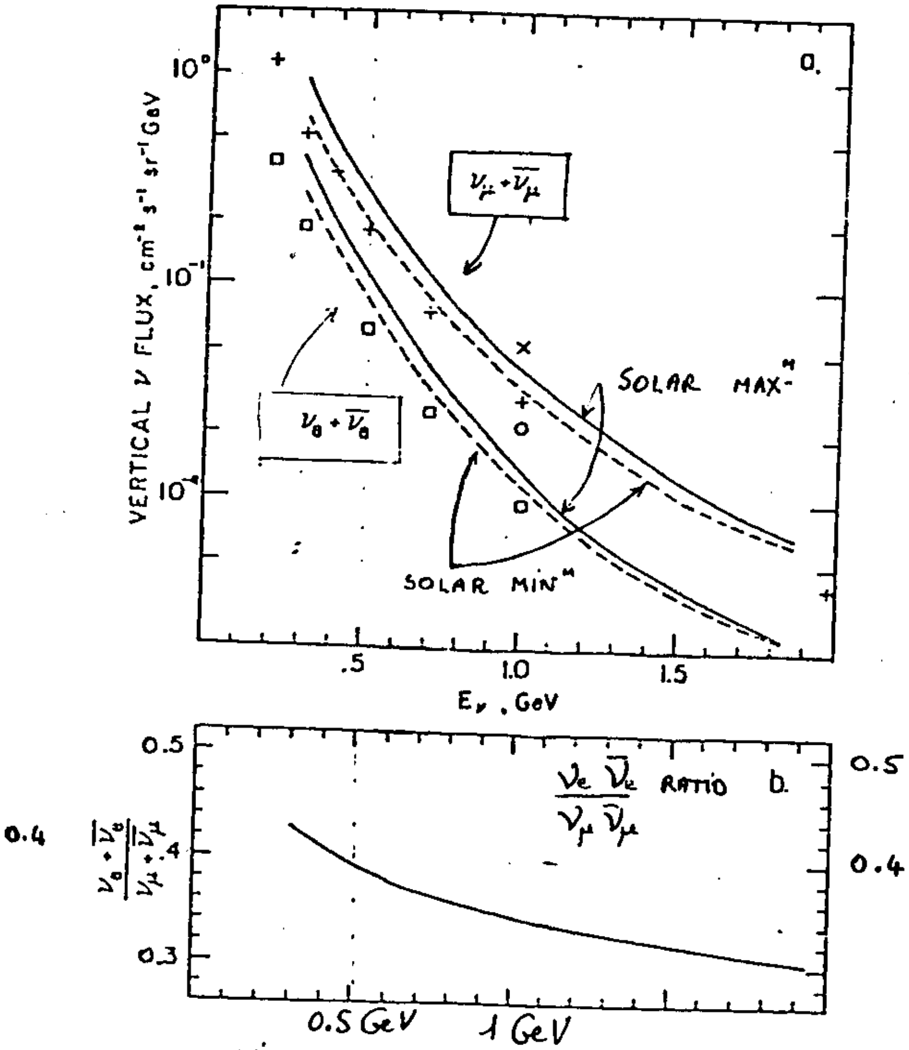



Fig. 10. Comparison between calculated and measured spectrum of contained neutrino interactions in IMB (from Ref. 4).

ATMOSPHERIC NEUTRINOS

FLUX CALCULATIONS

Gaisser & Stanev P.R.L. 51 (1983) 223




WITHOUT GEOMAGNETIC CUT-OFF

... BUT ONE MUST TAKE SEVERAL EFFECTS INTO ACCOUNT BEFORE CLAIMING ANY EXOTIC INTERPRETATION

- FLUXES KNOWN TO ± 20%.
  - PRIMARIES IN SEVERAL GeV RANGE.
  - PARTICLE PRODUCTION AT RATHER LOW ENERGIES.
- $\frac{\nu_e \bar{\nu}_e}{\nu_\mu \bar{\nu}_\mu}$ RATIO LESS SENSITIVE BUT SPECTRUM IS DIFFERENT FOR BOTH SPECIES.

$$\frac{d\phi}{dE_\nu} = \frac{K}{(E_0 + E_\nu)^\gamma} \quad \begin{cases} \gamma(\nu_\mu) = 3.1 \\ \gamma(\nu_e) = 3.4 \end{cases}$$

STILL UNCERTAINTIES ON FLUX RATIO (up to 10%)

- GEOMAGNETIC CUT-OFF IS IMPORTANT AT LOW ENERGY. DEPENDS ON LATITUDE OF PRODUCTION : A DIFFERENT EFFECT FOR DOWNWARD-GOING AND UPWARD-GOING ν'S.

$\begin{cases} 42° \text{ LATITUDE} & \text{CUT-OFF} \quad 1.8\ GeV/c \\ \text{EQUATOR} & \text{CUT-OFF} \quad 17\ GeV/c \end{cases}$

FOR DOWNWARD-GOING PROTONS

FOR $E_\nu < 1$ GeV THIS EFFECT INDUCES ANISOTROPIC ANGULAR DISTRIBUTION

⇓

UP / DOWN ASYMMETRY,

$\frac{\nu\uparrow}{\nu\downarrow}$ from 0.57 → 0.66 ($E_\nu > 200$ MeV IMB SITE) (Gaisser & Stanev 83)

$\frac{\nu_e}{\nu_\mu}$ RATIO LESS AFFECTED

ONE MUST ALSO TAKE ACCOUNT OF:

- SOLAR MODULATION:

  DUE TO INTERACTION WITH THE SOLAR WIND THE LOW-ENERGY PRIMARY COSMIC RAYS CANNOT PENETRATE INSIDE THE SOLAR CAVITY.

  MAXIMAL SOLAR ACTIVITY ⟹ MINIMAL COSMIC-RAY INTENSITY
  (11 years cycle) + LAG ~ 1 year

  THIS AFFECTS LOW ENERGY FLUX: 5 ÷ 10% BELOW 1 GeV

- DETECTOR RESPONSE:

  Threshold: e.g. 165 MeV/c $\mu$'s for KAMIOKA II

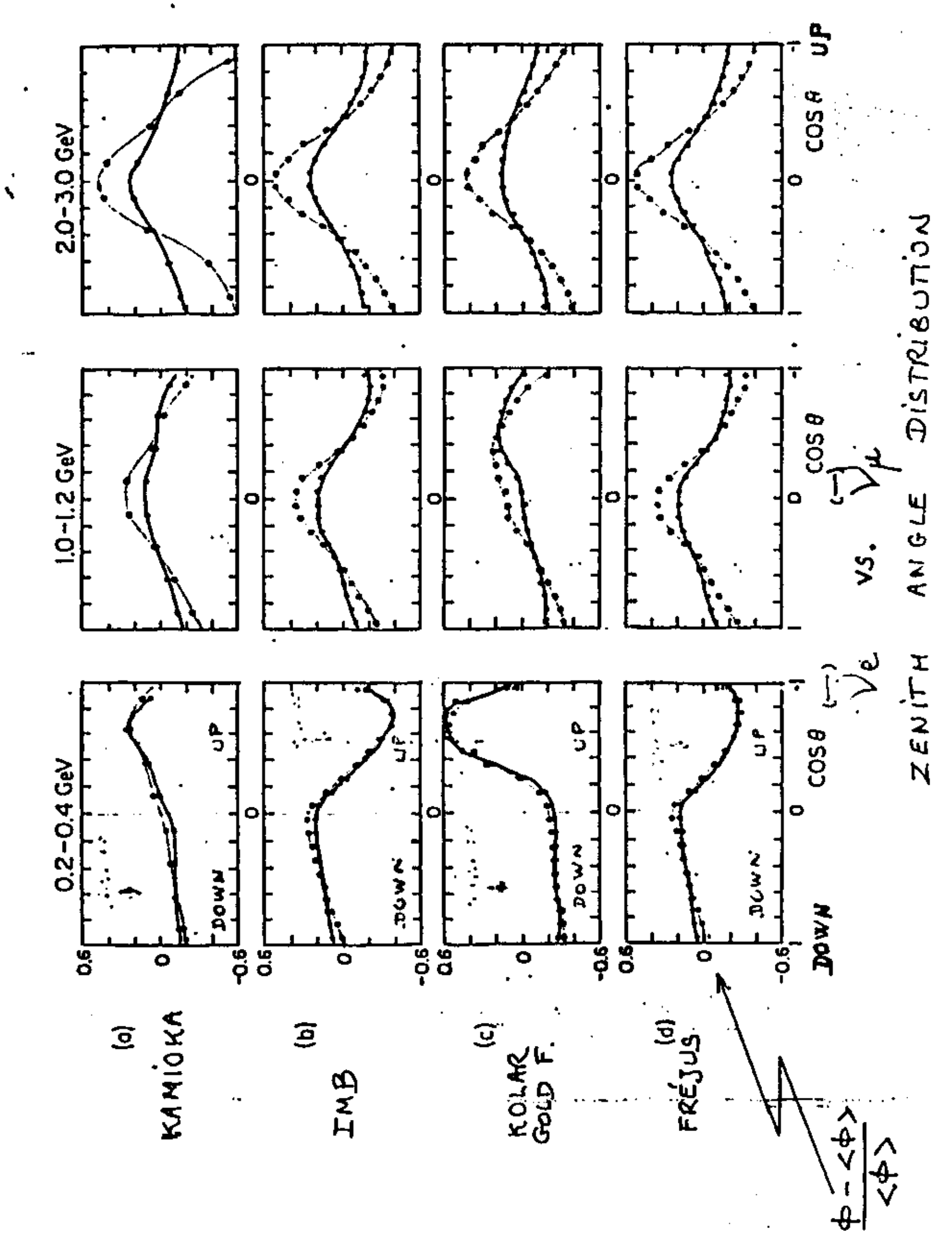
  Trigger efficiency: 200 MeV/c for <u>single</u> $\mu$'s for FRÉJUS.

  Event identification:

  1-RING EVENT IN CHERENKOV (NON-SHOWERING)

  MAY CORRESPOND TO A 2-PRONG EVENT ($\mu$ + p) IN A TRACKING CALORIMETER (p being lost below 1 GeV/c in CHERENKOV DETECTORS)

"VISIBLE" ENERGY ≠ TRUE ENERGY OF $\nu\bar{\nu}$



SEARCHES FOR $\nu_\mu$ DECAY
OR FOR NEUTRINO OSCILLATIONS
WITH ATMOSPHERIC NEUTRINOS

- $\nu_\mu$ DECAY (ANY FINAL STATE)

  IF $\frac{p_\nu}{m_\nu} \cdot c\tau_\nu \sim 10^7\,m$

  THE EXPECTED ANGULAR DISTRIBUTION WILL BE AFFECTED. THIS REQUIRES $\left(\frac{\tau}{m}\right)_{\nu_\mu} \sim 3.10^{-5}\,s/Me$

  EXPERIMENTALLY, $\nu$ ENERGY IS NEEDED. USE FULLY CONTAINED EVENTS.

  { I.M.B. Single $\mu$'s $\left(\frac{\tau}{m}\right)_{\nu_\mu} \gtrsim 10^{-4}\,s/Me$
  { FRÉJUS $0.3\,GeV < E_{\nu_\mu} < 2\,GeV$ $\left(\frac{\tau}{m}\right)_{\nu_\mu} \gtrsim 3.3\,10^{-5}\,s/MeV$

  LIMITS ARE NOT CONSTRAINING, BUT THEY ARE INDEPENDENT OF THE DECAY MODE.

- $\nu_\mu \rightleftarrows \nu_{e,\tau}$ OSCILLATIONS

  OSCILLATIONS "IN VACUO".

  $$P(\nu_\mu \to \nu_e) = \frac{1}{4} \sin^2 2\theta \cdot \sin^2 \frac{\pi D}{\lambda_v}$$
  2 FLAVOURS

  $\theta$ = Cabibbo-like mixing angle
  D = Source-Detector distance
  $\lambda_v$ = Oscillation length in vacuo

  $$\underset{(km)}{\lambda_v} = 2.5 \frac{E_\nu\,(GeV)}{\Delta m^2\,(eV/c^2)^2}$$

OSCILLATIONS IN MATTER (Mikheiev, Smirnov, Wolfenstein or MSW effect).

- IN MATTER (containing $e^-$'s) $\nu_e$'s BEHAVE DIFFERENTLY FROM $\nu_\mu$'s or $\nu_\tau$'s.

OSCILLATION AMPLITUDE IS ENHANCED

$$\sin^2 2\theta \to \frac{\sin^2 2\theta}{1 + \left(\frac{\lambda_v}{\lambda_0}\right)^2 - 2\frac{\lambda_v}{\lambda_0}\cos\theta}$$

WITH $\lambda_0$, CHARACTERISTICS OF MATTER:

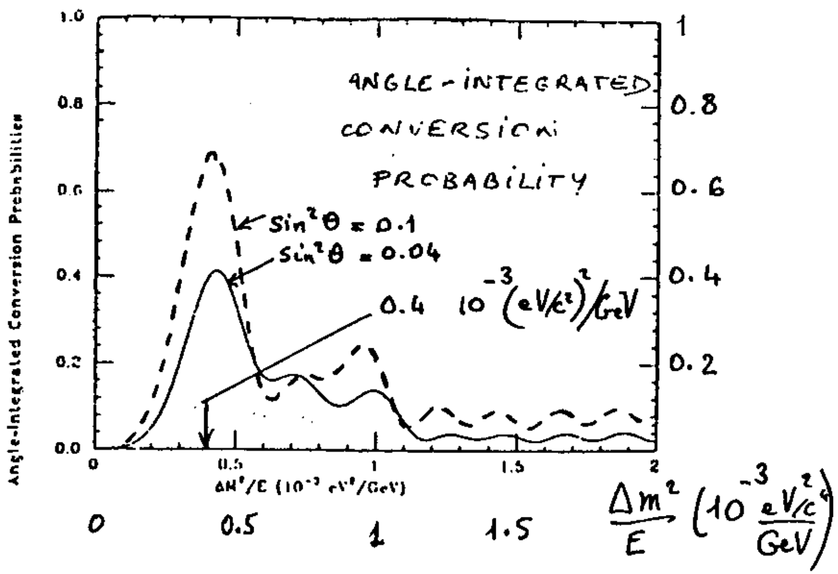
$$\lambda_0 = \frac{1.63\,10^7\,m}{\left(\frac{Z}{A}\right)\rho\,g/cm^3}$$

AT 'RESONANCE': $\lambda_v \approx \lambda_0 \sim 0.9 \div 1.8\,R_\oplus$ FOR EARTH

SINCE $\lambda_v = 2.5\,km. \frac{E\,(GeV)}{\Delta m^2\,(eV/c^2)^2}$,

ONE PREDICTS MAXIMAL EFFECT IF

$$\Delta m^2/E_\nu \sim 3\;10^{-4}\,(eV/c^2)^2/GeV$$



SEARCH FOR NEUTRINO OSCILLATIONS
WITH ATMOSPHERIC NEUTRINOS
EXPERIMENTAL RESULTS

- ZENITH ANGLE DISTRIBUTION OR UP/DOWN ASYMMETRY

  WARNING: GEOMAGNETIC EFFECTS MUST BE TAKEN INTO ACCOUNT and accurately calculated.

  EXPERIMENTS MEASURE THE "VISIBLE" MOMENTUM DIRECTION (LEPTON DIR. AT LOW ENERGY).

  ANGULAR DISTRIBUTIONS ARE COMPATIBLE WITH EXPECTATIONS (FOR THE SHAPE at least

  IMB result: $\nu_e$ CANDIDATES, VISIBLE ENERGY $\leq$ 350 MeV
  LOOK AT A POSSIBLE EXCESS OF UPWARD GOING $\nu_e$'s DUE TO $\nu_\mu$ CONVERSION
  (14 "UPWARD" $\nu_e$'s)
  Conversion rate < 0.55 (90%)
  but many assumptions ($\nu_\mu/\nu_e$; $\bar{\nu}_e/\nu_e$; UP/DOWN)

- $\dfrac{\nu_e \bar{\nu}_e}{\nu_\mu \bar{\nu}_\mu}$ RATIO

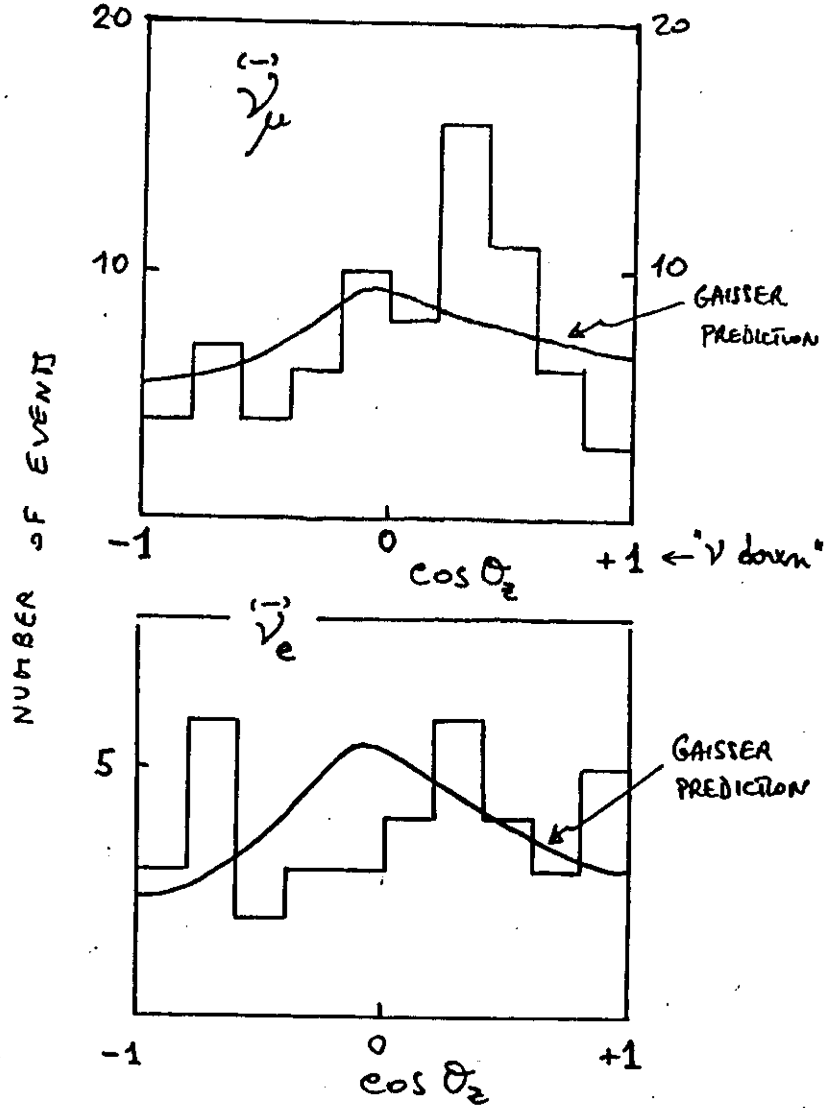
  THE KAMIOKANDE EFFECT
  LACK OF $\nu_\mu$



FULLY CONTAINED + VERTEX ONLY CONTAINED EVENTS

($P \geq 0.3$ GeV/c)

AZIMUTHAL DISTRIBUTIONS



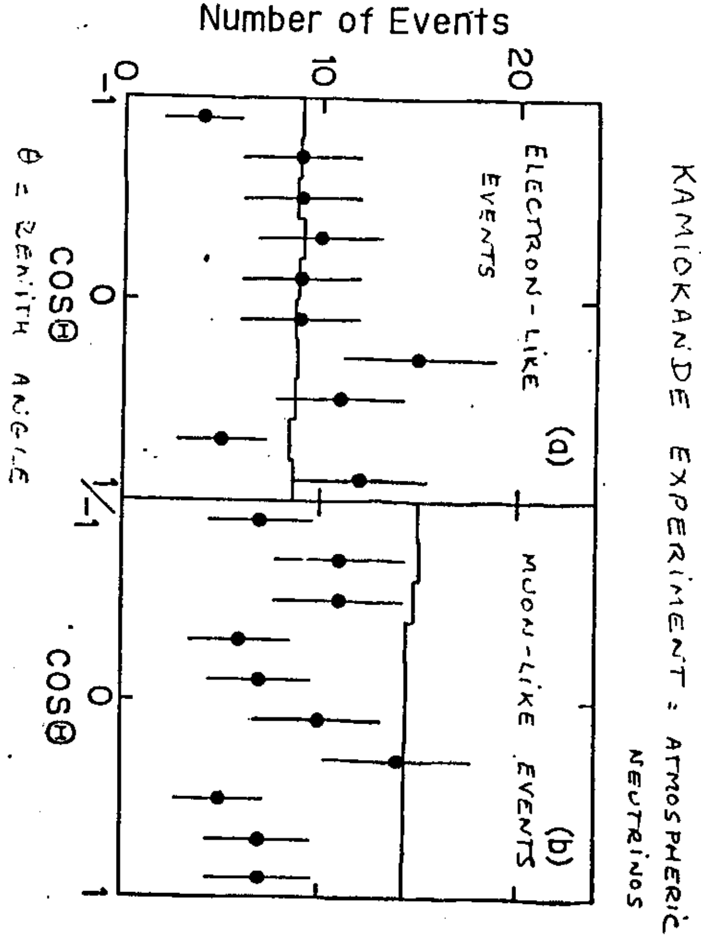



Fig. 2

# $\nu_e \bar{\nu}_e$ / $\nu_\mu \bar{\nu}_\mu$

## AND THE KAMIOKANDE EFFECT - - -

KAMIOKANDE EXPERIMENT (Y. Totsuka ; Aix-LES-BAINS '89)

KAMIOKANDE I : 1.3 } 2.87 kilotonnes x years
KAMIOKANDE II : 1.57 }

FULLY CONTAINED EVTS ; SINGLE RING : 178

$\mu$-LIKE ($P_\mu$ > 205 MeV/c) 85

e-LIKE ($P_e$ > 100 MeV/c) 93

| RATIOS | e-LIKE | $\mu$-LIKE | e-LIKE / $\mu$-LIKE |
|---|---|---|---|
| EXPL DATA / MONTE-CARLO | 1.05 ± 0.11 | 0.59 ± 0.06 | 1.78 ± 0.26 (3 σ effect) |

* ERRORS ARE STATISTICAL

AVOID UNCERTAINTIES IN FLUX NORMALIZN

SIMILARLY $\frac{\text{EVTS 1 RING} + \mu\text{ DECAY (EXPL DATA)}}{\text{EVTS 1 RING} + \mu\text{ DECAY (MONTE-C.)}} = 0.72 \pm 0.1$ 2.5 σ

EFFECT LOOKS MORE IMPORTANT BELOW $p_{vis} \sim 700$ MeV/c

$\mu$-DETECTION EFFICIENCY ?

IDENTIFICATION e vs $\mu$ ?

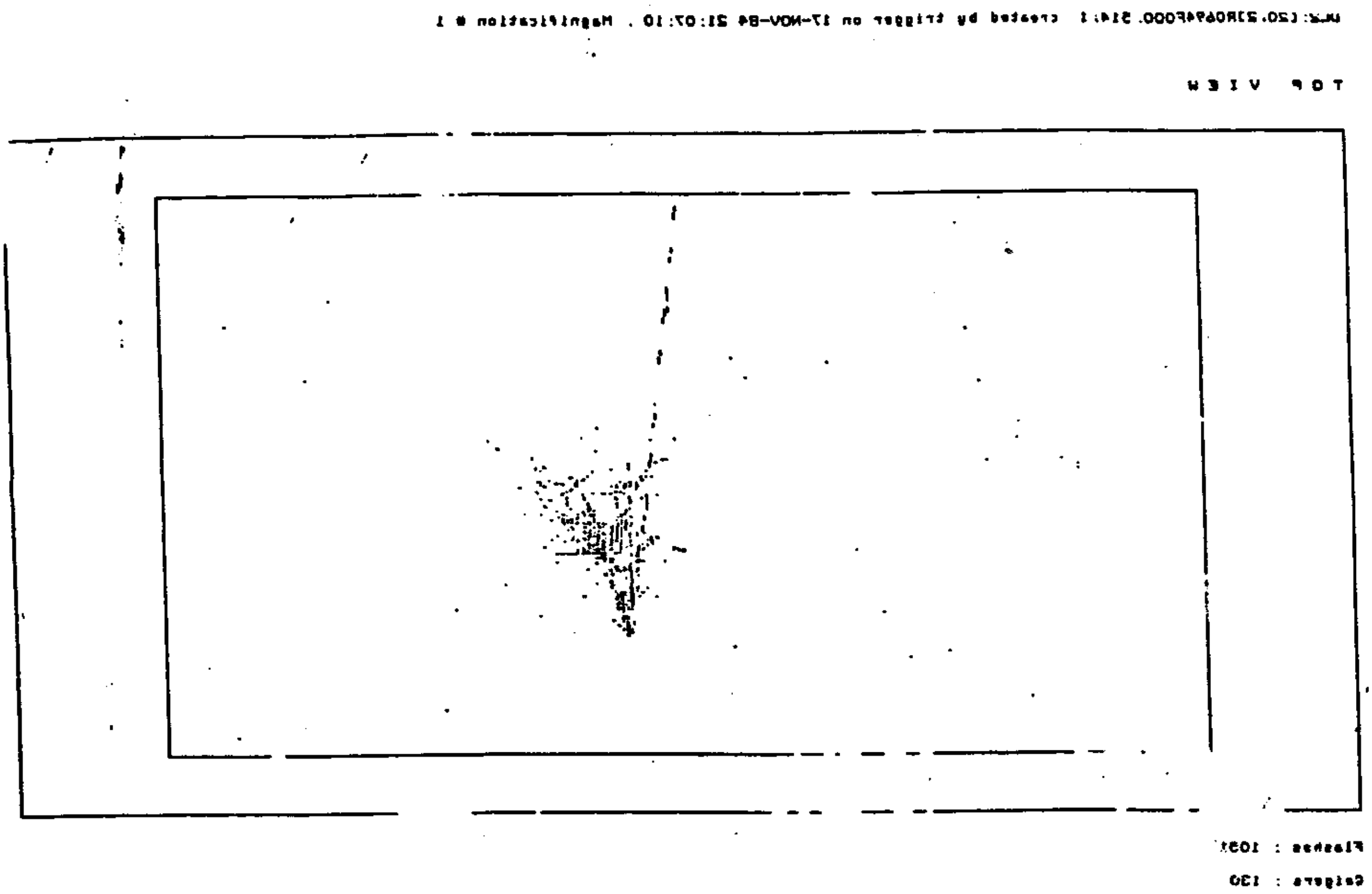
CLAIM MISIDENTIFN PROBY 2.2 ± 0.9 % KAM. I
integrated over ν spectrum 1.4 ± 0.7 % KAM. II

IMB EXPERIMENT (J. Vander Velde ; Aix-LES-BAINS '89)

IMB III (PRELIMINARY)

171 FULLY CONTAINED EVENTS

$\frac{\text{FRACTION OF EVTS WITH } \mu\text{ DECAY (EXPL DATA)}}{\text{FRACTION OF EVTS WITH } \mu\text{ DECAY (MONTE-CARLO)}} = 0.88 \pm 0.11$ STATISTICAL



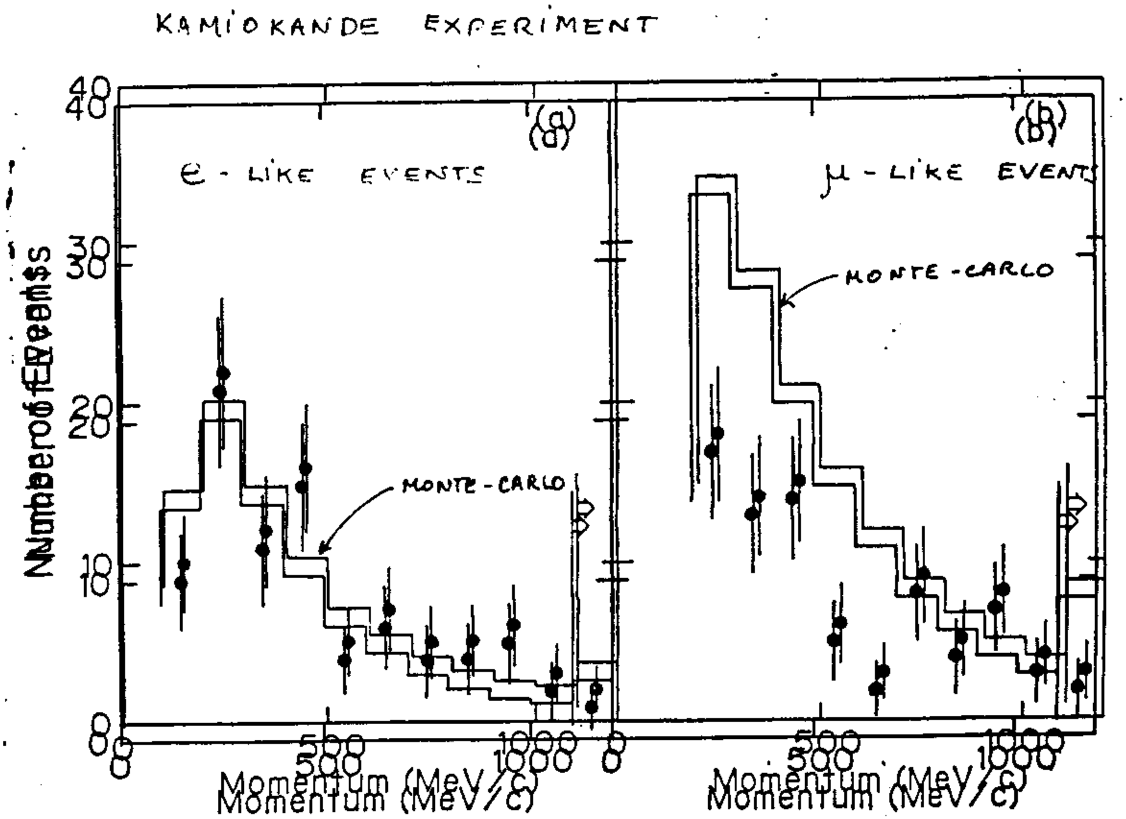

KAMIOKANDE EXPERIMENT
(a)
e - LIKE EVENTS
MONTE - CARLO
(b)
μ - LIKE EVENTS
MONTE - CARLO
Number of Events
0
10
20
30
40
0
500
1000
Momentum (MeV/c)
Momentum (MeV/c)

Fig 11

# $\nu_e \bar{\nu}_e / \nu_\mu \bar{\nu}_\mu$ RATIO

FRÉJUS EXPERIMENT (C. Longuemare, Aix-les-Bains)
(PRELIMINARY)

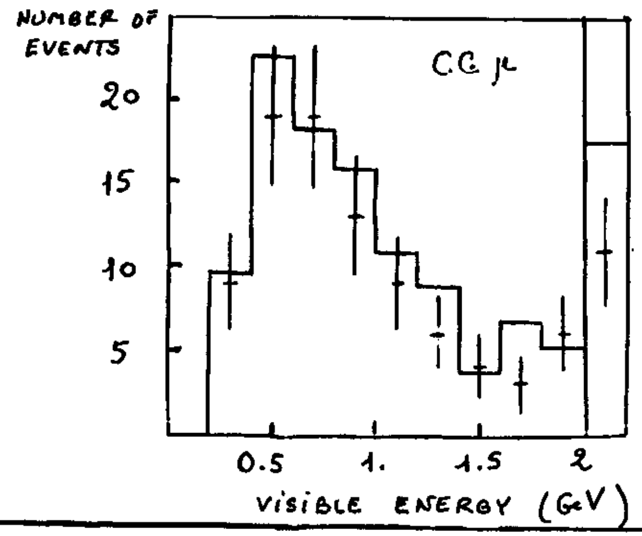
1.3 kilotonnes x year

- FULLY CONTAINED (117) + VERTEX CONTAINED ([illegible]) EVENTS : 165
- LEPTON IDENTIFICATION : 3 categories
  - "C.C. e" : ELECTROMAGN. SHOWER LINKED TO THE VERTEX AND $E_{SHOWER} > 200$ MeV — 47 events
  - "C.C. μ" : LONGEST TRACK LEAVES OR STOPS AND LENGTH > 50 cm ($P_\mu > 200$ MeV/c) — [illegible] events
  - "N.C." : OTHER CONTAINED EVENTS — 49 events

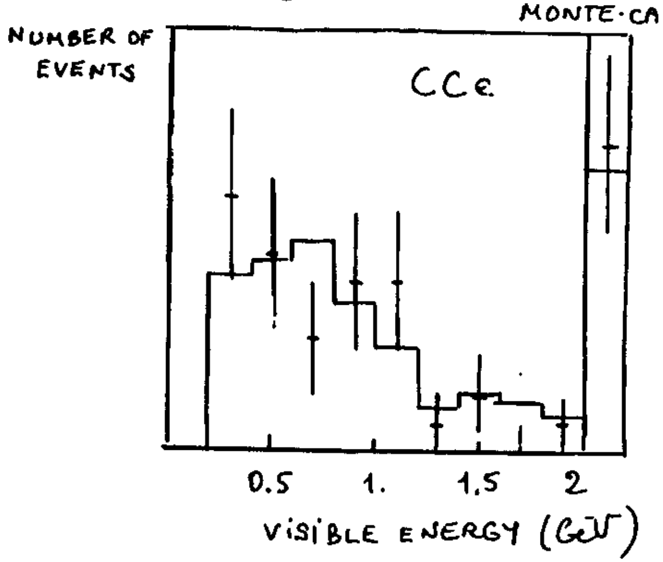
| "CC e" / "CC μ" RATIOS | DATA | MONTE-CARLO | DATA / MONTE-CARLO |
|---|---|---|---|
| ALL EVENTS | 0.47 ± 0.05 | 0.39 ± 0.03 | 1.21 ± 0.22 |
| FULLY CONTAINED EVENTS | 0.82 ± 0.16 | 0.58 ± 0.06 | 1.41 ± 0.31 |
| EVENTS WITH $E_{vis} < 700$ MeV | 0.40 ± 0.12 | 0.43 ± 0.06 | 0.93 ± 0.31 |

## FRÉJUS RESULTS (PRELIMINARY)

ALL "CCμ" EVENTS — DATA : 89, MONTE-CARLO : 119




ALL "CCe" EVENTS — DATA : 47, MONTE-CARLO : 46.2



IS THERE AN ANOMALOUS LACK OF $\nu_\mu$ ($\bar{\nu}_\mu$) IN ATMOSPHERIC NEUTRINOS ?

- KAMIOKANDE (I + II) FINDS AN EFFECT.
  AUTHORS CANNOT EXPLAIN IT BY EXPERIM^L BIASES (DETECTION / IDENTIFIC^N EFFICIENCIES)
  - EFFECT SEEMS MORE IMPORTANT AT LOW VISIBLE MOMENTA ($p_{vis}$ < 700 MeV/c).
  - NO EXOTIC ANGULAR DISTRIBUTION.

  IF $\nu$ OSCILL^N IS INVOKED, IT SHOULD NOT AFFECT MORE UPWARD-GOING THAN DOWNWARD-GOING $\nu$'s ($\neq$ OSCILL^N IN THE EARTH ...)

- IMB AND FRÉJUS HAVE DATA COMPATIBLE WITH CONVENTIONAL EXPECTATIONS
  (EVEN IN THE RANGE $p_{vis} < 700$ MeV/c ; FRÉJUS)
  BUT CANNOT RULE OUT THE KAMIOKANDE RESULT

- FOR THE FUTURE :
  AN ACCURATE SEARCH FOR $\nu$ OSCILLATIONS IN ATMOSPHERIC $\nu$'s WILL NEED $\sim$ 1000 EVENTS
  (cf SUPERKAMIOKA)
  AND A GOOD ANGULAR RESOL^N.
  (cf ICARUS)

## EXTRA-TERRESTRIAL NEUTRINOS IN GeV RANGE ?

2 POSSIBLE ANALYSES :

- "VERTEX-CONTAINED" EVENTS.
  $\nu_e$ ($\bar{\nu}_e$) AS WELL AS $\nu_\mu$ ($\bar{\nu}_\mu$)
  VERTEX MUST LIE WITHIN FIDUCIAL VOLUME.
  * WELL ADAPTED TO TRACKING CALORIM^RS (High spatial resolution & angular resolution)

- THROUGH-GOING MUONS PRODUCED BY $\nu_\mu$ INTERACTIONS IN THE ROCK
  $\nu_\mu$ ($\bar{\nu}_\mu$) ONLY
  * VERY LARGE ZENITH ANGLE OR UPWARD-GOING $\mu$'s TO DISCRIMINATE AGAINST ATMOSPHERIC (DOWNWARD-GOING) MUONS
  * WELL ADAPTED TO DETECTORS WITH TIME-OF-FLIGHT MEAS^T & TO CHERENKOV DETECTORS
  * INTERESTING AT HIGH ENERGY SINCE ($\nu$, $\mu$) ANGLE SMALLER AND LARGE EFFECTIVE TARGET MASS.

WHEN IS IT PREFERABLE TO USE VERTEX - CONTAINED EVENTS ?

FOR LOWER ENERGIES :

$E_\mu \lesssim 5\,GeV$ FOR PRESENT DETECTORS

$E_\nu \lesssim 10\,GeV$

STATISTICS + ANGULAR RESOLUTION

- "DARK MATTER" PARTICLES (MASS $M_x$) TRAPPED IN THE SUN CAN BE A SOURCE OF $\nu \bar{\nu}$'s : $\langle E_\nu \rangle \sim \frac{M_x}{3}$

  ENERGY RANGE : SEVERAL GeV ÷ SEVERAL × 10 GeV is POSSIBLE.

- EXTRATERRESTRIAL SOURCE WITH POWER-LAW SPECTRUM :

$$\frac{d\phi_\nu}{dE_\nu} = \frac{K}{E_\nu^{\gamma}} \leftarrow \text{SPECTRAL INDEX}$$

Ratio $\frac{\text{UPW}^{D}\text{ GOING } \mu\text{'s}}{\text{VERTEX - CONTAINED EVTS}} > 1$

IF SPECTRAL INDEX $\gamma \lesssim 3.5$ (FRÉJUS DETECTOR)

SIMILAR TO ATMOSPH$^{c}$ $\nu$'s

HIGH - ENERGY SOURCES (100 GeV → multi TeV) ARE STUDIED USING THROUGH - GOING $\mu$'s.

## IS THE SUN A SOURCE OF HIGH ENERGY NEUTRINOS ?

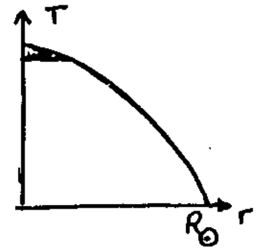
DARK MATTER SCENARIO TO SOLVE THE SOLAR $\nu$ PUZZLE (Faulkner-Gilliland)

- COLD DARK MATTER (Massive particles)
- CAN BE GRAVITATIONALLY ATTRACTED BY THE SUN, THEN TRAPPED (Scattering) IN SOLAR CORE, THEN THERMALIZED

  No evaporation if $M \gtrsim 4\,GeV/c^2$
- WEAKLY INTERACTING PARTICLES

  Mean free path ~ a few orbits

  $\sigma \sim 10^{-37}\,cm^2 - 10^{-34}\,cm^2$




MAKE THE TEMPERATURE UNIFORM FOR $R \lesssim 0.1\,R_\odot$

DECREASE RATE OF $^{8}B - \nu_\odot$

- BALANCE BETWEEN { TRAPPING OF NEW MASSIVE PARTICLES / ANNIHILATION OF 2 SUCH PARTICLES }

WEAKLY INTERACTING MASSIVE PARTICLES (WIMP's)

ANNIHILATE → HEAVY FLAVOURS → $\nu \bar{\nu}$ PAIRS (GeV range)

$\overset{(-)}{\nu}_e$ as well as $\overset{(-)}{\nu}_\mu$

CANDIDATES FOR WIMP's :

SUSY PARTICLES : photino

MASSIVE NEUTRINOS : DIRAC OR MAJORANA

# WIMP'S IN THE SUN ?

$\nu(\bar{\nu})$ IN GeV ENERGY RANGE MIGHT SHOW UP ABOVE THE ATMOSPHERIC $\nu$ BACKGROUND.

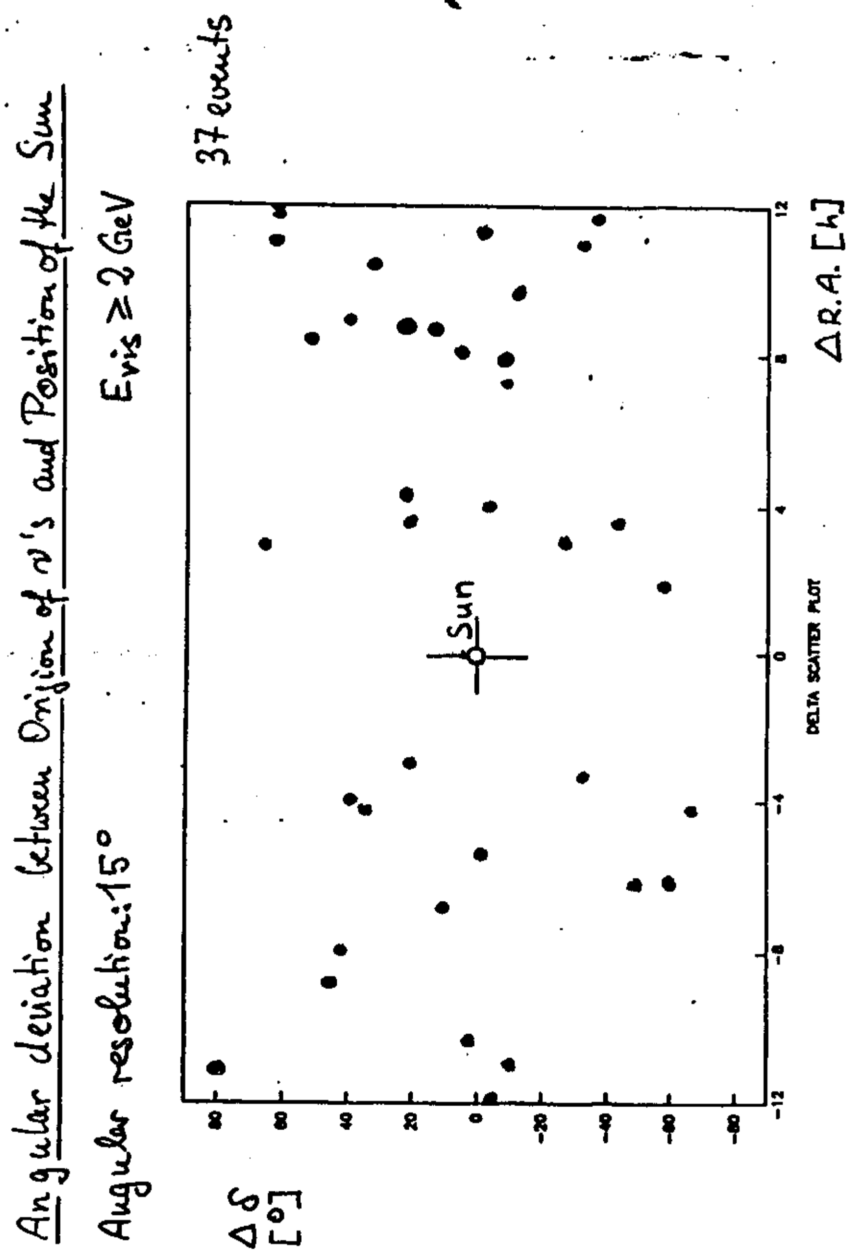
ANGULAR RESOLUTION ON $\nu$ DIRECTION IS ESSENTIAL FOR BACKGROUND REJECTION

$\Sigma \vec{P_i}$

- IMB : USE ONLY "SINGLE PRONG" CONTAINED EVENTS.
- FRÉJUS : USE EVENTS AT HIGHER ENERGIES (smaller angle between $\mu$ and $\nu$)

| Experiment | ANGULAR ERROR ON $\nu(\bar{\nu})$ | EXCESS FROM SUN event /1000 t-years |
|---|---|---|
| IMB | 30° | < 4.9 |
| FRÉJUS | 15° $E_{vis} > 2$ GeV | < 1.6 based on 37 evts |

BUT LIMITS THAT CAN BE SET ON WIMP-MASSES ARE MODEL-DEPENDENT



# CONTAINED EVENTS IN GeV RANGE
## SUMMARY & PERSPECTIVES.

- **NUCLEON DECAY**
  - BACKGROUND-FREE WITH PRESENT DETECTORS

    $p \rightarrow e^+ \pi^0 \quad p \rightarrow \mu^+ \pi^0 \quad p \rightarrow e^+ \eta^0 \; (\hookrightarrow \gamma\gamma)$

    LIMITS BEYOND $10^{32}$ years

    CAN BE PUSHED UP WITH LARGER MASSES → SUPERKAMIOKANDE CHERENKOV (32 kilotonnes)

  - OTHER MODES:

    LIMITS $\sim 10^{31}$ years

    BETTER REJECTION OF ATMOSPH$^c$ $\nu$'s NEEDED (AT PRESENT, 1÷2% OF ATM$^c$ $\nu$'s)

    CHERENKOV : 40% LIGHT COLLECTED IN SUPERKAMIOKANDE.

    ICARUS : $\frac{dE}{dx}$, very fine spatial res$^n$

    BACKGROUND CALIBRATION : $\nu$ EXPERIMENTS AT ACCELERATORS WITH HIGH STATISTICS ($10^5$ events)

- **ATMOSPHERIC NEUTRINOS**
  - NO COMPELLING EVIDENCE OF ANOMALOUS LACK OF $\nu_\mu$ (FRÉJUS, IMB), BUT KAMIOKA FINDS A $3\sigma$-EFFECT.
  - FUTURE DETECTORS → 10 × STATISTICS MORE ADAPTED TO SEARCH FOR $\nu$ OSCILLATION IN THE EARTH.